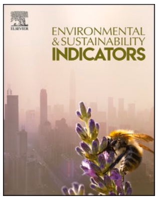
Environmental and Sustainability Indicators 16 (2022) 100205

Contents lists available at ScienceDirect

Environmental and Sustainability Indicators

journal homepage: www.sciencedirect.com/journal/environmental-and-sustainability-indicators



Trade-offs and synergies in agricultural landscapes: A study on soil-related ecosystem services in the Brazilian Atlantic rainforest

Gabriel Spínola Garcia Távora [a], Ana Paula Dias Turetta [b,c,*], Antonio Soares da Silva [a], Bruno Francisco Teixeira Simões [d], Udo Nehren [e]

[a] *Department of Physical Geography, Rio de Janeiro State University, Brazil*
[b] *Brazilian Agriculture Research Corporation – Embrapa Soils. Rio de Janeiro, RJ, Brazil*
[c] *Program of Territorial Development and Public Policy, Federal Rural University of Rio de Janeiro, Brazil*
[d] *Department of Mathematics and Statistics Center of Exact Sciences and Technology (CCET), Federal University of the State of Rio de Janeiro, Brazil*
[e] *Institute for Technology and Resources Management in the Tropic and Subtropics (ITT), University of Applied Sciences TH Köln, Brazil*

ARTICLE INFO

Keywords:
Land use
Sustainable agriculture
Soil properties
Nutrients regulation
Soil carbon

ABSTRACT

In recent years, numerous studies have addressed the theme of ecosystem services as a means of promoting the protection, sustainable use, and recovery of ecosystems. However, these studies mainly have not been fully evaluated the soil-related ecosystem services and the different land uses and land cover. Taking this as a background, our main goal is to evaluate the trade-offs and synergies in the provision of soil-related ecosystem services in a watershed located in the highlands of Rio de Janeiro state - Brazil. To do so, we evaluated soil properties as indicators. In addition, statistical methods were applied to analyze any significant differences between the variables for the different land use classes, and Spearman correlation matrix to evaluate the trade-offs and synergies. No significant difference ($p > 0.05$) was found between the different land uses for soil fertility parameters, bulk density, and organic matter; however, the trade-offs analysis demonstrated the impact of anthropogenic actions in ecosystem services provision. The methodology showed potential to be used in different studies that focus on ecosystem services evaluations.

1. Introduction

In recent years the number of studies investigating the effects of agriculture management on ecosystem services (ES) provision have increased. These studies usually analyze the dynamics between the ES provision and their impacts on different land uses and land covers (Morán-Ordónez et al., 2019; Baude et al., 2019; Milheiras and Mace et al., 2019).

Although these studies mention soils as support for regulation services such as flood mitigation, nutrient filtering, and waste treatment, they do not explicitly identify their service's delivery role (Dominati et al., 2010). Furthermore, the soil and its properties that contribute to service delivery are not directly assessed in most studies (Dominati, 2013).

Soil properties often change slowly due to land use and management practices and for that reason, it can be more difficult to detect changes in ES provision. Therefore, to select a set of sensitive soil indicators that reflect the dynamics of changes in the soil functions and can be used to assess the ES provision remains a challenge (Bünemann et al., 2018). Additionally, the lack of soil data is another factor to impose more difficulties in this scenario.

One strategy to overcome the lack of soil data, common in the literature, is to consider the proxy approach, that means of using certain environmental variables and soil properties to quantify soil ecosystem services indirectly (Ellili-Baraoui et al., 2021). One of the most used proxies are land use and land cover data, which have been useful in regions where soil data are scarce (Vrebos et al., 2015; Adhikari and Hartemink, 2016). According to FAO (2016), land cover is the bio-physical features that cover earth's surface, meanwhile, the land use is the materialization of human occupations and activities over the geographic space.

However, considering the multiple ES provided by agricultural landscapes, for improving decision making and their sustainable use, it is important to identify and understand the relationships between the ES. These relationships can occur as trade-offs, where the offering of one service increases as the other decreases, or as synergies, where the

---

[*] Corresponding author. Brazilian Agriculture Research Corporation – Embrapa Soils. Rio de Janeiro, RJ, Brazil.
E-mail address: ana.turetta@embrapa.br (A.P.D. Turetta).

https://doi.org/10.1016/j.indic.2022.100205
Received 23 June 2022; Received in revised form 5 September 2022; Accepted 13 September 2022

supply of two services increases or decreases simultaneously (Rodriguez et al., 2006; Dade et al., 2019).

The ES relationships occur as a response to diverse impacts in the system. Bennett et al. (2009) refers to these exogenous or endogenous impacts as drivers, which can be related to human actions and/or natural variability, such as public policies, land use, climate change and technological advances.

70% of the population and 80% of the Brazilian economy are concentrated in the Brazilian Atlantic Forest biome, which has historically suffered with the deforestation process, keeping the biome at a high level of threat and risk (SOS Mata Atlântica, 2022). This critical level of land use change process impacts the ES provision, thus being necessary to develop a methodological framework to assess the ES interlinkages and how different forms of land use may impact their provisioning.

The hypothesis raised in this work is that the preservation of forest fragments in agricultural areas of the Atlantic forest biome as well the adoption of conservative practices can support the ES provisioning, reducing the negative impact of agricultural activity on soil-related ecosystem services (SRES). Hence, this paper aims to evaluate tradeoffs and synergies in the provision of SRES – Carbon Storage, Water Infiltration, Nutrients Regulation and Production – in a typical watershed in the highlands of Rio de Janeiro state, Brazil.

2. Materials and methods

2.1. Study area: The Pito Aceso watershed

The research was developed in the Pito Aceso watershed, which has 500 ha and is located in Bom Jardim's municipality, in the mountains region of Rio de Janeiro State in Southeast Brazil (Fig. 1). Pito Aceso watershed standard rural landscape of Atlantic Forest highlands, characterized by steep relief – the watershed has slope declivity classes ranging from 20%–30% to 60%–70%. – and the prevailing climate is Humid Mesothermal, with high temperatures throughout the year, and the annual rainfall is around 1,400 mm. The July–August is the driest period, while December- March is the rainiest season (Távora and Turetta, 2016). Agriculture and pasture are the primary land use in the watershed. They are located mainly in the Acrisols, Cambisols, and Ferrasols because these soil classes are found in areas with less declivity, which facilitates the soil use and management of these areas by farmers (Chagas et al., 2012; Távora et al., 2013; Távora, 2019).

Thus, the watershed represents a typical rural landscape of Atlantic Forest highlands, because it is a land-use mosaic formed by the interaction of forest ecosystems located in upstream basin areas and the agroecosystems established in the downstream basin areas (Silva et al., 2018). This area is also a "living lab" of studies about the interaction between rural landscape and soil performance, with a vast database that can be accessed by researchers (Chagas et al., 2012; Távora et al., 2013; Távora and Turetta, 2016).

2.2. Soil samples and laboratory analysis

We collected thirty soil samples in March 2011 and July 2016. Fifteen samples were collected each year, seven in pasture areas, five in annual crop areas, and three in perennial crop areas. The collection points were determined by random sampling. It allowed us to uniform coverage of the most significant possible land use (Fig. 1).

Following Dominati et al. (2010) and Dominati (2013) recommendation that the topsoil is most influenced by land use and management activities, we collect the samples in the soil's 0–5 cm layer. Three disturbed and three undisturbed samples were collected at each point. These agriculture areas are under Acrisols, Ferralsols, and Cambisols.

Undisturbed samples were collected using a Kopecky ring (100 cm^3). The deformed samples were collected using a metal shovel and stored in a 1-kilo plastic bag. The soils' physicochemical analyses (granulometric analyzes, bulk density, organic matter, soil fertility) were performed at LAGEFIS /UERJ (Physical Geography Laboratory of the State University of Rio de Janeiro) and at Embrapa Solos, following an appropriate methodology for soil sample analysis (Empresa Brasileira De Pesquisa Agropecuária – EMBRAPA, 1997).

