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Impact of crop-livestock-forest integration on soil quality

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Abstract Integrated agricultural production systems with trees, grain crops and forage species are important for land use optimization. However, they can result in non-uniform changes in physical and chemical soil properties. The objective of this work was to evaluate chemical and physical soil properties in a eucalyptus-based agroforestry system. The experiment was conducted in a Red–Yellow Argisol in Southeast Brazil. Eucalyptus (*Eucalyptus grandis* × *E. camoldulensis*) seedlings were planted in rows 12.0 m apart, and 2.0 m between plants. For 4 years the inter-row space was cropped to soybeans (*Glycine max* L. Merrill), Sunn hemp (*Crotalaria juncea*) and maize (*Zea mays* L.) in association with palisade grass (*Urochloa brizantha*). After that, the forage was grazed by beef cattle. Five years after the implementation of the experiment, chemical and physical soil analyses were performed along the profile. Non-uniform changes were observed in fertility and soil physics in the transect between the eucalyptus planting lines, both at the soil surface layers and in depth. Integrated crop/livestock production systems, where eucalyptus is intercropped with annual crops and forage grasses for grazing, results in lower soil fertility near tree lines and up to 100 cm deep over time. Next to the tree line there is an increase in soil compaction and reduced aggregate stability in the uppermost soil layer, while microporosity and soil structuring are increased in the soil deeper layers. These effects are probably due to animal trampling under the trees.

Keywords Sustainable soil management · Eucalyptus · Cropping systems · Integrated systems

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Introduction

Integrated agricultural production systems (IAPSs) are interesting options for addressing global issues such as food security, climate change and sustainable agriculture and improving social conditions in the rural environment. They have been reported to have positive synergistic effects on soil physical, chemical and biological properties, which help decrease degradation compared with single land-use strategies (Lemaire et al. 2014). Systems integrating three components, crop, livestock and forestry increase species diversity and allow an array of cropping models (Balbino et al. 2011). Therefore, it is expected that environmental impact can be decreased by integrating grain, forest and animal production in the same area (Franzluebbers 2007), especially in systems under no-till (Franzluebbers and Stuedemann 2014). In addition, IAPSs are an alternative to remediate degraded pastures, increasing animal support capacity. These degraded pastures usually present very low stocking, pressing deforestation of native forests to maintain the livestock population (Dias-Filho 2011). The use of IAPSs under no-till results in improvements in the physical, chemical and biological properties of the soil (Macedo 2009).

In forest-pasture systems under tropical climate with high air temperatures, animals tend to gather under the tree canopy seeking relief from the heat (Paes Leme et al. 2005). Therefore, in IAPSs the animals cluster near the tree lines, which can affect physical and chemical soil properties, due to the greater trampling and the deposition of feces and urine in these spots. However, there are many reports showing the benefits of no-till on soil physical and chemical properties, since the soil remains covered with live plants and/or straw most of the time (Calonego and Rosolem 2010; Castro et al. 2011). It is also known that integrated agricultural systems such as crop-livestock results in improvements in the physical quality of the soil, since the inclusion of forages in the crop rotation rapidly increases the stability of the soil aggregates, macroporosity and hydraulic conductivity, which is important mainly in extreme fragile soils such as sandy soils. This is due to the combination of the absence of soil turnover by tillage, the presence of a dense root system that acts as an aggregating agent, and the greater macrofauna activity of the soil in the pasture phase (Marchão et al. 2007). The aggressive and voluminous root system of forage crops has contributed to enhancing soil physical properties, mainly when the pasture is not degraded (Loss et al. 2011; Fonseca et al. 2007), with effects not only in the soil uppermost layer, but also through the soil profile (Lanzanova et al. 2007; Castro et al. 2011).

