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Changes in organic carbon in soil of natural grassland converted to *Pinus taeda* plantations at three ages

Alterações no carbono orgânico do solo de campo natural submetido ao plantio de *Pinus taeda* em três idades

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Abstract

Pine plantations on former natural grassland (NG) areas can change the forms and stocks of organic carbon (OC) in the soil. To quantify these changes, the contents and stocks of the total OC (TOC), consisting of particulate OC (POC) and the mineral-associated OC (MAC) fractions, were determined in five layers, at depths between 0.0 and 0.40 m, in soil under NG and pine plantations aged five (P5), 16 (P16) and 21 (P21) years. The study was carried out in areas of Cambissolo Húmico, dystrophic, on the southern plateau of Santa Catarina state. The TOC content in the different layers and under different land uses ranged from 15.0 to 44.5 g kg^{-1} and the TOC stock, in all layers together, from 86 to 144 Mg ha^{-1}. The POC content varied from 2.1 to 23.2 g kg^{-1} and the POC stock from 7.4 to 21.8 Mg ha^{-1}, while the MAC content varied between 12.2 and 23.7 g kg^{-1} and MAC stock between 79 and 122 Mg ha^{-1}. In general, the TOC stocks and contents and MAC and POC fractions in the soil increase with the age of the pine plantations up to 21 years. The TOC and POC contents and POC stock usually decrease with depth under NG, P5 and P21, whereas the MAC content and MAC and TOC stocks generally remain unchanged in layers to a depth of 0.40 m.

Keywords: Organic matter; Carbon sequestration; Planted forests

Resumo

O plantio de pinus em áreas de campo natural (NG) pode alterar as formas e estoques de carbono orgânico (OC) do solo. Visando quantificar essas alterações, foram determinados os teores e estoques de OC total (TOC) e das frações particulada (POC) e associadas aos minerais (MAC) em cinco camadas, entre 0,0 e 0,4 m de profundidade, do solo sob usos com NG e plantios de pinus aos cinco (P5), 16 (P16) e 21 (P21) anos. O estudo foi realizado em áreas de Cambissolo Húmico na região do planalto sul de Santa Catarina. O teor de TOC, nas diferentes camadas e usos, variou entre 15,0 e 44,5 g kg^{-1} e seu estoque, na soma das camadas, entre 86 e 144 Mg ha^{-1}. O teor de POC variou entre 2,1 a 23,2 g kg^{-1} e seu estoque, entre 7,4 e 21,8 Mg ha^{-1}, enquanto o teor de MAC variou entre 12,2 e 23,7 g kg^{-1} e seu estoque, entre 79 e 122 Mg ha^{-1}. Em geral, os teores e estoques de TOC e das frações MAC e POC do solo aumentam com a idade dos plantios de pinus até 21 anos. Os teores de TOC e POC e o estoque dessa fração, em geral diminuem com a profundidade do solo sob NG e P5 e P21, mas o teor de MAC e os estoques dessa fração e do TOC geralmente não variam entre as camadas até 0,40 m de profundidade

Palavras-chave: Matéria orgânica; Sequestro de carbono; Reflorestamento

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Introduction

The southern plateau region of Santa Catarina state is characterized by large areas of montane grassland that were exploited in the past by extensive cattle production (UBERTI, 2005). However, since the 1950s, the region became a wood production center, where sawmills and pulp mills exploited the abundantly available Brazilian pine (*Araucaria angustifolia*). Due to the depletion of the reserves of this native tree, forest planting on the grassland areas expanded rapidly since the 1980s, especially with species of the genus *Pinus*, increasing the share of the state of Santa Catarina to approximately 34% of the Brazilian pine production, with forests covering an area of around 540 thousand hectares (INDÚSTRIA BRASILEIRA DE ÁRVORES, 2016).

The substitution of the natural grassland with predominantly grass species by pine plantations modifies the dynamics of soil organic matter (BALDOCK; NELSON, 2000; LOPES et al., 2010; DICK et al., 2011). This may alter the levels and stocks of organic carbon (OC) accumulated in this environment (BUTNOR et al., 2017). In pine forests, the large majority of OC is accumulated in the plant biomass (RICHTER et al., 1999; WATZALAVICK; SANQUETTA; CALDEIRA, 2005; HUANG et al., 2011; SAMUELSON et al., 2017). However, these forests can also accumulate significant amounts of OC in the soil, mainly derived from the turnover of fine roots (LOPES et al., 2010; HUANG et al., 2011; PERSSON, 2012) and residues of dead leaves and branches, forming the forest litter (BALDOCK; NELSON, 2000; CORREIA; ANDRADE, 2008). In soils under forest, this accumulation is favored by the absence of tillage, thus preserving the aggregation of the colloidal particles, promoting the physical protection of organic compounds within these structures (FELLER; BEARE, 1997; SIX et al., 2000).

