Medium to long-term patterns of soil properties in forest restoration models in seasonally dry Atlantic Forest biome

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Research Article

Keywords: Forest restoration, land uses, ecosystem services, soil fertility, soil organic carbon

Posted Date: January 27th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1300388/v1

Medium to long-term patterns of soil properties in forest restoration models in seasonally dry Atlantic Forest biome

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HIGHLIGHTS

- NF regenerated after coffee was the most depleted soil fertility and SOC storage
- Grass pasture and legume plantations showed smaller soil acidity and larger base concentration than NF areas
- SOC was large in NF regenerated after selective cutting and grass pasture
- Legume trees decreased SOC storage by 35% after planting on grass pasture

ABSTRACT

The medium- to long-term impacts of forest restoration models on soil properties are not well documented in the Atlantic Forest biome, especially in a seasonally dry climate. We assessed patterns of topsoil fertility, soil organic carbon (SOC) storage, and isotopic signatures of ^{13}C in gradient with three areas with natural regeneration of native forest (NF) with 50 years of old, two areas with monocultures of N_2-fixer and non-N_2-fixer tree species, six years after planting on grass pasture, and one area with grass pasture in the last 40 years of age. In each area, three to nine composite soil samples were collected at 0-20 cm soil depth during the rainy season for analysis. The topsoil of the NF regenerated after coffee was the most depleted soil fertility and SOC storage in our vegetation gradient. The grass pasture and forest plantations showed smaller soil acidity and a larger base concentrations than the NF areas. The SOC storage was larger in NF after grass pasture and selective cutting, followed by grass pasture, with 80, 76, and 69 Mg ha^{-1}, respectively. The planting of legume trees decreased SOC storage by approximately 35% during SOC storage, independent of N_2-fixing capacity. The SOC derived from trees increased rapidly in the first six years of tree plantation (≈ 3 Mg SOC ha^{-1} year^{-1}). The

recovery of soil fertility and SOC storage by long-term natural regeneration differs according to historical land use. Differences in N_2-fixation capacity had little effect on soil properties in the medium term.

Keywords: Forest restoration, land uses, ecosystem services, soil fertility, soil organic carbon.

INTRODUCTION

The promotion of forest restoration and ecosystem services has been extensively debated in the Atlantic Forest biome of Brazil (Latawiec et al., 2015; Chazdon et al., 2017). This biome has the last 12 million hectares of abandoned land to be restored, and the other 15 million hectares of pasture (Chazdon et al., 2016). The planting of trees and natural regeneration are the two most used restoration interventions in the Atlantic Forest biome. The improvement of soil fertility and soil organic carbon (SOC) storage is one of the ecosystem services expected from the medium to long term after the restoration of agricultural lands. However, there are few field studies showing soil data for restorations with monocultures of native trees that have been established in the Atlantic Forest biome in the last decade (Mendes et al., 2019). In tropical regions, these concerns have mainly been evaluated for some tree genera, mainly *Eucalyptus* and *Pinus*, and N_2-fixing trees such as *Acacia*, *Albizia*, *Leucaena*, and *Casuarina* genera (Marín-Spiotta and Sharma, 2013; Shi et al., 2016).

Soil carbon loss due to land-use change is the second major cause of the increasing CO_2 in atmosphere after fossil fuels, and is mainly responsible for the increase in greenhouse gas emissions in tropical countries (Assad et al., 2013; Locatelli et al., 2015). Moreover, the conversion of land use affects several soil properties besides SOC (Guo and Gifford, 2002; Don et al., 2011), such as acidity, nitrogen, phosphorus, and cation exchange (Shi et al., 2016). In general, the pools of C, N, and other nutrients in natural forest soil (NF) are significantly reduced due to the conversion of NF to traditional agriculture, mainly with non-sustainable practices (Don et al., 2011; Lal, 2018). The conversion of NF to grass pasture has a controversial impact in the short to medium term (Guo and Gifford, 2002; Don et al., 2011). However, the recovery of soil properties often occurs when agriculture and grass pastures are restored by afforestation over the long term (Don et al., 2011). At the same time, there is an equal lake of soil data in natural forests regenerated after agriculture and grass pasture in the last half century, when it intensified the protection of native forests in Brazil (from 1964).

