Impact of forest–pasture conversion on soil physical and chemical properties

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Abstract

The objective of this paper is to assess the changes in soil physical and chemical properties resulting from the conversion of native forest to pasture and pasture to secondary forest in the state of Santa Catarina, Brazil. Seven forest–pasture successional stages were identified using aerial photographs and satellite images acquired in 1957, 1978, and 2008. Successional stages were coded as FFF, FPF, PFF, PPF, FPP, FFP, and PPP, where the first, second, and third letters refer to the land uses (P, pasture; F, forest) practiced in 1957, 1978, and 2008, respectively. Soil samples were collected by layer at depths of 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm. Clay contents, soil bulk density (D_b), macroporosity (MP), microporosity (mP), pH, Aluminum (Al), cation exchange capacity (CEC), calcium (Ca), potassium (K), phosphorus (P), total organic carbon (TOC) content, carbon stock, and $\delta^{13}C$ abundance were quantified. Conversion of forest to pasture increased soil P, K, Ca, D_b, and mP; and reduced MP, TOC content, and carbon stocks. The largest carbon stocks occurred in sites occupied by forests but previously used as pastures. Forest and pasture age influenced $\delta^{13}C$ values, resulting in different isotopic signatures for different sites, confirming the transition from C_3 to C_4 plants. In 50-year-old pastures, about 66 % of soil TOC is still derived from the primary forest biomass.

Keywords: Carbon stocks. Soil use conversion. ^{13}C natural abundance. Soil fertility.

Introduction

Alterations in ecological systems previously in equilibrium, such as the replacement of native vegetation by pasture or the succession from meadow to secondary forest, imply changes in soil properties. Such changes are influenced by several factors, including climate, soil type, crop cultivation, and land management practices. Because soil chemical, physical, and biological properties may vary greatly, soils under native vegetation are commonly used as a reference in the study of local soil quality. And the soil quality assessment should specify the functions and ecosystem services (BÜRGI *et al.*, 2017; BÜNEMANN *et al*., 2018).

Soil's physical and chemical properties are important indicators of changes resulting from land conversion. Degradation of soil physical properties is one of the major processes leading to the loss of soil structural quality and increased water erosion. In view of its importance for the sustainability of agricultural systems, soil physical quality needs to be closely monitored. Each soil-health goal requires a different set of parameters to be monitored, compared with reference states when appropriate and managed (LEHMANN *et al*., 2020; ALAWAMY *et al*., 2022).

Several studies have assessed soil chemical properties to identify which types of land use have the least impact on the environment. It is expected that changes in land use and management or application of agricultural waste will affect carbon (C) stocks in soil, but their effects are limited (TORU *et al.*, 2019; ALAWAMY *et al.*, 2022). There is a limit to C saturation and loss in soil, as losses or gains occur until the system achieves

C stock stabilization. That is, soil carbon stocks depend on the inputs and outputs of C in the soil. (DIGNAC *et al*., 2017).

Natural isotopic tracers can be used to better understand the complexity of landscape transformations. For instance, ^{13}C natural abundance measurements can reveal the origins of soil organic C and the plant material from which is derived (BALLESDENT *et al.*, 1987; VOLK *et al.*, 2018). ^{13}C variations can be used to examine the effects of time on the structure of anthropic ecosystems (SENA-SOUZA *et al.*, 2019; SMITH; CHALK, 2021).

Isotopic analyses have also been used to study organic matter cycling in the medium term in tropical regions where forests (C_3 photosynthetic cycle) have been replaced by crops (C_4 photosynthetic cycle) (MACHADO *et al*., 2019; LIMA *et al*., 2020). Compared with C_3 plants, C_4 plants discriminate less between C isotopes and are more enriched in ^{13}C; as a result, $\delta^{13}C$ values range from −6 to −19‰ (mean of −13‰) in C_4 plants and from −20 to −34‰ (mean of −27‰) in C_3 plants (SMITH; CHALK, 2021). C isotope ratios were used to study changes in soil caused by alterations in the Amazon forest cover (SILVA *et al.*, 2021).

Based on the above considerations, this paper aimed to assess the changes in soil physical and chemical properties resulting from the conversion of native forest to pasture and pasture to secondary forest in Santa Catarina state, Brazil.

