Effect of Land Use Changes in Eastern Amazonia on Soil Chemical, Physical, and Biological Attributes

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Abstract: Land use change in rural settlements of the Amazon influences the abundance, diversity, and survival of soil fauna, especially earthworms, affecting the supply of ecosystem services. This study evaluated the effects of forest conversion to pasture on soil attributes and how the changes on the earthworm community affect soil porosity. Soil samples were collected from two toposequences (forest and pasture) at the summit (T1), midslope (T2) and footslope (T3) positions in July 2012 (dry season) and January and March 2013 (wet season). Samples were taken in five replicates at the depths of 0 to 10, 10 to 20, and 20 to 30 cm for determination of moisture, bulk density, total porosity, micromorphometry of pores, surface litter dry matter, chemical properties, and abundance and richness of earthworms. The numbers of macropores and micropores and S index (*S*) were calculated. The change on land use increased soil organic matter, pH, and calcium and reduced dry matter, moisture, and *S* index in pasture, as well as the loss of earthworm morphospecies highly related to the maintenance and formation of soil macroporosity, especially large rounded pores and, secondarily, large complex pores. This resulted in a loss of soil physical quality.

Key Words: Amazonia, macroporosity, pore morphology, soil biology, soil fauna

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Amazonia has the largest area of tropical continuous forest in the world (Aleixo et al., 2010) but is also one of the areas in Brazil with most rural settlement projects, mainly in the state of Pará (Michelotti et al., 2008; Incra, 2014). Driven by government financing and lack of technical knowledge, the settlers remove the forest and replace it with pasture for cattle grazing, strengthening the cycle of deforestation and changes in land use (Guedes et al., 2011; Martins and Pereira, 2012).

Land use change influences directly quantity, diversity, and survival of soil fauna, which affect the maintenance and supply of ecosystem services, influencing and being influenced by soil chemical and physical attributes (Blouin et al., 2013).

Ecosystem services are benefits provided by the ecosystem to humanity (MEA, 2005) and are directly related to biodiversity. Soil organisms and biodiversity offer many of these services (Blouin et al., 2013). Edaphic organisms act on organic matter (OM) incorporation, nutrient mobilization, and soil structure organization, building galleries, pores, and forming aggregates, thereby increasing aeration, permeability, and root growth conditions (Silva et al., 2011). Soil fauna studies in Amazonia show that soil organisms are primarily responsible for the soil structure organization in superficial layers (up to 30-cm depth) (Lavelle, 1997; Barros et al., 2004; Velásquez et al., 2012).

Most of the biomass of soil organisms is represented by earthworms (Lavelle and Spain, 2001). The feeding and movement activities of earthworms are responsible for OM incorporation and the creation of galleries and pore networks. They influence directly on soil hydrophysical attributes such as porosity, bulk density (BD), infiltration, and water retention that influence runoff and erosion processes. Because of their capability of causing physical changes in biotic and abiotic materials, earthworms modulate resources availability for other species, being recognized as "ecosystem engineers" (Jones et al., 1994).

The type of land use directly influences the survival and development of earthworms. Forest and pasture environments present different composition of earthworms, both in abundance and in diversity (Chauvel et al., 1999). Thus, we hypothesize that for the sustainability of soil conservation the maintenance of the ecological functions of the original biota is necessary, especially in fragile soils, such as those in the Amazon (Rousseau et al., 2014). Thus, knowing that land use change influences both abundance and composition of earthworms and that these influence the hydrophysical attributes of the soil, the present study aimed to evaluate the effects of forest conversion to pasture on soil attributes and how the changes on the earthworm community affect soil porosity.

MATERIALS AND METHODS

The present study was conducted at the Praialta Piranheira agroextractivist settlement in Nova Ipixuna, southeast of Pará State, Brazil. The climate is Af according to Köppen (tropical rainforest climate), characterized by high annual temperatures (minimum of 21°C), annual rainfall of 2,000 mm, and well-defined seasons with rainy season that extends from October to May and dry season from June to September (INMET, 2014). Predominant vegetation is Dense Ombrophylous Forest (IBGE, 2014) and approximately 20% of the study area was converted into pasture (Freitas, 2007) (Fig. 1).

The study area chosen covered 100 ha, of which 20 ha was converted into pasture (*Brachiaria brizantha*) in 2004 and used until 2008 for cattle grazing. Pasture has good coverage and was managed like other pastures in Amazonia, without machinery use, without chemical fertilization or lime application, and using fire as a pasture renovation strategy every 3 years. In 2008, cattle grazing was abandoned in the area, and since then, the pasture is used only sporadically (50 days per year) under a lease system for neighbors. Two toposequences were selected under similar landscape conditions: one under forest and another under pasture, one facing the other in a North-South orientation, following the line of maximum slope gradient, distanced 20 m from each other at the baseline and separated by a small river. The soils on both toposequences were classified as Typic Haplustults (Soil Survey Staff, 2014) (Fig. 1).

Soil classification pits of 1.5 × 1.8 m were opened on both toposequences in three landscape positions: summit (T1), midslope (T2), and footslope (T3). T3 in the forest and pasture was located near the creek that separates the toposequences. Both

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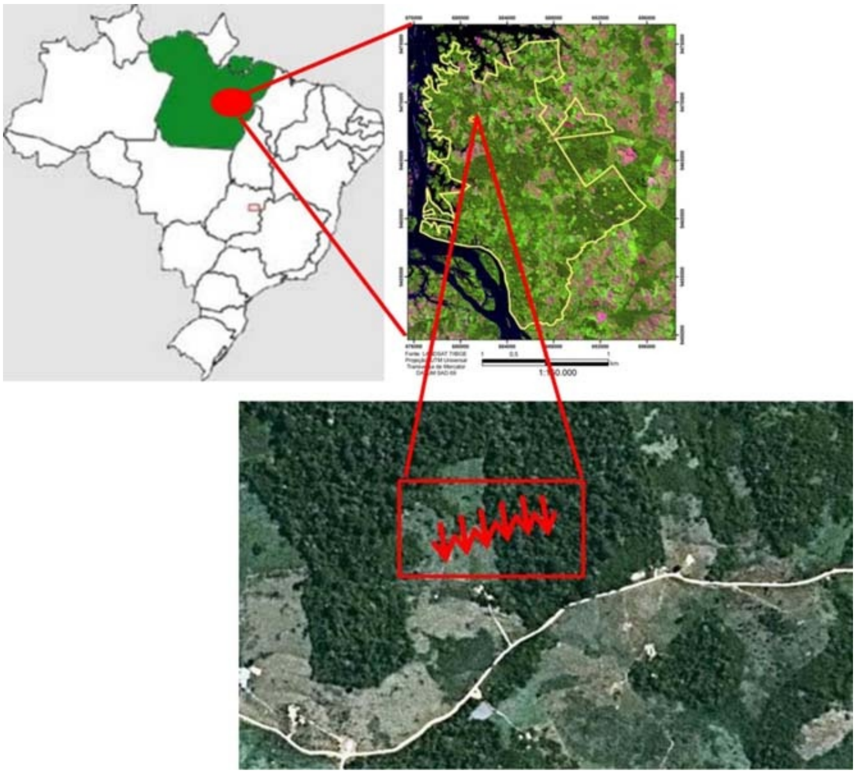