Tree insertion in IAPSs can enhance the diversity of ecosystem services and economic benefits compared with conventional agriculture or exclusive livestock by improved nutrient cycling, as tree roots can capture nutrients in greater depths, which are not taken up by agricultural and forage crops (Franzluebbers et al. 2017). However, when the tree component is distributed in rows and there are cattle grazing in the agro-forest-pasture system, alterations in the physical and chemical properties of the soil may be non-uniform due to the imbalanced concentration of the animals in the area (Assis et al. 2015). The objective of this work was to evaluate changes in the soil chemical and physical attributes in the linear transect perpendicular to the lines of eucalyptus trees grown in an agroforestry system with pasture.

Materials and methods

The experiment started in May 2009 in Votuporanga, State of São Paulo, Brazil (20°20′S, 49°58′W and 510 m altitude), in a Typic Hapludalf (Soil Survey Staff 2010), in a degraded area with a slope $< 5\%$, whose previous use was with pasture for ten consecutive years. According to Köppen classification the climate is Cwa, humid subtropical with dry winter and hot rainy summer. Soil samples were taken from the depths 0–20 and 20–40 cm for chemical (Raij et al. 2001), physical (Danielson and Sutherland 1986), granulometric (Day 1965) and structural characterization (Kemper and Chepil 1965), and the results are shown in Table 1.

The area was tilled with plowing and disking. In September 2009, millet (*Pennisetum glaucum*) was sown between Mangum terraces (Cates 1912) built decades ago, and in October 2009 eucalyptus hybrid Grancam 1277 (*Eucalyptus grandis* × *E. camaldulensis*) was planted on the terraces, in a single line system. Mangum terrace is a broad bank of earth contouring the field, especially applicable on moderately rolling lands (Cates 1912). The area between eucalyptus lines was cropped under no-till. After millet desiccation, soybean (*Glycine max* L. Merryll) was grown in the summer season of 2009/10, Sunn hemp (*Crotalaria juncea*) was grown in winter-spring of 2010 and maize (*Zea mays*) was grown in association with palisade grass (*Urochloa brizantha* cv. Marandu) in the 2010/11 season. After maize harvest, a pasture was established with palisade grass, which was kept up to 2014, when the soil samples were collected. Eucalyptus was planted spaced 2.0 m from each other and rows were 12.0 m apart. The amounts

Table 1 Selected chemical and physical characteristics of the soil, before the experiment was started

Depth (cm)	P (Resin) (mg dm^{-3})	SOM[(a)] (g dm^{-3})	pH ($CaCl_2$)	K ($mmol_c$ dm^{-3})	Ca ($mmol_c$ dm^{-3})	Mg ($mmol_c$ dm^{-3})	H + Al ($mmol_c$ dm^{-3})	BS[(b)] (%)
0–20	7	17	5.2	2.8	18	8	16	64
20–40	3	12	5.0	1.7	16	6	16	59

	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
0–20	815	104	81
20–40	783	142	75

	M[(c)] m^3 m^{-3}	μ[(d)] m^3 m^{-3}	TP[(e)] m^3 m^{-3}	BS[(f)] (kg dm^{-3})	> 2 mm[(g)] (%)	MWD[(h)] (mm)
0–20	0.03	0.33	0.36	1.66	54.07	2.52
20–40	0.03	0.32	0.36	1.64	44.87	2.25

[(a)]soil organic matter; [(b)]soil base saturation; [(c)]macroporosity; [(d)]microporosity; [(e)]total porosity; [(f)]bulk density; [(g)]aggregates > 2.0 mm; [(h)]mean weighed diameter

of nutrients applied from 2009 to 2014 are presented in Table 2. Freshly weaned beef cattle were introduced in September 2011 at a stocking rate of 4.4 heads per hectare weighting 174 kg on average, and grown up to slaughtering in June 2014, weighting 492 kg on average, in a continuous grazing system. After the slaughter of the first batch a new batch of freshly weaned beef cattle was introduced at a stocking rate of 3.2 heads per hectare, weighting 179 kg on average, in September 2014, and kept up to the end of the experiment, when the average weigh was 342 kg.