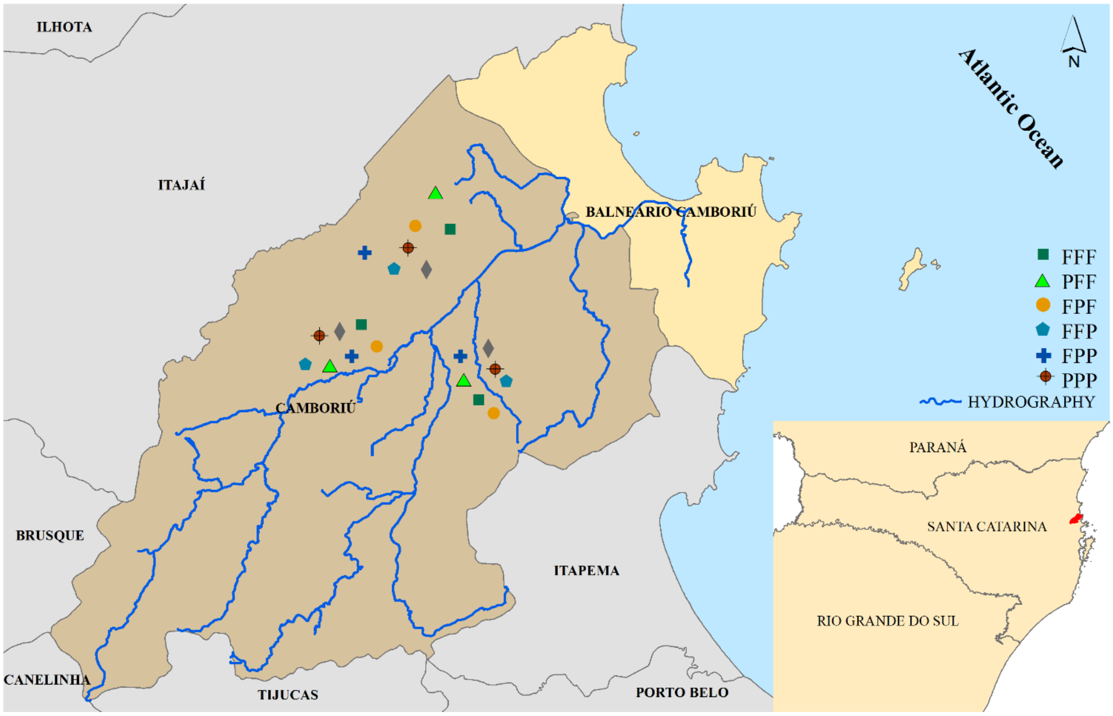
Material and methods

This study was conducted in an area of 25,824.83 ha located in the Camboriú River Basin (between geographic coordinates 26°57'15" and 27°9'20"S and 48°33'30" and 48°48'45"W), in the municipalities of Camboriú and Balneário Camboriú, coastal region of Santa Catarina, Brazil (FIGURE 1). The local climate is humid subtropical with hot summers (Cfa in the Köppen system). The area belongs to the Dense Ombrophilous Forest region, Submontane Forest Formation, with a vegetation cover characterized by a large number of plant species that develop in four distinct strata (SANTA CATARINA, 1986). The dominant soils in the region are Acrisols, Cambisols, and Gleysols (WRB, 2015). In the Brazilian Soil Classification System (EMBRAPA, 2018), the soils are Argissolo Vermelho-Amarelo Distrófico típico, Cambissolo Háplico Distrófico típico, and Gleissolo Háplico Tb Distrófico típico. However, for this study, three areas were selected, all in the middle third of the slope and under the same soil class (Acrisol – Argissolo Vermelho-Amarelo Distrófico típico), as described in Dortzbach (2015). The decimal coordinates and altitude of the collection points are shown in Table 1.

Changes in land use and cover were analyzed using georeferenced panchromatic aerial photographs taken in 1957 and 1978 at a 1:25,000 scale and orthorectified synoptic satellite images acquired by QuickBird in 2008 with a spatial resolution of 60 cm. Sites were represented by polygons generated by vectoring.

Crosstab analysis of thematic images on consecutive dates was performed using ArcGIS®. Combinations were performed among all uses and dates to select the most representative successional stages. Seven successions related to forest and pasture use were selected (FFF, FPF, PFF, PPF, FPP, FFP, and PPP), which together represented more than 75 % of the changes in land use during the studied period. Sites were coded with three letters, where the first, second, and third letters denote respectively the land uses practiced in 1957, 1978, and 2008 (FIGURE 2). F represents forest, and P indicates cattle pasture sites with a mean stocking density of 1.5 animal units ha^{-1} throughout the year. FFF represents areas with Submontane Dense Ombrophilous Forest, either non-degraded or in

Figure 1. Location of the municipalities of Balneário Camboriú (SC) and Camboriú (SC), and collection points of soils



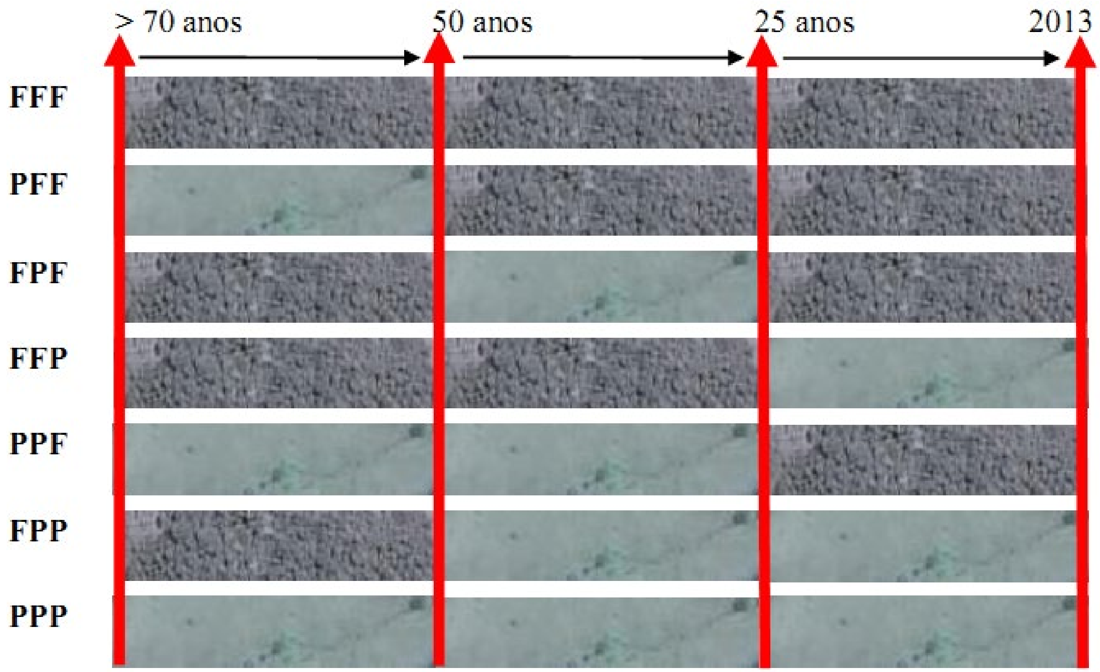
Source: Elaborated by the authors (2021).