FIGURE 1. Ilustrative scheme of the area and indentification of chosen topossequences. A color version of this figure is available in the online version of this article. full color online

disturbed and undisturbed soil samples were collected from the soil classification pits at the depths of 0 to 10, 10 to 20, and 20 to 30 cm, in order to determine the soil particle size distribution and the micromorphometric parameters. At a distance of 3 m above each pit, five sampling points were established on an arc. Each of these sampling points was distanced 2 m from each other and was used to collect samples at the soil surface for litter dry matter (DM) determination and the depths of 0 to 10, 10 to 20, and 20 to 30 cm for soil macrofauna, soil moisture (U), soil chemical attributes, BD, and total porosity (TP) determinations.

The particle size distribution was evaluated according to Gee and Or (2002). The micromorphometric analyses were performed according to Castro et al. (2003), where quantity of macropores and mesopores was evaluated according to Bullock et al. (1985) and pore shape classified as rounded (channels and vughs), elongated (fissures), and complex (packing voids) (Cooper et al., 2010).

The litter DM sampling was carried out in a square of 25 × 25 cm and was determined by the relationship between wet weight and dry weight at 60°C after reaching a constant value. After DM removal, soil monoliths with 25 × 25 × 30 cm were collected for the determination of soil macrofauna according to the Tropical Soil Biology and Fertility method (Anderson and Ingram, 1993). Disturbed samples were collected at the depths of 0 to 10, 10 to 20, and 20 to 30 cm for determination of pH, calcium (Ca), and OM (Raij, 1987) and soil moisture (Topp and Ferré, 2002). At the same soil depths, undisturbed samples were collected with metallic cylinders (100 cm^3) in order to determine the soil water retention curve (Dane and Hopmans, 2002). The soil water retention curves were used to determine the TP, macroporosity, and microporosity according to Flint and Flint (2002), and the *S* index calculated using the Dexter equation that considers the slope of the soil water retention curve (n), saturated moisture (θs), and residual moisture (θr) (Dexter, 2004). Samples were taken in July 2012 (dry season) and January and March 2013 (wet season) in five replicates.

Earthworms were separated by hand, preserved in formaldehyde solution (4%), and identified in the laboratory at the family level (Righi, 1966). *Glossoscolecidae* genus was identified according to Righi (1995), and exotic genuses were identified according to Blakemore (2006). When the identification was not possible, juveniles and adults were separated according to external and/or internal morphological characteristics and numbered. From the identification of earthworms into species or morphospecies, the Shannon and Simpson richness diversity indexes and the Berger-Parker dominance index were calculated.

The soil chemical and physical data were individually analyzed based on a general mixed linear model, used to describe data that vary according to fixed and random factors. In the model used for DM, the fixed factors were land use and landscape position, and the random factors were the sampling time and the sample. Error variance structure was modeled using Var (Exp) in the nlme library of R version 3.0.0 (R Core Team, 2013) as a variance function (Pinheiro and Bates, 2000). Subsequently, tests were performed using the Di Rienzo, Guzmán, and Casanoves (DGC) test (Di Rienzo et al., 2002). In the models used for the chemical and physical attributes, soil depth was also included as a fixed factor. These analyses were performed using the statistical software Infostat (Di Rienzo et al., 2013).

For the univariate analysis of earthworms, a generalized mixed linear model was used because the individuals counting data do not present a normal distribution of errors. In the model used, the fixed factors were land use, landscape position, and soil depth, and the random factors were the sampling time and all the soil fauna samples. These analyses were performed using the Infostat statistical software (Di Rienzo et al., 2013) and tested using the DGC test. The DCG test is a cluster-based method for identifying groups with nonhomogeneous means that overcomes two common problems of the classic multiple-comparisons methods that (1) lead to the construction of groups that often have substantial overlap and (2) do not have a known level of significance and are not easy to apply (Di Rienzo et al., 2002).

As the soil is a complex environment allowing interactions between all the variables, a canonical correspondence analysis (CCA) was performed considering the interaction between soil physical and chemical attributes and earthworm morphospecies. This analysis was performed using the statistical software CANOCO (ter Braak and Šmilauer, 2002).

To establish the relationship between earthworms and soil physical and chemical attributes, multivariate analyses were used. The analyses were performed at three scales, according to the detailing of soil physical attributes. At the first scale, TP was used; at the second scale, TP was replaced by macroporosity and microporosity, and, finally, at the most detailed scale, the macroporosity and microporosity were replaced by pore morphology obtained by micromorphometric analysis, with separation of pores in three shape classes (rounded, elongated, and complex) and size.

RESULTS

Soil and Litter Characterization

The soils on both toposequences were classified as Typic Haplustults (Soil Survey Staff, 2014) with a sandy loam texture in the surface horizons (750 g kg^{-1} of sand) presenting clay increase in depth (150–400 g kg^{-1} of clay) (Fig. 2). Textural gradient calculated for different landscape positions in the forest and pasture showed that clay content increases in depth. This gradient is not homogeneous and varies according to landscape position. Textural gradients of 2 for forest and 2.5 for pasture were found in positions T1 and T2. For T3, a slight reduction in the textural gradient for forest (1.6) and an increase for pasture (3) were observed.

