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ALTERAÇÕES DE PROPRIEDADES FÍSICO-HÍDRICAS EM SOLOS ARENOSOS DO BIOMA PAMPA SOB USOS DISTINTOS

Santa Maria, RS
2023

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Dissertação apresentada ao Curso de Pós-Graduação em Ciência do Solo da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para a obtenção do título **de Mestre em Ciência do Solo.**

Orientador: Prof° Dr. Paulo Ivonir Gubiani

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Santa Maria, RS
2023

DEDICATÓRIA

Sem palavras para descrever o que consigo sentir. Para o meu anjinho que me espera em algum lugar, dedico este trabalho e provavelmente a minha vida inteira. Como aprender ou viver ou sonhar sem nunca ter escutado a tua voz ou visto a cor dos teus olhos? A imaginação é o único lugar em que vamos poder conversar. Teria muitas coisas para aprender junto contigo, minha filha, o que me ensinaste em pouco menos de nove meses jamais vou esquecer, e que em cada dobra cruel do tempo vou lembrar do teu nome. Manoela Conceição, o pai dedica este trabalho para você.

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Um trabalho nunca é feito sozinho, existem várias pessoas por trás dos autores dando dicas, conversando no corredor ou enquanto espera-se o tempo de agitação dos agregados, e destas conversas sempre saem bons frutos, então relembro nestas linhas aqueles coadjuvantes de ouro que foram fundamentais.

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A Pampa é um lugar que se transcende

Fronteiras são impostas pelas guerras

Y el gaúcho com certeza não entende

Três nomes, três brasões pra mesma terra

Pampa, Leonel Gomez - Joca Martins - Cezar Oliveira, 2008

RESUMO

ALTERAÇÕES DE PROPRIEDADES FÍSICO-HÍDRICAS EM SOLOS ARENOSOS DO BIOMA PAMPA SOB USOS DISTINTOS

AUTOR: Rodrigo de Moraes Galarza
ORIENTADOR: Prof° Dr. Paulo Ivonir Gubiani

Os solos arenosos naturalmente frágeis do bioma pampa (BP) estão sendo degradados com a introdução de culturas agrícolas mal administradas. O uso antrópico pode diminuir acentuadamente a cobertura vegetal em solos arenosos, deixando-os mais expostos a agentes erosivos. Diminuição do teor de matéria orgânica, biodiversidade, e disponibilidade de nutrientes, maior compactação do solo e menor disponibilidade de água são também algumas consequências desse tipo de uso. No Rio Grande do Sul, em áreas com solos mais arenosos, a intensa substituição do BP por culturas comerciais que ocorreram nos últimos anos (2000-2020) pode estar iniciando um ciclo desastroso de degradação destes solos. No entanto, ainda não se sabe o quanto estes solos estão degradados pelo recente uso antrópico. Não existem publicações científicas locais dedicadas ao diagnóstico da degradação destes solos por uso antrópico. Portanto, a necessidade deste estudo foi baseada no objetivo de avaliar as propriedades físicas e hidráulicas dos solos arenosos do BP com a inserção de usos agrícolas. O estudo foi conduzido em três solos diferentes, onde foram coletadas amostras de solo sob três sistemas de uso (pecuária extensiva em pastagens nativas, florestamento de eucalipto, e cultivos de soja). Nossos resultados mostram que estes solos arenosos podem levar mais de 10 anos para indicar alguns níveis de degradação em suas propriedades físicas e hidráulicas após a substituição do BP por culturas anuais.

Keywords: Disponibilidade da água, estabilidade de agregados, degradação do solo, mudança do uso do solo.

ABSTRACT

CHANGES IN PHYSICAL AND HYDRAULIC PROPERTIES IN SANDY SOILS OF THE PAMPA BIOME UNDER DIFFERENT USES

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The naturally fragile sandy soils of the pampa biome (BP) are being 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 lower water availability are also some crops. In Rio Grande do Sul, in areas with sandier soils, the intense BP replacement for commercial crops that occurred in recent years (2000-2020) may be initiating 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 BP sandy soils with the insertion of agricultural crop soils. The study was conducted on three different soils, where soil samples were collected under three use systems (extensive cattle ranching on native pastures, eucalyptus afforestation, and soybean crops). Our results show that these sandy soils can take more than 10 years to indicate some levels of degradation in their physical and hydraulic properties after replacement of BP by annual crops.

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

SUMÁRIO

1. APRESENTAÇÃO

Solos arenosos naturalmente frágeis podem ser acentuadamente degradados quando o uso natural é substituído por cultivos agrícolas. No sul da América do Sul, a substituição do campo nativo (CN) por monoculturas está aumentando a susceptibilidade à degradação dos solos do BP. A combinação de solos frágeis a processos erosivos com a ocorrência de chuvas intensas no sul do Brasil caracteriza grande parte do BP como sendo naturalmente susceptível à degradação. O BP ocupa uma área total de 700.000 ha^2 e se estende pelo sul do Brasil, Argentina e Uruguay. No Estado do Rio Grande do Sul, Brasil este bioma ocupa 62% do estado, compreende uma área de 178.243 km^2, cerca de 2% do território brasileiro.

Ao longo dos últimos 20 anos (2001 – 2021), houve um avanço da substituição da vegetação natural do BP pelo cultivo de soja e eucalipto. Algumas práticas de manejo adotadas nesses cultivos, como gradagem em todos os anos e plantio sem considerar nível topográfico, podem acelerar o processo de degradação dos solos do BP. Estudos indicam que a substituição do CN por *Eucaliptus spp* promoveu alterações de propriedades químicas do solo, como elevação da acidez potencial, redução dos teores de matéria orgânica e do teor de nutrientes (Leite, 2002; Pillar et al., 2009).