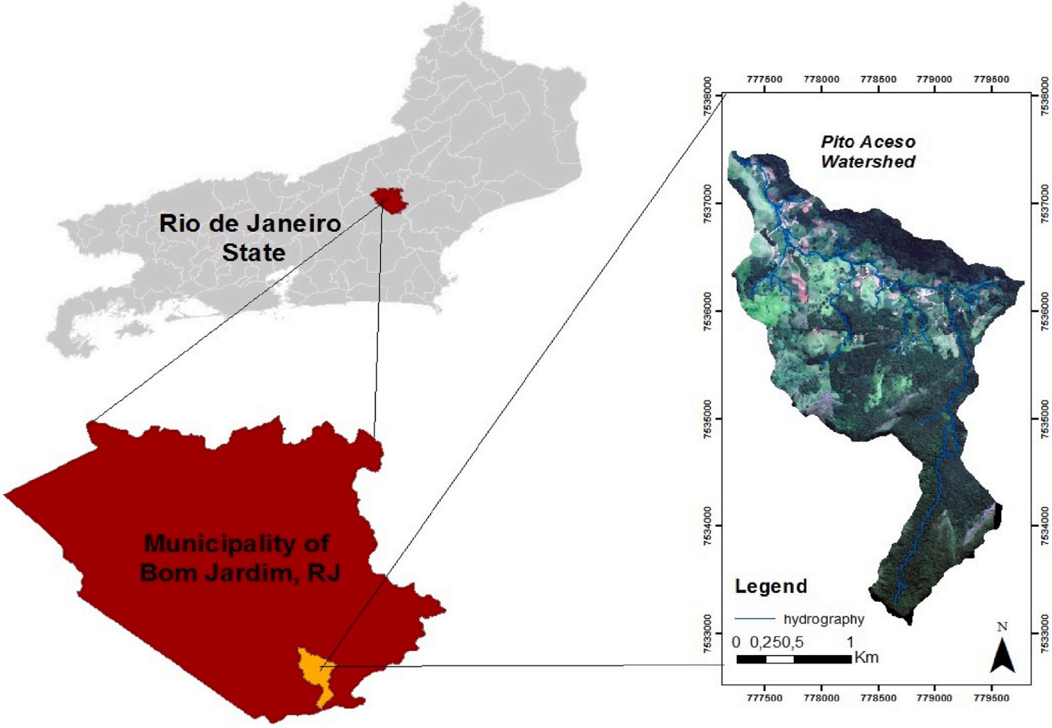


Fig. 1. Pito Aceso watershed (Modified from Prado et al., 2009).

2.3. Ecosystem services analysis

The selection of ecosystem services was based on the study of Dominati et al. (2010). However, we also included the nutrient regulation service, which the above authors did not consider. In total, three regulatory services and one provision service were selected (Table 1).

Dominati (2013) states that it is necessary to investigate soil processes and properties (soil natural capital stock) to understand how soils provide ES. The author adds that the quantitative and qualitative assessment of properties is the easiest way to measure ES. Therefore, indicators related to soil properties used in this research included bulk density, texture, soil organic carbon, and soil fertility. Also, the indicators of agricultural production selected were area produced and total production t /ha (Table 1).

2.3.1. Carbon storage service

The analysis of the carbon storage service (CSS) was based on the methodology employed by Parron et al. (2015) and Rosendo and Rosa (2012). These authors used total soil organic carbon (SOC), bulk density (BD), and sampled soil layer size (*e*) to determine the CSS stock (equation (1)).

$$CSS = SOC*BD*e\_x005F\_x0001\_ \tag{1}$$

2.3.2. Water infiltration service

In this research, we chose to use the degree of soil compaction as a method to evaluate the infiltration service, since the degree of compaction is inversely proportional to the water infiltration rate in the soil, especially in the superficial layer (Drescher et al., 2016).

The degree of compaction was determined from the methodology proposed by Drescher et al. (2016):

$$DC = \frac{BD}{MSD}*100 \tag{2}$$

where DC is the degree of compaction and Bd is the soil density and MSD is the maximum soil density.

The method for determining the degree of compaction is simple but quite efficient to evaluate the infiltration capacity of the soil. Bulk density was determined according to the method developed by Empresa Brasileira De Pesquisa Agropecuária – EMBRAPA (1997). Based on this method, the soil sample is collected with the help of a Kopecky ring. The sample is weighed and taken to an oven at a temperature of 105 °C to dry and, after this procedure, the sample is weighed again. The bulk density will be given by the ratio between the value obtained from the dry sample and the volume of the Kopecky ring. Therefore, it was given by the following formula (equation (3)):

$$BD = a/b \tag{3}$$

where BD is the value for bulk density (g/cm3); a represents the weight value of the dry sample at 105 °C (g) and b is the volume of the Kopecky ring. (cm^3).

While the maximum soil density was based on the work of Drescher et al. (2016), who used the soil pedotransfer functions proposed by Marcolin and Klein (2011) adapted to the reality of Brazilian soils (equation (3)) ($R^2 = 0{,}95$)(equation (4)):

$$MSD = 2,03133855 - (0,00320878 * OM) - (0,00076508 * Clay) \tag{4}$$

where MSD is the maximum soil density, OM is the value of the organic matter in the given area, and Clay is the content rate of Clay in the given area. In the Marcolin and Klein (2011) papers, the authors sought how organic matter and Clay rates affected the soil density. Therefore, the soil pedotransfer functions seek to be an essential tool when it is a lack of information regarding soil analysis.

Table 1

Ecosystems services and indicators.

Soil related Ecosystem services	ES category (MEA, 2005)	Definition	Soil properties/ Indicators
Carbon Storage	Regulatory	Soils' ability to store greenhouse gases	Soil Organic Carbon, bulk density, and Layer Depth
Water Infiltration	Regulatory	The ability of soils to allow infiltration and consequent storage of water within the system	Bulk Density, Porosity, and Degree of Compression and Texture
Nutrients Regulation	Regulatory	Soil's ability to adsorb nutrients and release them to plants	Cation exchange capacity
Production	Provision	Harvested plants used for food. Pasture produced for livestock consumption	Production amount per hectare /year

Source: Adapted from Dominati et al. (2010).

2.4. Nutrient regulation service

We consider that one of the main soils ES is the nutrient regulation service, which is directly related to soil fertility. Soil fertility is an important stock of natural capital because it directly influences plant growth and the macronutrients and micronutrients absorbed by plant roots from soil solution (Ronquim, 2010; Lepsch, 2011; Dominati et al., 2010).

Nutrient retention capacity is one of soils' main properties affecting fertility.

We considered the cation exchange capacity (CEC) to evaluate the nutrient retention capacity (Drobnik et al., 2018). The effective CEC analysis was the sum of cations (Ca^{2+}, Mg^{2+}, K^+, Al^{3+}) resulting from the routine fertility test (Empresa Brasileira De Pesquisa Agropecuária – EMBRAPA, 1997).

2.5. Agricultural production data and forage production data

The agricultural production data were obtained from secondary data produced by the Rio de Janeiro Technical Assistance and Rural Extension Company (EMATER-RJ). These data are part of the Systematic Monitoring of Agricultural Production - ASPA. We collected information regarding perennial and annual crop productions from the municipality of Bom Jardim and the Pito Aceso basin from 2010 to 2016.

According to the information gathered from farmers in the study area during the fieldwork, the pasture areas are mostly cultivated with *Brachiaria decubens cv*. Thus, the estimated forage productivity was determined based on the works of Alvim et al. (1986, 2002), Botrel et al. (2003), and Paciullo et al. (2010).

According to Dias-Filho (2014), there is, on average, a 30% loss of dry matter in pasture areas. Besides, according to the authors (op. cit), overall, a portion of what is available to herds is not consumed either. Thus, it is necessary to determine the efficiency of grazing, which, according to Dias-Filho (2014), is the relationship between *what* is consumed by cattle and the available dry matter. According to the author, grazing efficiency is an index ranging from 80% to 30%, varying with water availability, higher soil fertility, breed, and animal category. Thus, a value of 50% is generally established for grazing efficiency (Dias-Filho, 2014; Martha Junior et al., 2003).