The OC of the soil consists of a great diversity of compounds, which motivated the development of analysis techniques to determine more specific fractions, in particular with regard to their nature, dynamics and function in the soil (CAMBARDELLA; ELLIOTT, 1993; SIX et al., 2000). Among these techniques, there is the physical particle-size fractionation that separates the soil OC in two fractions, one of particulate organic carbon (POC), composed of particles with diameters of > 0.053 mm and the other of organic mineral-associated carbon (MAC), with diameters of < 0.053 mm (CAMBARDELLA; ELLIOTT, 1993). The POC is a more recently formed fraction and reflects the contributions of crop residues and management type (FELLER; BEARE, 1997; BAYER et al., 2004; WENDLING et al., 2010). The MAC fraction on the other hand has a longer residence time, and is derived from processes of formation and accumulation of humic substances in the medium and long term that are more stable, due to the protection by chemical bonds between organic and clay minerals (PARFITT et al., 1997; SIX et al., 2002).

The POC is generally smaller than the MAC fraction (BAYER et al., 2004), but has been used as an indicator of soil organic matter dynamics (SOM), for indicating the alterations caused by changes in the management in the short term (FELLER, 2000; BAYER et al., 2004; BRUN, 2008).

The influence of pine cultivation on soil organic carbon (OC) stocks under the different soil and climatic conditions still require studies and assessments to determine the potential of atmospheric CO_2 fixation or sequestration by this forest type (BALBINOT et al., 2003; BUTNOR et al., 2017). The goal of this study was to determine the changes in the content and stock of total organic carbon (TOC) and of the POC and MAC fractions, in layers up to 0.40 m deep of the Cambissolo Húmico, dystrophic, under natural grassland and second crop cycle of *Pinus taeda* L. plantations after 5, 16 and 21 years.

Material and methods

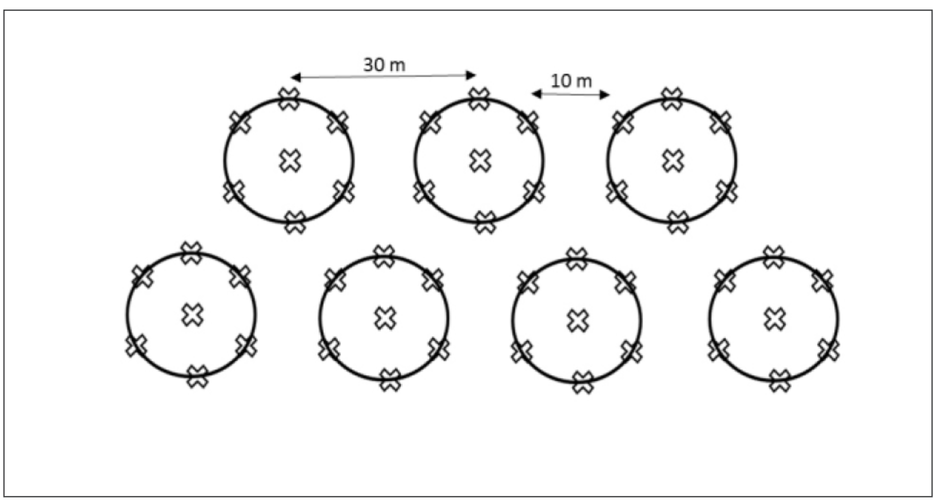
The study was carried out in areas of Cambissolo Húmico, dystrophic, derived from sedimentary rocks of the Rio do Rastro formation (UBERTI, 2005), a region on the southern plateau of the state of Santa Catarina, at altitudes between 950 m and 1000 m asl. The climate of the region is humid mesothermal with mild summers, Cfb by the classification of Köppen, with an annual average temperature of 16ºC and annual rainfall of around 1500mm (EMPRESA DE PESQUISA AGROPECUÁRIA E EXTENSÃO DE SANTA CATARINA, 2017).

