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Changes in physical and hydraulic properties in sandy soils of the Pampa Biome under different uses

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ABSTRACT: The naturally fragile sandy soils of the Pampa Biome (PB) may be degraded with the introduction of poorly managed agricultural crops. Anthropic use can markedly decrease vegetation cover on sandy soils, leaving them more exposed to erosive agents. Decreases in organic matter content, biodiversity, and nutrient availability, increased soil compaction, and decreased water availability are also some of the impacts caused on PB soils by implementing poorly managed agricultural crops. In Rio Grande do Sul, in areas with sandier soils, the intense replacement of PB with commercial crops that has occurred in recent years (2000-2020) may be starting a disastrous cycle of degradation of these soils. However, it is not yet known how much these soils are degraded by recent anthropic use. There are no local scientific publications dedicated to the diagnosis of the degradation of these soils by anthropic use. Therefore, the need for this study was based on the objective of evaluating the physical and hydraulic properties of sandy PB soils with the insertion of agricultural crops. The study was conducted on three different soils, where soil samples were collected under three systems of use (extensive cattle raising on native grassland, eucalyptus afforestation, and soybean crop). Our results show that it can take more than nine years for soybean and ten years for eucalyptus land-use change to indicate some level of degradation in soil physical and hydraulic properties after replacing PB with these cultivated crops.

Keywords: water availability, aggregate stability, soil degradation, land-use change.

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INTRODUCTION

Pampa Biome (PB) extends over 700.000 km^2 from southern Brazil to Argentina and Uruguay (Roesch et al., 2009). In the state of Rio Grande do Sul - Brazil, the PB occupies 62 % of its area, which represents 176.500 km^2, about 2 % of the Brazilian territory (IBGE, 2019). The vegetation of the PB is composed of grasses, legumes, trees, and shrubs, of which more than 150 species of legumes and almost 450 grasses have been cataloged (Roesch et al., 2009).

The great advance and intensification of agriculture in regions of South America (Fuentes-Llanillo et al., 2021) have caused the substitution of approximately 47 % of the Brazilian PB by monocultures (Projeto MapBiomas, 2022). In the municipality of Sant'Ana do Livramento, for example, there has been a large increase in the area cultivated with soybeans from 30 km^2 in 2000 to 550 km^2 in 2022 (IBGE, 2021). The average soybean yield of Sant'Ana do Livramento is 30 % lower than the national average (IBGE, 2021). This suggests limitations to crop yield that are probably related to the soil and climatic conditions of these locations. Because the PB soils are loamy and sandy, the yield may be limited by the lower natural fertility and lower water retention capacity of these soils compared to soils with higher clay content (Streck et al., 2018).

These soil characteristics associated with inadequate management make the replacement of natural vegetation of PB with monocultures increase the soil susceptibility to degradation (Roesch et al., 2009; Overbeck et al., 2015). In poorly managed crops, the soil is more exposed, and aggregates are less stable due to the low reactivity of the particles as a consequence of the higher sand content and the lower density of electric charges in the clay fraction (kaolinite 1:1 and iron oxides) (Schaefer et al., 2008). The higher fragility of aggregates is also associated with the lower carbon content of sandy soils (Franzluebbers et al., 1996), which is a cementing component in the aggregation process (Bongiorno et al., 2021). Aggregates with these characteristics are more susceptible to the compaction process (Keller et al., 2019). Consequently, there is a reduction in water infiltration capacity, as well as in water retention and availability, which can decrease the potential soybean yield (Obour and Ugarte, 2021).

Evidences from studies carried out at PB indicate that land-use change reduces organic matter and nutrient availability (Pillar et al., 2009), aggregate stability (Santos et al., 2011), and biodiversity (Pillar et al., 2009). Besides the greater susceptibility to degradation, the recovery of degraded sandy soils can be slow and partial (Morandi et al., 2018). Therefore, it is necessary to investigate the impact on soil susceptibility to degradation with the replacement of native vegetation by monocultures.

Other studies have also investigated the impacts of changes in natural vegetation on soil chemical, physical and mineralogical dynamics (Castro et al., 2010; Korchagin et al., 2019; Chaves et al., 2021; Tian et al., 2023). However, diagnostics focused on physical and hydraulic properties are still needed to evaluate the implication of soybean and eucalyptus cultivation on soil ability to resist disaggregation and to store and supply water to plants.

A diagnosis with this purpose needs to consider some soil properties related to aggregate stability, hydraulic conductivity, available water capacity, and structural properties such as soil porosity and density. With these properties, it is possible to diagnose the physical and hydraulic condition of the soil. The objective of this study was to identify if the replacement of native grassland by eucalyptus and soybean crops harms physical and hydraulic capacity properties of fragile soils in the Pampa Biome.

MATERIALS AND METHODS

Description of the studied sites

This study was conducted in three sites in the Brazilian PB, named Pampeiro (30° 39’ 37.8” S, 55°14’ 24.2” W) (Figure 1) and Ibicuí (30° 44’ 42.5” S, 55° 09’ 10.8” W) (Figure 2), both located in the municipality of Sant’Ana do Livramento-RS, and Quaraí (30° 27’ 24.6” S, 56° 15’ 26.4” W) (Figure 3), located in the municipality of Quaraí-RS. The region’s climate is Cfa, humid subtropical, with annual precipitation of approximately 1.800 mm and an average temperature of 17 °C (Alvares et al., 2013).

These sites were selected because (i) their soils are sandy (>75 % sand), (ii) soybean (SOY) and eucalyptus forest (EUC) have been cropped longer than 5 and 7 years, respectively, after land-use change from natural grassland (GRA), (iii) the distance between SOY, EUC and GRA land-uses was not greater than 500 m, and (iv) there was no history of cultivation in GRA. Soybean have been cropped for 5, 6, and 9 years in Quaraí, Ibicuí and Pampeiro sites, and eucalyptus for 10, 9 and 10 years, respectively.

Soybean is cropped in succession with winter grass (black oat or ryegrass) in conventional tillage. In all sites, soil was plowed and harrowed in the first year of land-use change. This tillage was repeated in 2nd year at Ibicuí site and in 3rd and 7th years at Pampeiro site. In all other years, soil was only harrowed before soybean sowing. Tillage was used for weeds control (harrowing) and lime incorporation (disc plowing and harrowing). After soybean harvesting, soil was harrowed and black oat (*Avena strigosa*) was sown for grazing purpose at Ibicuí and Pampeiro sites, and black oat or ryegrass (*Lolium multiflorum*) was sown as cover crops at Quaraí site (Table 1). Cattle stocking rate on winter grasses was about 600 kg ha^{-1}. Soybean sowing density, soil fertilization and pesticides application were similar in all sites.