The effect of tree planting on soil fertility and SOC storage varies with previous use and management intensity (Laganière et al., 2010), and functional traits of the species (De Deyn et al., 2008). Positive effects on soil fertility and C status are often found when bare land and cropland are converted in tree plantations with stand age higher than 10-30 years (Guo and Gifford, 2002; Shi et al., 2016). However, the same patterns were less frequent when grass pastures were converted to tree plantations (Shi et al., 2016). Moreover, plantations using management practices with minimum soil interventions show higher SOC storage than plantations with high management intensity (Laganière et al., 2010). The N_2-fixing legume tree species are an exception because several studies have shown a faster positive effect of these functional groups on soil properties when established in agricultural and grass pasture areas (Shi et al., 2016; Marín-Spiotta and Sharma 2013). However, few studies have been conducted to compare the effects of legume trees with different capacities to N_2-fixation on soil properties after afforestation of grass pastures in the Atlantic Forest biome (Barroso et al., 2018).

We carried out a field investigation to assess patterns of soil fertility (*i.e.*, pH, Al, P, K, Ca, Mg, base exchange), C and N concentrations, SOC storage, and isotopic signatures of ^{13}C in a gradient of vegetation localized in the seasonally dry Atlantic Forest biome in Southeast Brazil. The gradient of vegetation was composed of NF with at least 50 years of natural regeneration after selective logging, and after coffee agriculture or grass pasture, one grass pasture area with at least 40 years of age, and two monocultures with N_2-fixing *Anadenanthera peregrina* var. peregrina (L.) Speg. and non-N_2-fixing *Schizolobium parahyba* var. amazonicum (Huber & Ducke) Barneby, six years after planting on grass pastures. Our hypotheses were as follows: 1) NF with at least 50 years of natural regeneration would show similar soil property patterns, and 2) the N_2-fixing legume trees would improve soil properties by a major magnitude compared to non-N_2-fixing legume trees.

MATERIAL AND METHODS

Study area

The study was carried out at the campus of *the Instituto Federal do Espírito Santo* (IFES), municipality of Alegre, in southern Brazil (Fig. 1). The vegetation was spread over an area that describes a vegetation gradient ordinary to the Atlantic Forest biome of southeast Brazil. It involves the regeneration of NF, grass pastures, and tree plantations. The climate is classified as Aw, with rainy summers and dry winters. The mean annual rainfall is approximately 1200 mm with a dry period (< 50 mm) from May to September, and the mean annual temperature is 23 °C (Alvares et al., 2013). The relief region varies from wavy to mountainous, with the occurrence of mountains and culvert chains and an average altitude of 150 m (IBGE, 1987). The slope ranged between 15% and 45% in most sampling areas, and the main soil type was Ferralsols (Lorenzoni-Paschoa et al., 2019; Bighi et al., 2021).