The following four land uses were evaluated: natural grassland (NG), five-year-old (P5), 16-year-old (P16) and 21-year-old (P21) pine (*Pinus taeda*) plantations. The areas of these land uses were located along the dirt road SC 281 (geographical coordinates: 27°29’09” S and 50°19’21” W; 27º29’05” S and 50°17’57” W; 27°24’53” S and 50°10’08” W; and 27°23’38” S and 50°11’32” W, respectively), at a mean distance of 6.1 km and a maximum distance of 16 km away from each other. The areas were chosen based on the similarity in altitude, position in the toposequence, soil depth and texture, among the available pine plantations with the desired age ranges. The natural grassland area consisted of a pasture of spontaneous grasses, with predominance of species of the genera *Paspalum* and *Axonopus* under continuous beef cattle grazing and managed with pasture burning at the end of winter. The evaluated pine plantations were in the second crop rotation, planted about 3 months after the harvest of the previous crop, performed at the age of 21 years. The seedlings were planted in the interrow of the trunks of the previous crop, spaced 2.5 m x 2.5 m, with crop residues scattered in the area, but with soil tillage by ripping with equipment composed of a plow stem to 0.40 m deep and two lateral discs forming a groove in the soil without moving it, nor leaving the groove open. The trees were not pruned or thinned.

Seven disturbed soil samples were collected with a Dutch auger from each land use, stratified in the layers of 0.00-0.05; 0.05-0.10; 0.10-0.20; 0.20-0.30; and 0.30-0.40 m. Each sample consisted of seven subsamples, collected within a circle with a radius of 10 m, one of which in the center and the others distributed approximately on the circle line (see Figure 1). The center-to-center distance between the sampling circles was approximately 30 m. Undisturbed samples were also collected from the five soil layers near the central point of the circles, using cylindrical steel rings with sharp edges and a volume of 50 cm^3 (EMBRAPA, 1997) to determine the soil bulk density. Soil of P5 were sampled in December 2010 and NG, P16 and P21 in March 2011.

Figure 1 – Diagram of distribution of the soil sampling points (marks in the center and on the circle line) for each land use.

Figura 1 – Ilustração da distribuição dos pontos de coleta (marcações no centro e sobre a linha dos círculos) das amostras de solo em cada uso do solo.



Source: Authors (2019)

Fonte: Autores (2019)

The undisturbed soil samples were maintained in the sampling rings and immediately packed in aluminum containers sealed with a lid. In the laboratory, after quantification of the wet mass, these samples were dried for 48 hours at 105ºC, to determine the dry mass (DM). The samples of the disturbed soil were packed in polyethylene bags shortly after sampling and at the beginning of the following day, they were oven-dried at 65°C to constant mass. These samples were then crumbled and sieved (2.0 mm mesh) for further analysis. The TOC content and total N content (TN) in soil were determined by the methods of Walkley-Black and Kjeldhal, respectively, as described by Tedesco et al. (1995).

For the determination of the POC, 20 g soil was mixed with 60 ml of a 5 g L^{-1} aqueous solution of sodium hexametaphosphate. This mixture was stirred for 16 hours in a horizontal orbital shaker at 200 rpm and then the particles with a diameter of > 0.053 mm were separated. The separation was done by sieving the soil suspension and hexametaphosphate through a mesh (<0.053 mm) by washing with small water jets, according to the methodology described by Cambardella and Elliott (1993), with modifications of Costa et al. (2004). The OC content of the particles retained in the sieve was also determined by the Walkley-Black method and the MAC content was estimated by the difference between TOC and POC.

The organic carbon stock in the soil (CSt) was calculated by the expression: CSt = (OC x BD x Th)/10, where: OC = organic carbon content in g kg^{-1}; BD = soil bulk density in kg dm^{-3}; and Th = thickness of the soil layer in cm. Soil particle-size distribution was analyzed by the pipette method described by Gee and Bauder (1986) after mechanical dispersion with an electrical stirrer.

The results were subjected to analysis of variance by the SAS® program (SAS INSTITUTE, 2003), using a Proc Mixed model, by which the land uses were considered a fixed factor, using an autoregressive (order 1) covariance structure (Ar1) to repair the spatial dependence of the soil layer factor, as described by Littell et al. (2006). The means were compared by the t-test at 5% significance using a Proc Mixed model (SAXTON, 1998). The analysis of simple linear correlation between the TOC, POC and MAC variables and the soil particle-size fractions was also carried out using the t-test at 5%.