In October 2014, 5 years after the experiment had started, soil samples were taken in soil depths of 0–5, 5–10, 10–20, 20–40 and 40–60 cm, at 0.0, 2.0, 4.0 and 6.0 m from the eucalyptus tree rows for chemical analysis as in Raij et al. (2001). In October 2014 eucaliptus trees were 22.1 m tall and the diameter at breast height was 21.8 cm on average. The samples were collected in open trenches at three random points of each plot. For each sampling position and depth, three soil samples were taken, homogenized and mixed into one composite sample (Table 3). The total number of composite samples was 60, considering three blocks X four positions X five depths.

In the same trenches open for soil chemical analysis, non-deformed samples, 5 cm in diameter and 4 cm high, were taken from the center of the layers of 0–5, 5–10, 10–20 and 20–40 cm, of each of the four sampling positions in relation to the eucalyptus line for soil physical analysis. Macroporosity, microporosity, total porosity and soil density were evaluated as in Danielson and Sutherland (1986). To assess soil aggregate stability, monoliths 5 cm high, 15 cm wide and 20 cm long were collected. The soil of each sample was pre-classified using a set of overlapping sieves, with the top and bottom sieve meshes of 8 and 4 mm, respectively. A 25 g subsample of the pre-classified soil, with aggregates between 8 and 4 mm, with known humidity, was used for wet sieving in a vertical oscillation apparatus (Yoder 1936), containing overlapping sieves with 2, 1, 0.5, 0.25 and 0.105 mm meshes. After 15 min of sieving, the soil

Table 2 Amount of nutrients applied during the experiment

Nutrient	Season				
	2009/10 (kg ha^{-1})	2010/11 (kg ha^{-1})	2011/12 (kg ha^{-1})	2012/13 (kg ha^{-1})	2013/14 (kg ha^{-1})
Nitrogen	15	116	45	33	100
Phosphorus	124	91	–	–	–
Potassium	60	86	–	–	–

Table 3 Soil chemical characteristics as affected by the distance from eucalyptus rows and soil depth, 5 years after the experiment was set

Distance (m)	P (mg dm^{-3})	SOM[(a)] (g dm^{-3})	pH	K (mmolc dm^{-3})	Ca (mmolc dm^{-3})	Mg (mmolc dm^{-3})	$H^{+}+Al^{3+}$ (mmolc dm^{-3})	BS[(b)] (%)
	0–5 cm							
0.0	2.0b[(c)]	22.1	4.6b	2.3ab	15.3c	13.3b	26.0a	29.4c
2.0	5.9a	26.6	5.4ab	2.2ab	37.0ab	29.0a	21.6b	75.9a
4.0	7.6a	26.9	6.3a	3.7a	41.5a	38.1a	14.3c	84.4a
6.0	3.1b	24.0	5.6ab	1.8b	14.6c	10.2b	17.1c	60.7b
	5–10 cm							
0.0	1.9c	20.6	4.4b	0.4c	3.0c	4.5b	24.9b	24.3c
2.0	4.6a	21.5	4.5b	1.3b	5.6bc	6.8ab	33.0a	29.1bc
4.0	2.5c	21.2	5.2a	1.2b	7.7b	6.8ab	21.6b	41.7ab
6.0	3.6b	22.3	5.2a	2.1a	12.6a	10.6ab	21.3b	54.8a
	10–20 cm							
0.0	1.5	19.5	4.4	0.3d	4.0	4.3	30.9	21.6
2.0	3.5	19.9	4.5	1.6b	5.0	2.9	32.2	23.4
4.0	1.8	19.9	4.7	0.8c	6.5	4.0	25.7	31.1
6.0	3.1	20.8	4.7	1.8a	8.0	2.6	25.4	32.6
	20–40 cm							
0.0	1.3b	17.7	5.1	0.6ab	7.0	5.8	21.3b	39.3
2.0	3.3a	17.2	4.7	0.4b	6.5	3.9	28.5a	27.3
4.0	1.1b	17.7	5.0	0.7ab	8.2	5.2	22.4ab	39.3
6.0	1.0b	17.5	5.0	0.8a	6.1	5.2	19.2b	38.8
	40–60 cm							
0.0	0.7	21.49	4.6b	1.0	5.3	3.1	27.2a	25.4c
2.0	2.3	15.37	4.9ab	0.5	5.9	3.6	21.8b	31.5bc
4.0	1.0	16.15	5.1a	1.0	10.3	3.9	19.2b	44.0a
6.0	1.1	15.96	5.1a	1.1	7.6	4.0	18.1b	40.8ab
	60–80 cm							
0.0	0.6	19.83a	4.7b	0.6	4.4b	3.4	19.4	30.0c
2.0	1.0	15.89b	5.1ab	0.3	6.8ab	3.9	18.8	36.4b
4.0	1.4	16.41b	5.4a	0.8	7.4a	3.5	16.5	41.5a
6.0	1.2	15.96b	5.3ab	1.1	6.1ab	3.3	16.0	39.6ab
	00–100 cm							
0.0	1.4	16.61	4.9	0.7	5.3	2.7b	18.0a	32.5b
2.0	1.9	14.72	5.4ab	0.8	6.2	3.0b	15.9b	38.5ab
4.0	1.5	15.76	5.6ab	0.5	7.9	3.9a	15.2b	44.3a
6.0	1.5	13.55	5.6ab	1.0	7.4	3.2b	14.3b	44.2a