Table 1. Location and altitude of collection sites in each of the areas evaluated in Camboriú (SC)

Sample		Site 1	Site 2	Site 3
FFF	Latitude (°)	-27,124223	-27,073517	-27,108475
	Longitude (°)	-48,696132	-48,727235	-48,787928
	Altitude (m)	31	44	33
PFF	Latitude (°)	-27,100626	-27,092556	-27,065794
	Longitude (°)	-48,713436	-48,699781	-48,718768
	Altitude (m)	31	32	33
FPF	Latitude (°)	-27,094953	-27,070376	-27,070374
	Longitude (°)	-48,735210	-48,729755	-48,729753
	Altitude (m)	79	25	25
FFP	Latitude (°)	-27,068070	-27,094953	-27,054437
	Longitude (°)	-48,729538	-48,735210	-48,681542
	Altitude (m)	24	79	28
PPF	Latitude (°)	-27,082313	-27,107025	-27,105217
	Longitude (°)	-48,733386	-48,773840	-48,770616
	Altitude (m)	47	60	109
FPP	Latitude (°)	-27,067879	-27,069620	-27,105010
	Longitude (°)	-48,723862	-48,729646	-48,745899
	Altitude (m)	25	24	44
PPP	Latitude (°)	-27,092311	-27,092556	-27,079366
	Longitude (°)	-48,701035	-48,699781	-48,729220
	Altitude (m)	31	32	37

F=forest, P=pasture.
Source: Elaborated by the authors (2021).

Figure 2. Representation of the composition of the treatments FFF, PFF, FPF, FFP, PPF, FPP and PPP in relation to time of use of land, > 70 years, 50 years, 25 years, until the year 2013 (year of soil collection)



Source: Elaborated by the authors (2021).

an advanced stage of regeneration. In other sites coded with an F, the original forest vegetation was completely cleared for pasture implementation.

Land use successions were considered as treatments, mapped, and plotted for identification in the field. Three sample collection points (repetitions) were defined for each treatment on the basis of map observation and interviews with local residents. In secondary forest sites (FPF, PFF, and PPF), collections were performed in areas of intermediate succession (FIGURE 2).

Disturbed and undisturbed soil samples were collected by layers at depths of 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 am, and 80–100 cm. Disturbed samples were a composite of three individual samples for each soil depth. After collection, samples were identified, packed in plastic bags, and transported to the laboratory. Then, samples were air-dried, ground, and passed through a 2 mm mesh sieve to obtain air-dried fine earth (ADFE) for analysis. The following chemical properties were evaluated: pH in water, Ca^{2+}, Mg^{2+}, K^+, P, Al^{3+}, and cation-exchange capacity (CEC) at pH 7.0 (TEIXEIRA *et al*., 2017).

Undisturbed soil samples were collected using metallic volumetric rings (5 cm height and 6 cm diameter). Soil bulk density, total porosity, microporosity, macroporosity, and granulometry (clay fractions) were determined by the pipette method (TEIXEIRA *et al*., 2017).

Total organic carbon (TOC) and isotopic abundance ($\delta^{13}C$) analyses were performed at the Center for Nuclear Energy in Agriculture (CENA) of the University of São Paulo (USP), Piracicaba, Brazil. $\delta^{13}C$ values were determined in 300 mg of ADFE, previously milled and sieved through a 100-mesh sieve. Measurements were performed with a precision of 4 decimal places. Then, samples were packed in tin capsules and subjected to continuous-flow isotope-ratio mass spectrometry using a Finnigan Delta Plus mass spectrometer coupled to Carlo Erba EA 1108 elemental analyzer. Isotopic results are expressed in relation to the Pee Dee Belemnite (PDB) standard.

Organic C stocks were calculated by layer using the equation proposed by Veldkamp (1994) (EQUATION 1):

$$CS = \mathrm{TOC} \times D_\mathrm{b} \times L \div 10 \quad (1)$$

at which: CS is the organic C stock (Mg ha^{-1}) in the soil layer, TOC is the total organic C content (g k^{-1}) in the soil layer, D_b is the soil bulk density (Mg m^{-3}) of the soil layer, and L is the thickness (cm) of the soil layer.

After calculation, C stocks were corrected for soil equivalent mass (SISTI *et al.*, 2004), using FFF soil as a reference. This procedure was necessary because, after compression, pasture soil samples, for example, cannot be directly compared with forest soil samples collected at the same depth. Correction for soil equivalent mass is used to minimize the effects of soil use and management on soil bulk density, according to Ellert and Bettany (1995).

The percentage of C derived from pasture (C_p) and forest (C_f) was obtained by calculating the isotopic dilution, as shown in Equations 2 and 3:

$$\mathrm{C_p} = \frac{\delta - \delta_\mathrm{o}}{\delta_\mathrm{c} - \delta_\mathrm{o}} \times 100 \quad (2)$$

$$\mathrm{C_f} = 100 - \mathrm{C_p} \quad (3)$$

at which: δ is the δ^{13}C value of the soil sample, δ_c is the δ^{13}C value of C_4 plants (−12.4‰), (BALBINOT, 2009), and δ_o is the δ^{13}C value of forest soil.

Means were compared at $p < 0.05$ by Tukey's test. Pearson correlation analysis and linear regression were performed. Statistical analyses were conducted using Assistat version 7.7 beta (2011) and Microsoft Excel.