Results and discussion

Soil texture and density

The clay content of soil under the evaluated land uses (Table 1) was generally similar between the layers to a depth of 0.40 m, except for P21, where the clay fraction was around 10% higher in the layers below 0.20 m. However, P16 had a higher clay content than the soils of the other land uses and P21 had the lowest one. The clay content may affect the soil OC content (SIX et al., 2002; GOH, 2004), due to the bonds established by organic compounds with clay mineral surface sites and that favor the protection and stabilization of that soil component (FELLER; BEARE, 1997; PARFITT et al., 1997). However, a negative correlation between TOC, POC and MAC contents and clay content was observed (Table 2), indicating that this attribute was not the predominant factor for OC accumulation in the studied soils.

Table 1 – Mean* clay, silt and sand contents in five layers (0.00-0.05; 0.05-0.10; 0.10-0.20; 0.20-0.30; and 0.30-0.40 m) of a Cambissolo Húmico, dystrophic, on the southern highland of Santa Catarina state under natural grassland (NG) and Pinus taeda plantations in the second rotation, aged five (P5), 16 (P16) and 21 (P21) years.

Tabela 1 – Teores médios* das frações granulométricas argila, silte e areia de cinco camadas (0,00-0,05; 0,05-0,10; 0,10-0,20; 0,20-0,30; e, 0,30-0,40 m) de um Cambissolo Húmico Distrófico do planalto sul de Santa Catarina sob usos com vegetação de campo natural (NG) e plantios de *Pinus taeda* de segunda rotação, aos 5 (P5), 16 (P16) e 21 (P21) anos de idade.

Particle-size fraction	Land use			
	NG	P5	P16	P21
	g kg^{-1}			
Clay	319 B	284 B	382 A	178 C
Silt	220 C	272 B	291 B	323 A
Sand	461 A	444 A	327 B	499 A

Means followed by different letters in the row differ from each other by the Least Significant Difference (LSD) test at 5% probability.

* Weighted average, considering four layers with a thickness of 0.10 m, where the two uppermost layers were computed by their mean content.

Table 2 – Pearson's correlation coefficient between the contents of total organic carbon (TOC), particulate organic carbon (POC) and mineral-associated organic carbon (MAC), and the contents of soil particle size fractions (sand, clay and silt) in the 0.00–0.40 m soil layer of a Cambissolo Húmico, dystrophic, on the southern highland of Santa Catarina under grassland (NG), and *Pinus taeda* plantations in the second rotation, aged five (P5), 16 (P16) and 21 (P21) years.

Tabela 2 – Coeficiente de correlação de Pearson entre os teores de carbono orgânico total (TOC), carbono orgânico particulado (POC) e carbono orgânico associado aos minerais (MAC) e os teores das frações granulométricas do solo (areia, argila e silte), na camada de 0,00–0,40 m de Cambissolo Húmico Distrófico sob usos com campo natural (NG) e *Pinus taeda* de segunda rotação, aos cinco (P05), 16 (P16) e 21 (P21) anos de idade.

Particle-size fraction	Organic carbon fraction		
	TOC	POC	MAC
Sand	0.15^{ns}	0.08^{ns}	0.21^{ns}
Clay	-0.53^{**}	-0.48^{**}	-0.44^{**}
Silt	0.60^{**}	0.65^{**}	0.33^{*}

(1) non-significant (p<0.05); * significant (p<0.05); ** significant (p<0.01).

The soil bulk density under NG in the surface layer (0.00 - 0.05 m deep) was higher than under the other land uses (Table 3). This was mainly attributed to animal trampling, as mentioned by Vizzotto et al. (2000), since this area had been used for continuous beef cattle grazing for more than five years, leading to soil compaction that decreases porous space and increases soil density

(KLEIN, 2006). Under P21, the soil density was lowest in all layers, which can be explained mainly by the highest TOC content under this use, since the particle density of this component is lower than that of minerals, thus decreasing soil density (BRAIDA et al., 2006; KLEIN, 2006).

Table 3 – Soil bulk density of a Cambissolo Húmico, dystrophic, on the southern highland of Santa Catarina state under grassland (NG) and *Pinus taeda* plantations in the second rotation, aged five (P5), 16 (P16) and 21 (P21) years.