Soils located on both toposequences showed homogeneous composition for the top 30-cm layer, with the surface presenting a darker color, sandy loam composition, and granular structure. The layers below 30 cm showed yellowish colors, an increase in clay and gravel content, the presence of mottles, and a blocky structure with angular and subangular types for all landscape positions (Oliveira, 2014).

Organic matter, pH, and Ca^{+2} were analyzed because of the high influence of these chemical attributes on earthworm activity

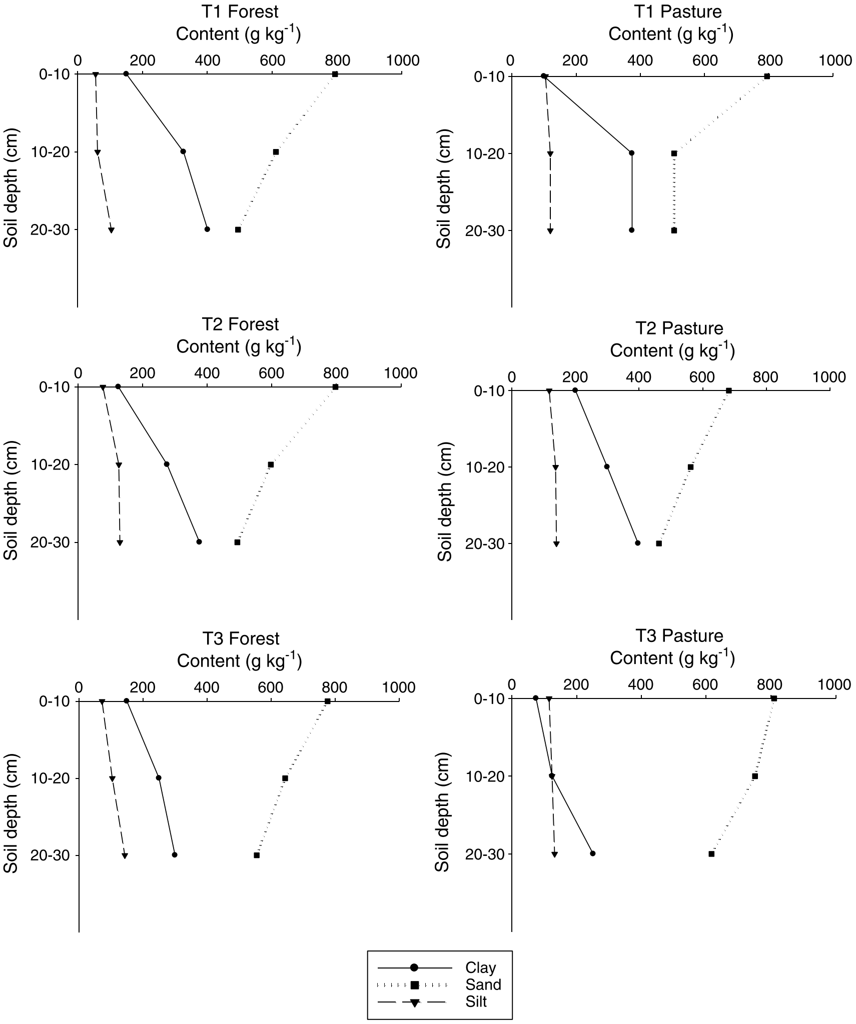

FIGURE 2. Soil clay, sand, and silt contents from forest and pasture for the first 30 cm of soil depth.

and growth. The areas under pasture presented higher values of pH (>5), Ca^{+2} (>4 $mmol_c$ kg^{-1}), and OM compared with the forest areas (Figs. 3A–C). Organic matter content decreased with depth regardless of the land use type ($P < 0.05$). The OM content in forest areas changed from 23 g kg^{-1} at the surface to 13 g kg^{-1} in deeper layers; in pasture, it changed from 30 g kg^{-1} at the surface to 15 g kg^{-1} in the deeper layers ($P < 0.05$) (Figs. 3D, E).

Soil moisture also changes significantly according to land use, with higher moisture contents in the forest (0.25 g g^{-1}) when compared with the pasture (0.15 g g^{-1}) ($P < 0.05$) (Fig. 4A). For the toposequence under forest, no moisture variation was observed in the soil profiles, whereas in the pasture, moisture values reduced with increasing soil depth (Fig. 4B).

Analysis of BD did not show differences between forest and pasture, except for position T3, where the pasture presented higher values ($P < 0.05$) (Fig. 5A). Differences in BD were observed with increasing depth, wherein BD increases from 1.4 magnesium (Mg) m^{-3} at the surface to 1.6 Mg m^{-3} in the deepest horizon for both land usages ($P < 0.05$) (Fig. 5B).

As was seen for BD, TP does not show any significant differences between forest and pasture, except for position T3, where pasture presents smaller TP than the forest (Fig. 6A). Changes in TP are also seen with increasing depth; they reduced from 0.46 m^3 m^{-3} at the surface to 0.39 m^3 m^{-3} in depth (Fig. 6B).

The macroporosity and microporosity analyses indicated a reduction in macroporosity with increasing depth, passing from 0.26 m^3 m^{-3} at the surface to 0.16 m^3 m^{-3} in the deepest horizon in both land uses (Fig. 7A). When comparing the macroporosity between land usages, a reduction in macroporosity, going from