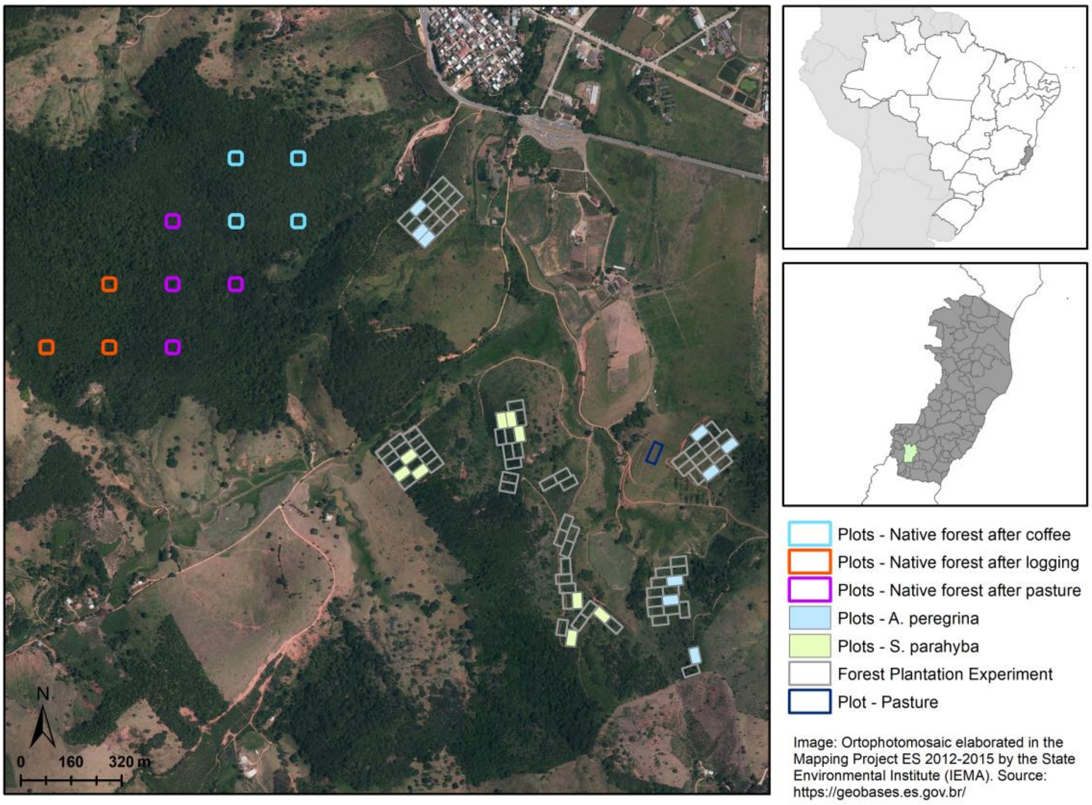

Fig. 1 Localization of plots in the vegetation gradient

The natural forest is a forest fragment of seasonally dry forest with a total area of 109.6 hectares. The fragment was previously subjected to three different disturbances: coffee plantations, African grass pasture, and selective tree cutting (Lorenzoni-Paschoa et al., 2019). This previous land use and management occurred at least 50 years ago. The fragments contained a minimum of 153 identified tree species. However, the main tree species were *Pseudopiptadenia contorta*, *Parapiptadenia pterosperm,* and *Apuleia leiocarpa*. The mean value of the basal area in the fragment was 29 m^2 ha^{-1}, and there was no statistically significant difference between previous land use and management (Lorenzoni-Paschoa et al., 2019).

The plantation of *A. peregrina* trees and *S. parahyba* trees was established in areas managed with grass pastures for more than 40 years with *Brachiaria* sp. dominant species. We used data from nine of these experimental plots per species planted in 2011 with a 3 m × 3 m tree spacing (stand density of 1111 trees ha^{-1}) (Bighi et al., 2021). The seedlings were produced from seeds originating from stock plants located in Dom Elizeu, state of Pará, Brazil, in Reserva Natural Vale in Linhares, state of Espirito Santo (Instituto Ambiental Vale). The seedlings of *A. peregrina* were not inoculated with rhizobial strains. However, natural nodules were observed in the study area (Mendes et al., 2021). The cattle were removed before planting, and the pasture was desiccated by applying glyphosate. The seedlings were planted in pits with dimensions of 30 cm × 30 cm × 30 cm. Each seedling received 220 g of commercial fertilizer (NPK 06-30-06) more micronutrients (0.4 g of B, Cu; and Zn) per hole at the time of planting. Maintenance occurred in the first 12 months after planting, with replanting, crowning, and the control of leaf cutter ants.

Soil sampling

For the regenerated NF, the soil data determined by Lorenzoni-Paschoa (2016) and Neves (2018) at the 0-20 cm soil layer in 11 permanent plots were used. Each plot had an area of 400 m² (20 m × 20 m). Four plots were localized in the zones with NF regenerated after grass pasture and agriculture (coffee), and three plots were localized in the zone with the selective cutting of trees (Fig. 1). During the rainy season of 2015, ten soil samples per plot were collected and mixed in one soil sample. Soil fertility and texture were assessed in this study (Lorenzoni-Paschoa, 2016). Soil N and C concentrations and SOC storage were determined in the rainy season of 2018 from five simple soil samples collected per plot and mixed (Neves, 2018). Soil density was also measured at two points per plot, using a metal ring with a volume of 106.7 cm^3 (Neves, 2018). Finally, the same soil samples collected by Neves (2018) were used to determine the natural abundance of ^{13}C in each plot.