Results and discussion

Clay contents did not differ significantly between sites (FIGURE 3a), with a tendency to higher levels in pasture sites. It is probable that pasture sites were subjected to intense erosion, facilitated by the land slope. Therefore, coarse grains were carried off from surface horizons and fine grains remained in subsurface layers. In landscape points with greater slope, surface water runoff is intensified, leading to selective removal (loss) of clay particles from surface horizons by erosion, characterizing the specific pedogenetic process of elutriation, which results in a relative increase in clay content in depth (KÄMPF; CURI, 2012). In all areas evaluated, there was a significant increase in the clay content at depth (Figure 3a), which is due to the pedogenetic process of Argiluviation, with subsequent formation of the textural diagnostic horizon B (KÄMPF; CURI, 2012). In all areas of this study, we have the class of Acrisols (Argissolos).

Soil bulk density varied significantly between sites and soil depths (FIGURE 3b). At the 0–10 cm depth layer, the bulk density of sites that were last covered by forest (FFF, PFF, FPF, and PPF) was significantly lower than that of sites last covered by pasture (FFP, FFP, PPP). In forest sites, bulk density ranged from 0.79 Mg m^{-3} to 0.92 Mg m^{-3}; and in pasture sites, from 1.12 Mg m^{-3} to 1.20 Mg m^{-3}. The higher density in the latter is likely due to mechanical pressures from cattle trampling (FIGURE 3b). Similar results for pasture sites were observed by Freitas *et al*. (2012). The authors assessed the bulk density of orthic Quartzarenic Neosol under four land uses: native forest, pasture, agroforest, and cropland (recently converted). Pasture sites were shown to have the highest soil bulk density, attributed to long-term grazing by cattle and horses at a stocking rate of 1.30 animal units ha^{-1}.

Machado *et al*. (2019) evaluated the soil bulk density in three areas of Seasonal Semideciduous Forest, with different successional stages (initial-stage forest – ISF, medium-stage forest – MSF, and advanced stage forest – ASF), located in areas of the middle third of slopes in Pinheiral (RJ). The authors found lower values of bulk density in the ASF area, and these results are due to the constant deposition of plant residues on the soil surface in this area. Prior to the use of forest, all areas were used for pasture. These results corroborate those found in the present study, in which 25 years of forest cover following pastureland use (FPF and FFP) led to reductions in soil bulk density.

At the 10–20 cm depth layer, differences between pasture and forest sites became less evident. The highest bulk density was observed in PPP, which differed from the other sites, except PFF. PPP had the highest bulk density at all depths, but no differences were observed between sites in the 80–100 cm depth layer.

The lower values of soil bulk density in the Forest areas are due to the fact that this area is in good edaphic conditions, with greater biological diversity, and higher content of organic matter, which is characterized as one of the factors responsible for maintaining the physical conditions of the soil, and which also has more influence on the reversal of the state of soil compaction. The higher values of soil bulk soil for the surface layers of pasture areas are a consequence of animal traffic, poor soil management due to overgrazing, and other forms of pressure, which favored greater compaction (Santos *et al*., 2020).

There is a progressive increase in soil bulk density values with increasing depth for all areas evaluated (FIGURE 3b). This pattern was also observed for clay values (FIGURE 3a), which suggests that this increase in soil bulk density may be associated with the soil type (Acrisol), which presents a block structure in the subsurface horizons, and an increase in the clay content due to the clay translocation process. This usually causes higher soil density values. As reported by Padua *et al.* (2015), the eluviation of clay particles and the presence of a block or prismatic structure tend to favor the highest values of soil bulk density at depth. And this is due to the lower macroporosity, under similar texture and mineralogy conditions. These results corroborate the highest values of the micro/macroporosity ratio in areas with pasture (3d).