From the amount of dry matter available (ADMA) and grazing efficiency (G), it is possible to estimate the amount of dry matter that may be consumed by the herd (ADMC). This calculation was made using the average yield value of *Brachiaria decumbens cv*. proposed by Alvim et al. (2002), which is 15 tons per hectare, multiplied by 0.7 and 0.5, which represent the amount of dry matter available after loss and how much is consumed by an animal unit, respectively (equation (5)) (Dias-Filho, 2014).

$$ADMC = 15ton/ha*ADMA*G\_x005F\_x0001\_ \tag{5}$$

The estimate for production of each pasture point was determined by multiplying the pasture area of each collection point by the value obtained in the estimated dry matter quantity (ADMC), which was 5,250 kg Ms/ha.

2.6. Statistical analyses

We ran the variance analysis to test whether there was any significant difference between the means of the variables for the different land use classes (Annual, Pasture, and Perennial). At first, the Shapiro-Wilk normality test was performed, with a significance level of 5%. This test was applied to understand if the samples have a normal distribution (Rogerson, 2012). In this study only the variables clay, bulk density, porosity, and degree of compaction follow normal distribution. After confirming the hypothesis test one-way analysis of variance (ANOVA) was performed. This analysis aims to compare whether the differences between the mean levels of the factor are significant. The Tukey test was applied, which considers a level of significance of 5% between means of different land uses.

However, for data sets that rejected the null hypothesis in the normality test, the Kruskal-Wallis non-parametric test was applied. We applied this test to the following parameters: CEC data, basic cations (K+, Mg2+, and Ca2+), exchangeable acidity (Al3+), potential acidity (H+, Al3+), Maximum Soil Density (MSD), Carbon Soil Storage (CSS); Soil Organic Carbon (SOC) and Soil organic matter (SOM). Besides, we did a Dunn test as a complementary analysis based on the Bonferroni method of multiple comparisons (Rogerson, 2012). This test is used for multiple comparisons involving all pairs of treatments. That comparison was made between each of the land use classes to assess which ones had significant differences between their distributions at the 5% level of significance (Bianconi et al., 2008). All analyzes were performed using the software R 3.4.3 (R Core Team, 2019).

The trade-offs and synergies were evaluated based on the work of Dai et al. (2017) and Feng et al. (2017). The Spearman correlation matrix (non-parametric method) was used as the evaluation method. Unlike the data presented by these authors, the variables collected in this research do not follow the normal distribution, which is one of the necessary assumptions to apply the Pearson correlation matrix.

The matrix is formed by correlation coefficients ranging from -1 to 1 and expressing the degree of linear dependence between different pairs of variables. Thus, pairs of ES negatively correlated represent trade-offs, while pairs with positive correlation denote synergy. All analyzes at this stage were performed using software R 3.4.3 (R Core Team, 2019). For this step, the data was also normalized. Normalization aims to remove the differences between the measurement units and make the data on a scale from 0 to 1. Standardization was based on the following equation (equation (6)):

$$ESstd = (ESobs - ESmin) / (ESmax - Emin)\_x005F\_x0001\_ \tag{6}$$

where *ESstd* represents the normalized value, *ESobs* represent the value of an observation, and *ESmin* and *ESmax* represent the minimum and maximum observed value for that ES.

3. Results

The carbon storage services results (Table 2) are the outcome between the interaction of in soil organic matter and bulk density. Meanwhile, the water infiltration services in the surface layer are the resulting degree of compaction (DC), i.e., the outcome of the interaction between organic matter, bulk density, and land use (Drescher et al., 2016). Despite the different land uses and management, only CSS presented a significant difference between annual and perennial crop areas in relation to pasture areas (Table 2).

Table 2
Results of the soil properties.

Land Use	CSS (Mg C ha-1)	SOC (g Kg -1)	BD (Mg m-3)	DC (%)	MSD (mg m-3)	Poro (%)	SOM (%)
Annual Crop	8.21 a	15.35 a	1.07 a	0.52 a	1.92 a	60.51 a	26.46 a
Perennial Crop	7.04 a	12.05 a	1.07 a	0.55 a	1.94 a	58.84 a	20.77 a
Pasture	11.56 b	19.40 a	1.18 a	0.62 a	1.90 a	56.21 a	33.45 a

Source: authors. The values are the median. Means followed by similar letters in each column are not significantly different from one another at 5% level of significance. Carbon Soil Storage (CSS); Soil Organic Carbon (SOC); Bulk Density (BD); Degree of Compaction (GC); Maximum Soil Density (MSD); Porosity (Poro); Soil organic matter (SOM).

Annual and perennial crop areas showed the highest average values of exchangeable basic cation contents (Ca^{2+}, Mg^{2+}, K^{+}). It should be noted that higher Ca^{2+} and Mg^{2+} contents were found when compared to K^{+}. The pasture areas presented higher average values of exchangeable acidity (Al^{3+}) and potential acidity (H^{+}, Al^{3+}). (Table 3).

The statistical analysis indicated no significant difference ($p > 0.05$) in the different land uses for the CEC data, basic cations (K^{+}, Mg^{2+}, and Ca^{2+}), exchangeable acidity (Al3+), potential acidity (H^{+}, Al^{3+}), and organic matter. The statistical analysis also presented a significant difference in phosphorus contents between crop areas and pasture areas. About the clay contents, the results showed there is no significant difference ($p > 0.05$) between the different uses (Table 3).

Regarding food supply provision in the watershed area, the leading annual crops observed were: cabbage, sweet potato, yam, and tomato (Table 4). Data generated by EMATER-RJ (EMATER-RJ, 2021;Távora, 2019), from 2010 to 2016, showed a decline of annual crop production, from 19.88 t ha^{-1} in 2010 to 16.39 t ha^{-1} in 2016, which corresponds to -17.56%.

The main perennial crops in the watershed area are bananas, coffee, and passion fruit. According to data obtained from EMATER-RJ (EMATER-RJ, 2021) (Table 4), banana is the main perennial crop in terms of yield in the watershed, with an annual average of 74.29 tons produced from 2010 to 2016. Coffee production has declined since 2013 and showed a 14.29% fall in the period.

The pasture areas in the watershed decreased from 23.57% to 22.80% from 2010 to 2016 (Távora, 2019). However, it still corresponds to one-fifth of the watershed area.

According to Alvim et al. (2002), *Brachiaria decumbens cv.* has an average growth of 15 tons.ha.$year^{-1}$ of dry matter. However, calculating the amount of dry matter consumed shows that only 5,250 kg.ha.$year^{-1}$ are available for animal consumption. Thus, based on the 2010 and 2016 land use and land cover mappings (Távora, 2019), it can be estimated that approximately 619 tons of dry matter were produced in 2010 and 598.5 tons in 2016.

The correlation matrix in the annual crop areas showed that there are trade-offs (Fig. 2A) between production x nutrient regulation, water infiltration x nutrient regulation, and carbon storage x water infiltration. The main synergy for this use is between the production x infiltration services and carbon storage x nutrient regulation.

Based on the correlation matrix (Fig. 2B), perennial crop areas' synergy occurs between production x nutrient regulation. Another synergy observed in perennial agriculture areas, which also occurs in annual crop areas, is between carbon storage x nutrient regulation. The trade-offs between production service and water infiltration are also the result of associated agricultural practices.

In the pasture, the main trade-offs occur between production services x nutrient regulation services and production services x carbon storage service in the pasture areas. The main synergies observed in this land-use class are related to the water infiltration service, which positively

Table 3
Results of soil fertility, organic matter, and clay.

Lande Use	Ca (cmolc Kg-1)	K(cmolc Kg-1)	Mg(cmolc Kg-1)	Al(cmolc Kg-1)	H + Al(cmolc Kg-1)	CEC	P (cmolc Kg-1)	SOM (g Kg-1)	Clay (%)
Annual Crop	4.25 a	0.45 a	1.40 a	0.20 a	5.80 a	6.10 a	48.50 b	26.46 a	30.70 a
Perennial Crop	4.20 a	0.48 a	1.50 a	0.05 a	4.70 a	6.05 a	35.80 ab	20.77 a	28.50 a
Pasture	2.05 a	0.29 a	1.40 a	0.30 a	6.20 a	4.55 a	5.00 a	33.45 a	30.60 a

Source: authors. The values are the median. Means followed by similar letters in each column are not significantly different from one another at 5% level of significance. Soil organic matter (SOM).

Table 4
Annual and perennial crops produced in the watershed (in tones).