Em solos arenosos com pastagem natural comparado com cultivo de *Eucaliptus spp*, houve uma grande diferença na qualidade da matéria orgânica, sendo que mais de 90 % do C presente na matéria orgânica do solo foi proveniente da floresta (Severo, 2015). Outros estudos mostrando que a substituição de áreas de CN pelo uso do solo com lavouras diminui os teores de matéria orgânica, a biodiversidade e a disponibilidade de nutrientes, bem como aumenta a compactação do solo, alterando os teores de umidade e a dinâmica da água no solo (Pillar et al., 2009).

A substituição do CN do BP por cultivos comerciais pode estar iniciando um ciclo desastroso de degradação dos solos. Diante do exposto, o propósito do estudo foi avaliar as consequências de uso dos solos para identificar alterações em propriedade físico-hídricas que estão acontecendo no BP. Os resultados estão apresentados e discutidos em um artigo científico, apresentado a seguir, formatado para publicação na Revista Brasileira de Ciência do Solo.

2. ARTIGO: CHANGES IN PHYSICAL AND HYDRAULIC PROPERTIES IN SANDY SOILS OF THE PAMPA BIOME UNDER DIFFERENT USES

HIGHLIGHTS

- Soil physical and hydraulic properties (PHP) were studied in the Pampa Biome (PB).
- PHP may not be sensitive to degradation in sandy soils of PB.
- Eucalyptus ad soybean kept the soil carbon contents similar to native grasslands.
- Long-term studies are needed to better detect changes in PHP in the PB.

2.1. ABSTRACT

The naturally fragile sandy soils of the pampa biome (BP) are being 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 BP soils by the implementation of 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 BP 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 ranching in native grassland, eucalyptus afforestation, and soybean crops). Our results show that these sandy soils can take more than 10 years to indicate some level of degradation in their physical and hydraulic properties after replacing PB with cultivated crops.

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

2.2. INTRODUCTION

The Pampa Biome (PB) extends over an area of 700.000 km^2 from southern Brazil to Argentina and Uruguay (Embrapa, 2022). In the state of Rio Grande do Sul - Brazil alone, the PB occupies 62% of its area, which represents 176.500 km^2, about 2% of the Brazilian territory (Ibfloresta, 2022). The vegetation of the BP is composed of grasses, legumes, trees, and shrubs, of which more than 150 species of legumes and almost 450 grasses have been cataloged (Embrapa, 2022).

The great advance and intensification of agriculture in regions of South America Fuentes-Llanillo et al. (2021) have caused the substitution of approximately 45 % of the Brazilian PB by monocultures (Mapbiomas, 2022). In the municipality of Sant'Ana do Livramento, there has been a large increase in the area cultivated with soybeans from 30 km² in 2000 to 550 km² in 2022 (Ibge, 2022). The average soybean yield of Sant'Ana do Livramento is 30% lower than the national average (Ibge, 2022). This suggests limitations to crop yield that are probably related to the soil and climatic conditions of these locations. Because they are loamy and sandy soils, the productivity 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 (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 soybean potential yield (Obour and Ugarte, 2021).

Evidences from studies carried out at PB indicate that land use change implies a reduction in organic matter and nutrient availability (Leite et al., 2002; 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 (Chaves et al., 2021; Castro et al., 2010; Korchagin et al., 2019; Tian et al., 2023). With all this, diagnostics focused on physical and hydraulic properties are still needed to evaluate the impacts that soybean and eucalyptus cultivation are having on the soil's ability to resist erosion 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 and available water capacity, as well as structural properties such as soil porosity and density. With these properties, it is possible to diagnose the physical and hydraulic condition of the soil. Thus, 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.

2.3. MATERIAL AND METHODS

2.3.1. Description of the studied sites

The work was conducted in three sites in the Brazilian BP, 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 cultivated for more than 5 and 7 years, respectively, (ii) land use is conventional in soybean management, (iii) there are areas of native grassland (GRA) with no cultivation history, (iv) the collection distance within each study site was no more than 0.45 km, and (v) within each study site the trenches were at similar elevations. The land use change at all sites is less than 10 years.

The technologies applied to eucalyptus and soybean cultivation at all sites were similar with respect to fertilization rates, herbicide applications, and other pesticide applications. The plantations were managed and harvested mechanically. Before the implementation of each crop (soybean or eucalyptus), the soil was tilled, after harvest a cover crop was sown, and at the Pampeiro and Ibicuí sites the winter cover areas were used with beef cattle, on average of 600 kg of animal load. Soybean replanting was done after plowing and SOY seeding was done in rows spaced 0.45 m apart. There was no irrigation on any of the crops. When the eucalyptus seedlings were established, limestone was incorporated. Up to the time of soil sampling, EUC had not been harvested. In the GRA areas, the animal stocking rate was adjusted according to the season and the pasture height was preserved at 8-12cm throughout the year, on average of 450 kg live weight per year, which characterizes the extensive cattle raising system.

2.3.2. Sampling and soil measurements

Sampling was carried out between April and May 2022. In each site, the soil was sampled in four trenches in each management system. Soil samples were collected in four layers (0-5, 5-10, 10-20, and 20-50 cm). In each layer, undisturbed samples - Kopecky cylinder and soil clod - and disturbed samples were collected.