[(a)]soil organic matter; [(b)]soil base saturation; [(c)]means followed by the same letter are not different (Tukey. $P < 0.05$)

retained in each sieve was collected in aluminum cans, dried at 105 °C for 24 h and weighed. Aggregate content greater than 2 mm and the weighed mean diameter (WMD) were determined according Kemper and Chepil (1965).

The experimental design was a randomized block with three replications. Four positions in the transect between the eucalyptus lines: that is, distances of 0.0, 2.0, 4.0 and 6.0 m from the planting line were sampled. Each plot was approximately 1.0 ha. Data were submitted to ANOVA (F test) and the averages were compared by the Tukey test ($P < 0.05$) using the software Assistat (Silva and Azevedo 2016).

Results

The soil chemical characteristics in the transect between eucalyptus rows were affected ($P < 0.05$) by the distance from the tree line and soil depth (Table 3). Lower levels of P were observed in the 0–5 cm, 5–10 cm and 20–40 cm layers under the trees, in the planting line (0.0 m position) and in positions farther from the tree lines. Soil K was higher under the trees at 0–5 cm, and lower from 5 to 40 cm. Lower Ca and Mg contents were observed under the tress up to 10 cm depth.

In deeper layers, Ca content was lower in the tree line in the layer of 60–80 cm depth. Except for the 10–20 cm and 20–40 cm layers, a lower nutrient content in the soil profile in the eucalyptus row, mainly of the basic nutrients, was accompanied by a decrease in pH and base saturation (BS %). This decrease was sharper up to the 0.10 cm depth (Table 3). Between 2.0 and 4.0 m distance from the tree lines, there were higher levels of P, K, Ca and Mg on the surface layer (0–5 cm). For other cases, the soil nutrient contents were similar.

Soil physical degradation was observed under the tree lines up to 20 cm depth (Tables 4 and 5). In the 0–5 cm soil layer there was a lower proportion of aggregates larger than 2 mm in the planting line compared with of 6.0 m from the trees, and in the layers of 5–10 cm and 10–20 cm, higher soil bulk density was observed at this sampling position between the eucalyptus lines. In the 20–40 cm layer, less structured soil characteristics were observed 6.0 m from the eucalyptus rows, with a lower proportion of aggregates larger than 2 mm and WMD.