Crops		2010 (ton/ha)	2011(ton/ha)	2012(ton/ha)	2013(ton/ha)	2014(ton/ha)	2015(ton/ha)	2016(ton/ha)
Annual	Zucchini	10	10	10	10	10	10	10
	Sweet potato	150	150	130	130	130	150	150
	Eggplant	50	50	50	50	50	50	50
	Cauliflower	45	45	40	40	40	37	37
	Bean	15	15	15	15	12	12	12
	Yam	150	150	120	120	120	100	100
	Scarlet Eggplant	65	65	65	65	65	63	63
	Corn	12	12	10	10	10	7,0	7,0
	Cucumber	60	60	60	60	50	50	58
	Bell pepper	62	62	62	62	62	62	62
	Cabbage	250	250	250	250	250	250	215
	Tomato	100	100	100	100	100	80	80
	Pod	25	25	25	25	25	25	25
Perennial	Coffee	35	35	35	32	32	32	30
	Banana	70	70	70	70	80	80	80
	Passion Fruit	12	12	12	12	12	12	12

Source: EMATER-RJ, Systematic Monitoring of Agricultural Production – ASPA (2010–2016)

correlates with carbon storage and the nutrient regulation service (Fig. 2C).

4. Discussion

Regarding the carbon storage service, some factors may explain the significant difference in this service (Table 2). First, in the perennial and annual crop areas, the soil revolving associated with the use of fertilizers contributes to the microbial action, which intensifies the organic matter oxidation and the leaching process, which leads to a lower concentration of soil organic carbon (Rocha Junior et al., 2018; Blanco-Canqui and Wortmann 2020). In contrast, the lower soil revolving in pasture areas in association to the Brachiaria spp. can increase carbon accumulation in tropical soils (Braz et al., 2013; Cook et al., 2014; Gichangi et al., 2017; Dos Santos et al., 2019). According to Costa et al. (2009), the increase of carbon content in pasture areas is related to the grass root system that contributes to subsurface organic matter input from the soil (Neves et al., 2004; Costa et al., 2009). Therefore, the lack of conservationist practices in the cultivation sites, as observed in the area, led to less storage of organic carbon in the soil when compared to pasture areas. Although the pasture is also under conventional management practices, they are underused, as we could verify during the field works. It contributes to maintaining the structure of the grasses root system.

The degree of compaction in this study (Table 2) goes in the opposite direction to those already found in the literature. Ortigara et al. (2014) and Owuor et al. (2018) observed significant differences in the degree of soil compaction between the pasture and croplands. Nevertheless, this difference between ours results and the literature may indicate the lack of proper management in the cultivated areas, especially since all the variables did not show significant differences. Another factor is that soils' physical properties did not change due to lack of time despite the dynamic change in land use in the watershed (Távora et al., 2013; Távora, 2019). Also, the high content of organic matter in the pasture areas hinders soil compression by dissipating compaction energy and promoting aggregate stabilization, which favors pore formation (Ortigara et al., 2014; Silva et al., 2019; Okach et al., 2019).

Therefore, anthropic activity and the type of management employed in each area influence the water infiltration service in the Pito Aceso watershed. They affect the stabilization of aggregates and impact pore size, especially macropores (Braida et al., 2006; Alves et al., 2007; Suzuki et al., 2007; Ortigara et al., 2014; Collares, et al., 2011; Shiferaw, et al., 2019).

The outcomes for the nutrients regulation services can be understood base on the organic matter and clay. Since soil carbon contributes to the formation of electrically charged surfaces that are important for cation exchange, thus soils with high organic carbon contents also have high CEC values (Diekow et al., 2005; Enang et al., 2022; Baldotto et al., 2015). Also, the higher clay content in pasture areas contributes to CEC values because it has a vital role in forming colloidal surfaces that are electrically chargeable (Medeiros et al., 2018). Hence, the high content of organic matter and clay in the pasture areas observed in the Pito Aceso watershed contributes to a lack of significant CEC differences against the agricultural areas.

Moreover, according to Leal et al. (2019), the intensive use of NPK chemical fertilizer in Pito Aceso annual and perennial crop areas explains the results found for P levels in the area. Therefore, the concentration of soil organic matter, the intensity of inputs in the soils, and their management are the factors that influence the performance of the nutrient regulation service.

Regarding production services, although the agricultural areas expanded from 2010 to 2016, according to Távora (2019), the results showed a decline in productivity. That can be understood as a reflection of the severe climate events that have occurred in the area since 2010 (e.g., heavy rainfall that affected the entire Serrana Region in 2011 and the drought that occurred at the end of 2014) that ended up affecting all agricultural production in the state of Rio de Janeiro (Nehren, et al., 2019). And secondly, as a sign of the agricultural system's unsustainability, as no significant difference between the nutrients services provision between pasture and croplands, despite the use of fertilizers. Based on field observations, pasture areas in the watershed have few degraded areas and a low concentration of cattle. Thus, the estimates for forage production were designed for areas under good pasture

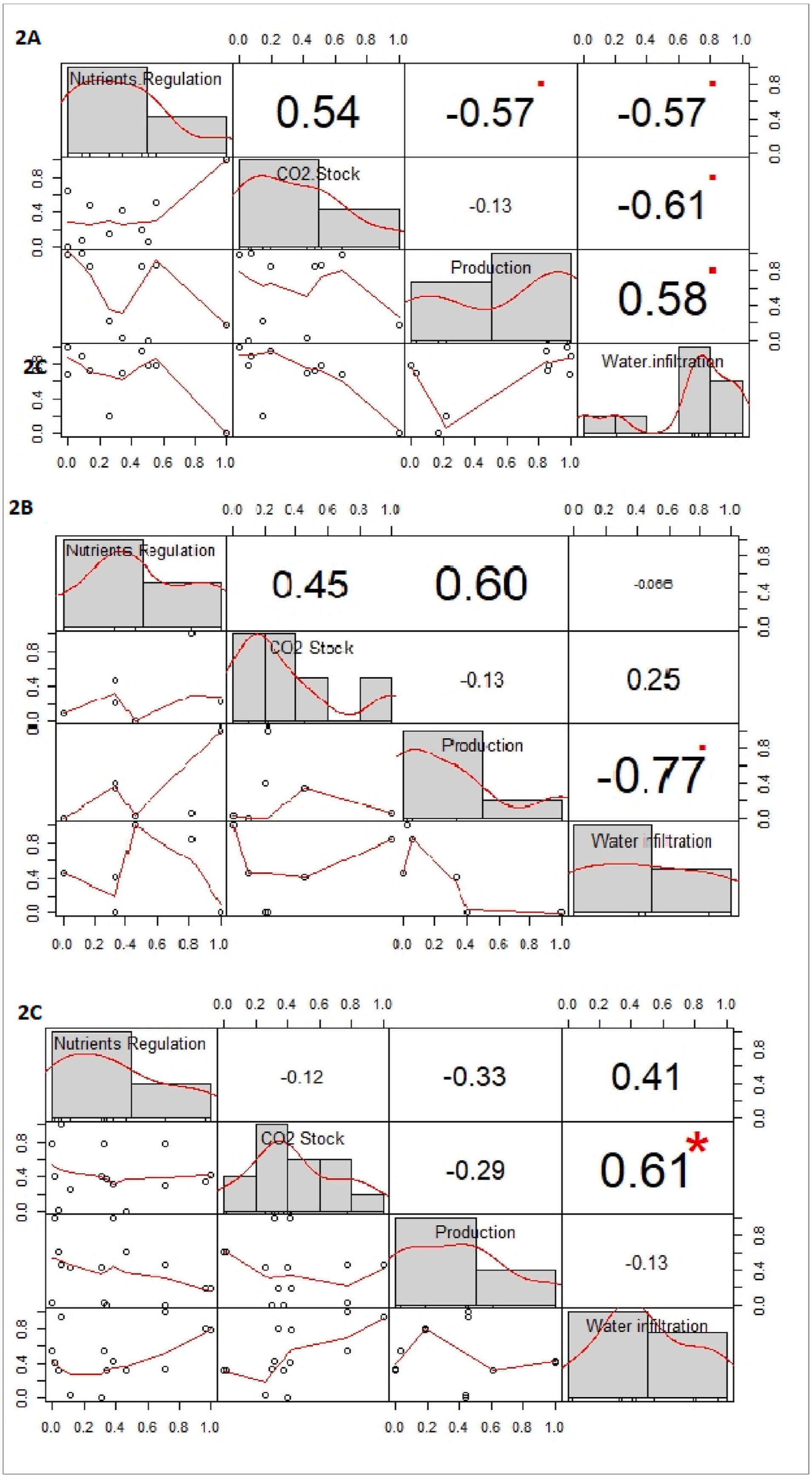


Fig. 2. Histogram with Correlation Matrix of annual (2A) and perennial crops (2B) and pasture areas (2C).

conditions and proper management (Alvim et al., 2002).