For the grass pasture area, soil samples collected in the 0-20 cm layer on two occasions were used. Soil fertility and soil density were determined in soil samples collected from grass pasture areas during the rainy season of 2010, 12 months before tree plantation (Campanharo, 2017). On this occasion, 360 simple samples distributed systematically in all areas with tree plantations were collected (Fig. 1). The samples were mixed into six composite samples for the fertility analysis. Soil density was measured in 60 samples distributed systematically in all areas used for planting tree legumes. For N and C concentrations, natural abundance of ^{13}C, and texture, one area with grass pasture adjacent to the forest plantation was used for soil samples collected (Fig. 1) during the rainy season of 2017. In this area, 18 soil samples were mixed into three composite soil samples for analysis.

For the tree plantation area, soil fertility and soil density in the 0-20 cm layer determined by Campanharo (2017) in the rain season of 2017, six years after planting, were used. In each plot with tree plantation, the 0-20 cm soil layer was collected from six different horizontal points from six different trees (Mendes et al. 2021). These six simple soil samples were mixed in one composite sample per plot and used for fertility analysis. The soil density was determined using a 5 cm diameter metal ring in a single sample collected from the central region of each plot. Furthermore, the N and C concentrations, SOC storage, isotopic composition of ^{13}C, and soil texture were determined using soil samples collected by Campanharo (2017).

Laboratory analysis

All analyses of soil fertility, soil density, and soil texture were carried out according to Embrapa (1997). The soil samples for soil density assessment were weighed on a precision balance after drying at 105 °C for 72 h. The proportions of clay, silt, and sand were determined using a pipetting method. The soil samples used for chemical analysis were air-dried, macerated, and sieved (0.5 mm). pH_{H2O} was determined to be 1:2.5. Phosphorus (P) and potassium (K) were extracted using Melich 1. Exchangeable Al, Ca, and Mg were extracted using KCl (1 mol L^{-1}).

Soil N concentration was determined according to the Kjeldahl method (Mendonça and Matos, 2005). Soil C concentration and $\delta^{13}C$ were determined using a 20–20 Hydra mass spectrometer (ANCA-GSL, SERCON Co., Crewe, Uk) (Boutton, 1991). The $\delta^{13}C_{VPDB}$ signature (i.e., using the Vienna Pee Dee Belemnite standard) was calculated.

Data analysis

The SOC storage (Mg ha^{-1}) at 0-20 cm was estimated using the soil C concentration (%) multiplied by the soil mass measured in each vegetation.

The amounts of SOC derived from trees and grass were calculated by multiplying the SOC storage by the proportion of C derived from each vegetation. The proportion of SOC derived from trees and grass was estimated using Equations 1 and 2, respectively:

$$\%\ C\ trees = \left(\frac{\delta\ soil\ tree - \delta\ soil\ pasture}{\delta\ soil\ ref - \delta\ soil\ pasture}\right) * 100 \quad (1)$$

$$\% \ C\ grass = 100 - \% \text{ C trees} \quad (2)$$

Where: % C trees or % C grass is the proportion of SOC derived from trees and grass; δ is the $\delta^{13}C$ (‰) value determined in each plot by tree plantation (N=9), and in each plot with NF regenerated after pasture (N=4); δ soil pasture is the mean value of $\delta^{13}C$ (‰) in soil sampled in pasture area; and δ soil ref is the mean value of $\delta^{13}C$ (‰) in soil sampled in NF regenerated after selective cutting (N=3).

The mean values of the chemical and physical properties of the soil were compared among areas using one-way ANOVA for normal data or the Kruskal-Wallis test for non-normal data. The mean values of soil properties in each of the five areas were compared with the control group NF after selective cutting using Dunnett's method for normal data, or Dunn's method for non-normal data. Normality was tested using the Shapiro-Wilk test. Statistical analysis was performed with SigmaPlot 13 (Systat, 2014), using a statistical threshold value of $P = 0.05$.