Eucalyptus seedlings were planted in pits with no previous soil tillage at Ibicuí and Pampeiro sites. At Quaraí site, lime was applied, and soil was plowed and harrowed before seedling planting. Planting density was approximately 1300 trees per hectare (2.5 × 3 m), and there were no soil tillage or machinery traffic (e.g., harvesting) on the forest in all sites after planting. The areas under GRA land-use had no history of soil management (as tillage, liming or fertilization), and its natural vegetation was only grazed by extensively raised beef cattle. The cattle stocking rate (average of 450 kg ha^{-1}) was adjusted according to the season to keep pasture heigh in 8-12 cm.

Sampling and soil measurements

Sampling was carried out between April and May 2022. In each site, soil was sampled in four trenches in each land-use. Trenches were located at similar elevation to minimize soil variability among land-uses. Undisturbed (Kopecky cylinder and soil clod) and disturbed soil samples were collected in four layers (0.00-0.05, 0.05-0.10, 0.10-0.20, and 0.20-0.50 m) of each trench.

At layers 0.00-0.05 and 0.05-0.10 m, soil was sampled in triplicates with steel rings (5.6 cm in diameter and 3.9 cm in heigh), totaling 216 samples (3 sites × 3 land-uses × 4 trenches × 2 layers × 3 rings). Bigger steel rings (6.1 cm in diameter and 5.0 cm in heigh) were used to sample soil at layers 0.10-0.20 and 0.20-0.50 m, totaling 72 samples (3 sites × 3 land-uses × 4 trenches × 2 layers × 1 rings). In the laboratory, these samples

Figure 1. Soil profile of the sampling points in each land-use (EUC – eucalyptus forest; GRA – natural grassland; SOY – soybean crop) in Brazilian Pampa Biome.

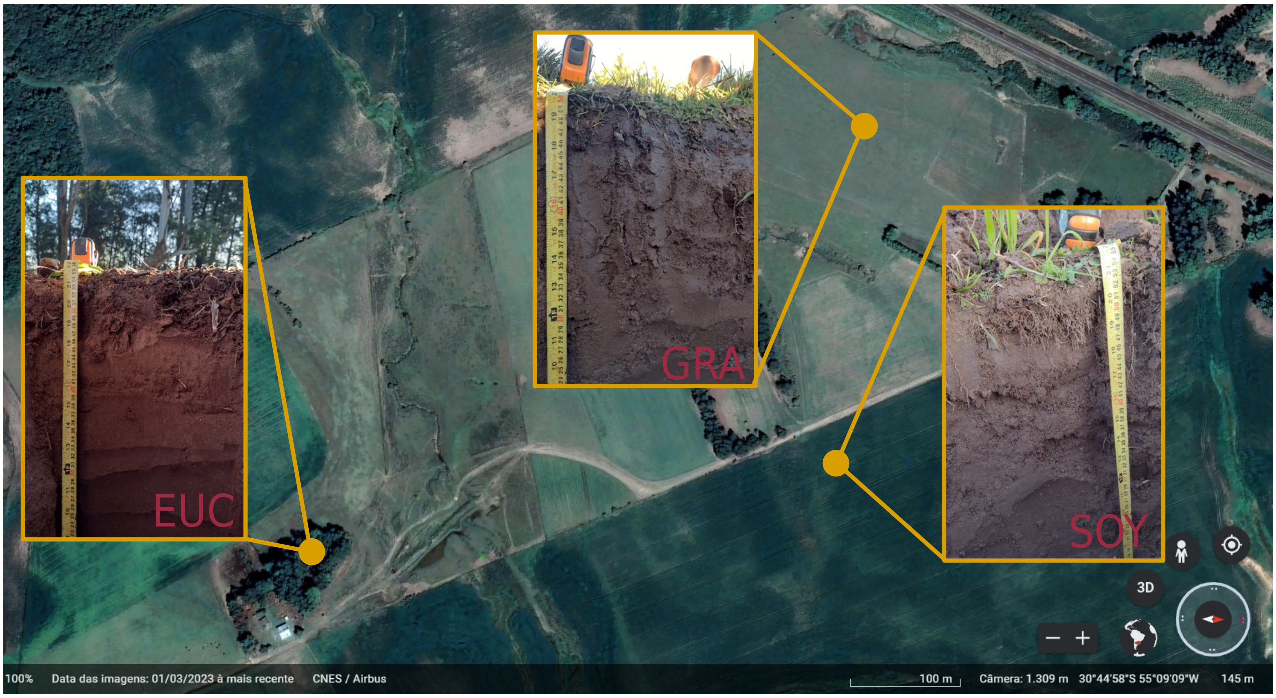

Figure 2. Soil profile of the sampling point in each land-use (EUC: eucalyptus forest; GRA: natural grassland; SOY: soybean crop) at Ibicuí site in Brazilian Pampa Biome.