At layers 0-5 and 5-10 cm, three undisturbed subsamples were collected (100 cm^3 Kopecky cylinders), totaling 216 cylinders, and at layers10-20 and 20-50 cm, one sample (145 cm^3) was collected, totaling 72 cylinders. In the laboratory, these samples were saturated by capillary rise for 24 h and then drained at -100 kPa using Richards' chamber. After draining at -10 and -100 kPa, the samples were subjected to the air permeability test (Ka, μm^2). Samples were saturated by capillary rise for 24 h again and drained at -6 and -10 kPa in sand columns (Reinert and Reichert, 2006). Then, the samples were again saturated to determine the hydraulic conductivity (Ks, mm h^{-1}) in a constant head permeameter (Teixeira et al., 2017). During the test, a layer of 1 cm of water was kept over the samples and, after flow stabilization, the volume of water that flowed through the samples in a 15 min period was quantified to calculate Ks. Finally, the samples were dried in an oven at 105° to obtain total porosity (Tp) and soil bulk density (Bd), according to (Teixeira et al., 2017).

Soil clods were also sampled. One block of approximately 4000 cm^3 (20 x 20 x 10 cm) was collected at each layer and immediately wrapped with PVC plastic film to preserve soil structure. In the laboratory, blocks were detached in small clods to determine mean weigh diameter aggregates (MWD) (Kemper and Rosenau, 1986).

A total of 144 disturbed samples were also collected from all collection layers. In the laboratory, these samples were air-dried and sieved with a 2mm mesh. Samples of all trenches at each management system were mixed to determine soil texture. These samples were used to determine the silt, clay and sand fractions by the pipette method (Suzuki et al., 2015).

Water retention was characterized using the field capacity and permanent wilting point estimates. Field capacity was considered the water held at -10 kPa in the sand table, and the permanent wilting point was estimated as a function of clay with a pedotransfer function proposed by (Reichert et al., 2009).

Disturbed samples were also used to determine C and N content. Samples of layers 0-5 and 5-10 cm were mixed to compose one sample for 0-10 cm layer of each trench (four samples per management system). For layers 10-20 and 20-50 cm 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).

2.3.3. Statistical analysis

As the three soil 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 soil 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).

2.4. RESULTS

The soil at Ibicuí and Pampeiro sites were similar in particle size distribution, with averages of 81 and 79 % of sand, 11 and 14 % of silt and 8 and 6 % of clay, respectively. At Quaraí site, clay content was close to other sites (6 %), but silt was lower (3 %) and sand higher (91 %) (Table 1). 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 0-5 cm 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 1).

The 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 description of results was made by comparing the differences in soil variables between GRA and EUC, and between GRA and SOY. For this comparison, we assumed GRA as a control plot that represents soil conditions at natural vegetation before land use change.

The soil bulk density (Bd) and total porosity (Tp) were significatively affected by land use change mainly in superficial layers (0-5 and 5-10 cm) (Figure 4). Bd in SOY increased 8 % in layer 5-10 cm at Ibicuí site, and 18 % in layer 0-5 cm at Pampeiro site. In layer 0-5 cm at Quaraí site, Bd in EUC decreased 12 % (Figure 4A). Pt of the layer 20-50 cm 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 Pt increase of 18 % in layer 0-5 cm, and a Pt decrease of 7 % in layer 5-10 cm (Figure 4B).

The 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). Ks was lower in SOY in 10-20 and 20-50 cm layers at Ibicuí and in 5-10 and 10-20 cm 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). 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 10-20 cm (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 neither in superficial layers at Pampeiro site. AW at Ibicuí site decreased in SOY in layer 5-10 cm and in EUC in layer 20-50 cm, but the reduction in both layers was lower than 0.035 cm^3 cm^{-3} (Figure 6C).

Aggregate stability, evaluated by the mean weight diameter of aggregates (MWD), was enhanced by changing GRA to EUC in superficial 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 0-10 cm (Figure 7B). No statistical effect of land use change was detected in nitrogen content (Figure 7C).

Significative Spearman correlation between Bd and retention properties (CC and AW) ranged from -0.38 to -0.58, with the greatest correlation between Bd an AW. Correlation between Bd and flux properties (Ks, Ka_{10} and Ka_{100}) was more variable, ranging from -0.29 to -0.66. Higher correlation was observed between Ka_{10} and Ka_{100} with Ks, with values greater than 0.73 (Table 2).

2.5. DISCUSSION

The 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 loamy sandy and at Quaraí site are sandy (Table 1), therefore, the sites chosen for sampling represent the most fragile soils of PB.

The low variability of particle size distribution (< 9 %) between land uses at Ibicuí and Quaraí sites and between natural grassland (GRA) and soybean crop (SOY) at Pampeiro site (Table 1), 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 eucalyptus stand (EUC) and the others land use may had 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 significative decrease in Pt (Figures 4A and 4B). The management operations for soybean cultivation as sowing, spraying, harvesting and transportation, are executed 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 greater than 18 %, whereas Santos et al., (2021) observed a greater increase in Bd, up to 28 %, in all layers until 30 cm 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 10 years), compared to 22 years of Santos et al., (2021). However, the little increase in Bd even at superficial 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 1). 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 Pt 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.

Conversion from GRA to EUC resulted in a decrease in Bd and an increase in Pt only in the superficial layer at Quaraí site (Figure 4). 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 during 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.

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 year by year, 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 0-5 cm layer at Quaraí site even with an increase in Pt (Figure 4B). On the other hand, the roots of soybean 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 as a result of soil compaction.

Soil compaction (represented by Bd) correlation with flux-related variables was moderated to low (ranged from -0.66 to -0.29) (Table 2). But a small decrease in macropores can reduce Ks and Ka even if an increase in soil degree of compaction is not detected by increased Bd or decreased Pt, as observed in SOY in layers 5-10 and 10-20 cm 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, which can increase the risk of degradation and reduce water conservation in the ecosystem (Reichert et al., 2017). But soil functionality for water retention is also important to be evaluated because it determines soil capacity to supply water for crops that are replacing natural vegetation.