RESULTS

There were different patterns of soil fertility among the areas in the studied vegetation gradient (Tab. 1). Soil acidity and Al concentration were higher mainly in the regenerated coffee than in the grass pasture or legume plantations. The mean P concentrations were generally larger in legume tree plantations, but the difference was not statistically significant. The base concentrations were often smaller in the NF-coffee culture than in the other areas. In addition, the base concentrations were often larger in grass pasture and legume tree plantations than in NF areas. However, statistical differences among the areas were found only for Mg concentrations.

The mean N concentration values ranging from 0.19 to 0.25 % were statistically equal among the areas (Tab. 1). In contrast, the C concentration was larger in NF-SC and NF-grass, followed by grass pastures. At the same time, the C concentrations were similar in legume trees and NF-coffee plantations. The C concentration was 1.6 time higher in the reference area NF-SC than in the tree plantation and NF-coffee. The $\delta^{13}C$ values were statistically higher in grass pasture and tree plantation areas than in the reference NF-SC. $\delta^{13}C$ assumed intermediate values between NF and grass pastures.

Soil density was higher in grass pasture areas than in forest areas (Tab. 1). The soil texture was statistically equal among areas, with clay concentrations ranging from 50% to 56%, and sand concentrations from 35% to 42%.

The SOC storage values were 1.7 times higher in NF-SC, NF-grass, and grass pasture (≈ 75 Mg ha^{-1}) than in tree plantation and NF-coffee areas (Fig. 2). At the same time, the SOC storage was similar among the NF-coffee and legume tree plantations, with mean values ranging from 41 to 44 Mg ha^{-1}.

The SOC derived from the tree increased from 0.7 in grass pasture to 78 Mg ha^{-1} in NF-grass. In addition, the SOC derived from the tree was slightly larger in *S. parahyba* than in *A. peregrina*, with 19 and 15 Mg ha^{-1}, respectively. Furthermore, the SOC derived from grass decreased from 68 Mg ha^{-1} in grass pasture to ~ 29 Mg ha^{-1} in legume tree plantations and 2 Mg ha^{-1} in NF-grass.

Tab. 1 Soil proprieties in vegetational gradient composed of native forest (NF) regenerate after the selective cutting of trees (SC), grass pasture (grass), agriculture (coffee), grass pasture, and legume tree species plantations. * Significant differences among areas. † Significant difference between each area and the NF-SC control

	Vegetational gradient					
Variables	**NF - SC**	**NF - grass**	**NF - coffee**	**Grass pasture**	***S. parayba***	***A. peregrina***
pH (water) *	5.15 ± 0.70	5.18 ± 0.63	4.46 ± 0.13	5.74 ± 0.33	5.45 ± 0.53	5.33 ± 0.19
Al ($cmol_c$ dm^{-3}) *	0.29 ± 0.44	0.30 ± 0.22	0.78 ± 0.28†	0.09 ± 0.12	0.09 ± 0.12	0.06 ± 0.04
P ($cmol_c$ dm^{-3})	1.55 ± 0.47	2.23 ± 0.31	1.80 ± 0.41	2.00 ± 0.40	2.71 ± 0.78	2.79 ± 2.41
K ($cmol_c$ dm^{-3})	92.77 ± 41.71	101.03 ± 33.04	44.83 ± 13.82	72.46 ± 18.65	69.67 ± 38.40	53.33 ± 24.27
Ca ($cmol_c$ dm^{-3})	1.72 ± 1.09	1.95 ± 1.46	0.47 ± 0.47	2.44 ± 1.37	2.52 ± 2.03	3.07 ± 2.04
Mg ($cmol_c$ dm^{-3}) *	1.16 ± 0.35	1.21 ± 0.38	0.66 ± 0.24	1.51 ± 0.66	1.33 ± 0.81	2.21 ± 1.11
CEC ($cmol_c$ dm^{-3})	3.43 ± 1.15	3.73 ± 1.69	2.04 ± 0.47	4.23 ± 1.91	4.14 ± 2.68	5.49 ± 3.14
C (%) *	2.74 ± 0.26	2.88 ± 1.04	1.70 ± 0.53†	2.28 ± 0.25	1.75 ± 0.30†	1.80 ± 0.31†
N (%)	0.21 ± 0.07	0.20 ± 0.05	0.25 ± 0.07	0.21 ± 0.04	0.19 ± 0.05	0.20 ± 0.03
$\delta^{13}C$ (δ ‰) *	-26.16 ± 0.45	-25.88 ± 0.46	-26.43 ± 0.38	-16.75 ± 0.27†	-20.33 ± 1.40†	-19.59 ± 1.30†
Density (g cm^{-3}) *	1.39 ± 0.03	1.37 ± 0.14	1.21 ± 0.04	1.51 ± 0.04	1.28 ± 0.11	1.24 ± 0.06
Clay (%)	54.85 ± 2.77	55.13 ± 5.54	49.76 ± 3.89	52.88 ± 20.09	51.46 ± 8.33	56.46 ± 4.45
Sand (%)	37.10 ± 3.78	35.99 ± 2.62	42.18 ± 4.98	40.98 ± 12.62	39.73 ± 4.69	35.15 ± 6.31