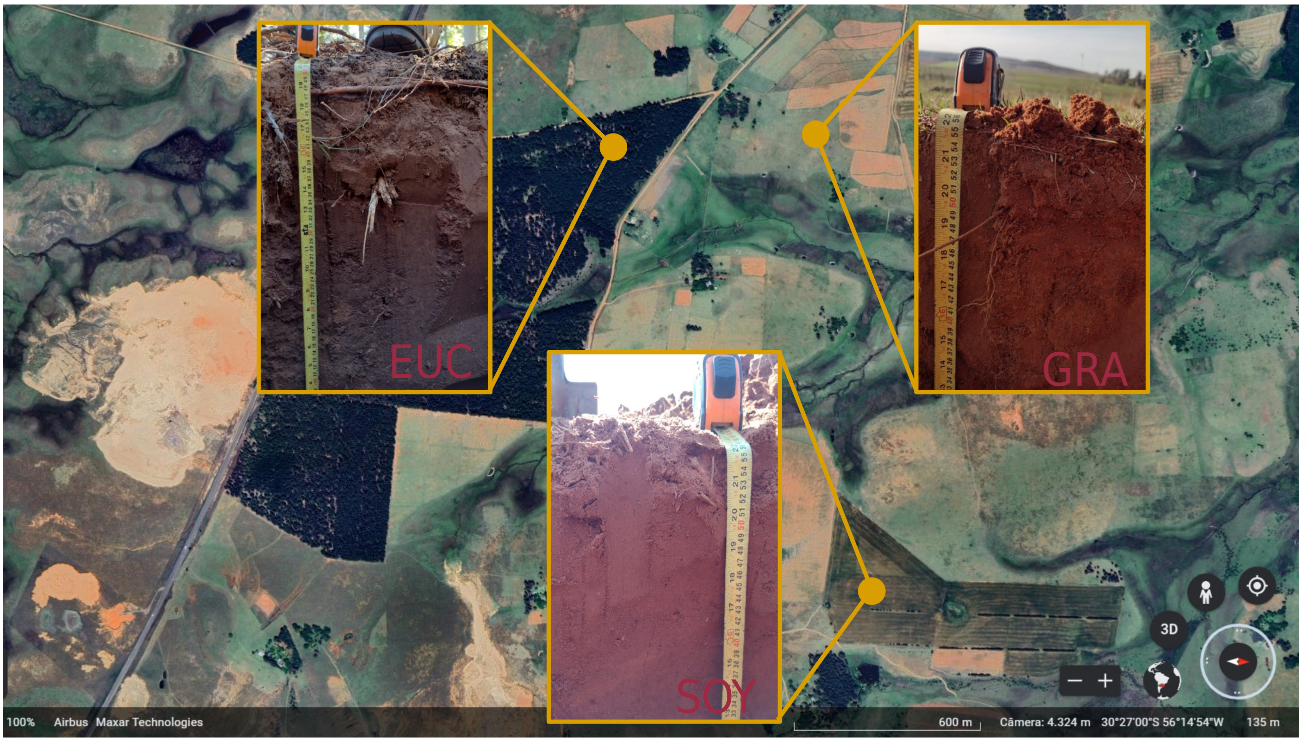

Figure 3. Soil profile of the sampling point in each land-use (EUC: eucalyptus forest; GRA: natural grassland; SOY: soybean crop) at Quaraí site in Brazilian Pampa Biome.

were saturated by capillary rise for 24 h and then subjected to suctions of 6 and 10 kPa in sand box (Reinert and Reichert, 2006), and 100 kPa in Richards chamber (Klute, 1986). Air permeability (Ka, μm^2) was determined in samples at suctions of 10 and 100 kPa in a constant head permeameter with air pressure of 0.1 kPa [equipment details in Mentges et al. (2016)]. Samples were again saturated to determine the hydraulic conductivity (Ks, mm h^{-1}) in a constant head permeameter (Teixeira et al., 2017). During Ks determination, a layer of 1 cm of water was kept over the samples and, after steady state flow, the volume of water that flowed through the samples for 15 min was quantified to calculate Ks. Finally, the samples were dried at 105 °C to obtain total porosity (Tp), and soil bulk density (Bd) (Teixeira et al., 2017). Macroporosity (Ma) was calculated as the difference between Tp and water content at 6 kPa.

Soil clods were also sampled. One block of approximately 4000 cm^3 (20 × 20 ×10 cm) was sampled at each layer, totaling 144 blocks (3 sites × 3 land-uses × 4 trenches × 4 layers). After sampling, blocks were immediately wrapped with PVC plastic film to preserve soil structure and moisture. In the laboratory, blocks were detached in small clods to the determination of mean weight-diameter of soil aggregates (MWD). Aggregate stability was determined by wet sieving in a set of sieves with opening of 4.75, 2.00, 1.00 and 0.212 mm (Kemper and Rosenau, 1986).

A total of 144 disturbed samples (3 sites × 3 land-uses × 4 trenches × 4 layers) were also collected. In the laboratory, these samples were air-dried and passed through a 2 mm mesh sieve. Samples of all four trenches of each land-use were mixed to compose one disturbed sample by layer for texture analysis, which was carried with the pipette method (Suzuki et al., 2015) to determine sand, silt and clay in two replicates.

Table 1. Soil management and land-use at Ibicuí, Pampeiro and Quaraí sites since land use changed from natural grassland to soybean crop (SOY) in Brazilian Pampa Biome

Site		2013 and before	2014 Hot	2014 Cold	2015 Hot	2015 Cold	2016 Hot	2016 Cold	2017 Hot	2017 Cold	2018 Hot	2018 Cold	2019 Hot	2019 Cold	2020 Hot	2020 Cold	2021 - 2022 Hot	2021 - 2022 Cold
		Management of SOY land use																
Ibicuí	Management	Natural grassland	Natural grassland	Natural grassland	Natural grassland	Natural grassland	Natural grassland	Natural grassland	Disc plow and harrow	Harrow	Lime + disc plow and harrow	Harrow	Harrow	Harrow	Harrow	Harrow	Harrow	Harrow
	Use	Beef cattle	Beef cattle	Beef cattle	Beef cattle	Beef cattle	Beef cattle	Beef cattle	Soybean	Black oat (grassing)	Soybean	Black oat (grassing)	Soybean	Black oat (grassing)	Soybean	Black oat (grassing)	Soybean	Black oat (grassing)
Pampeiro	Management	Natural grassland	Disc plow and harrow	Harrow	Harrow	Harrow	Disc plow and harrow	Harrow	Harrow	Harrow	Harrow	Harrow	Harrow	Harrow	Lime + disc plow and harrow	Harrow	Harrow	Harrow
	Use	Beef cattle	Soybean	Black oat (grassing)	Soybean	Black oat (grassing)	Soybean	Black oat (grassing)	Soybean	Black oat (grassing)	Soybean	Black oat (grassing)	Soybean	Black oat (grassing)	Soybean	Black oat (grassing)	Soybean	Black oat (grassing)
Quaraí	Management	Natural grassland	Natural grassland	Natural grassland	Natural grassland	Natural grassland	Natural grassland	Natural grassland	Natural grassland	Natural grassland	Lime + disc plow and harrow	Harrow	Harrow	Harrow	Harrow	Harrow	Harrow	Harrow
	Use	Beef cattle	Beef cattle	Beef cattle	Beef cattle	Beef cattle	Beef cattle	Beef cattle	Beef cattle	Beef cattle	Soybean	Cover crop	Soybean	Cover crop	Soybean	Cover crop	Soybean	Cover crop

Hot	Hot season (spring and summer)
Cold	Cold season (fall and winter)
Natural grassland	Natural grassland grazed and trampled by cattle
Disc plow and harrow	Tillage with disc plow and harrow
Lime + disc plow and harrow	Lime application followed by disc plow and harrow
Harrow	Tillage only with harrow
Beef cattle	Beef cattle raising
Soybean	Soybean (*glycine max*)
Black oat (grassing)	Black oat (*Avena strigosa*) for grassing purpose
Cover crop	Black oat (*Avena strigosa*) or ryegrass (*Lolium multiflorum*) for cover crop purpose

Water retention was characterized using the field capacity and permanent wilting point estimates. Field capacity was considered the water content at 10 kPa, and the permanent wilting point was estimated by pedotransfer function with clay and sand contents (kg kg^{-1}). We used the equation PMP = 0.236 + 0.045Clay – 0.21Sand (R^2 = 0.44; $p<0.01$) developed by multiple regression analysis with 685 samples from soils of Rio Grande do Sul (Reichert et al., 2009).

Disturbed samples were also used to determine C and N content. Samples of layers 0.00-0.05 and 0.05-0.10 m were mixed to compose one sample for 0.00-00.10 m layer of each trench (four samples per management system). For layers 0.10-0.20 and 0.20-0.50 m, the same mixed samples used in texture analysis were taken for C and N determination (one sample per management system). The dry combustion technique at 900 °C was used in elemental analyzer equipment for C and N measurement (Flash EA1112, Thermo Electron Corporation, Milan, Italy).