The available water (AW) is commonly used as a measure of the maximum soil capacity to store water that roots can uptake. 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 1). The difference in AW between EUC and GRA at Pampeiro site estimated with texture-based pedotransfer function developed for Brazilian soils (Teixeira et al., 2021), was 0.069 cm^3 cm^{-3}, which is close to the difference observed at the same site between EUC and GRA in layer 20-50 cm (0.084 cm^3 cm^{-3}) and almost half of the difference in layer 10-20 cm (0.157 cm^3 cm^{-3}) (Figure 6C). If we subtract the AW estimated by 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 layer 10-20 cm at Ibicuí site coincided with a significative increase of Bd (Figure 4A), which is frequently observed in subsurface layers in soils cropped with soybean (Pott et al., 2019). At the same site, the decrease of AW in EUC in layer 20-50 cm coincided with an increase of Pt (Figure 4B). Greater Pt observed in forests compared to grasslands or crops is a consequence of more macropores (Santos et al., 2021). The greater Ks in EUC in layer 20-50 cm at Ibicuí site (Figure 5A) is evidence of more macropores at the layer, and a greater proportion of macropores results in a lower AW because macropores do not contribute to water retention inside AW range.

Despite the coherent reduction on AW with land use change, this effect was observed only in two layers of one site, and its magnitude was small (< 0.035 cm^3 cm^{-3}). 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 variation on porosity are site-specific, as it depends on soil texture and organic matter content (Blanco-Canqui and Ruis, 2018). Therefore, there was little evidence that land use change can cause expressive restriction in water availability for plants at 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 site (Figura 7A). But, as was observed for AW, it is difficult to separate the land use effect from the texture effect on MWD at Pampeiro site because clay plus silt content in EUC is ~ 30 % greater than in GRA (Table 1), 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 are not effective to protect the topsoil, where the most natural and anthropic desegregating forces act.

The non-significative effect of land use change on aggregate stability at superficial layers can be related to the non-expressive 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 (Tisdall and Oades, 1982). 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 comparing grassing, cropping and forest land uses, 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 significative impact of land use change on soil carbon and, consequently, on structural resistance in the sandy soils of PB may take more time.

The 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 subject to a more expressive 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 too low that land use change did not affect it expressively, 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.

2.6. CONCLUSION

After 10 years of land use change from natural grassland to soybean crop or eucalyptus forest, 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 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, 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 if the soil is little disturbed and remains covered most of the time.

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Table 1. Particle size distribution by soil layers and land use at Ibicuí, Pampeiro and Quaraí sites in Brazilian Pampa Biome.

Site	Layer (cm)	Coarse sand (%)			Fine sand (%)			Areia total (%)			Silt (%)			Clay (%)		
		EUC	GRA	SOY	EUC	GRA	SOY	EUC	GRA	SOY	EUC	GRA	SOY	EUC	GRA	SOY
Ibicuí	0-5	**39**	**45**	**48**	**37**	**40**	**37**	76	85	84	**13**	**12**	**10**	**11**	**3**	**6**
	5-10	**30**	**38**	**36**	**51**	**42**	**47**	81	79	83	**10**	**11**	**11**	**9**	**9**	**7**
	10-20	**33**	**37**	**41**	**50**	**42**	**40**	82	79	80	**10**	**11**	**11**	**8**	**9**	**8**
	20-50	**28**	**38**	**42**	**51**	**46**	**38**	79	83	80	**11**	**7**	**11**	**10**	**10**	**9**
Pampeiro	0-5	**18**	**59**	**40**	**42**	**32**	**48**	60	91	88	**27**	**5**	**9**	**13**	**3**	**3**
	5-10	**18**	**49**	**40**	**42**	**42**	**47**	60	91	88	**28**	**5**	**9**	**12**	**3**	**3**
	10-20	**18**	**51**	**42**	**42**	**41**	**45**	60	91	87	**28**	**5**	**9**	**12**	**3**	**3**
	20-50	**21**	**50**	**37**	**38**	**41**	**48**	59	91	85	**28**	**4**	**11**	**13**	**4**	**5**
Quaraí	0-5	**38**	**34**	**48**	**54**	**59**	**43**	92	94	90	**4**	**3**	**3**	**4**	**3**	**7**
	5-10	**35**	**37**	**54**	**57**	**57**	**37**	92	93	91	**3**	**2**	**2**	**5**	**4**	**7**
	10-20	**35**	**41**	**54**	**56**	**52**	**36**	91	93	89	**4**	**2**	**2**	**5**	**5**	**8**
	20-50	**34**	**52**	**55**	**54**	**39**	**33**	88	90	88	**6**	**3**	**2**	**7**	**7**	**10**

Table 2 - Spearman's correlation coefficient between soil bulk density (Bd) and water retention (FC, PWP and AW) and flow properties (Ks, Ka10 and Ka100), and between water (Ks) and air (Ka10 and Ka100) flow properties for each site in Brazilian Pampa Biome.

Correlations	Ibicuí	Pampeiro	Quaraí
Ds vs CC	-0.38 (0.0079)	-0.56 (<0.0001)	-0.49 (0.0005)
Ds vs PMP	0.05 (0.7086)	-0.14 (0.3335)	0.28 (0.0534)
Ds vs AD	-0.48 (0.007)	-0.57 (<0.0001)	-0.58 (<0.0001)
Ds vs Ks	-0.66 (<0.0001)	-0.45 (0.0018)	-0.57 (<0.0001)
Ds vs Kar_{10kPa}	-0.54 (<0.0001)	-0.29 (0.0459)	-0.38 (0.0080)
Ds vs $Kar_{1000kPa}$	-0.56 (<0.0001)	-0.37 (0.0106)	-0.48 (0.0006)
Kar_{10kPa} vs Ks	0.83 (<0.0001)	0.80 (<0.0001)	0.73 (<0.0001)
Kar_{100kPa} vs Ks	0.87 (<0.0001)	0.81 (<0.0001)	0.83 (<0.0001)

Figure 1. Soil profile of the sampling points in each management system (natural grassland – GRA, soybean crop – SOY and eucalyptus forest – EUC) at Pampeiro site.