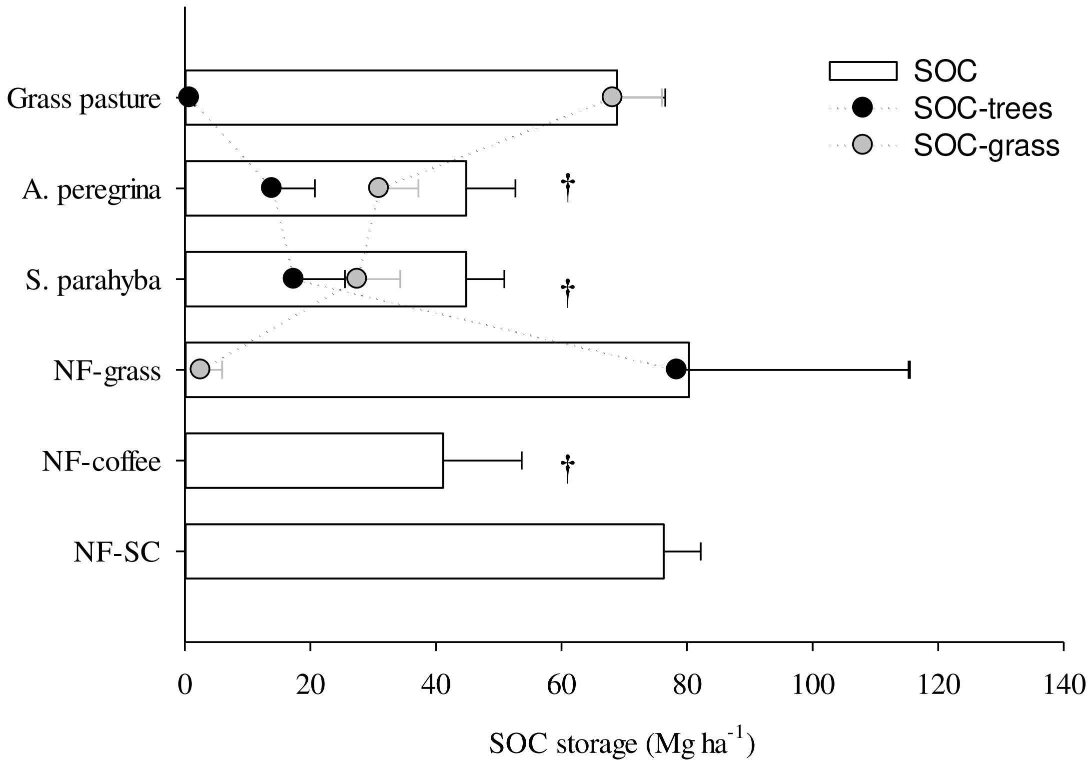

Fig. 2 Mean values of SOC storage (± standard deviation) at 0-20 soil layer in vegetational gradient compose by native forest (NF) regenerate after the selective cutting of trees (SC), grass pasture (grass), agriculture (coffee), and in grass pasture, and legume tree species plantations. The amounts of SOC derived from trees (black) and grass (grey) plants area showed by scattering lines. † Difference significant between each area and control NF-SC

DISCUSSION

The topsoil of NF regenerated after coffee culture was depleted in most soil properties compared to other NF after selective cutting and grass pasture. In fact, the soil acidity, Al, and base concentrations in the NF-coffee area were the lowest soil fertility class of soil fertility for the Espírito Santo state (Prezotti et al., 2007). In contrast, NF regenerated after grass pasture showed similar patterns of soil fertility and C pools compared to the NF after selective cutting. Guo and Gifford (2002) showed that the replacement of natural forests by agriculture was responsible for the reduction of C stocks by up to 60% in the first 30 cm of depth. However, the authors found that the conversion of natural forests to grass pastures does not result in a reduction in the C stock in regions with annual rainfall ranging from to 1000-3000 mm.