Tabela 3 – Densidade em cinco camadas de um Cambissolo Húmico Distrófico do planalto sul de Santa Catarina sob usos com campo natural (NG) e plantios de *Pinus taeda* de segunda rotação, aos 5 (P5), 16 (P16) e 21 (P21) anos de idade.

Layers (m)	Land use			
	NG	P5	P16	P21
	g dm^{-3}			
0.00 - 0.05	1.2 b A	0.9 b B	1.0 c B	0.8 b C
0.05 a 0.10	1.4 a A	1.4 a A	1.1 b B	0.9 a C
0.10 a 0.20	1.5 a A	1.4 a A	1.2 a B	0.9 a C
0.20 a 0.30	1.4 a A	1.4 a A	1.2 ab B	0.9 a C
0.30 a 0.40	1.4 a A	1.4 a A	1.2 ab A	1.0 a B

Means followed by different capital letters in a row and lowercase letters in a column differ from each other by the LSD test, at 5% probability.

Total, particulate and mineral-associated organic carbon content

The TOC contents (Table 4) in the soils under NG and P21 were similar between the two layers to a depth of 0.10 m, but were higher than in the other layers, whereas the contents were lower in the deeper layer (0.30 – 0.40 m) of these two uses. However, the soil under P5 had a higher TOC content in the 0.00 - 0.05 m layer than in the others, in which the contents were similar.

The higher TOC content in the uppermost layer and its decrease with depth agrees with the normally observed pattern in soils under forests of the genus *Pinus*, as reported by Balbinot et al. (2003), Mafra et al. (2008) and Butnor et al. (2017). This trend is mainly due to the turnover of fine roots with a diameter of ≤ 2 mm, which grow at a higher concentration in the surface layer, usually to a depth of 0.1 m (LOPES *et al*., 2010), and contributes decisively to OC accumulation in the soil (HUANG et al., 2011; PERSSON, 2012). On the soil surface of these forests, significant amounts of residues are generally deposited from the above-ground part of the trees, forming the litter. A part of these residues is incorporated by the action of organisms of the soil fauna, especially in the layer of the first 0.1 m below the soil surface (LAVELLE et al., 2006) and is source of OC and, therefore, also contributing to a higher TOC (GOH, 2004) in this layer.

However, in the soil under P16, the TOC content was similar between the layers up to 0.40 m, which is attributed to pedogenic factors (CHADWICK; GRAHAM, 2000). Among these, the effect of natural grassland vegetation prior to the pine trees, with predominantly grasses, mainly the forage grass *Andropogon Lateralis* Nees was relevant (UBERTI, 2005). In the fasciculate root system of this vegetation type, fine roots generally grow intensively, also in the sub-surface layers, mainly to a depth of 0.40 m, accumulating soil organic carbon (SOC) by the turnover process (JOBBÁGY; JACKSON, 2000; CARVALHO et al., 2010). Thus, it is believed that prior to the pine forest, the root system of the natural grassland in this soil was more vigorous in depth than in the other studied areas promoting a similar distribution of the TOC content in the studied layers. This was also observed by Morales (2007) in a Cambissolo Húmico under pine forest in the same region as this study, which had SOC content between 34 and 37 g kg^{-1} in the A horizon with a similar distribution up to a depth of 0.42 m.

Table 4 – Content of total organic carbon (TOC), particulate organic carbon (POC) and mineral-associated organic carbon (MAC) in five layers of a Cambissolo Húmico, dystrophic, on the southern highland of Santa Catarina under natural grassland (NG) and *Pinus taeda* plantations in the second rotation, aged five (P5), 16 (P16) and 21 (P21) years.

Tabela 4 – Teores de carbono orgânico total (TOC), carbono orgânico particulado (POC) e carbono orgânico associado aos minerais (MAC) em cinco camadas de um Cambissolo Húmico Distrófico do planalto sul de Santa Catarina sob usos com campo natural (NG) e plantios de *Pinus taeda* em segunda rotação, aos cinco (P05), 16 (P16) e 21 (P21) anos de idade.