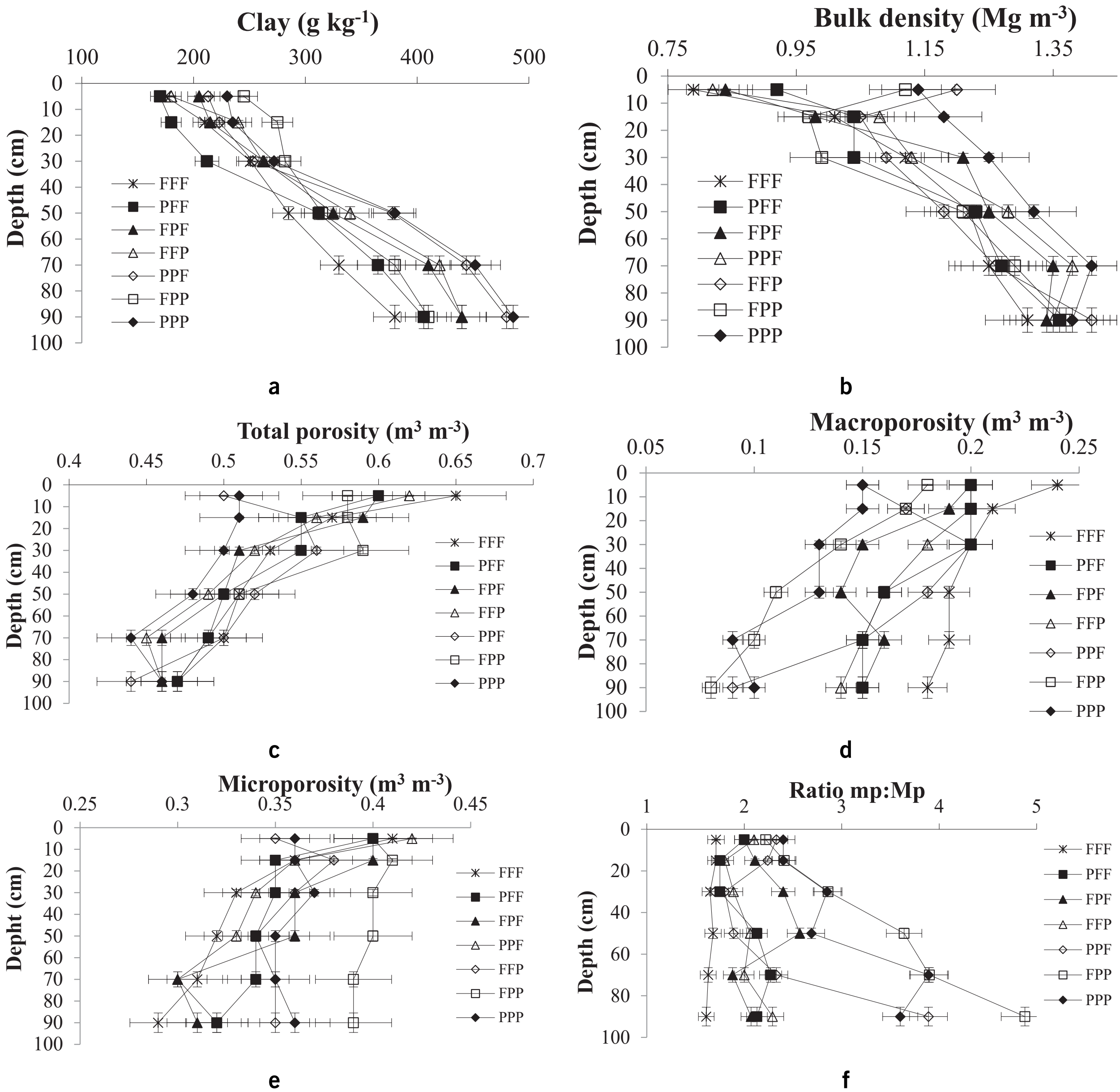
The total porosity of surface layers (FIGURE 3c) at all sites was in accordance with the considered ideal for most crops, i.e., above 50 %. According to Camargo and Alleoni (1997), for most non-irrigated crops, soils should ideally have a pore volume of 50 %, of which, at field capacity, 33.5 % is occupied by water and 16.5 % by air. The higher total porosity observed in FFF is probably due to the environmental balance made possible by the lack of anthropogenic disturbances. In addition, the contribution of soil organic matter and biological activity in the soil aggregation process is added, as reported by Machado *et al*. (2019) and Toru *et al.* (2019).

FFF had a higher macroporosity than FPP and PPP in surface layers, although the differences were not significant (FIGURE 3d). All values were higher than the minimum required for good air and water flow, 0.10 dm^3 dm^{-3} (HILLEL, 1998). Pore volume to microporosity was higher than macroporosity (FIGURE 3e). Clay soils tend to have a predominance of micropores, whereas sandy soils have a predominance of macropores (BRADY; WEIL, 2013). In the surface layer, the micropore volume of PPP and FFP was significantly lower than that of other sites. In the deepest layers, the highest values were found in FPP (FIGURE 3e).

Microporosity/macroporosity ratios indicated that, in most sites, soil conditions were adequate for agricultural crops; that is, the ratio was close to 2:1 (BRADY; WEIL, 2013). PPF, FPP, and PPP had less favorable soil properties, particularly in the deepest layers (FIGURE 3f). According to Kiehl (1979), under ideal conditions, two-thirds of the pore volume should be formed by micropores and one-third by macropores.

The results show that the conversion of forest to pasture had negative effects on soil's physical

Figure 3. Values of the physical properties of the soil at depths of 0-10 cm, 10-20 cm, 20-40 cm, 40-60, 60-80 and 80-100 cm, in treatments FFF, PFF, FPF, FFP, PPF, FPP and PPP



Source: Elaborated by the authors (2021).

properties. The reduction in macroporosity and total porosity and increase in microporosity and soil density can alter the flow of water and nutrients in the soil, affecting crop development and erosion processes. In addition to the effect of converting the forest to pasture, the increase in microporosity and soil density, with a consequent decrease in macroporosity and total pore volume, may also be related to the increase in clay content at depth (FIGURE 3a), due to the eluviation process. It is also due to the decrease in organic carbon contents at depth (FIGURE 5a), which causes a decrease in biological activity.

Soil chemical properties varied greatly between sites because of the differences in soil management systems. For instance, pasture sites are fertilized and limed. Nevertheless, the changes in soil properties resulting from land-use conversion were evident.

Soil pH was higher on the surface horizon of FFP and FPP than of sites last covered by forest (FIGURE 4a). This result can be attributed to lime application, used to increase pasture productivity. Secondary forest sites converted from pasture (PFF, FPF, PPF) and FFF had similar pH levels, indicating that, with time and without anthropogenic activity, soil pH levels decrease and tend toward levels found in non-degraded soils. The differences in pH between sites became less prominent in deeper layers. Below the 60 cm depth, no differences were found between pasture and forest sites.

Soils with high pH also had low Al levels, although no significant differences were found between sites (FIGURE 4b). In surface layers, Al content was highest in FFF and lowest in FFP and FPP. In general, Al levels increased with depth, surpassing 4 $mol_c\ dm^{-3}$, a concentration that is toxic to plants.

Cation exchange capacity (CEC) levels had similar behavior to pH levels: values were higher in surface layers and decreased with depth, except for the PPP site (FIGURE 4e). This result may be related to the presence of organic matter, as the highest total organic carbon (TOC) values are found in the surface layer, with a consequent decrease in-depth (FIGURE 5a). Ca levels were much higher in FPP, followed by PPF and PPP, than in FFF and PFF (FIGURE 4c). The high levels of Ca in pasture sites were due to the application of lime, a major source of Ca. The highest levels were found in the 0–10 cm depth layer in all sites.