Agriculture areas have been considered mainly as sources of provisioning services, but more recently their contributions to other types of ecosystem services have been recognized (MEA 2005; Power, 2010). The provision of production services often results in suppressing other ecosystem services, such as nutrient regulation, soil water infiltration, and erosion control (Jónsson et al., 2017; Gissi et al., 2018; Jafarzadeh et al., 2021). In agricultural areas, this correlation is most noticeable. However, considering the land use as the proxy to understand the relationships among ES in this study, we could highlight the main trade-offs and synergies in agricultural landscapes (Fig. 3).

In the annual crop areas, the trade-offs can be explained based on soil management in these areas. The constant process of soil revolving affects soil quality and, mainly, formation and stabilization of aggregates. Besides, clay dispersion and organic matter removal due to overturning negatively affect nutrient regulation. Clay is one of the solid fractions in the soil responsible for the colloid formations, which are electrically charged surfaces responsible for cation exchanges (Ronquim, 2010; Strawn, 2021). Therefore, soil management practices that remove clay content from the soil affect nutrient bases and the CEC (Medeiros et al., 2018; Visscher et al., 2021). The removal of soil organic matter also influences decreasing water infiltration into the soil, as carbon plays a crucial role in stabilizing aggregates and forming pores (Reichert et al., 2003; Lepsch, 2011; Parron et al., 2015; Yu et al., 2020). Despite this, at first, the soil tillage, especially in the superficial layers, contributes to the fixation of annual crops and allows an increase in production (Parron et al., 2015; De Oliveira et al., 2019). Due to that we can observe the synergy between production services and water infiltration.

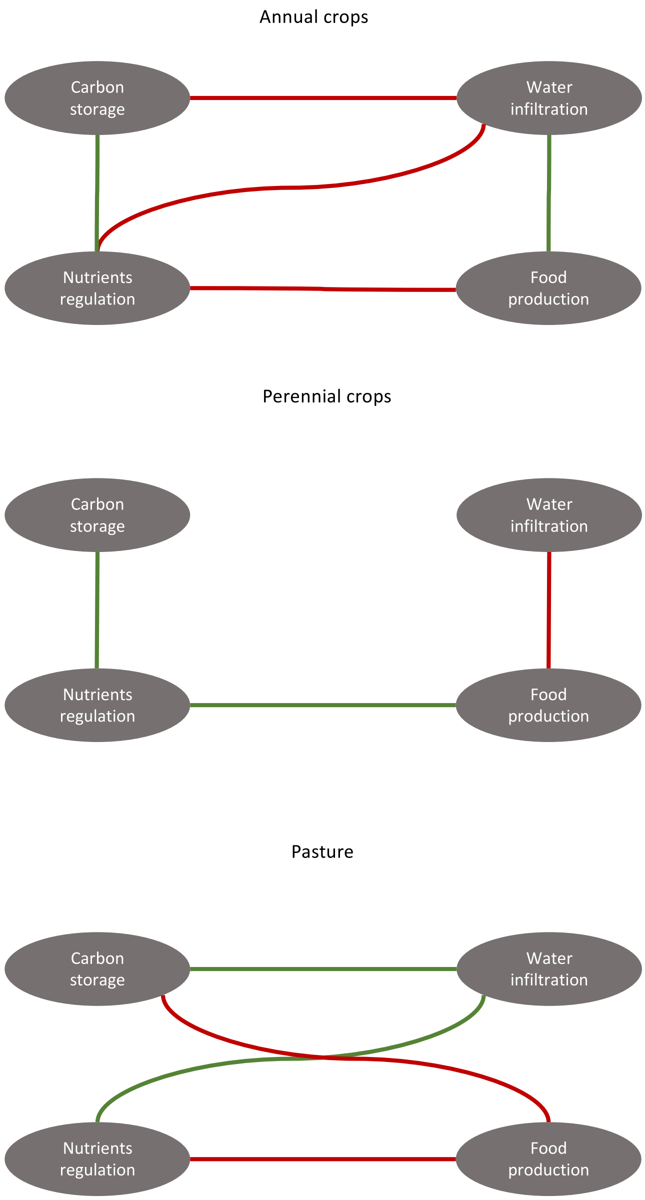


Fig. 3. Main trade-offs and synergies identified at the study area. Red connections indicate trade-offs and green connections indicate synergies. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Unlike annual crop areas, the plant decomposition material plays a vital role in nutrient cycling in the perennial crop areas (Espindola et al., 2006; Petit-Aldana et al., 2019; Froufe et al., 2020; Sileshi et al., 2020). Thus, the positive correlation between carbon storage service and the nutrient regulation service occurs because the concentration of organic carbon contributes to soil humic fractions, which, along with mineral clays and iron and aluminum sesquioxide, form the electrically charged surface - those are the main colloids responsible for cation exchange capacity (Roscoe et al., 2006; Craft et al., 2018; Rakhsh et al., 2020; Paramisparam et al., 2021). In the same way, the nutrient cycling has an essential role in the increase of the production service. However, the trade-offs in this area show that the intensification of use for food production, over time, leads to decreased soil infiltration (Santos et al., 2017; Keesstra et al., 2018; Kopittke et al., 2019).

Comparing the results of the two crop areas, it is evident the effects of the continuing revolving of the soils to annual crops in the SRES provision. Our study reinforces the recommendation that, especially in tropical areas, where the mineralization of organic matter is faster, it is fundamental the adoption of soil conservationists' practices, to minimize the trade-offs among SRES.

The trade-offs in pasture areas can be understood in the light of three factors. the first would be in relation to cattle grazing, which intensifies the process of soil compaction and, consequently, negatively influences the bulk density and the degree of compaction (Sharrow, 2007; Lai and Kumar 2020; Bonetti et al., 2021). The second question is related to carbon cycle within the pasture areas, according to Taboada et al. (2011), despise the CO2 stock decreases due to the grazing of the herds, more than 80% of the nutrients are returned in the form of excrement. The third is that the grass root system contributes to the contribution of subsurface organic matter to the soil (Ferraz de Almeida et al., 2019; Li et al., 2021).

Therefore, the positive relationship between the water infiltration service and the carbon storage services can be explained because the increase in carbon concentrations has a considerable influence on the stabilization of soil aggregates and on the formation of pores and, consequently, on the infiltration of water (Rayne and Aula, 2020). Meanwhile, synergies between the water infiltration service in the soil and the regulation of nutrients can be explained by the high level of SOM present in the area. The SOM increases the aggregation stability, positively affecting the water infiltration capacity. At the same time, it contributes to the balance of nutrients in the soil since SOM is a reservoir of soil nitrogen (N) and phosphorus (P). (Bayer and Mielniczuk, 2008; Hatten and Liles, 2019; Wang et al., 2022).

5. Conclusions

The Pito Aceso watershed has unique dynamics formed by the interaction between natural and anthropo-natural systems. Therefore, the evaluation of the SRES under different land uses is a way to understand these interactions. Such knowledge will enable public managers, decision-makers, and stakeholders to better understand how to manage the agricultural landscapes to reduce the trade-offs and maximize the synergies, promoting benefits to the society.

Regarding the selection of indicators, soil chemical and physical properties analysis effectively evaluated soil services, providing a quantitative and holistic analysis of ES provisions. However, we highlight that the selection of the indicators will depend on the ecosystem services that will be evaluated, and the availability of data and methods would interfere in the analysis.

In this study, we could observe the influence of organic matter on the ES dynamics in agricultural areas. Because it influences the concentration of carbon in soils, the degree of soil compaction (water infiltration service) has a crucial role in forming colloidal surfaces that contribute to CEC (regulatory services). Therefore, this indicator showed the most influence on the results of the trade-offs and synergies between the ecosystem services.