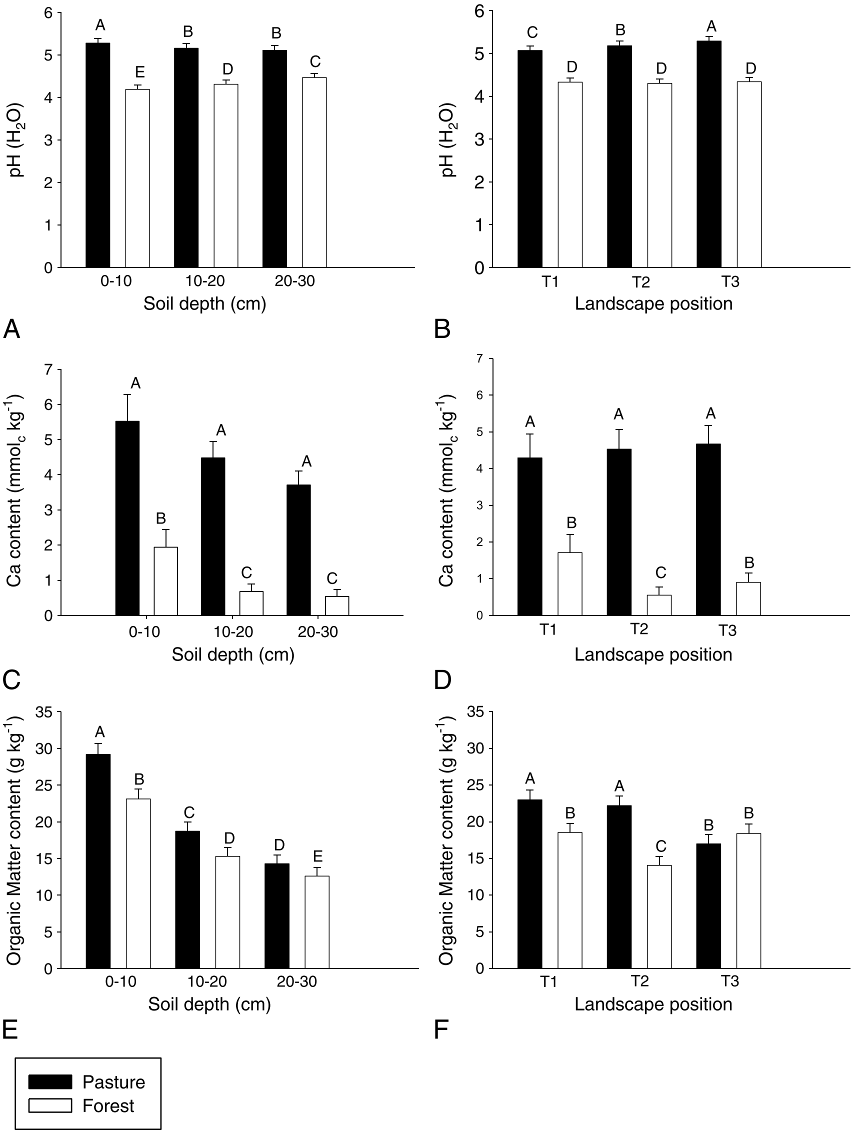

FIGURE 3. Soil chemical properties (A) pH in water considering interaction between land use and soil depth. B, pH in water considering interaction between land use and landscape position. C, Ca content considering interaction between land use and soil depth. D, Ca content considering interaction between land use and landscape position. E, OM content considering interaction between land use and soil depth. F, OM content considering interaction between land use and different landscape position. All data were obtained by mean of five replicates in three landscape positions and sampling periods. Different capital letters show 5% difference by DGC test. Bars show mean S.E.

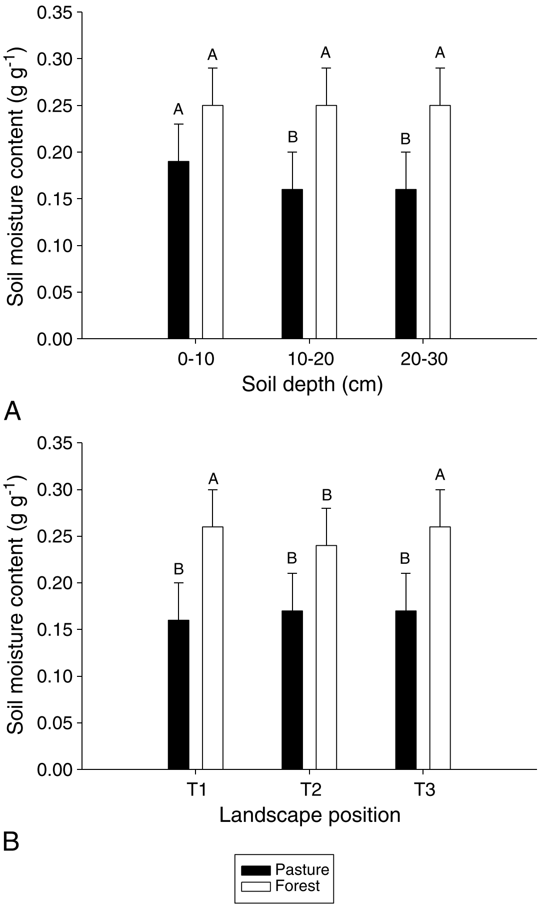

FIGURE 4. A, Soil moisture content considering interaction between land use and soil depth. B, Soil moisture content considering interaction between land use and different landscape position. All data were obtained by mean of five replicates in three landscape position and sampling periods. Different capital letters show 5% difference by DGC test. Bars show mean S.E.

0.25 $m^3\ m^{-3}$ in forest to 0.15 $m^3\ m^{-3}$ in pasture, is observed (Fig. 7B). This reduction in macroporosity is followed by the increase in microporosity, regardless of depth or landscape position, going from 0.20 $m^3\ m^{-3}$ in forest to 0.25 $m^3\ m^{-3}$ in pasture (Figs. 7C, D).

In addition to the data observed for macroporosity and microporosity, the analyses of the size and shape of pores indicate that, for all topographic positions and soil usages, the increase in depth causes a reduction in large complex pores and an increase in smaller rounded and elongated pores (Figs. 8 and 9).

Pore morphology at the soil surface under forest varies according to landscape position and presents 5% to 8% of rounded pores distributed in small, medium, and large sizes; 2% to 3% of elongated pores, primarily medium and large; and 12% to 17% of large complex pores (Figs. 8A, D, G). Under pasture, the superficial horizons present, for all landscape positions (T1 to T3), approximately 7% of small, medium, and large rounded pores, with predominance of the small and medium sizes and 3% to 4% of medium and large elongated pores. In T1 and T2, 5% to 10% of large complex pores were found and 16% in T3 due to its sandy composition (Figs. 9A, D, G).

Comparing the soil pore morphology for forest and pasture (Figs. 8 and 9), regardless of topographic position, it is observed that the change in land use caused a reduction in large complex pores and an increase in small rounded and elongated pores. This behavior was most noticeable in the surface horizons of T1 and T2 positions, where the total area of pores passed from approximately 24% in forest to approximately 20% in pasture (Figs. 8A, D, and Figs. 9A, D).

The replacement of forest by pasture caused the drop of S values at all soil depths ($P < 0.05$), going from 0.06 to 0.03 in the forest to the pasture surface horizons and from 0.04 to 0.02 in the deeper horizons of the forest and pasture, respectively (Fig. 10).