All sites had higher K levels than FFF, resulting from soil fertilization. This shows that K is persistent in soil, as, even in sites with more than 50 years of secondary forest cover (PFF), the levels of K were much higher than those in FFF (FIGURE 4d). However, significant differences between FFF and PPP and FPF were only observed in the 0–10 cm depth layer. Overall, K levels did not differ significantly with depth.

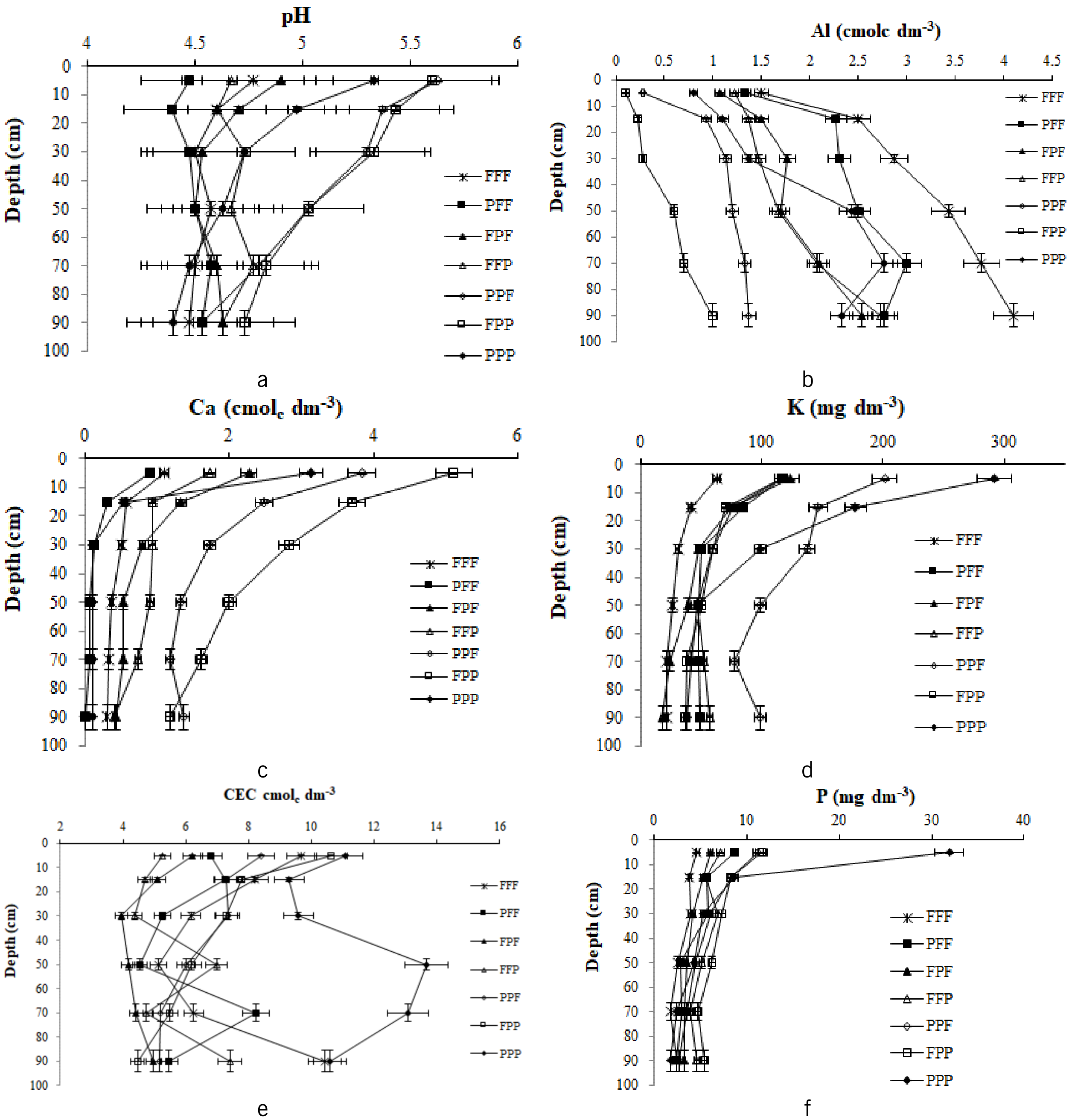
The highest P level was found in the surface layer of PPP (FIGURE 4f), which differed significantly from other sites. Low values were observed in secondary forest sites with a history of pastureland use (PFF, FPF, PPF), but P contents were higher than that in FFF. Even after long periods of land abandonment and the establishment of secondary vegetation, P levels did not decrease to levels found in sites without anthropogenic disturbances (FFF), although differences were not significant.

The PPP area stands out from the others in relation to the highest levels of P and K in the surface layer of the soil (FIGURES 4d; 4f). In addition to the effect of fertilization, forage grasses are efficient in cycling nutrients, as well as favoring soil aggregation, which favors soil fertility. Added to these factors, there is the deposition of bovine feces and urine on the surface of the pasture soil, which also favors the contribution of P and K (ZIN BATTISTI *et al*., 2018). The higher values of CEC in the PPP site in depth are due to the high values of Al (FIGURE 4b).

Sites differed in TOC content only in the surface layer. The highest values were observed in PFF, FFF, and PPF (FIGURE 5a), demonstrating that forest cover increased organic matter deposition, except in FPF, which had lower TOC contents. The results for PFF and PPF suggest that regeneration for more than 25 years can favor TOC recovery after deforestation. However, TOC recovery was not observed in FPF, in which pasture was maintained for 25 years, followed by secondary forest development. It is possible to assume that FPF sites had low natural fertility or another impediment, which consequently affected pasture crop productivity and organic matter input, leading to land abandonment.