Discussion

The decreased concentration of some nutrients in the soil profile in the eucalyptus planting line can be explained by the greater presence of fine eucalyptus roots (Laclau et al. 2001; Witschoreck et al. 2003), which are highly efficient in nutrient acquisition in this phase of plant growth. The fertility gradient found from the eucalyptus rows towards the inter-row probably is a result of the distance between rows, and consequently root population, since in conventional spacings (about 3.0 m distance) the number of fine roots found in rows and inter-rows is similar (Martins et al. 2004). In addition, the soil samples taken 5 years after planting allowed the plants to pass through the period of faster vegetative growth, resulting in the extraction of large amounts of nutrients from the soil. According to Santana et al. (2008), 4.5 year-old eucalyptus trees accumulate the highest amount of nutrients in the phytomass, with a great part of these nutrients extracted being extracted from the upper layers of the soil, where there is a great concentration of fine roots (Witschoreck et al. 2003; Fabião et al. 1987).

According to Martins et al. (2004), the concentration of 3-year-old eucalyptus fine roots in the 0–10 cm layer is 4 times higher than the 10–30 cm layer. However, the activity of deep roots under the tree line can not be disregarded, as soil Ca was decreased and soil organic matter (SOM) increased in the layer of 60–80 cm. Leite et al. (1999) also observed greater activity of roots close to eucalyptus plantation lines, even in deeper layers, after verifying a reduction of soil water contents below 45 cm, which could impair the yield of intercropped crops, decreasing the useful range of cultivation between the tree lines.

The increase in SOM content under the eucalyptus rows, as previously mentioned, is an indication of the presence of fine roots at this site (Calonego and Rosolem 2010), corroborating results obtained by Madeira et al. (2002), in forest stands with *Eucalyptus globulus*. Pulrolnik et al. (2009) observed an increase in the SOM up to 100 cm depth in a *Eucalyptus urophylla* forest, as compared with areas maintained with the native Cerrado vegetation and with cultivation of brachiaria. These results were attributed to the large amount of C added by eucalyptus litter, characterized by slow decomposition, that is, with a high C/N ratio and high levels of lignin and polyphenols (Myers et al. 1994), favoring the maintenance of organic substances in the soil (Kuzyakov and Domanski, 2000). According to the authors, the contribution of the eucalyptus root system to the increase of SOM in the profile was demonstrated by the higher content of light organic matter, that is, recently deposited and slightly altered by the humification process. On the surface, there was no significant difference in the SOM

Table 4 Soil physical characteristics as affected by the distance from eucalyptus rows and soil depths (0–5, 5–10, 10–20, and 20–40 cm) 5 years after the experiment was set

Distance (m)	Macroporosity ($m^3\ m^{-3}$)	Microporosity ($m^3\ m^{-3}$)	Total porosity ($m^3\ m^{-3}$)	Bulk density ($kg\ dm^{-3}$)
	0–5 cm			
0.0	7.39	34.69	42.09	1.56
2.0	6.67	35.75	42.42	1.53
4.0	7.82	35.46	43.28	1.48
6.0	5.22	34.08	39.30	1.59
	5–10 cm			
0.0	6.89	34.22	41.11	1.68a[(a)]
2.0	7.67	32.50	40.17	1.57b
4.0	5.29	32.26	37.54	1.59b
6.0	5.05	31.56	36.61	1.62ab
	10–20 cm			
0.0	7.39	34.03	39.48	1.70a
2.0	6.67	34.60	41.12	1.55b
4.0	7.82	31.98	38.69	1.57b
6.0	5.22	32.01	38.95	1.59b
	20–40 cm			
0.0	6.27	35.33a	41.60	1.58
2.0	6.78	32.84ab	39.62	1.54
4.0	6.64	31.74b	38.38	1.56
6.0	6.77	30.16b	36.92	1.54

[(a)]Means followed by the same letter are not different (Tukey. $P < 0.05$)

content due to the litter deposition because it was spread throughout the area, as well as the residues of the other species cultivated in association. However, in depth, the greater contribution of eucalyptus roots favored the increase of SOM in the planting line, since in this position in the transect there was no other species growing.