Our results could also evidence that intensive agriculture use and soil revolving without the adoption of soil conservationist management practices, can increase the trade-offs among ES. Hence, conservationist management practices, such as non-tillage, could improve the maintenance of SOM and thus improve the ecosystem services.

The analysis of trade-offs and synergies between ecosystem services has a key role in understanding how interactions among different soil properties and managements influence the flow of matter and energy in the system and how it interferes in the provision of the SRES. Spearman's correlation matrix has proved to be an important tool to understand how the ES interact under the same land use conditions. However, it is highly dependent on data availability - the more data available, the stronger the correlations among ES will be evidenced.

In short, the methodology framework showed the potential to be used in different studies that focus on SRES evaluation. To understand the dynamics of service delivery processes, the assessment should be continually done, mainly because of possible landscape changes that could affect the direct ES provision. However, the lack of soil indicators data at local level can represent a limitation to apply the proposed framework.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research is funded by the National Council for Scientific and Technological Development (CNPq) - 441595/2020-0. We would like to thank the reviewers for their constructive comments.

References

Adhikari, K., Hartemink, A.E., 2016. Linking soils to ecosystem services — a global review. Geoderma 262, 101–111.

Alves, M.C., Suzuki, L.G.A.S., Suzuki, L.E.A.S., 2007. Densidade do solo e infiltração de água como indicadores da qualidade física de um Latossolo Vermelho distrófico em recuperação. Rev. Bras. Ciência do Solo 617–625.

Alvim, M.J., de Botrel, M.A., Novelly, P.E., 1986. Produção de gramíneas tropicais e temperadas, irrigadas na época da seca. Revista da Sociedade Brasileira de Zootecnia, Viçosa, Mg 15 (5), 384–392.

Alvim, M.J., Botrel, M.A., Xavier, D.F., 2002. As principais espécies de Brachiaria utilizadas no país. Comunicado Técnico 22. Juiz de Fora: Ministério da Agricultura, Pecuária e Abastecimento, pp. 1–4.

Baldotto, M.A., Vieira, E.M., Souza, D.D.O., Baldotto, L.E.B., 2015. Estoque e frações de carbono orgânico e fertilidade de solo sob floresta, agricultura e pecuária. Rev. Ceres 62, 301–309.

Baude, M., Meyer, B.C., Schindewolf, M., 2019. Land use change in an agricultural landscape causing degradation of soil based ecosystem services. Sci. Total Environ. 659, 1526–1536.

Bayer, C., Mielniczuk, J., 2008. Dinâmica e função da matéria orgânica. In: Santos, G.D. E.A., Silva, L.S.D.A., Canellas, L.P., Camargo, F.A.D.E.O. (Eds.), Fundamentos da matéria orgânica do solo: ecossistemas tropicais e subtropicais. 2. Metrópole, Porto Alegre, pp. 7–18.

Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12 (12), 1394–1404.

Bianconi, A., Govone, J.S., Zuben, C.J.V., Pião, A.C.S., Pizano, M.A., Alberti, L.F., 2008. Transformação de Dados e Implicações da Utilização do Teste de Kruskal-Wallis em Pesquisas Agroecológicas. Pesticidas: Revista de Ecotoxicologia e Meio Ambiente 18, 27–34, 0.

Blanco-Canqui, H., Wortmann, C.S., 2020. Does occasional tillage undo the ecosystem services gained with no-till? A review. Soil Tillage Res. 198, 104534.

Bonetti, J.D.A., Anghinoni, I., Bredemeier, C., Moraes, M.T., Tormena, C.A., Gubiani, P.I., 2021. Physical recovery of an Oxisol under an integrated crop-livestock system in southern Brazil. Arch. Agron Soil Sci. 1–12.

Botrel, M.A., Alvim, M.J., Xavier, D.F., Pereira, A.V., 2003. Forrageiras para áreas montanhosas. Juiz de Fora - MG, vol. 74. Embrapa Gado de Leite, Circular Técnica.

Braida, J.A., Reichert, J.M., Veiga, M.D., Reinert, D.J., 2006. Resíduos vegetais na superfície e carbono orgânico do solo e suas relações com a densidade máxima obtida no ensaio Proctor. Rev. Bras. Ciência do Solo 30 (4).

Braz, S.P., Urquiaga, S., Alves, B.J., Jantalia, C.P., Guimarães, A.P., Dos Santos, C.A., et al., 2013. Soil carbon stocks under productive and degraded Brachiaria pastures in the Brazilian Cerrado. Soil Sci. Soc. Am. J. 77 (3), 914–928.

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., et al., 2018. Soil quality–A critical review. Soil Biol. Biochem. 120, 105–125.

Chagas, C.S., Calderano Filho, B., Donagemma, G.K., Fontana, A., Bhering, S.B., 2012. Levantamento semi-detalhado dos solos da microbacia do córrego do Pito Aceso, Município de Bom Jardim, região serrana do Estado do Rio de Janeiro – RJ. Rio de janeiro. Boletim de Pesquisa e Desenvolvimento (Embrapa Solos. Online) 1, 1–47.

Collares, G.L., Reinert, D.J., Reichert, J.M., Kaiser, D.R., 2011. Compactação superficial de Latossolos sob integração lavoura: pecuária de leite no noroeste do Rio Grande do Sul. Ciência Rural. 41, 246–250.

Cook, R.L., Binkley, D., Mendes, J.C.T., Stape, J.L., 2014. Soil carbon stocks and forest biomass following conversion of pasture to broadleaf and conifer plantations in southeastern Brazil. For. Ecol. Manag. 324, 37–45.

Costa, O.V., Cantarutti, R.B., Fontes, L.E.F., Costa, L.M.D., Soledade Nacif, P.G., Faria, J. C., 2009. Estoque de carbono do solo sob pastagem em área de tabuleiro costeiro no sul da Bahia. Rev. Bras. Ciência do Solo 33 (5).

Craft, C., Vymazal, J., Kröpfelová, L., 2018. Carbon sequestration and nutrient accumulation in floodplain and depressional wetlands. Ecol. Eng. 114, 137–145.

Dade, M.C., Miitchell, M.G., Mcalpine, C.A., Rhodes, J.R., 2019. Assessing ecosystem service trade-offs and synergies: the need for a more mechanistic approach. Ambio 48 (10), 1116–1128.

Dai, E.F., Wang, X.L., Zhu, J.J., Xi, W.M., 2017. Quantifying ecosystem service trade-offs for plantation forest management to benefit provisioning and regulating services. Ecol. Evol. 7 (19), 7807–7821.

De Oliveira, I.N., De Souza, Z.M., LoverA, L.H., Farhate, C.V.V., Lima, E.D.S., Esteban, D. A.A., Fracarolli, J.A., 2019. Least limiting water range as influenced by tillage and cover crop. Agric. Water Manag. 225, 105777.

Dias-Filho, M.B., 2014. Diagnóstico das pastagens no Brasil. Embrapa Amazônia Oriental-Documentos (INFOTECA-E).

Diekow, J., Mielniczuk, J., Knicker, H., Bayer, C., Dick, D.P., Kögel-Knabner, I., 2005. Carbon and nitrogen stocks in physical fractions of a subtropical Acrisol as influenced by long-term no-till cropping systems and N fertilization. Plant Soil 268, 319–328.

Dominati, E.J., 2013. Natural capital and ecosystem services of soils, 2013. In: Ecosystem Services in New Zealand—Conditions and Trends. Manaaki Whenua Press, Lincoln, New Zealand, pp. 132–142.

Dominati, E., Patterson, M., Mackay, A., 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecol. Econ. 69 (9), 1858–1868.

Dos Santos, C.A., Rezende, C.D.P., Pinheiro, É.F.M., Pereira, J.M., Alves, B.J., Urquiaga, S., Boddey, R.M., 2019. Changes in soil carbon stocks after land-use change from native vegetation to pastures in the Atlantic forest region of Brazil. Geoderma 337, 394–401.

Drescher, M.S., Reinert, D.J., Denardin, J.E., Gubiani, P.I., Faganello, A., Drescher, G.L., 2016. Duração das alterações em propriedades fisico-hidricas de Latossolo argiloso decorrentes da escarificação mecânica. Pesqui. Agropecuária Bras. 51 (2), 159–168.