Other studies have shown that TOC content is higher in forest sites than in pasture sites (Cardoso *et al*., 2010; Machado *et al*., 2019), as the organic matter input is higher in the former. The highest levels of TOC in PFF and

Figure 4. Values of the chemical properties of the soil at depths of 0-10, 10-20, 20-40, 40-60, 60-80 and 80-100 cm, in treatments FFF, PFF, FPF, FFP, PPF, FPP and PPP. 4a. pH; 4b. Aluminum ($cmol_c$ dm^{-3}); 4c. Calcium ($cmol_c$ dm^{-3}); 4d. Potassium (mg dm^{-3}); 4e. cation exchange capacity – CEC ($cmol_c$ dm^{-3}); 4f. Phosphorus (mg dm^{-3})



Source: Elaborated by the authors (2021).

PPF indicate that, as a function of the forest succession time, there is an increase in the C, which can be attributed to the structural complexity of the vegetation, mainly in terms of density and basal area, which in turn may influence the deposition and accumulation of litter (Machado *et al.*, 2019). However, contradictory results are found in the literature with regard to soil C stocks in forest and pasture, because this parameter depends on the initial C stock and the soil management strategies adopted in pasture systems. The results of this study do not agree with those of Guo and Gifford (2002), who found that the conversion of forest to pasture increased C stocks by 8 %. Alves *et al*. (2008) argued that the TOC content of pasture soil may be close to or even higher than that of forest soil, mainly in surface layers. C stocks generally increase with depth in forest soil.

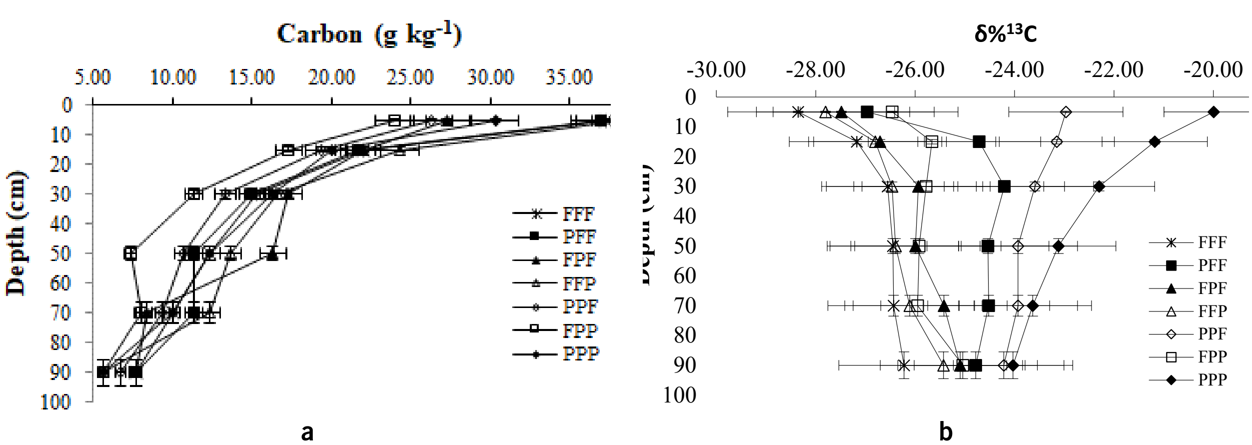
The low TOC content observed in pasture sites is likely due to soil degradation and lack of adequate management. According to Carvalho *et al*. (2011) and LAPIG (2021), in Brazil, more than half of the pastures used for livestock grazing are at some stage of degradation, resulting in low production of plant biomass and organic waste and, consequently, TOC contents. Conant *et al*. (2001), in an extensive review of the literature comprising more than 100 studies conducted in 17 countries, reported the importance of soil management strategies aimed at carbon buildup in pasture sites. The authors concluded that fertilization and the use of adequate animal stocking rates can increase C sequestration by up to 0.3 Mg C ha^{-1} year^{-1}.

In general, TOC content was lower in deeper horizons, as the organic matter input is normally greater in surface layers (FIGURE 5a). In 50–100 cm depth layers, no differences were observed between sites, showing that organic matter deposition has a higher effect on TOC content in surface layers.

The conversion of natural systems to cropland alters soil C dynamics, generally resulting in decreased C stocks. In surface horizons, FFF, PFF, and FPF differed significantly from other sites (FIGURE 6). C stocks were higher in the 0–10 cm depth layer (18.97–30.31 Mg C ha^{-1}) than in deeper layers, in accordance to the fact that organic matter is deposited at higher concentrations on the soil surface. In the 10 – 20 cm depth layer, C stocks decreased by up to 25 % (in FFF) in relation to the levels of C on the surface horizon, and significant differences were observed between PFF (24.71 Mg C ha^{-1}) and FFP and FPP. No differences between sites were observed in the 50–60 cm depth layer. In the deepest layer (60-80 cm), FFF, FPF, and PPF differed significantly from PFF, PPP, and FFP. In 80–100 cm depth soil, C stocks were higher in PFF (154 Mg C ha^{-1}) than in FFF (148 Mg C ha^{-1}), and the lowest C stocks were observed in FFP (112 Mg C ha^{-1}).