The area under forest had higher litter biomass (23 t ha^{-1}) than pasture (15 t ha^{-1}). (Fig. 11A). Besides the differences in DM quantities, the litter also differed in composition, from a heterogeneous litter in forest, composed of a mixture of leaf debris, stems, and seeds, to a homogeneous litter in pasture, composed mainly of grass leaves.

Regarding the different landscape positions in both land uses, the least amount of litter was observed at the landscape's intermediate positions ($P < 0.05$). This can be explained by the higher slope at this point, which favors erosion events and

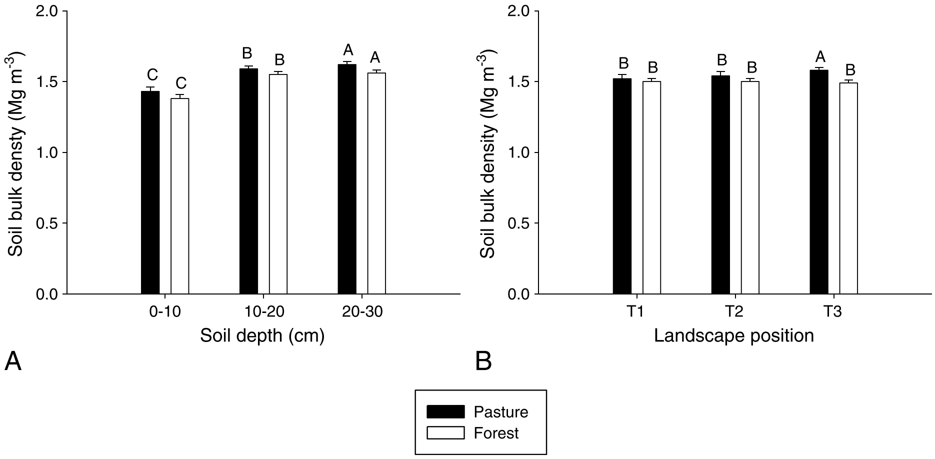

FIGURE 5. A, Soil BD considering interaction between land use and soil depth. B, Soil BD considering interaction between land use and landscape position. All data were obtained by mean of five replicates in three landscape positions and sampling periods. Different capital letters show 5% difference by DGC test. Bars show mean S.E.

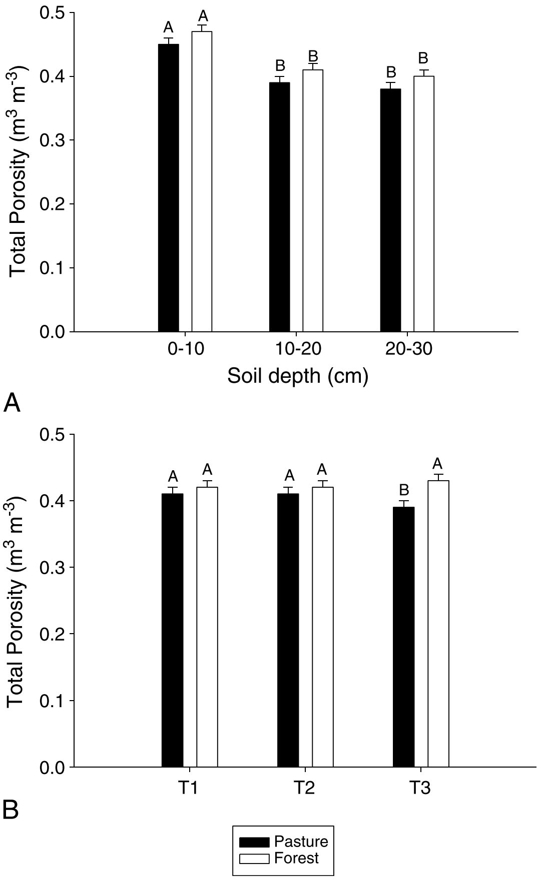

FIGURE 6. A, Total porosity considering interaction between land use and soil depth. B, Total porosity considering interaction between land use and landscape position. All data were obtained by mean of five replicates in three landscape positions and sampling periods. Different capital letters show 5% difference by DGC test. Bars show mean S.E.

transportation of litter to a lower position in the toposequence (Fig. 11B).

Earthworm Analysis

The area under pasture has a higher number of individuals (289 in pasture and 165 in forest) and more morphospecies with adult individuals (four adult morphospecies in pasture and one adult species in forest). The abundance of individuals varied depending on the depth and topographic position. More individuals, regardless of land use, were found in the 0- to 10-cm layer and reduced with increasing depth (Fig. 12A). Regarding the topographic positions, the areas under pasture presented more individuals than did the forest at T1 and T2, and at position T3, this behavior inverted (Fig. 12B).

Despite the lower number of individuals, the forest showed greater diversity and richness of morphospecies than did the pasture (15 morphospecies found in forest and 11 in pasture) (Table 1). The areas under forest also had a greater number of exclusive morphospecies, being 10 in forest and six in pasture.

Table 2 presents the data of body length, width, and density of earthworms morphospecies found in the forest and pasture toposequences. Earthworms found exclusively in forest presented lengths of 1 to 16 cm and body widths of 1 to 6.42 mm. The largest exclusive morphospecies of the forest (7 and 14) occupied all the landscape positions (T1–T3); morphospecies 16 (T2 and T3) and 19 (T1 and T2) occupy only two positions, and the rest occupy one landscape position. The number of exclusive morphospecies according to landscape position presented the following order: T1 (7) > T2 (5) > T3 (4). Most of the forest exclusive morphospecies present medium densities (minimum = 1.33 individuals/m^2, maximum = 6.67 individuals/m^2). Earthworms found exclusively in the pasture toposequence present body lengths of 2 to 13.5 cm and body widths varying from 1 to 3.29 mm. They were distributed in all landscape positions, with three exclusive morphospecies in T1 (2, 18, and 20) and T2 (2, 4, and 9) and one in T3 (3). No pasture exclusive morphospecies was found in all landscape positions. The exclusive morphospecies for pasture also presented medium densities (minimum = 1.33 individuals/m^2, maximum = 5.33 individuals/m^2).