Statistical analysis

As the three land-uses (SOY, EUC, and GRA) and the profile's soil layers cannot be randomly set, and the statistical distribution of several variables was not normal, the non-parametric Kruskal-Wallis test was used to evaluate if the land-uses affected the soil physical and hydraulic properties in each soil layer. The non-parametric Nemenyi test was used as a post-hoc test. These tests were run with the KW_MC SAS macro (Elliott and Hynan, 2011).

RESULTS

The soil texture of all sites was sandy loam, loamy sand or sandy (Table 2). The variability of particle size distribution was low among land-use at Quaraí and Ibicuí sites. Despite the variation observed in sand (9 %) and clay (8 %) at layer 0.00-0.05 m at Ibicuí site, sand, silt, and clay variation was less than 5 % in all the other layers at Ibicuí and Quaraí sites. At Pampeiro site, the variability of particle size distribution was low between natural grassland (GRA) and soybean crop (SOY), less than 7 %, but it was high between eucalyptus forest (EUC) and other land-uses. The mean sand content in EUC was 29 % lower, silt was 21 % higher and clay was 9 % higher compared to the mean of sand, silt, and clay of GRA and SOY (Table 2).

Statistical analysis pointed out significant differences in soil variables contrasting the three land-uses. However, we focused the evaluation on the differences caused by changing land-use from natural vegetation to crops (eucalyptus and soybean), rather than the difference between crops. Thus, the results were described by comparing the differences in soil variables between GRA and EUC, and between GRA and SOY when it was statistically significant. For this comparison, we assumed GRA as a control plot that represents soil conditions at natural vegetation before land-use change.

Soil bulk density (Bd) and total porosity (Tp) were affected by land-use change mainly in surface layers (0.00-0.05 and 0.05-0.10 m) (Figure 4). Bulk density in SOY increased 8 % in layer 0.05-0.10 m at Ibicuí site, and 18 % in layer 0.00-0.05 m at Pampeiro site. In layer 0.00-0.05 m at Quaraí site, Bd in EUC decreased 12 % (Figure 4a). Tp of the layer 0.20-0.50 m increased 19 % in EUC at Ibicuí site and decreased 14 % in SOY at Pampeiro site. At Quaraí site, changing land use from GRA to EUC resulted in a Tp increase of 18 % in layer 0.00-0.05 m, and a Tp decrease of 7 % in layer 0.05-0.10 m (Figure 4b). Macroporosity (Ma) was affected in all layers, increasing in SOY in three layers (0.00-0.05, 0.10-0.20 and 0.20-0.50 m) at Quaraí site and increasing in EUC in the profile at Pampeiro site, but decreasing in SOY in the layer 0.05-0.10 m and in EUC in the layer 0.20-0.50 m at Ibicuí site (Figure 4c).

Saturated hydraulic conductivity (Ks) and soil air permeabilities (with soil water content at 10 kPa, Ka_{10}, and with soil water content at 100 kPa, Ka_{100}) were negatively affected by changes in land-use (Figure 5). The Ks was lower in SOY in 0.10-0.20 and 0.20-0.50 m layers at Ibicuí and in 0.05-0.10 and 0.10-0.20 m layers at Quaraí site. It also was lower in EUC in the top layer at Pampeiro site (Figure 4a). At Ibicuí and Pampeiro site, Ka_{10} reduction was mainly observed in EUC, whereas at Quaraí site, Ka_{10} was lower in SOY (Figure 5b). The Ka_{100} was affected by land-use change only at Pampeiro and Quaraí sites. At Pampeiro site, Ka_{100} was lower in both EUC and SOY, and at Quaraí site it was lower in SOY in layer 0.10-0.20 m (Figure 5c).

Water content at field capacity (FC) and at permanent wilt point (PMP) were significantly affected by land-use in most layers in all sites, but in a different way in each site. At Pampeiro site, FC and PMP were greater in EUC, while at Quaraí, they were greater in SOY, and at Ibicuí site, there was no pattern (Figure 6a). As changes in FC and PMP at Pampeiro and Quaraí sites were in the same direction (both increased with land-use change from GRA to crops), the effect of land-use on available water (AW) was not observed at Quaraí site either in surface layers at Pampeiro site. The AW at Ibicuí site decreased in SOY in layer 0.05-0.10 m and in EUC in layer 0.20-0.50 m, but the reduction in both layers was lower than 0.035 $m^3 m^{-3}$ (Figure 6c).

Table 2. Particle size distribution of soils under different land-uses at Ibicuí, Pampeiro and Quaraí sites in Brazilian Pampa Biome

Site	Layer	Coarse sand			Fine sand			Total sand			Silt			Clay		
		EUC	GRA	SOY	EUC	GRA	SOY	EUC	GRA	SOY	EUC	GRA	SOY	EUC	GRA	SOY
	m	g kg^{-1}														
Ibicuí	0.00-0.05	394	454	476	365	396	368	760	850	844	134	123	101	106	27	55
	0.05-0.10	302	377	361	511	415	467	814	792	828	99	115	107	87	93	65
	0.10-0.20	326	375	405	496	419	399	822	793	804	99	115	112	80	92	84
	0.20-0.50	282	376	418	511	457	383	792	833	800	108	68	110	100	100	89
Pampeiro	0.00-0.05	182	592	398	421	320	480	603	912	878	268	55	91	129	33	31
	0.05-0.10	175	492	401	422	422	475	597	914	876	278	52	91	125	34	34
	0.10-0.20	182	508	418	417	406	454	599	913	872	282	52	95	119	34	33
	0.20-0.50	215	501	372	375	410	476	590	911	849	285	45	105	125	44	46
Quaraí	0.00-0.05	384	341	478	537	594	426	922	935	904	35	30	28	43	35	69
	0.05-0.10	353	367	539	568	568	368	921	935	906	32	23	22	47	42	72
	0.10-0.20	353	413	539	557	517	355	909	930	894	37	22	24	54	48	81
	0.20-0.50	341	517	546	537	387	330	878	904	876	55	26	22	67	70	102

EUC: eucalyptus forest; GRA: natural grassland; SOY: soybean crop.

Aggregate stability, evaluated by the mean weight diameter of aggregates (MWD), was enhanced by changing GRA to EUC in surface layers at Pampeiro site and in the deeper layer at Ibicuí site (Figure 7a). No statical difference in MWD was observed at Quaraí site. The effect of land-use change in carbon stock was observed only at Quaraí site, with an increase of 1.34 Mg ha^{-1} in SOY in 0.00-0.10 m (Figure 7b). No statistical effect of land-use change was detected in nitrogen content (Figure 7c).