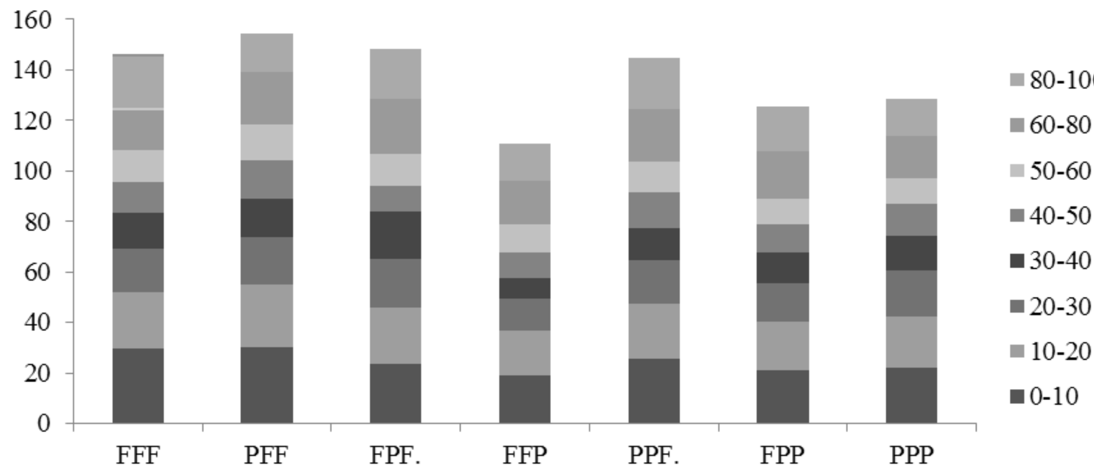
FFF had the lowest δ^{13}C values, varying from −28.35‰ in the 0–10 cm depth layer to −26.20‰ in the 60–80 cm depth layer (FIGURE 5b). This result indicates a predominance of C_3 plants (FIGURE 4f).

Figure 5 – Values of the carbon (g kg^{-1}, 5a) and natural abundance of δ^{13}C (**‰, 5b**)



Source: Elaborated by the authors (2021).

Figure 6. Soil carbon stocks (Mg C ha^{-1}) for the treatments FFF, PFF, FPF, FFP, PPF, FPP and PPP at different depths



Means followed by the same letter in the column do not differ by Tukey's test ($p<0.05$).
Source: Elaborated by the authors (2021).

Similar findings were reported for Atlantic Forest sites (MACHADO *et al*., 2019) and other Brazilian biomes (LOSS *et al.*, 2014; PEREIRA *et al*., 2020).

$\delta^{13}C$ became enriched with depth in all sites, corroborating literature data. According to Ballesdent *et al*. (1987) and Smith and Chalk (2021), the enrichment of $\delta^{13}C$ with depth is due to the following factors: microbial decomposition of organic substrates may involve a normal isotope effect; thus, microbial products may become more enriched in $\delta^{13}C$ than substrates; the $\delta^{13}C$ of plants and organisms may have inter- and intramolecular variations; global and local climatic variations may modify $\delta^{13}C$ over time; and humification increases soil organic matter $\delta^{13}C$ values.

In sites other than the native forest, soil organic matter was composed of two types of residues of plant material, that of C_3 plants (−21 to −35 %) and that of C_4 plants (−9 to −17 %). When comparing the $\delta^{13}C$ values of FFF and PPP, it is possible to observe the influence of land use on the predominant vegetation. $\delta^{13}C$ values were much higher in PPP, covered by C_4 plants, than in FFF, covered by C_3 plants. Differences between sites were more expressive in the surface layer (8.36 %) but remained detectable up to the 80–100 cm depth layer (2.19 %). In the site used for pasture for more than 50 years (PPP), 48 % of the C content in the surface horizon, 60 % in the 10–20 cm depth layer, and up to 84 % in the deepest layer originated from previous forest cover (TABLE 2).

In PFF, FPF, and FFP, all of which had a short history of pastureland use, no significant differences in C composition were observed in any depth. No differences were observed in $\delta^{13}C$ signature between PFF, covered by secondary forests for the past 50 years, and FPF, covered by secondary forest for the past 25 years (TABLE 2). These results indicate that a 25-year period of pasture interspersed with periods of forest cover is not sufficient to afford significant differences in the $\delta^{13}C$ signature, mainly because of the presence of native forest C. The storage of C in soil may be due to the low rate of C loss observed in forest remnants, the physical characteristics of soil (texture and structure), and the low rate of soil organic matter decomposition resulting from low microbial activity. Therefore, only long periods of pastureland use promote significant

Table 2 – Percentage of C from forest (F) and pasture (P) at different depths

Depth	FFF		PFF		FPF		FFP		PPF		FPP		PPP	
	F	P	F	P	F	P	F	P	F	P	F	P	F	P
cm	%													
0-10	100	0	97	3	95	5	88	12	91	9	66	34	48	52
10-20	100	0	98	2	97	3	90	10	83	17	73	27	60	40
20-40	100	0	99	1	96	4	95	5	85	15	80	20	73	27
40-60	100	0	98	2	93	7	95	5	87	13	83	17	80	20
60-80	100	0	96	4	94	6	93	7	93	7	86	14	83	17
80-100	100	0	94	6	92	8	92	8	90	10	86	14	84	16

Source: Elaborated by the authors (2021).

differences in the $\delta^{13}C$ of soil organic matter, especially if periods of pasture are interposed between long periods of forest cover. In such cases, the isotopic signature will reflect values from old C_3 plants, C_4 plants, and new C_3 plants.

Stable C isotope analysis of soil is an important tool for the detection of C isotopes from different systems, such as forest and pasture (TARRÉ *et al*., 200; PEREIRA *et al.*, 2020). However, pasture age is not solely responsible for changes in $\delta^{13}C$ values; soil management techniques, predominant vegetation, and environmental characteristics must also be considered.

Conclusions

Forest conversion to pasture increased soil P, K, and Ca levels, pH, soil bulk density, and microporosity, while decreasing macroporosity and soil C stocks. After more than 50 years of pasture use, 48 % of the TOC content in the soil surface layer is still derived from the original forest vegetation.

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