The morphospecies that are found in both land uses presented lengths that vary from 1.9 to 7 cm and widths that vary from 1 to 3.06 mm (Table 2). Common morphospecies 1 and 11 are found in all landscape positions in the forest and pasture, morphospecies 10 is found in two landscape positions (T1 and T2) in the pasture and all in the forest, morphospecies 21 is found in one landscape position in the pasture (T1) and two in the forest (T2 and T3), and, finally, morphospecies 12 is found in only one position in the pasture and forest (T2 and T1, respectively). Independently of the landscape position that these common morphospecies are found in the forest or the pasture, they always present higher densities in the pasture (minimum = 2.67 individuals/m^2, maximum = 44 individuals/m^2) than in the forest (minimum = 1.33 individuals/m^2, maximum = 20.67 individuals/m^2).

Relationship Between Soil Physical, Chemical, and Biological Attributes

The first CCA relating activities of earthworms to the soil attributes, considering the TP variable, showed the creation of three niches according to land use, represented in circles with different colors (Fig. 13). The environmental variables explained 69.0% of the variability of the data. From that total, the first axis explained 31.1%, and including the second, the cumulative percentage explained is 49.0%. The forest was related to the values of U and BD, without distinguishing landscape positions or soil depths. The areas under pasture were divided into 2 niches, one grouping superficial layers at T1 and T2, better related with OM, pH, and TP, and the second corresponding to the deepest layers of T1 and T3, relating better to BD, pH, and OM. Data not shown in CCA graphs are due to the absence of earthworms in the analyzed samples.

The areas under forest exhibit high richness of earthworms and high soil U contents, showing a dependency between earthworms and moisture. Areas under pasture showed lowest richness of earthworms, dividing it into two niches, with morphospecies 2, 4, 9, 12, and 13 related to higher contents of OM.

The division of TP into macroporosity and microporosity allowed a clearer distinction between the types of land use, with the forest area showing segregation with respect to depth, and the pasture area presenting segregation with respect to the landscape positions, showing that for this land use there was a greater variation related to the topography of the area (Fig. 14). In this case, the environmental variables explained 54.0% of the variability of the data. From that total, the first axis explained 37.5% and together with the second explained 55.6% of the variability.

In the area under forest, a relationship was identified between the superficial layer, soil macroporosity, *S*, and U, associated to earthworm morphospecies numbers 5, 14, 16, 17, and 19, found

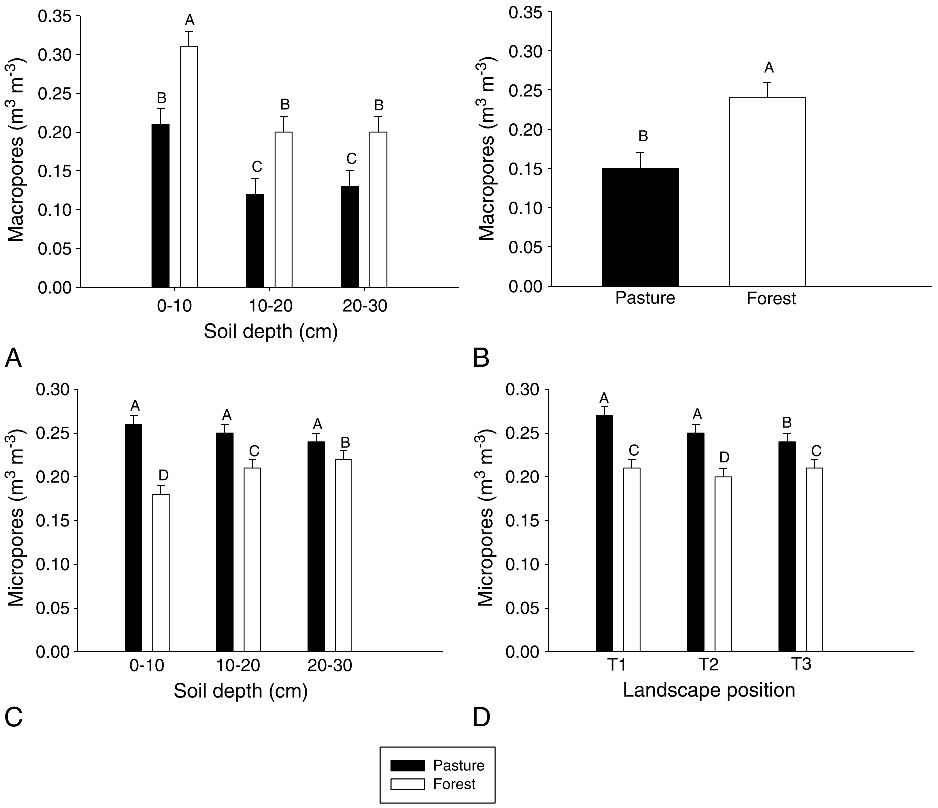

FIGURE 7. Macroporosity and microporosity data. A, Macroporosity considering interaction between land use and soil depth. B, Macroporosity considering different land uses. C, Microporosity considering interaction between land use and soil depth. D, Microporosity considering interaction between land use and landscape position. All data were obtained by mean of five replicates in three landscape positions and sampling periods. Different capital letters show 5% difference by DGC test. Bars show mean S.E.

exclusively in this type of land use. For deeper layers, there is a better relationship with U and BD, associated to morphospecies 6, 7, 8, 10, 15, and 21.

In pasture, a distinction regarding the landscape positions is observed. T1 shows better relationships with microporosity and BD, and it relates to earthworms 2, 18, 20, and 21. From these, earthworms 2 and 18 are exclusive to the pasture and exhibit strong relationship with microporosity.

Further detailing of the porosity using micromorphometric analysis resulted, as in the previous analysis, in the separation of niches according to the type of land use. However, it was also possible to relate the soil depths, the landscape positions, and morphospecies of earthworms to the shape and size of pores (Fig. 15). In the CCA analysis, the environmental variables explained 90.73% of the variability of the data. From that total, the first axis explained 25.0%, and including the second, the cumulative percentage explained is 44.2%.

The areas under forest had better relationships with U, BD, and large round (>6,000 μm) and complex pores (>8,000 μm), whereas the pasture showed strong relationships with OM, pH, and small complex pores (up to 4,000 μm). This analysis also showed distinctions according to soil depth, although it was not as strong as in the previous analysis. For T2, associated to morphospecies 5, the surface layer presents a strong relationship with complex pores larger than 7,000 μm and small rounded pores (1,000–2,000 μm).