Figure 2. Soil profile of the sampling point in each management system (natural grassland – GRA, soybean crop – SOY and eucalyptus forest – EUC) at Ibicuí site.

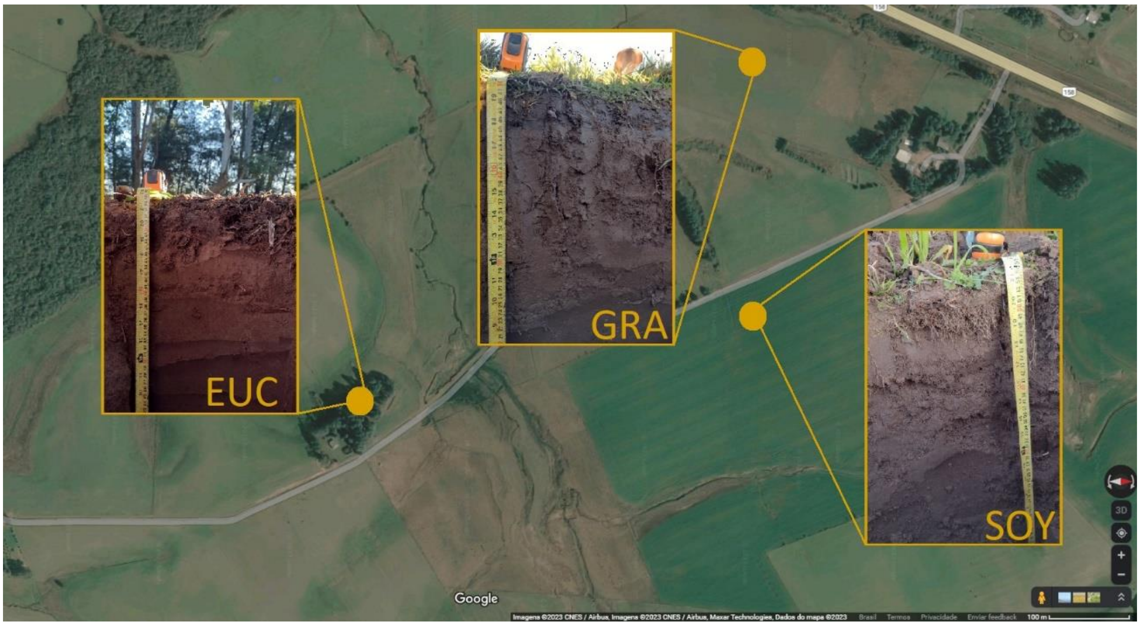


Figure 3. Soil profile of the sampling point in each management system (natural grassland – GRA, soybean crop – SOY and eucalyptus forest – EUC) at Quaraí site.