DISCUSSION

Brazilian Pampa Biome (PB) extends over an area with soils varying from highly structured clayey to very sandy poor-aggregated ones. Sandy soils with a fragile structure are more susceptible to degradation when land-use changes from natural vegetation to a more intensive cropping system (Vityakon, 2007). Soils at Ibicuí and Pampeiro sites are sandy loam or loamy sandy and at Quaraí site are sandy (Table 2), therefore, the sites chosen for sampling represent the most fragile soils of PB.

The low variability of particle size distribution among land-uses at Ibicuí and Quaraí sites and between natural grassland (GRA) and soybean crop (SOY) at Pampeiro site (the greatest difference in sand, silt or clay was lower than 9 % - Table 2), allow us to assume that differences in soil properties were caused mainly by change in land-use than by horizontal variability of soil texture. The greater differences of sand, silt, and clay at Pampeiro site between the eucalyptus stand (EUC) and the other land-use may have added some bias to the land-use effect over soil properties, which required more care about the interpretation of the results for this site.

In a general overview of changes in soil porosity, the transition from GRA to SOY resulted in an increase in the degree of compaction near to surface, without a significant decrease in Tp (Figures 4a and 4b). Management operations for soybean cultivation as sowing, spraying, harvesting and transportation, are performed with heavy machinery, that associated with conventional soil tillage (plowing and harrowing) implies in soil structure degradation (Keller et al., 2019). However, the increase in Bd was observed in few layers and not in all sites (Figure 4a). Besides, the magnitude of Bd increase was not

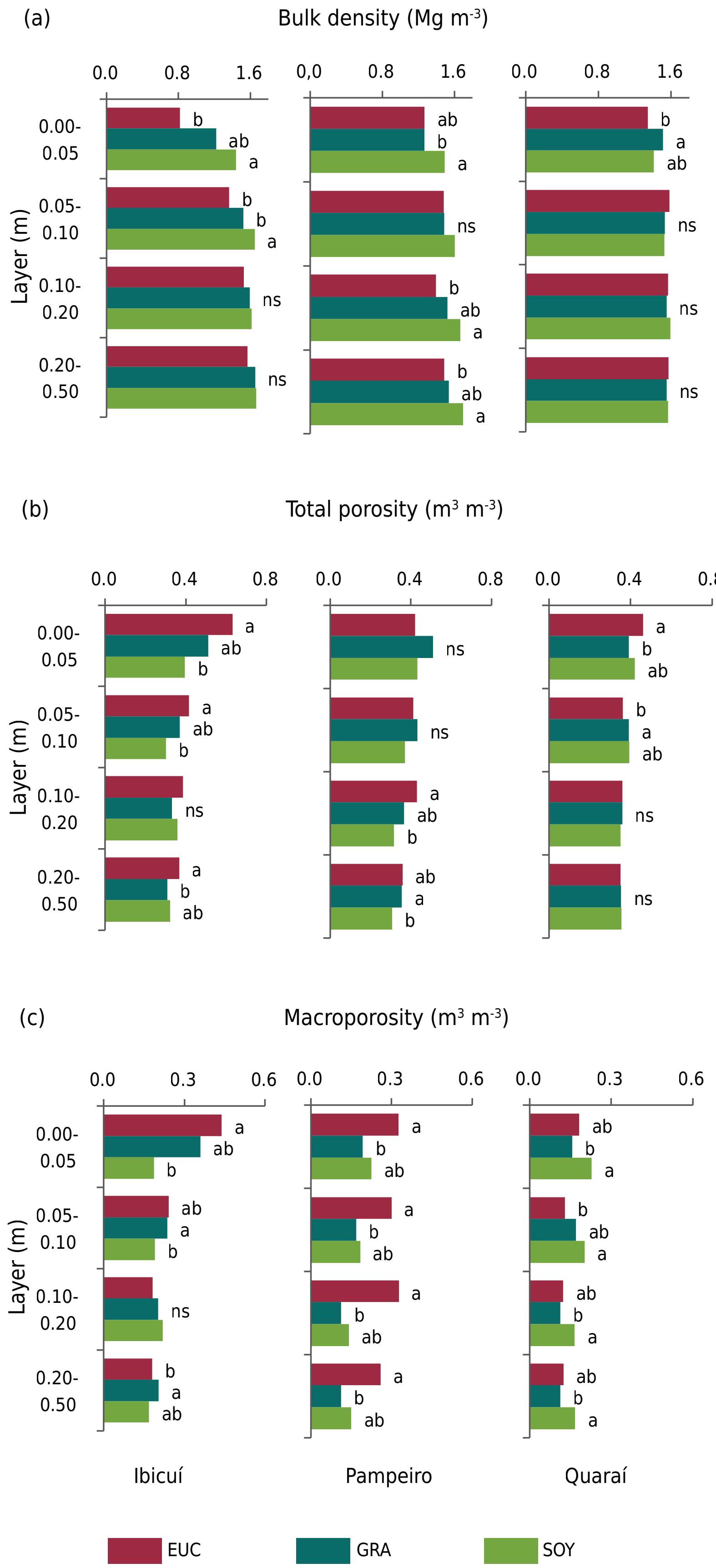

Figure 4. Effect of land-use (EUC: eucalyptus forest; GRA: natural grassland; SOY: soybean crop) on soil bulk density, total porosity and macroporosity in each layer at Ibicuí, Pampeiro and Quaraí sites in Brazilian Pampa Biome. Land-uses with the same letter within each layer do not differ by the non-parametric Nemenyi test at 0.05 error probability.