As in the previous analysis, the pasture presents distinctions regarding landscape positions, with T1 and T3 closely allocated, with superficial layers presenting a better relationship with small complex pores (1,000–2,000 μm). However, for T2, there was a better relationship with medium complex pores (2,000–4,000 μm) and with morphospecies 4, 9, and 12 found in this location.

DISCUSSION

The toposequences presented similar soils and landscape conditions, although with different land usages, one under forest and another under pasture. For both toposequences, soils were classified as Typic Haplustults, with a yellowish brown surface horizon, sandy loam texture, and granular structure. With increasing depth, the horizons present yellowish coloring, mottles, sandy clay loam texture, higher contents of gravel and coarse sand, and subangular blocky structure (Oliveira et al., 2013).

Despite the topographic and morphological similarities between the toposequences, the land use change leads to significant differences regarding some soil properties and characteristics such as litter DM values and chemical, physical, and some biological attributes.

The larger amount of DM in the forest area is justified by the composition of the litter, originated from a diversity of fallen leafs, stems, and seeds of the Ombrophylous Dense Forest, especially in the dry season (Tapia-Coral et al., 2005). In the pasture, the litter comes from the grass leaves of *Brachiaria*, poorly lignified and prompt to a faster decomposition (Moreira and Malavolta, 2004), resulting in lower amounts of DM. The litter

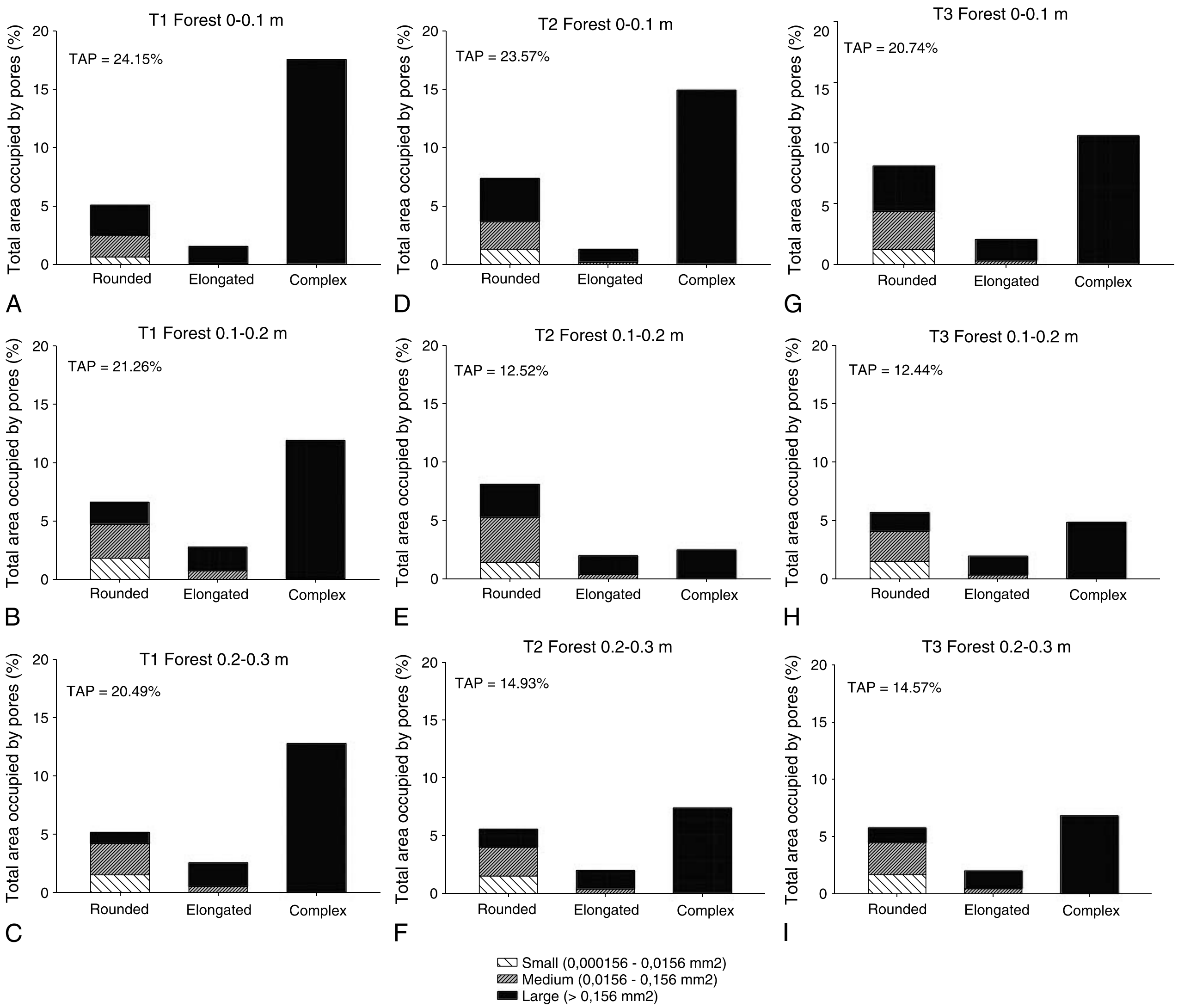

FIGURE 8. Pore size and shape in forest areas. Pores are separated in rounded (channels and vughs), elongated (fissures), and complex (packing voids). TAP, total area of soil blocks dominated by pores.

deposition on the toposequences is influenced by slope. The steeper areas (T2) have lower amounts of DM, which is removed to the lower slope position (T3) probably by erosion processes (Araújo et al., 2011). Litter decomposition in forests, associated to root exudation and macrofauna excretions, causes slight acidification of the soils, making it more acidic than soils under pastures (Fujii, 2014). The pasture presents rapid litter decomposition, which, associated with burring activities, increases both Ca and OM content, especially in the soil superficial layers (Aita and Giacomini, 2003). Similar results were found by Freitas et al. (2013), where the areas under pasture presented better chemical quality than under forest, primarily by the immobilization of nutrients by the forest biomass.