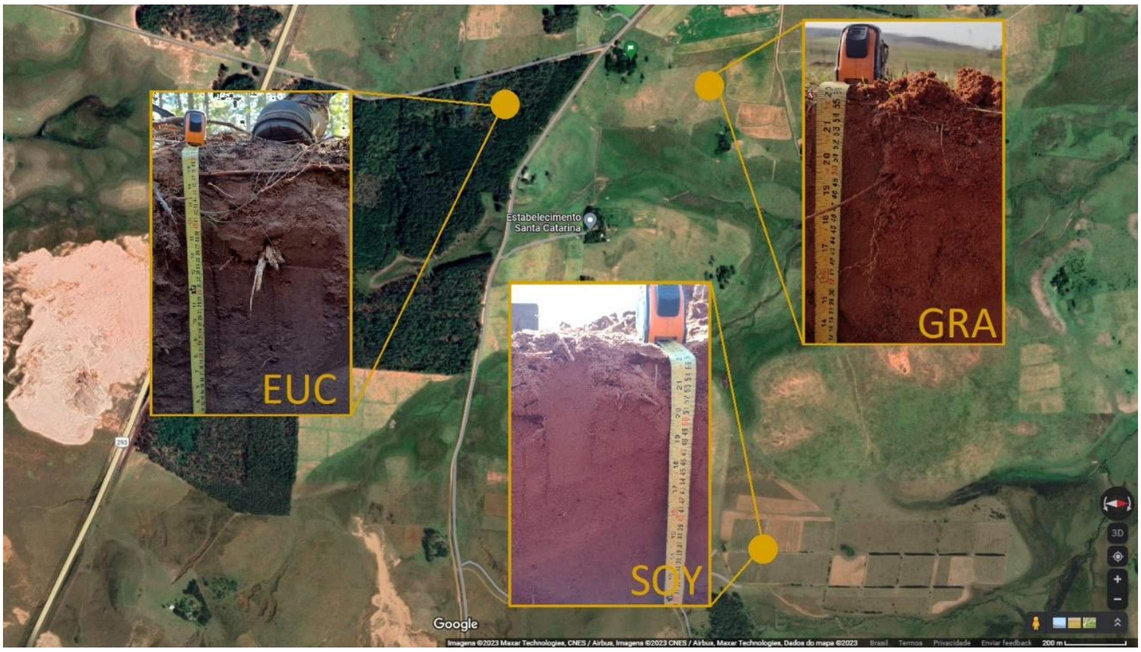
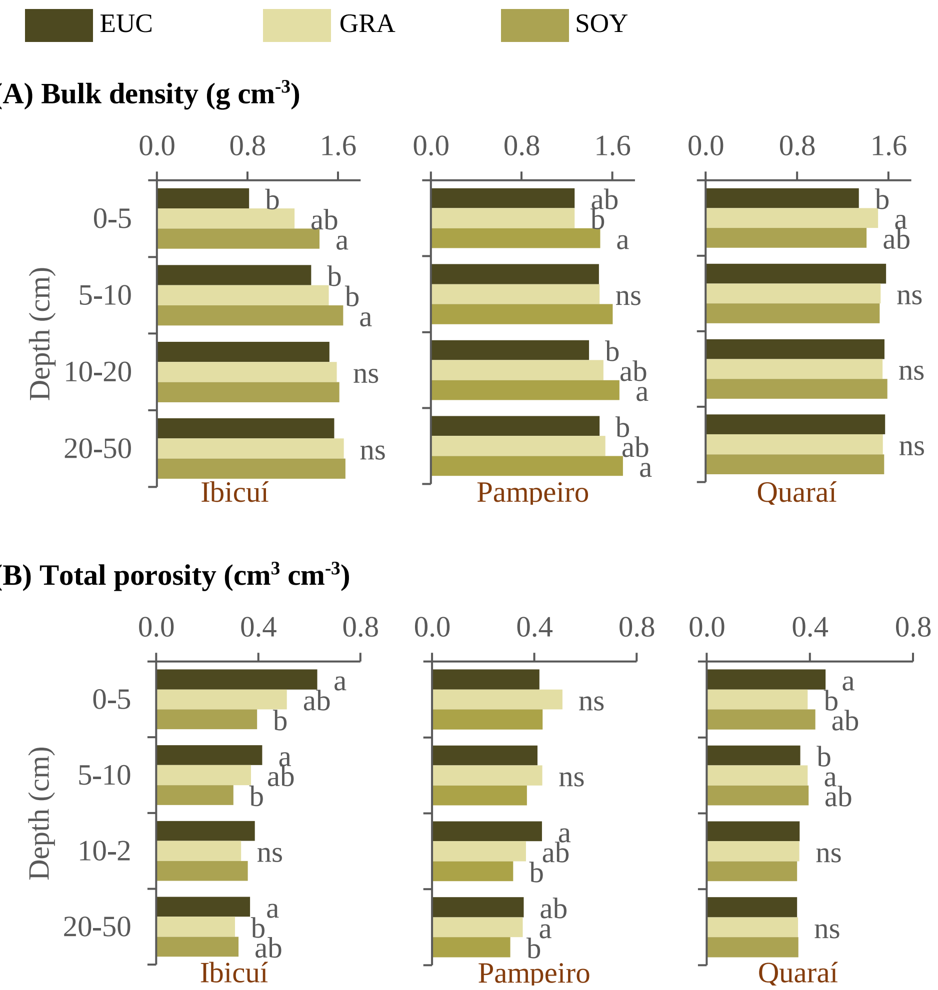
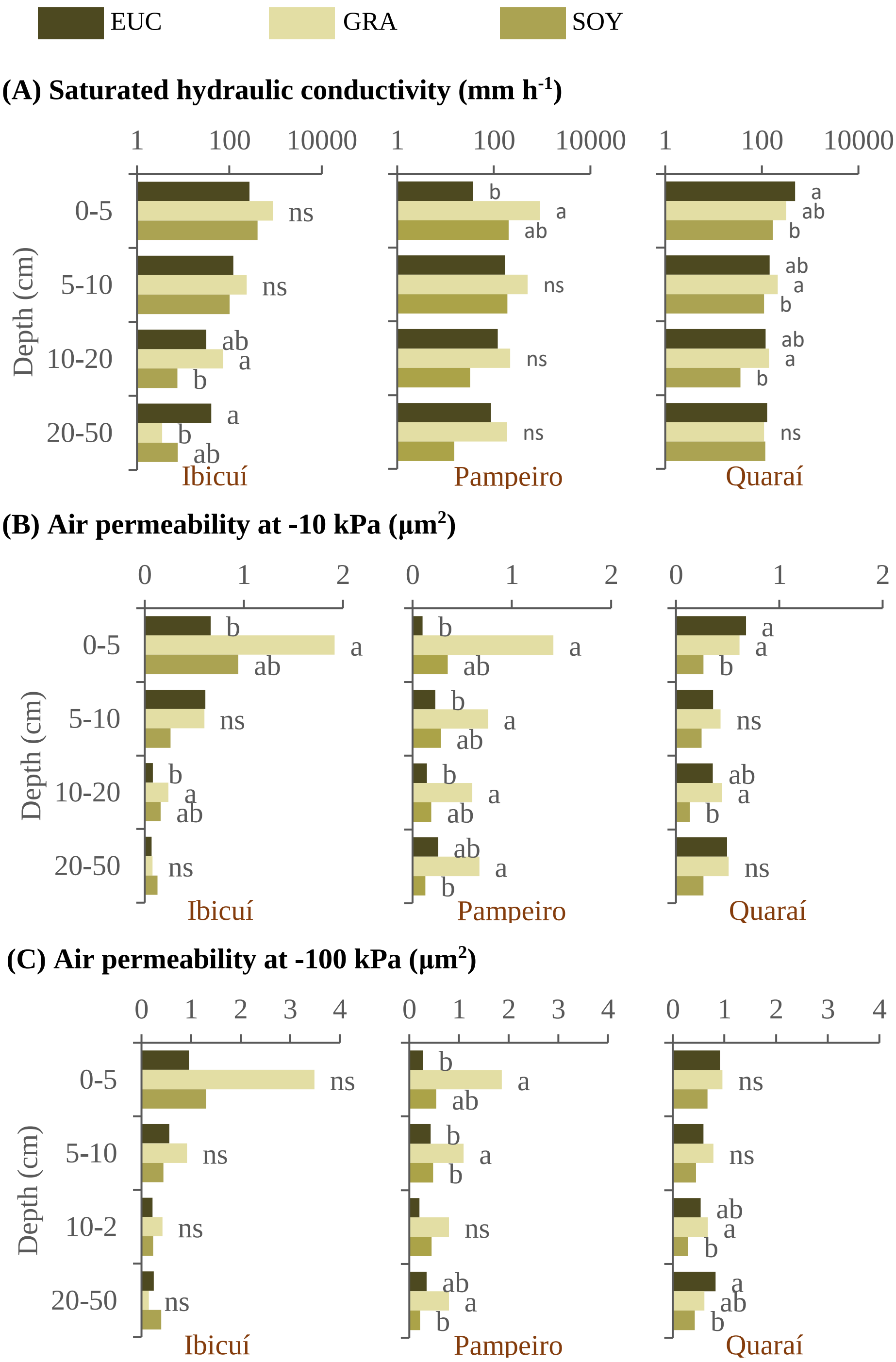