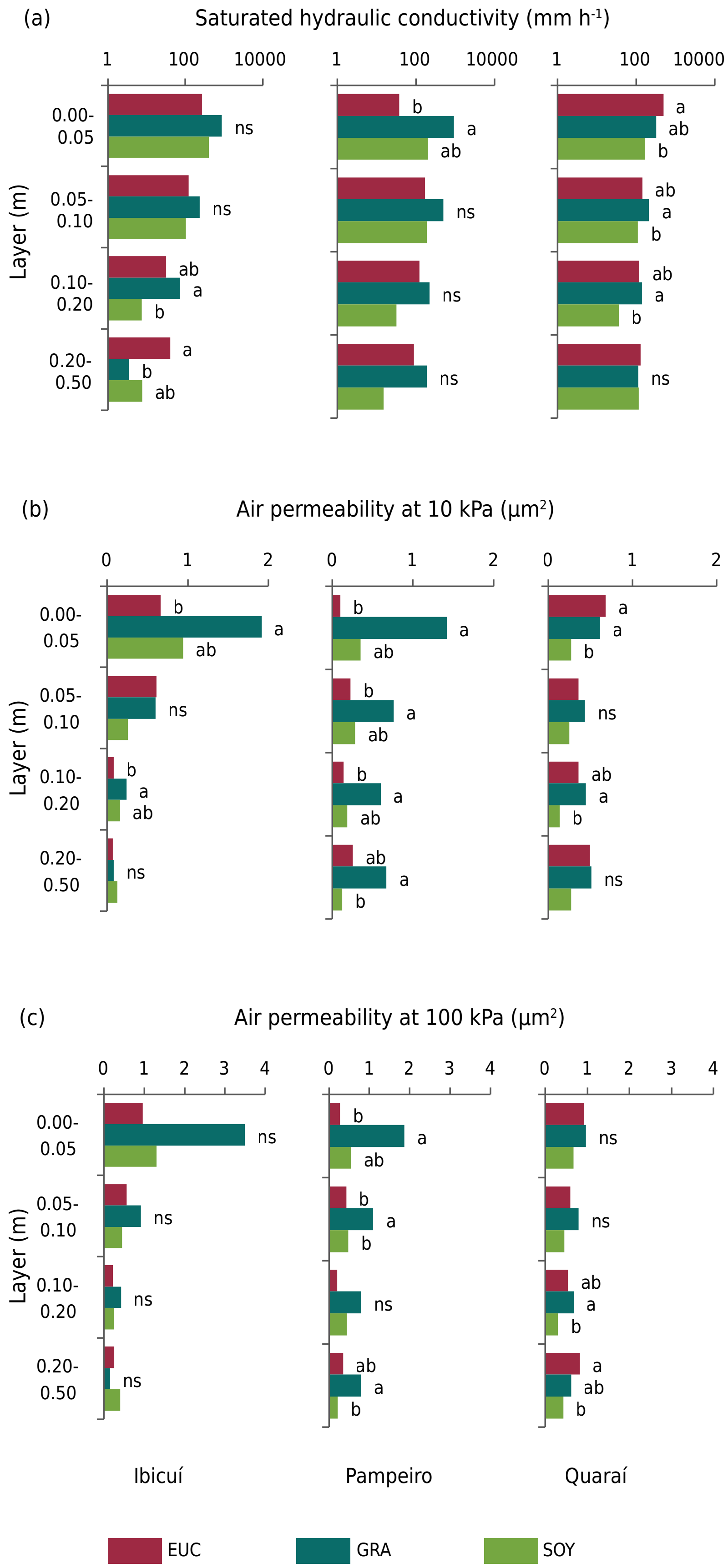

Figure 5. Effect of land-use (EUC – eucalyptus forest; GRA – natural grassland; SOY – soybean crop) on saturated hydraulic conductivity, air permeability measured at 10 and 100 kPa suctions in each layer at Ibicuí, Pampeiro and Quaraí sites in Brazilian Pampa Biome. Land-uses with the same letter within each layer do not differ by the non-parametric Nemenyi test at 0.05 error probability.

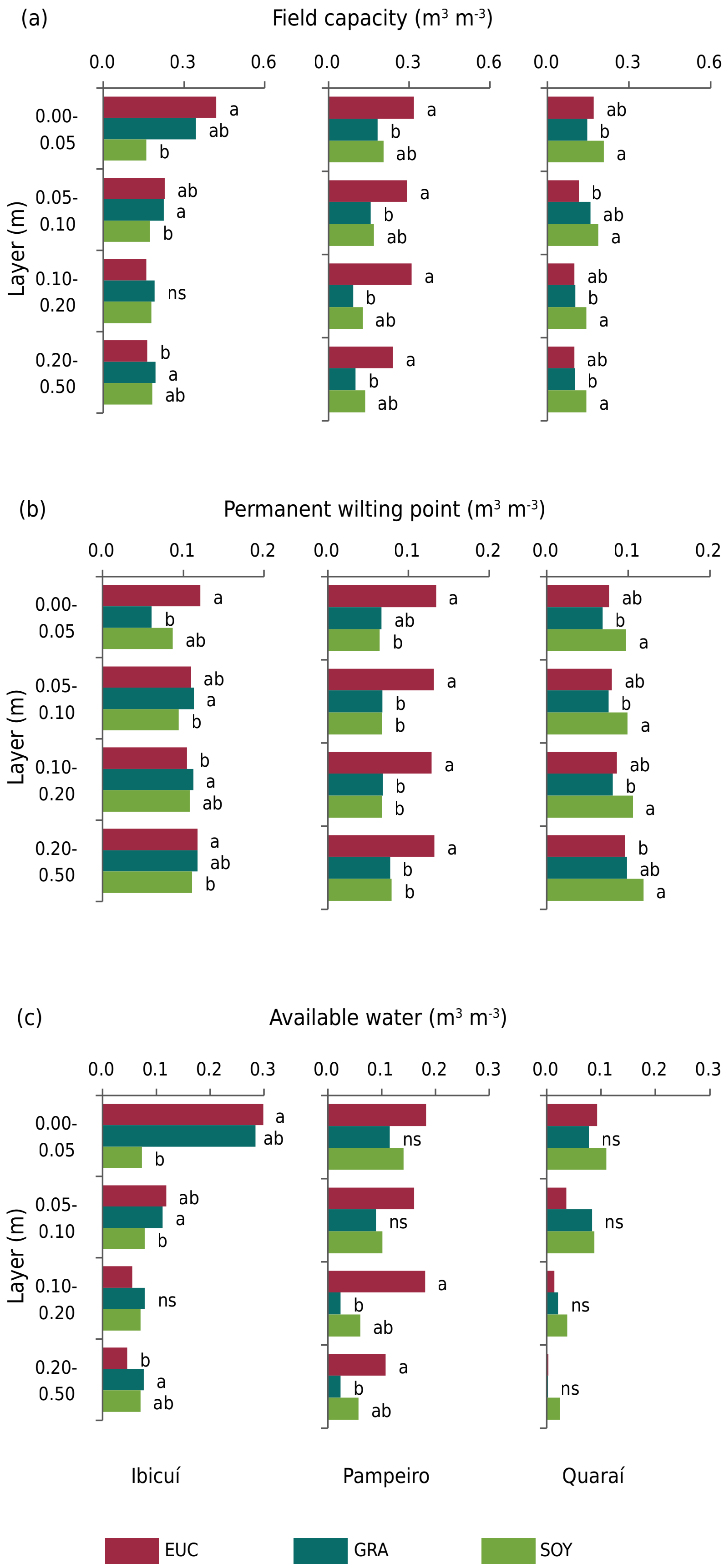

Figure 6. Effect of land-use (EUC – eucalyptus forest; GRA – natural grassland; SOY – soybean crop) on field capacity, permanent wilting point and available water in each layer at Ibicuí, Pampeiro and Quaraí sites in Brazilian Pampa Biome. Land-uses with the same letter within each layer do not differ by the non-parametric Nemenyi test at 0.05 error probability.