Layers (m)	NG	P5	P16	P21
	TOC g kg^{-1}			
0.00 - 0.05	27.2 a B	23.8 a B	23.7 a B	44.5 a A
0.05 - 0.10	24.3 a B	17.9 b C	24.0 a B	44.2 a A
0.10 - 0.20	20.2 b B	15.1 b C	22.2 a B	40.0 b A
0.20 - 0.30	18.3 b BC	15.0 b C	21.3 a B	40.9 b A
0.30 - 0.40	15.2 c C	16.2 b C	20.8 a B	34.0 c A
Mean* (0.00 - 0.40)	19.86 BC	16.78 C	22.03 B	39.81 A
	POC g kg^{-1}			
0.0 - 0.05	9.1 a B	10.7 a B	9.2 a B	23.2 a A
0.05 - 0.10	6.2 b B	4.8 b B	7.6 ab B	20.5 b A
0.10 - 0.20	3.8 c B	2.9 b B	6.0 b B	19.6 b A
0.20 - 0.30	2.6 c C	2.3 b C	6.5 ab B	17.5 c A
0.30 - 0.40	2.1 c B	2.1 b B	5.0 b B	13.0 d A
Mean* (0.00 - 0.40)	4.03 C	3.76 C	6.47 B	17.98 A
	MAC g kg^{-1}			
0.0 - 0.05	18.2 a A	13.1 a B	14.5 a B	21.3 ab A
0.05 - 0.10	18.0 a B	13.1 a C	16.3 a BC	23.7 a A
0.10 - 0.20	16.4 ab B	12.2 a C	16.3 a B	20.4 b A
0.20 - 0.30	15.8 ab B	12.7 a B	14.9 a B	23.4 ab A
0.30 - 0.40	13.1 b B	14.1 a B	15.8 a B	21.0 ab A
Mean* (0.00 - 0.40)	15.85 B	13.02 B	15.6 B	21.82 A

Means followed by different capital letters in a row and lowercase letters in a column differ from each other by the LSD test at 5% probability. *Weighted average based on the thickness of the soil layers.

The TOC content was higher in the soil under P21 than under NG in all five studied layers, showing that planted *Pinus* sp. forests can promote OC accumulation in the soil, according to results published by Almeida et al. (2012), Abrão et al. (2015) and Butnor et al. (2017). Moreover, there was a positive correlation (r = 0.78, p <0.05) between the TOC content and pine tree age. This result means that OC accumulation in the soil increases during the development phase of pine trees until the forest maturation, as similarly observed by Mafra et al. (2008) in Campo Belo do Sul – SC state, in the region of this study, where the mean TOC content of the layers to a depth of 0.4 m of a Nitossolo Háplico was higher under 20 years old than 12 years old *Pinus taeda* trees. This is explained by the increase in the amount of residues left on the soil, which usually increases with the growth of the *Pinus* trees, especially in the first two to three decades after planting, by the turnover of fine roots (MAKKONEN; HELMISAARI, 2001; PERSSON, 2012; SAMUELSON et al., 2014) and of litter accumulated in the soil surface (VALERI; REISSMANN, 1989; SCHUMACHER et al., 2008; PÉREZ-CRUZADO et al, 2013; SAMUELSON et al., 2017).

Aside from the significant addition of plant residues, other factors also contribute to TOC accumulation in the forest soil, particularly those that limit the decomposition of humic substances by the microbial population. In this sense, it is worth mentioning excess moisture and very low temperatures (BALDOCK; NELSON, 2000), as well as the physical protection within soil microaggregates (CAMBARDELLA; ELLIOTT, 1993; FELLER, 2000; SIX et al., 2000) and chemical protection by bonds between organic and clay mineral compounds (PARFITT et al., 1997). However, in this study, the soil clay content was not the preponderant factor for OC accumulation, as reported elsewhere by Razafimbelo et al. (2013). Therefore, the pine trees were decisive for soil TOC accumulation, as also shown by the negative correlation between the TOC and clay contents, and because the TOC levels and their POC and MAC fractions were highest precisely in the soil with the lowest proportion of this particle-size fraction.

The POC content (Table 4) and its proportion in relation to TOC were also higher in P21 than under the other land uses in all soil layers. In the comparison of the weighted average of the 0.0 - 0.40 m layers, this soil OC fraction was also higher under P21 than P16 and higher under P16 than P5. The increase in POC with the maturation of the plantation up to 21 years can be explained by the higher input of plant residues by the turnover of fine roots and litter accumulation (WENDLING et al., 2010), since the content of this soil OC fraction is usually higher under land uses that favor a high organic residue input (CAMBARDELLA; ELLIOTT, 1993; FELLER, 2000; BAYER et al., 2004). It is noteworthy that in the first years of tree growth, which applies to the youngest forest (P5), the organic residue input in the soil may be insufficient to compensate for losses resulting from the mineralization of the existing SOM (BRUN, 2008; WIESMEIER et al., 2009; BUTNOR et al., 2017).