Soil nutrient exploration was decreased with the distance from the eucalyptus plants, while there was excrement deposition by the grazing animals in the tree shade. The concentration of animals under the tree canopy is common in tropical regions, due to the greater thermal comfort provided, especially during the hottest months of the year (Souza et al. 2010; Baliscei et al. 2012). At 6.0 m of the eucalyptus line, despite the lower influence of the trees in the nutrient extraction from the soil, lower levels of P, K, Ca and Mg were observed in the 0–5 cm layer. The decreased nutrient concentration in soil at the central range of the eucalyptus inter-rows is justified because it is the position of the transect where there is less competition between the intercropped crops, especially regarding water and light availability (Almeida et al. 2014), which favors growth and nutrient acquisition of the grain and forage crops (Almeida et al. 2014; Dias-Filho 2000; Guenni et al. 2008). When maize and soybean were used in the association, a better performance of these crops in the central range of the inter-row resulted in greater export of nutrients in the harvested grains. And when a forage was used for pasture (brachiaria), in addition to the greater extraction of nutrients in the central range (6.0 m), the return of these nutrients through the feces and urine of grazing animals occurred in positions closer to the planting line, since it is common the preferential concentration of the animals under the canopy of trees, taking advantage of a milder air temperature (Souza et al. 2010; Baliscei et al. 2012). Although the differences in soil nutrient content between the sampling distances were more noticeable in the surface layers, it was verified that both BS% and pH and H + Al were affected throughout the soil profile.

Table 5 Mean weighed diameter (MWD) and soil aggregates bigger than 2.0 mm as affected by the distance from eucalyptus rows and soil depth. Five years after the experiment was set

Distance (m)	MWD (mm)	> 2 (mm)
	0–5 cm	
0.0	3.90	82.66b[(a)]
2.0	4.27	87.51ab
4.0	4.28	87.95ab
6.0	4.39	89.45a
	5–10 cm	
0.0	4.25	86.13
2.0	4.75	87.86
4.0	4.38	89.43
6.0	4.45	90.13
	10–20 cm	
0.0	4.12	83.39
2.0	4.16	85.67
4.0	4.41	89.50
6.0	4.25	86.82
	20–40 cm	
0.0	3.46a	70.85a
2.0	3.46a	69.57a
4.0	3.39a	68.23a
6.0	1.75b	33.72b

[(a)]Means followed by the same letter are not different (Tukey. $P < 0.05$)

Souza et al., 2010, reported that cattle escape intense tropical heat and concentrate close to the planting line resulting in soil compaction (Lanzanova et al. 2007) in this region, due to the pressure exerted by their hooves (Schiavo and Colodro 2012). These results differ from those found by Paciullo et al. (2010) who observed no modification on soil bulk density values throughout the profile and throughout the linear transect. According to them, the greatest trampling of animals in this area of the terrain is compensated by the large amount of plant residues deposited by the trees, which cushion the load applied. This result shows that soil disruption caused by animal trampling on the land strip near the tree lines is limited to the topsoil and that the plant roots have an important role in soil structuring in depth up to a distance of 4.0 m towards the inter-row. The action of eucalyptus thin roots in the soil structure in depth (0.20–0.40 m) and near the planting line is demonstrated by the increase in soil porosity, mainly in microporosity, very important in sand textured soils with serious limitations in water retention. It is important to point out that this increase in soil microporosity was not accompanied by a decrease in macroporosity, as is usually observed with soil compaction, but due to the improvement of soil structure and the increase of organic matter content.

Conclusion

Under integrated crop-livestock-forest production systems, with eucalyptus grown in association with annual crops and forage grasses for grazing in the long term, soil fertility near tree lines and up to 100 cm deep is lower than in regions farther away from trees. The soil is more compacted next to the tree line, and aggregate stability is decreased in surface layers. However, microporosity and soil structuring are increased in the deeper soil layers. As hypothesized, the system with eucalyptus growing in lines, in association with annual crops and pastures induces lack of uniformity in the soil, which may require action to ensure the system sustainability.

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