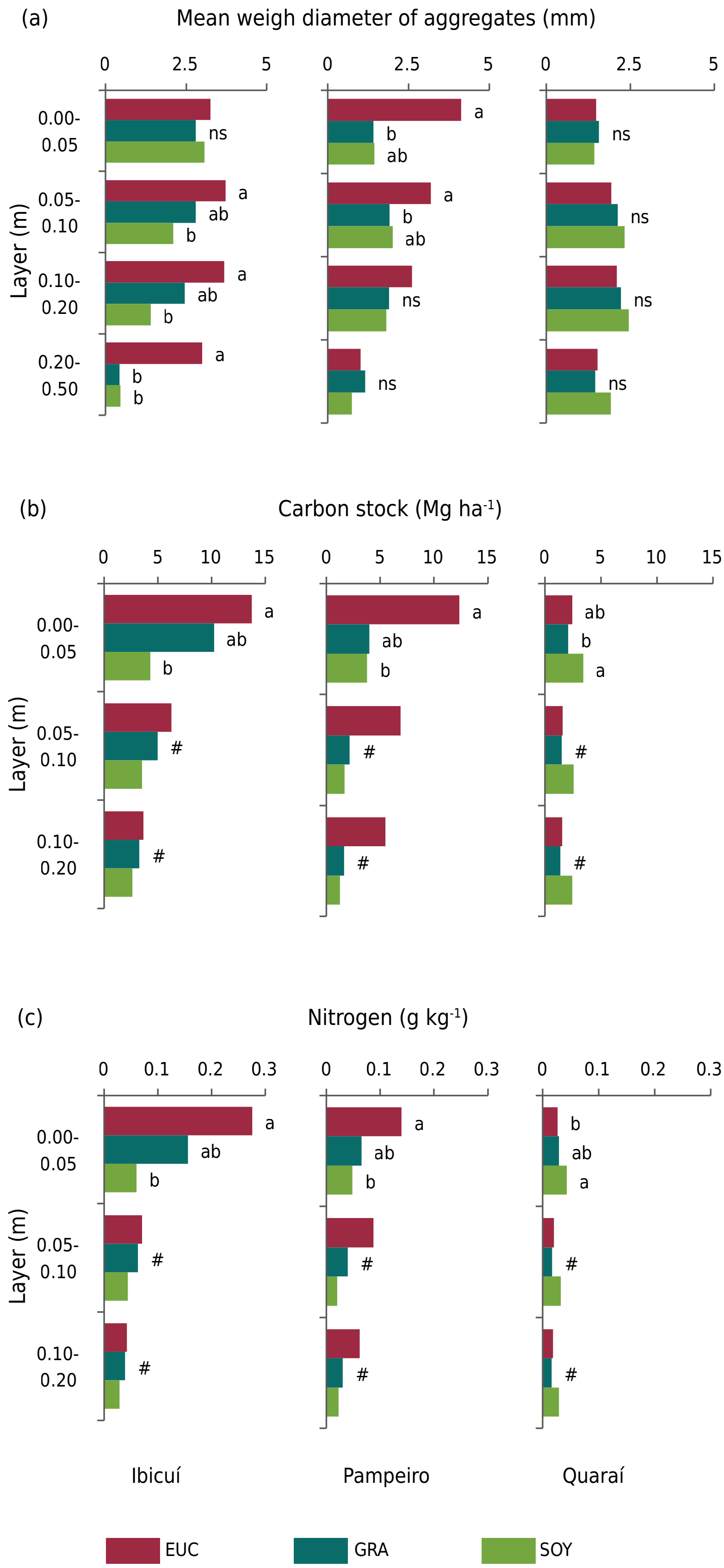

Figure 7. Effect of land use (EUC – eucalyptus forest; GRA – natural grassland; SOY – soybean crop) on the mean weigh diameter of aggregates, carbon stock and nitrogen in each layer of the soils at Ibicuí, Pampeiro and Quaraí sites in Brazilian Pampa Biome. Land-uses with the same letter within each layer do not differ by Nemenyi's nonparametric test with an error probability of 0.05. # no repetitions.

greater than 18 %, whereas Santos et al. (2021) observed a greater increase in Bd, up to 28 %, in all layers up to 0.30 m depth after the conversion of natural vegetation to agricultural crops in sandy clay loam soils at Brazilian Savannah (*Cerrado* Bioma). The absence of soil compaction in deeper layers of sandy soils of PB may be associated to the short time of the land-use change from GRA to SOY (no longer than 9 years), compared to 22 years of Santos et al. (2021). However, the little increase in Bd even at surface layers (Figure 4a), which were subject to machinery load since the first year of land-use change, is probably more related to the low clay content (average of 7 %, Table 2). As soil compressibility is positively related to clay content (Reichert et al., 2018), sandy soils of PB are more resistant to compaction compared to soils with higher clay content [e.g., Santos et al. (2021)]. Thus, the little effect on Bd and Tp with the transition from GRA to SOY suggests that soil compaction may be a minor problem on physical degradation of soils of PB with high sand content, as this has been observed when natural vegetation is replaced by annual crops in PB (Reichert et al., 2016).

Conversion from GRA to EUC decreased Bd and increased Tp only in the surface layer at Quaraí site (Figures 4a and 4b). This improvement in soil porosity is related to higher biological activity near soil surface in forests associated with the reduced or absence of machinery traffic between eucalyptus planting and harvesting (Reichert et al., 2017), since harvesting is the main cause of soil compaction in cropped forests (Horn et al., 2007). As the soil in EUC at all sites was not subject to heavy machinery traffic yet, conversion of GRA to EUC did not decrease soil porosity. Even though Tp was not significantly affected by land-use change to EUC at Pampeiro site (Figure 4b), there was a systematic increase in Ma at this site (Figure 4c). However, the greater Ma is probably more related to the higher clay content in EUC at Pampeiro (Table 2) than land-use's effect.

Soil flux-related variables (Ks, Ka_{10}, and Ka_{100}) were the soil properties more systematically affected by land-use change because Ks, Ka_{10}, or Ka_{100} decreased at least in one layer at each site with the conversion from GRA to EUC or to SOY (Figure 5). One reason for the reduction in water and air fluxes when vegetation changes is the distinct occupation of soil porosity by roots. In the initial forest growing, soil volume occupied by roots increases yearly, with roots filling soil voids, mainly macropores (Ilek et al., 2019). Macropore occupation by roots is probably the cause of the decrease in water and air fluxes in EUC at Ibicuí and Pampeiro sites and the non-increase in 0.00-0.05 m layer at Quaraí site even with an increase in Tp (Figure 4b). On the other hand, soybean roots fill soil macropores only temporarily, releasing them after root decomposition. Thus, if macropores are free, the decrease in flux-related properties is due to a decrease in the total volume of macropores, almost always due to soil compaction.