A set of factors could explain the differences observed in soil properties between NF regenerated after coffee and grass pasture areas, in addition to natural soil variability. The conversion of land use from NF to agriculture and livestock is achieved by harvesting all valuable wood species followed by the burning of forest slash. The traditional management of coffee culture, where the plants are alone, favors the loss of SOC and soil nutrients (Sales et al., 2013), especially in the early ages due to little ground cover. In addition, coffee plants were likely unfertilized in the 1960s. Grass pastures are widely known for their ability to store organic matter in soil Abdalla et al. (2018). The lower values of SOC storage in grass pasture area than in NF after selective cutting could be caused by occasional burning in the past of the seasonally dry Atlantic Forest. Although specific information about the historical burning in these areas is unknown, burning is a common practice used in agriculture and grass pastures in the region of study (Gobbo et al., 2016). Finally, we observed great stand deviation in SOC storage in the NF after the grass area. This was caused by one plot that showed high SOC storage (119 Mg ha^{-1}) and CEC concentration (6.24 cmol$_c$ dm^{-3}) in the gradient. This plot had the lowest altitude and the slope of the NF area. The CEC concentration found in this plot was the highest among soil fertility classes in the Espírito Santo state (Prezotti et al., 2007). Thus, we noticed the removal of this plot of the calculations, and the mean SOC storage values for NF after grass were reduced to 67 ± 13 Mg ha^{-1}. This value is very similar to that observed for grass pasture areas. The CEC value in the other three plots of NF after grass area was 2.89 $cmol_c\ dm^{-3}$.

The soil impact of coffee culture could be observed in the long term in the seasonally dry Atlantic Forest region. Although natural regeneration faced a more stressful soil environment in the coffee area than in the grass pasture area, the basal area of the stand was statistically equal between NF areas (Lorenzoni-Paschoa et al., 2019). Moreover, litterfall production and N, P, and C inputs were very similar among the NF areas (Neves, 2018, unpublished data). Thus, the availability of nutrients in the soil likely has less effect on the long-term accumulation of biomass after 50 years. However, differences in the structure and phytosociology of vegetation between NFs have been observed (Lorenzoni-Paschoa et al., 2019). These authors found similar species richness and diversity between NFs regenerated after selective cutting of the tree and after grass. At the same time, the pattern difference in NF after coffee showed slower advancement of the successional stage of vegetation in this area than in NF after grass (Lorenzoni-Paschoa et al., 2019).

Further studies could assess more details of soil type and parental material to confirm the tendencies in NF areas. Paz et al. (2016) showed that clay-rich soils have higher SOC storage than sandy-rich soils. However, in sandy soils, there was an increase in SOC storage over the time of forest succession. On the other hand, the slow recovery of SOC storage in NF regenerated after coffee may be explained by the high clay content in the topsoil layer. Moreover, the area with NF regenerated after grass pasture still presents recalcitrant forms of grass-derived C, possibly protected in macroaggregates (Six et al., 2002).

The planting of both legume trees decreased in about 35% the SOC storage in 0-20 cm layer in relation to pasture area at six years after planting. This difference in SOC storage is between the highest observed in reviews and meta-analyses (Guo and Gifford, 2002; Don et al., 2011; Shi et al., 2016). Mass correction (Don et al., 2011) was not used to minimize the effects of land use on topsoil density because of small differences in patterns observed for SOC storage. Using the correction of soil mass with native forest after selective logging as a reference por example, the estimated decrease in SOC by legume tree planting on grass pasture was 22%. However, we showed that the patterns are different for N_2-fixing tree species because, in general, there is an increase in SOC storage after the establishment of this species (Guo and Gifford, 2002; Shi et al., 2016). Moreover, the change in the isotopic composition of ^{13}C suggested a faster loss of labile soil C derived from grass in the first six years after planting. At the same time, the input of SOC derived from trees was slightly higher in *S. parahyba* than *in A. peregrina* trees up to six years after (2.8 versus 2.3 Mg SOC ha^{-1} $year^{-1}$). This indicates a more rapid turnover of SOC after the introduction of non-N_2-fixing legumes that have a higher growth rate in stem diameter and total height than the N_2-fixing *A. peregrina* Bighi et al. (2021).