In general, the POC contents also decreased with depth, especially in the soil under P21, where the contents in the layers differed more clearly from each other. This decrease was expected because POC originates mainly in the more recently decomposed residues that occur in greater quantity in the soil layer around 0.10 m below the surface (LOPES et al., 2010; HUANG et al., 2011). The long-term absence of soil tillage, which was the case in the more mature forests of this study, also favors accumulation in the POC fraction, since soil aggregation is preserved and, consequently, the physical protection of SOM particles within the aggregates (SOLLINS et al., 1996; BAYER et al., 2004).

In the soil under NG, the weighted average of the POC content of all layers was similar to that of P5. It should be noted that under these two uses, the proportion of the particulate fraction in relation to TOC was only 20 and 22%, respectively. This result was not expected, since in pastures with predominance of grasses, the turnover of fine roots is usually high (CERRI et al., 2007; LOPES et al., 2010), tending to accumulate POC in the soil (BAYER et al., 2004). However, as described above, the pasture of this study was intensively grazed and burned at the end of winter, which are factors that decrease the source of residues for POC formation in the soil (CONTE et al., 2011).

In general, the MAC content (Table 4) was also higher in the soil under P21 than under the other uses, both in the comparison of the layers and their weighted averages, indicating that the conditions for OC accumulation were most favorable under this land use. Mafra et al. (2008) also found a higher MAC content in a 20-year-old pine stand than under natural grassland, reflecting the higher OC addition due to root cycling and litter decomposition, and a reduced exposure of SOM to microbial mineralization in the forest. However, in general, the content of this fraction barely varied among the evaluated soil layers, since the humic substances contained in this fraction are little affected by recent residue deposition (WIESMEIER et al., 2009; ALMEIDA et al., 2012), but are derived from deposited material that is older than POC (HUANG et al., 2011). These substances are more stable in the soil, because they are protected from microbial degradation, mainly by the chemical bonds that they establish with soil clay minerals (SIX et al., 2002; COSTA et al., 2004; ALMEIDA et al., 2012).

In general, MAC accumulation is directly proportional to the soil clay content (SIX et al., 2002; BUTNOR et al., 2017). However, this does not seem to have been the predominant factor for MAC accumulation in the current study, since, as described above, there was a negative correlation between these two variables (Table 4). Thus, the greater accumulation of this OC fraction in the soil under P21 was mostly influenced by the continuous addition of organic residues, mainly by root turnover, for more than a decade, and was also favored by other limiting factors of the humic substance mineralization in this soil. Under P5, the MAC content was lower than under NG and P21, especially in the layers to a depth of 0.20 m, which was attributed to the favorable conditions for microbial degradation of SOM that occurred in this soil, after the mechanical harvesting operations and planting of new forest.

Soil C stocks

In the soil of P21, the TOC stock (Table 5) was higher than in the soils under the other land uses in all layers, except in the 0.00 - 0.05 m layer under NG, where the values were similar. However, this similarity of TOC stocks is explained by the higher density of the uppermost soil layer under NG, due to animal trampling (VIZZOTTO et al., 2000), which contributes to increase the organic C stock contained in this layer, as reported by Portugal et al. (2008).

In the sum of the 0.0 - 0.40 m layers, the accumulated TOC stock in the soil of P21 was also higher than under the other uses. However, the TOC stock of P16 was similar to that of NG, but higher than that of P5, confirming the finding that the SOC stock increases over time during the growth phase of pine forests, as reported by Richter et al, 1999. The amount of TOC stored in the soil of the more mature forest was similar to the 142 Mg ha^{-1}, in the 0 – 0.4 m layer of a Nitosol under 20-year-old pine trees in the region of this study reported by Mafra et al. (2008), i.e., a higher value than under 12-year-old pine trees. In the soil under natural grassland on the other hand, these authors observed a SOC stock about 15% higher than in the current study, a difference that is explained by the fact that this grassland was not grazed, which allowed a greater quantity of annually cycled plant residues (CONTE, 2011) than in the NG of the current study, and as described above, with grazing at high stocking density.