Soil compaction (represented by Bd) increase with land-use change was observed only in three layers (Figure 4a), while reduction in flux-related properties occurred in more layers (5 layers for Ks, 8 layers for Ka_{10}, and 4 layers for Ka_{100}). This indicates that decreases in air or water fluxes are not necessarily related to increases in soil compaction. But a small decrease in porosity can reduce Ks and Ka even if an increase in soil degree of compaction is not detected by increased Bd or decreased Tp, as observed in SOY in layers 0.05-0.10 and 0.10-0.20 m at Quaraí site (Figures 4 and 5). As conductivities and permeabilities are soil properties generally more sensitive to management and land-use change (Ambus et al., 2018; Valani et al., 2022), the reduction of soil functionality for water and air fluxes draws more attention than the soil compaction in relation to degradation of sandy soils of PB.

A lower soil functionality for water fluxes due to land-use change modifies the balance between infiltration and runoff, increasing the risk of degradation and reducing water conservation in the ecosystem. But soil functionality for water retention is also important to evaluate because it determines soil capacity to supply water for crops replacing natural vegetation.

Available water (AW) is commonly used as a measure of the maximum soil capacity to store water that roots can uptake. The AW was affected by land-use change only in two layers at Ibicuí and Pampeiro sites (Figure 6c), but the higher AW at Pampeiro site was probably influenced by higher clay plus silt content at EUC (Table 2). To evaluate this bias, we used a Brazilian texture-based pedotransfer function specifically developed to estimate AW (Teixeira et al., 2021). With this PTF, we evaluated the effect of changing clay content on AW for EUC and GRA at Pampeiro site. By changing only 10 % in clay results in a difference of 0.069 m^3 m^{-3} in AW, which is close to the difference in AW in the layer 0.20-0.50 m (0.084 m^3 m^{-3}) and almost half of the difference in the layer 0.10-0.20 m (0.157 m^3 m^{-3}) attributed to land-use change (GRA to EUC). If we subtract the AW estimated by the texture of the AW observed at Pampeiro site, the difference in water retention for plants between EUC and GRA probably becomes not significant, remaining differences only at Ibicuí site.

The decrease of AW in SOY in layers 0.05-0.10 and 0.10-0.20 m at Ibicuí site coincided with a significant increase of Bd and decrease in Ma (Figure 4a). At the same site, the decrease of AW in EUC in layer 0.20-0.50 m coincided with an increase of Tp (Figure 4b), and with a decrease in Ma again (Figure 4c). Greater Tp commonly is a consequence of more macropores (Mondal and Chakraborty, 2022). A greater proportion of macropores results in a lower AW because macropores do not contribute to water retention inside the AW range. However, land-use effect on Ma (Figure 4c) was identical to the effect on AW (Figure 6c), and the mean Ma (0.200 m^3 m^{-3}) was just 9 % greater than the mean water content at FC (0.184 cm^3 cm^{-3}) in the sandy soils of PB. Thus, the effect of changes in soil structure on AW is less predictable in poor-aggregated sandy soils than in clayey well-structured ones. The result reinforces that the relation between change in land-use or soil tillage and AW is non-generalizable (Blanco-Canqui and Ruis, 2018; Santos et al., 2021; Valani et al., 2022), because the conditions that determine the increase or decrease in AW with the porosity variation are site-specific, as it depends on soil texture and organic matter content (Blanco-Canqui and Ruis, 2018). Other studies also show low or no relation between Bd and porosity with AW in sandy soils (Reichert et al., 2016; Suzuki et al., 2023). Therefore, due to the great observed dependence of AW on texture, there was little evidence that land-use change can cause expressive restriction in AW for plants in sandy soils of PB.

The categorization of sandy soils as fragile soils is related to their poor structural resistance to disaggregation. Land-use conversion from GRA to EUC increased aggregate stability at Ibicuí and Pampeiro sites (Figure 7a). But, as was observed for AW, it is difficult to separate the land-use and texture effects on MWD at Pampeiro site because clay plus silt content in EUC is ~ 30 % greater than in GRA (Table 2), and fine particles content is positively correlated with aggregate stability (Rivera and Bonilla, 2020). Thus, aggregate stability was more probably improved by land-use change only in the deepest layer of Ibicuí site. Nevertheless, better structural resistance deep in the soil profile is not effective in protecting the topsoil where natural and anthropic desegregating forces act.

The non-significant effect of land-use change on aggregate stability at surface layers can be related to the little increase in soil carbon stock and nitrogen content at these layers (Figure 7). Carbon and nitrogen availability are necessary for activating microorganisms that are promoters of soil aggregation. The small change observed in carbon is probably due to the low clay content, which limits organic matter accumulation, and the short time of land-use change from natural vegetation to crops. After 8 years of comparing grassing, cropping, and forest land-use, Valani et al. (2022) observed little change in organic carbon and no difference in aggregate stability among them in a sandy clay loam soil, which is more clayey than soils of this study. The conversion of GRA to EUC and SOY is no longer than 10 years in the sites evaluated. Thus, a significant impact of land-use change on soil carbon and, consequently, on structural resistance in the sandy soils of PB may take more time.

Land-use change from natural vegetation to crops (soybean and eucalyptus) at PB is mainly driven by economic forces. However, the risk of biome ecosystem degradation with agricultural intensification needs to be considered along with economic interests. Therefore, from a soil conservation and functionality point of view, an overview of the results of this study indicates that sandy soils of PB are more likely subjected to a loss of its functionality to air and water fluxes than to water availability for plants. Moreover, compared to soils with higher clay content (Santos et al., 2021; Valani et al., 2022), sandy soils of PB seem to be less susceptible to soil compaction and its structural stability is less sensitive to land-use change. The little changes observed in the structure resistance of sandy soils of PB with land-use change may be evidence that they are too little aggregated under natural vegetation that they cannot be disaggregated even more.

A similar interpretation can be made for carbon dynamics. The carbon stock in PB grassland is so low that land-use change did not expressively reduce it, even with soybean being cropped with conventional tillage. In the case of eucalyptus, which can provide more carbon than annual crops, the soil carbon stock probably needs a longer time to increase due to the low capacity of the sandy soil to preserve organic matter.

CONCLUSION

After land-use change from natural grassland to soybean crop (up to 9 years) or eucalyptus forest (up to 10 years), the highly sandy soils of Brazilian Pampa Biome (PB) showed a systematic decrease of soil functionality only in flow-related properties (water conductivity and air permeability). On the other hand, variables related to soil porous system (bulk density, total porosity and macroporosity), and soil structural resistance (aggregate stability) showed low sensitivity to the conversion from natural vegetation to crops (soybean and eucalyptus), even where recommended soil conservation practices were not used. Thus, if no-tillage practices are used (e.g., minimal soil disturbance and soil covered most of the time), the land-use change from natural grassland to soybean and eucalyptus plantation in sandy soils of PB may not lead to a detectable degradation of soil physical properties.

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