Figure 4 - Effect of land use (EUC – eucalyptus forest, GRA – natural grassland, SOY – soybean CROP) on soil bulk density and total porosity in each layer at Ibicuí, Pampeiro and Quaraí sites in Brazilian Pampa Biome.



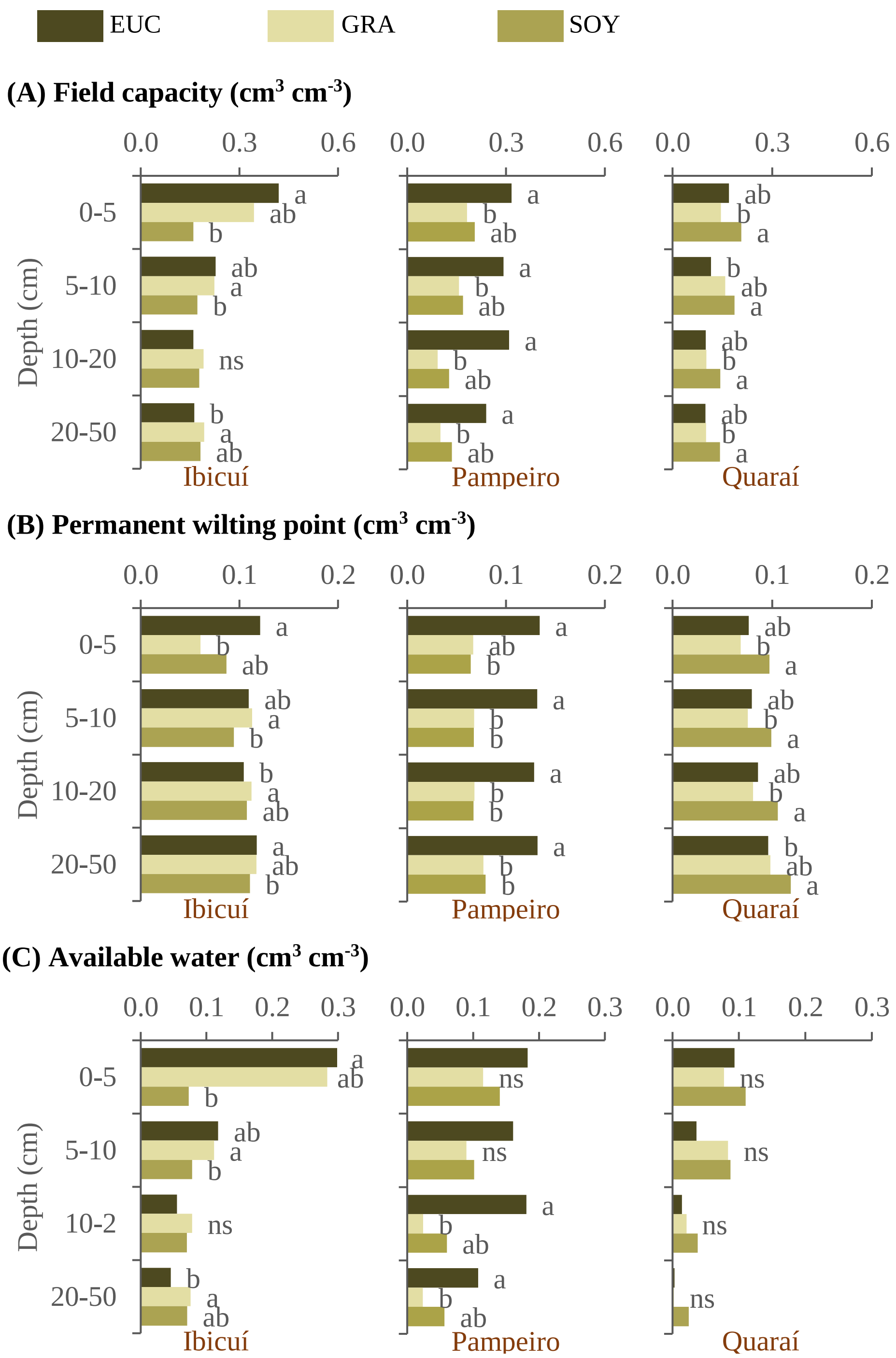
Uses with the same letter within each layer do not differ by the non-parametric Nemenyi test at 0.05 error probability.