Drobnik, T., et al., 2018. Soil quality indicators–From soil functions to ecosystem services. Ecol. Indicat. V94, 151–169.

Ellili-Bargaoui, Y., Walter, C., Lemercier, B., Michot, D., 2021. Assessment of six soil ecosystem services by coupling simulation modelling and field measurement of soil properties. Ecol. Indicat. 121, 107211.

EMATER-RIO – Empresa de assistência Técnica e Extensão Rural do Estado do Rio de Janeiro, 2021. –. Acompanhamento Sistemático da Produção Agrícola - ASPA. Disponível em. http://www.emater.rj.gov.br/tecnica.asp. (Accessed June 2021).

Empresa Brasileira De Pesquisa Agropecuária – EMBRAPA, 1997. Manual de métodos de análise de solo, 2 ed. Embrapa, Rio de Janeiro, p. 212.

Enang, R.K., Kips, P.A., Yerima, B.P.K., Kome, G.K., Van Ranst, E., 2022. Pedotransfer functions for cation exchange capacity estimation in highly weathered soils of the tropical highlands of NW Cameroon. Geoderma Regional 29, e00514.

Espindola, J.A.A., Marinho, G.J.G., Lopes De Almeida, D., Grandi Teixeira, M., Urquiaga, S., 2006. Decomposição e liberação de nutrientes acumulados em leguminosas herbáceas perenes consorciadas com bananeira. Rev. Bras. Ciência do Solo 30 (2).

FAO, 2016. Land Cover Classification System; Classification Concepts. Food and Agriculture Organization of the United Nations, Rome.

Feng, Q., Zhao, W., Fu, B., Ding, J., Wang, S., 2017. Ecosystem service trade-offs and their influencing factors: a case study in the Loess Plateau of China. Sci. Total Environ. 607, 1250–1263.

Ferraz De Almeida, R., Rodrigues Mikhael, J.E., Oliveira Franco, F., Fonseca Santana, L. M., Wendling, B., 2019. Measuring the labile and recalcitrant pools of carbon and nitrogen in forested and agricultural soils: a study under tropical conditions. Forests 10 (7), 544.

Froufe, L.C.M., Schwiderke, D.K., Castilhano, A.C., Cezar, R.M., Steenbock, W., Seoane, C.E.S., et al., 2020. Nutrient cycling from leaf litter in multistrata successional agroforestry systems and natural regeneration at Brazilian Atlantic Rainforest Biome. Agrofor. Syst. 94 (1), 159–171.

Gichangi, Elias M., NjaruI, Donald Mg, Gatheru, Mwangi, 2017. Plant shoots and roots biomass of brachiaria grasses and their effects on soil carbon in the semi-arid tropics of Kenya. Trop. Subtrop. Agroecosyst. 20 (1), 65–74.

Gissi, E., Gaglio, M., Aschonitis, Vg, Fano, Ea, Reho, M., 2018. Soil-related ecosystem services trade-off analysis for sustainable biodiesel production. Biomass Bioenergy 1 (114), 83–99.

Hatten, J., Liles, G., 2019. A 'healthy'balance–The role of physical and chemical properties in maintaining forest soil function in a changing world. Dev. Soil Sci. 36, 373–396. Elsevier.

Jafarzadeh, A.A., Mahdavi, A., Shamsi, S.R.F., Yousefpour, R., 2021. Assessing synergies and trade-offs between ecosystem services in forest landscape management. Land Use Pol. 111, 105741.

Jónsson, Jö, Davíðsdóttir, B., Nikolaidis, Np, 2017. Valuation of soil ecosystem services. Jan 1 Adv. Agron. 142, 353–384. Academic Press.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018. The superior effect of nature-based solutions in land management for enhancing ecosystem services. Sci. Total Environ. V6 (10), 997–1009.

Kopittke, P.M., Menzies, N.W., Wang, P., Mckenna, B.A., Lombi, E., 2019. Soil and the intensification of agriculture for global food security. Environ. Int. 132, 105078.

Lai, L., Kumar, S., 2020. A global meta-analysis of livestock grazing impacts on soil properties. PLoS One 15 (8), e0236638.

Leal, L.L., Turetta, A.P.D., Sampaio, M.C., Simoes, B.F.T., Melo, F.R.R., Donagemma, G. K., 2019. Phosphorus limits and 'Planetary Boundaries' approach applied to a case study in a tropical area. Environ. Earth Sci. 78, 119 (INTERNET).

Lepsch, I.F. 19 lições de pedologia (2011). São Paulo: Oficina de Textos, . 456 p.

Li, J., Li, L., Wang, Z., Zhang, C., Wang, Y., Wang, W., et al., 2021. The contributions of the roots, stems, and leaves of three grass species to water erosion reduction on spoil heaps. J. Hydrol. 603, 127003.

Marcolin, C.D., Klein, V.A., 2011. Determinação da densidade relativa do solo por uma função de pedotransferência para a densidade do solo máxima. Acta Sci. Agron. 33 (2).

Martha Junior, G.B., Barioni, L.G., Vilela, L., Barcellos, A.D., 2003. Área do piquete e taxa de lotação no pastejo rotacionado. Embrapa Cerrados-Comunicado Técnico (INFOTECA-E).

Medeiros, F.B., Francieli, S.M., Silveira, H., Nóbrega, M.T., 2018. Avaliação da estabilidade de agregados e a vulnerabilidade à erosão ao longo de uma vertente no município de Araruna, região noroeste do Paraná-Brasil. Caderno de Geografia 28 (55), 845–862.

Milheiras, S.G., Mace, G.M., 2019. Assessing ecosystem service provision in a tropical region with high forest cover: spatial overlap and the impact of land use change in Amapá, Brazil. Ecol. Indicat. 99, 12–18.

Millennium Ecosystem Assessment (MEA), 2005. Ecosystem and Human Well-Being: Synthesis. Island Press, Washington, DC.

Morán-Ordóñez, A., Roces-Díaz, J.V., Otsu, K., Ameztegui, A., Coll, L., Lefevre, F., Retana, J., Brotons, L., 2019. The use of scenarios and models to evaluate the future of nature values and ecosystem services in Mediterranean forests. Reg. Environ. Change 19, 415–428. https://doi.org/10.1007/s10113-018-1408-5.

Nehren, U., Sattler, D., Raedig, C., Hissa, H., Schlüter, S., 2019. Rio de Janeiro: a state in socio-ecological transformation. In: Strategies and Tools for a Sustainable Rural Rio de Janeiro. Springer, Cham, pp. 1–10.

Neves, C.M.N., Silva, M.L.N., Curi, N., Macedo, R.L.G., Tokura, A.M., 2004. Estoque de carbono em sistemas agrossilvopastoril, pastagem e eucalipto sob cultivo convencional na região noroeste do estado de Minas Gerais. Ciênc. agrotec., Lavras 28 (5), 1038–1046.

Okach, D.O., Ondier, J.O., Kumar, A., Rambold, G., Tenhunen, J., Huwe, B., Otieno, D., 2019. Interactive influence of livestock grazing and manipulated rainfall on soil properties in a humid tropical savanna. J. Soils Sediments 19 (3), 1088–1098.

Ortigara, C., Koppe, E., Bonini Da Luz, F., Kaiser, D.R., Rodrigues Da Silva, V., 2014. Uso do solo e propriedades físico-mecânicas de Latossolo Vermelho. Rev. Bras. Ciência do Solo 38 (2).

Owuor, S.O., Butterbach-BahlL, K., Guzha, A.C., Jacobs, S., Merbold, L., Rufino, M.C., et al., 2018. Conversion of natural forest results in a significant degradation of soil hydraulic properties in the highlands of Kenya. Soil Tillage Res. 176, 36–44.

Paciullo, D.S.C., Lopes, F.C.F., Junior, J.D.M., Viana Filho, A., Rodriguez, N.M., Morenz, M.J.F., Aroeira, L.J.M., 2010. Características do pasto e desempenho de novilhas em sistema silvipastoril e pastagem de braquiária em monocultivo. Pesqui. Agropecuária Bras. 44 (11), 1528–1535.