The TOC stocks and their POC fraction in the soil under P21 were higher than the respective values observed under NG, although this vegetation cover is characterized by the predominance of grasses, which generally provide high OC stocks in the soil (CERRI et al., 2007; WIESMEIER et al., 2009; DICK et al., 2011), mainly due to the intensive root renewal and consequently continuous crop residue input (BALDOCK; NELSON, 2000; CERRI et al., 2007). Thus, the lower TOC and POC stocks in the soil under NG than P21 were due to the intensive grazing in this land use. However, the 21-year-old pine forest in the second rotation of cultivation had the capacity to store OC in the soil, in agreement with results of Mafra et al. (2008) and Abrão et al. (2015). This is explained by the abundant addition of plant residues, as pointed out above, as well as by the consolidation of the physical protection structures of SOM, since the soil is not disturbed by tillage and the soil cover is not removed (SOLLINS et al., 1996).

Table 5 – Stocks of total organic carbon (TOC), particulate organic carbon (POC) and mineral-associated carbon (MAC) in five layers of a Cambissolo Húmico in the Southern highlands of Santa Catarina under native grassland (NG), and *Pinus taeda* plantations with five (P05), 16 (P16) and 21 years (P21), in the second rotation. Means of seven samples.

Tabela 5 – Estoques de carbono orgânico total (TOC), carbono orgânico particulado (POC) e carbono orgânico associado aos minerais (MAC) em quatro camadas de um Cambissolo Húmico Distrófico do planalto sul de Santa Catarina sob usos com campo natural (NG) e com *Pinus taeda* em segunda rotação aos cinco (P05), 16 (P16) e 21 (P21) anos. Médias de sete amostras.

Layers (m)	NG	P05	P16	P21
		TOC Mg ha^{-1}		
0.00 - 0.05	16.0 a	10.2 b	11.4 b	16.6 a
0.05 - 0.10	17.1 b	12.6 c	13.1 c	19.9 a
0.10 - 0.20	29.4 b	20.9 c	27.6 b	36.5 a
0.20 - 0.30	26.0 b	20.8 c	26.2 b	38.4 a
0.30 - 0.40	20.5 c	21.9 bc	25.4 b	32.7 a
Sum 0.0 - 0.40	109.0 b	86.4 c	103.7 b	144.1 a
		POC Mg ha^{-1}		
0.00 - 0.05	2.0 b	2.0 b	1.3 c	3.0 a
0.05 - 0.10	1.5 b	1.5 b	1.2 b	3.2 a
0.10 - 0.20	1.9 b	1.7 b	2.2 b	6.2 a
0.20 - 0.30	1.2 c	1.4 c	2.4 b	5.3 a
0.30 - 0.40	0.8 c	1.2 bc	1.8 b	4.1 a
Sum 0.0 - 0.40	7.4 b	7.8 b	8.9 b	21.8 a
		MAC Mg ha^{-1}		
0.00 - 0.05	14.1 a	8.3 b	10.2 b	TTT13.8 a
0.05 - 0.10	15.6 a	11.0 b	11.8 b	16.3 a
0.10 - 0.20	27.4 ab	19.2 c	25.4 b	30.4 a
0.20 - 0.30	24.8 b	19.4 c	23.8 b	33.1 a
0.30 - 0.40	19.7 b	20.7 b	23.7 b	28.6 a
Sum 0.00 - 0.40	101.6 b	78.6 c	94.9 bc	122.2 a

Means followed by different letters in a row differ from each other by the LSD test at 5% probability.

Conclusions

The contents and stocks of total organic carbon (TOC), particulate organic carbon (POC) and mineral-associated organic carbon (MAC) in the layers (0.0-0.05, 0.05-0.10, 0.10-0.20, 0.20-0.30, 0.30-0.40 m) of the profile of Cambissolo Húmico, dystrophic, of the southern plateau of Santa Catarina, generally increase with the age of the pine plantations on this soil, in evaluations performed at 5, 16 and 21 years.

The TOC and POC contents and the stock of this last fraction generally decrease with soil depth under natural grassland and pine plantations aged 5, 16 and 21 years, but the MAC content and the TOC and MAC stocks generally do not vary between layers of soil up to 0.40 m deep.

The carbon stocks of the POC fraction in the soil profile to a depth of 0.40 m corresponded to 6.9; 9.0; 8.6 and 15.1% of the total TOC of Cambissolo Húmico, dystrophic, on the southern plateau of Santa Catarina under natural grassland and 5, 16 and 21-year-old pine plantations, respectively.

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