Figure 5 - Effect of land use (EUC – eucalyptus forest, GRA – natural grassland, SOY – soybean CROP) on saturated hydraulic conductivity, air permeability measured at -10 kPa and at -100 kPa suction in each layer at Ibicuí, Pampeiro and Quaraí sites in Brazilian Pampa Biome.



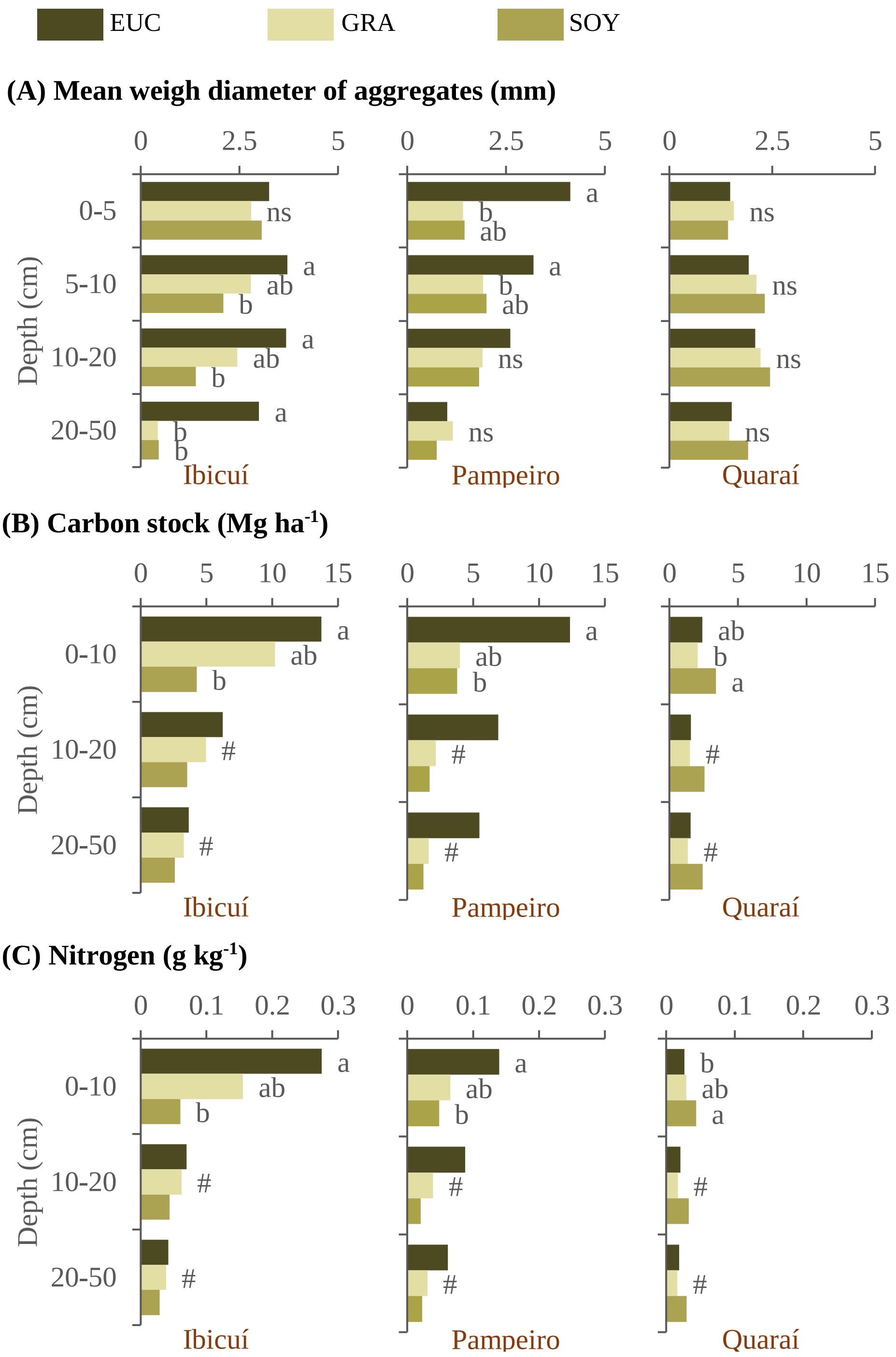
Uses with the same letter within each layer do not differ by the non-parametric Nemenyi test at 0.05 error probability.

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.



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 (MWD), carbon stock and nitrogen in each layer of the soils at Ibicuí, Pampeiro and Quaraí sites in Brazilian Pampa Biome.



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.

3. CONCLUSÃO

Os resultados apontaram para alterações no solo pouco expressivas quando se comparou a vegetação natural do Bioma Pampa (PB) com o cultivo de soja ou floresta de eucalipto. Após 10 anos de mudança de uso da terra de campo natural para cultivo de soja ou floresta de eucalipto, os solos altamente arenosos do BP apresentaram uma diminuição sistemática da funcionalidade do solo apenas nas propriedades relacionadas ao fluxo (condutividade da água e permeabilidade do ar). Por outro lado, variáveis relacionadas ao sistema poroso do solo (densidade do solo, porosidade total) e resistência estrutural do solo (estabilidade dos agregados) mostraram baixa sensibilidade à conversão de vegetação natural para culturas (soja e eucalipto), mesmo quando as práticas recomendadas de conservação do solo não foram usadas. Assim, a mudança de uso da terra de campo natural para plantio de soja e eucalipto em solos arenosos da PB pode não levar a uma degradação detectável das propriedades físicas do solo se o solo for pouco revolvido e permanecer coberto na maior parte do tempo.

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