Paramisparam, P., Ahmed, O.H., Omar, L., Ch'ng, H.Y., Johan, P.D., Hamidi, N.H., 2021. Co-application of charcoal and wood ash to improve potassium availability in tropical mineral acid soils. Agronomy 11 (10), 2081.

Parron, L.M., Maia, C.M.B.F., Rachwal, M.F.G., 2015. Estoques de carbono no solo como indicador de serviços ambientais. In: Lucilia Maria Parron; Junior Ruiz Garcia; Edilson Batista de Oliveira; George Gardner Brown; Rachel Bardy Prado. (Org.). Serviços Ambientais em Sistemas Agrícolas e Florestais do Bioma Mata Atlântica. 1ed.Colombo, vol. 1. PR: Embrapa, pp. 92–100.

Petit-Aldana, J., Rahman, M.M., Parraguirre-Lezama, C., Infante-Cruz, A., Romero-Arenas, O., 2019. Litter decomposition process in coffee agroforestry systems. J. Forest Environ. Sci. 35 (2), 121–139.

Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Phil. Trans. Biol. Sci. 365 (1554), 2959–2971.

Prado, R.B., Barcellos, T.B.C., Rego, L.F.G., Donagemma, G.K., Turetta, A.P., 2009. Utilização de imagens de alta resolução para o mapeamento do uso e cobertura do solo na microbacia do córrego Pito Aceso - região de Mata Atlântica - RJ. In: XXXII Congresso Brasileiro de Ciência do Solo, 2009, Fortaleza.

R Core Team, 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. Avaliable in: <https://www.R-project.org>. (Accessed 10 January 2019).

Rakhsh, F., Golchin, A., Al Agha, A.B., Nelson, P.N., 2020. Mineralization of organic carbon and formation of microbial biomass in soil: effects of clay content and composition and the mechanisms involved. Soil Biol. Biochem. 151, 108036.

Rayne, N., Aula, L., 2020. Livestock manure and the impacts on soil health: a review. Soil Systems 4 (4), 64.

Reichert, J.M., Reinert, D.J., Braida, J.A.(, 2003. Qualidade dos solos e sustentabilidade de sistemas agrícolas. Ci. Amb 27, 29–48.

Rocha Junior, P.R.D., Ribeiro, P.H., Mesquita, L.F., Andrade, F.V., MendonçA, E.D.S., 2018. Distribution of C and inorganic phosphorus fractions in different aggregate sizes under forestry, agroforestry system and pasture. J. Soil Sci. Plant Nutr. 18 (2), 361–375.

Rodriguez, J.P., Beard, T.D., Bennett, E.M., Cumming, G.S., Cork, S.J., Agard, J., Dobson, A.P., Peterson, G.D., 2006. Trade-offs across space, time, and ecosystem services. Ecol. Soc. 11, 28.

Rogerson, P.A., 2012. Métodos estatísticos para Geografia: um guia para o estudante. Bookman Editora.

Ronquim, C.C., 2010. Conceitos de fertilidade do solo e manejo adequado para as regiões tropicais. Campinas, Embrapa Monitoramento por Satélite, vol. 26p. Boletim de Pesquisa e Desenvolvimento vol. 8.

Roscoe, R., Boddey, R.M., Salton, J.C., 2006. Sistemas de manejo e matéria orgânica do solo. In: Roscoe, R., Mercante, F.M., Salton, J.C. (Org (Eds.), Dinâmica da matéria orgânica do solo em sistemas conservacionistas: Modelagem matemática e métodos auxiliares. Dourados: Embrapa Agropecuária Oeste, v., pp. 17–41.

Rosendo, J.S., Rosa, R., 2012. Comparação do estoque de C estimado em pastagens e vegetação nativa de Cerrado. Sociedade & Natureza v-2, 24.

Santos, J.C.N.D., Andrade, E.M.D., Medeiros, P.H.A., Guerreiro, M.J.S., Palácio, H.A.D. Q., 2017. Land use impact on soil erosion at different scales in the Brazilian semi-arid. Rev. Cienc. Agron. 48 (2), 251–260.

Sharrow, S.H., 2007. Soil compaction by grazing livestock in silvopastures as evidenced by changes in soil physical properties. Agrofor. Syst. 71, 215–223. https://doi.org/10.1007/s10457-007-9083-4.

Shiferaw, H., Bewket, W., Alamirew, T., Zeleke, G., Teketay, D., Bekele, K., et al., 2019. Implications of land use/land cover dynamics and Prosopis invasion on ecosystem service values in Afar Region, Ethiopia. Sci. Total Environ. 675, 354–366.

Sileshi, G.W., Mafongoya, P.L., Nath, A.J., 2020. Agroforestry systems for improving nutrient recycling and soil fertility on degraded lands. In: Agroforestry for Degraded Landscapes. Springer, Singapore, pp. 225–253.

Silva, R.F.D., Batistella, M., Moran, E.F., 2018. Regional socioeconomic changes affecting rural area livelihoods and Atlantic forest transitions. Land 7 (4), 125.

Silva, B.O., Moitinho, M.R., Santos, G.A.A., Teixeira, D.B., Fernandes, C., La Scala Jr., N., 2019. Soil CO2 emission and short-term soil pore class distribution after tillage operations. Soil Tillage Res. 186, 224–232.

SOS Mata Atlântica, 2022. Atlas dos remanescentes florestais da Mata Atlântica. Período 2020 – 2021. Relatório técnico. São Paulo. https://cms.sosma.org.br/wp-content/uploads/2022/05/Sosma-Atlas-2022-1.pdf. Assessed on August 30, 2022.

Strawn, D.G., 2021. Sorption mechanisms of chemicals in soils. Soil Systems 5 (1), 13.

Suzuki, L.E.A.S., Reichert, J.M., Reinert, D.J., De Lima, C.L.R., 2007. Grau de compactação, propriedades físicas e rendimento de culturas em Latossolo e Argissolo. Pesqui. Agropecuária Bras. 42 (8), 1159–1167.

Taboada, M.A., Rubio, G., Chaneton, E.J., 2011. Grazing impacts on soil physical, chemical, and ecological properties in forage production systems. In: Hatfield, Jerry L., Sauer, Thomas J. (Eds.), Soil Management: Building a Stable Base for Agriculture.

Távora, G.S.G., 2019. Avaliação dos serviços ecossistêmicos prestados pelos solos em áreas agrícolas inseridas no Bioma Mata Atlântica, na região serrana do estado do Rio de Janeiro, 194. Universidade do Rio de Janeiro, Igeo, Rio de Janeiro (Tese Doutorado em Geografia).

Távora, G.S., Turetta, A.P.D., 2016. An approach to map landscape functions in Atlantic Forest—Brazil. Ecol. Indicat. 71, 557–566.

Távora, G.S.G., Turetta, A.P.D., Fidalgo, E.C.C., Prado, R.B., 2013. Mapeamento de uso e cobertura da terra de uma bacia de drenagem no bioma Mata Atlântica com uso de imagem de alta resolução. Boletim de Pesquisa e Desenvolvimento (Embrapa Solos. Online) 229, 1–25.

Visscher, A.M., Da Silva, M.F.D.C., Kuyper, T.W., Lavres Jr., J., Cerri, C.E.P., Do Couto, H.T.Z., Righi, C.A., 2021. Moderate swidden agriculture inside dense evergreen ombrophilous forests can sustain soil chemical properties over 10–15 year cycles within the Brazilian Atlantic Forest. Catena 200, 105117.

Vrebos, D., Staes, J., Vandenbroucke, T., D'Haeyer, T., Johnston, R., Muhumuza, M., et al., 2015. Mapping ecosystem service flows with land cover scoring maps for data-scarce regions. Ecosyst. Serv. 13, 28–40. https://doi.org/10.1016/j.ecoser.2014.11.005.

Wang, J., Lin, C., Han, Z., FU, C., Huang, D., Cheng, H., 2022. Dissolved nitrogen in salt-affected soils reclaimed by planting rice: how is it influenced by soil physicochemical properties? Sci. Total Environ. 824, 153863.

Yu, Z., Zheng, Y., Zhang, J., Zhang, C., Ma, D., Chen, L., Cai, T., 2020. Importance of soil interparticle forces and organic matter for aggregate stability in a temperate soil and a subtropical soil. Geoderma 362, 114088.