The $\delta^{13}C$ values of the soil were slightly lower in the plantations of *S. parahyba* than *in A. peregrina*. Plots with *S. parahyaba* were completely occupied by *Brachiaria* sp., while the presence of grasses in the understory was drastically reduced in plots with *A. peregrina* (Campanharo, 2017). The presence of grasses should lead to higher $\delta^{13}C$ values in the soil with *S. parahyba* than *in A. peregrina* trees. This pattern may be explained by the functional traits of trees that influence the litter decomposition process De Deyn et al. (2008), as well as the presence of understory that may prevent loss of litter and SOC in *S. parahyba*. For example, the $\delta^{13}C$ value was smaller in the leaf litter of *S. parahyba* than *in A. peregrina* (Paula et al., unpublished data). Furthermore, it is likely that SOC derived from both legume trees occurred in the sand fraction because of the significant negative correlation by Spearman correlation between clay content and SOC derived from trees (-0.523; P=0.0255; N=18). Further studies should assess more details about the litter quality of this legume species, as well as the correlations between texture and SOC derived from species over the long term in this planting.

Soil fertility generally improved after the introduction of tree legumes into grass pasture areas, although the differences were not statistically significant. These results may also be explained by the effect of fertilizer in the planting, which has been cycled by trees over the years. However, the differences in chemical properties, although subtle, indicate that soil fertility (*e.g.*, CEC) was likely affected by the N_2-fixer trees compared to *S. parahyba*, but not by N and C pools. Faster improvement in soil fertility occurs with the introduction of fast-growing N_2-fixing trees, mainly on severely degraded land in the Atlantic Forest biome Macedo et al. (2008). However, this does not appear to have been the case for our grass pasture, since soil fertility parameters were similar or greater in the grass pasture than in the NF.

CONCLUSION

Our results identified different patterns of topsoil properties among restoration models with long-term natural regeneration areas and medium-term legume tree plantations. Fifty years after traditional coffee culture, the 0-20 cm soil depth still showed higher soil acidity and lower soil fertility parameters, as well as SOC storage, while soil properties were more similar between NF after grass pasture and selective cutting. Thus, the patterns of topsoil properties suggest that long-term natural regeneration may be insufficient to recover the original topsoil in previous coffee areas of seasonally dry tropical climates. However, further studies are needed to assess more soil and land historical details to confirm our results. Legume tree plantations established on grass pasture showed similar trends of decrease in approximately 35% of the SOC storage compared to grass pasture area. However, the SOC derived from trees increased rapidly in the first six years of tree plantation (≈ 3 Mg SOC ha^{-1} $year^{-1}$). Furthermore, the differences in soil fertility suggested a more positive effect of N_2-fixer *A. peregrina* than non-N_2-fixer *S. parahyba*, although statistically significant differences were not found up to six years after planting.

ACKNOWLEDGEMENT

We would like to thank *Conselho Nacional de Desenvolvimento Científico e Tecnológico* -CNPq - for the financial support (Post-Doc fellowships numbers 300369/2016-6 and 159972/2018-3) and *Fundação de Amparo à Pesquisa e Inovação do Espírito Santo* (grants 71416382/2016 and 64946088/2013). We are also grateful for *Laboratório de Recursos Hídricos e Solos* of DCFM/UFES and *Laboratório de Isótopos Estáveis* of CENA/USP for their technical support. We would like to thank *Instituto Federal de Ciência e Tecnologia do Espírito Santo*, Campus de Alegre, and your partners, for the available study area formally called the "Floresta Piloto" and “Polo Educação Ambiental da Mata Atlântica”.

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