The presence of litter on the soil, associated with the canopy of the forest area, protects the soil from direct sunlight incidence, thereby minimizing evaporation (Correia and Andrade, 2004; Stefanoski et al., 2013a). The forest area presented higher moisture contents than did the pasture area for all depths and landscape positions, except for the surface layer of the pasture, which was protected by high amounts of DM, above the minimum value (>1 Mg ha^{-1}) required for soil protection against excessive evaporation (Silva et al., 2000).

Soil Physical and Chemical Attributes

The replacement of the forest by pasture may lead to structural changes in the soil, increasing BD and reducing macroporosity, infiltration rate, hydraulic conductivity, and water retention and storage (Macedo et al., 2013). However, in the studied areas, the land use change did not affect significantly the BD and TP, as observed by Oliveira (2008) and Coutinho et al. (2010). Probably this was due to the high amount of DM (>1 Mg ha^{-1}) that protected the superficial layer of the soil from drying and minimized the effects of grazing over BD (Silva, et al. 2000; Ghosh et al., 2009; Guareschi, et al., 2012; Kondo et al., 2012). There was an exception at position T3, where the pasture presented higher BD (and consequently lower TP), related to a drop in OM content and a slightly sandier composition when compared with other positions.

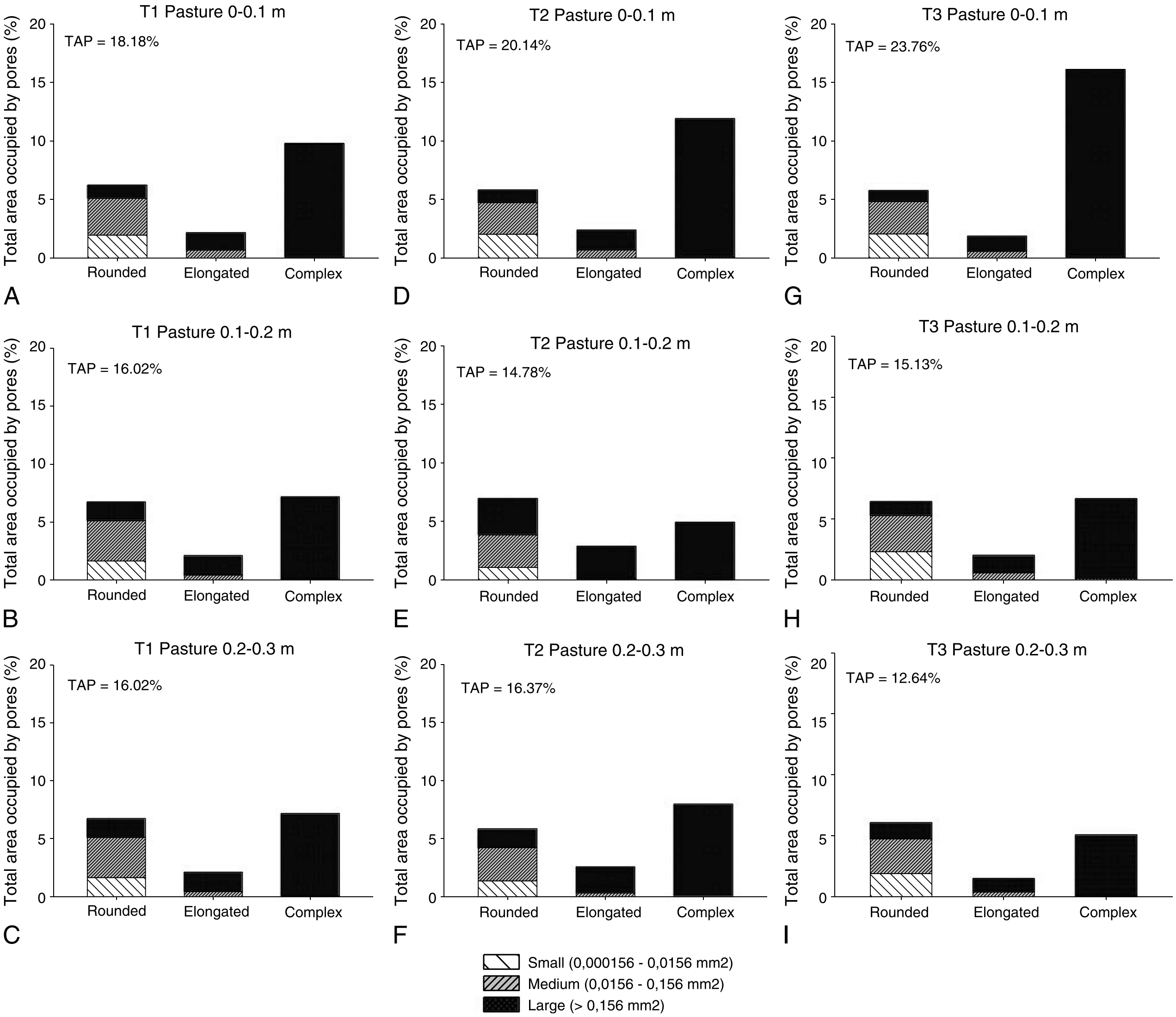

FIGURE 9. Pore size and shape in pasture areas. Pores are separated in rounded (channels and vughs), elongated (fissures), and complex (packing voids). TAP, total area of soil blocks dominated by pores.

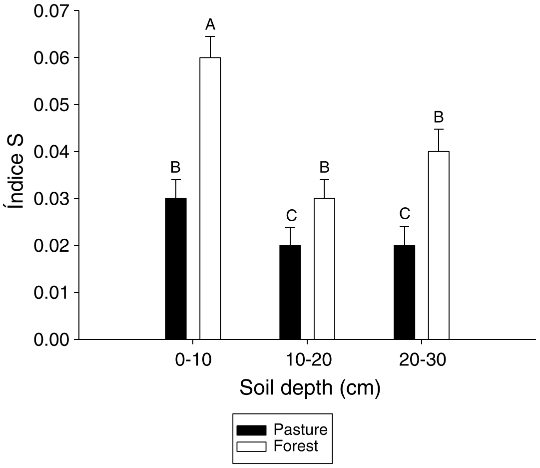

FIGURE 10. Value of S index considering interaction between land use and soil depth. Data were obtained by mean of five replicates in three landscape positions and sampling periods. Different capital letters show 5% difference by DGC test. Bars show mean S.E.

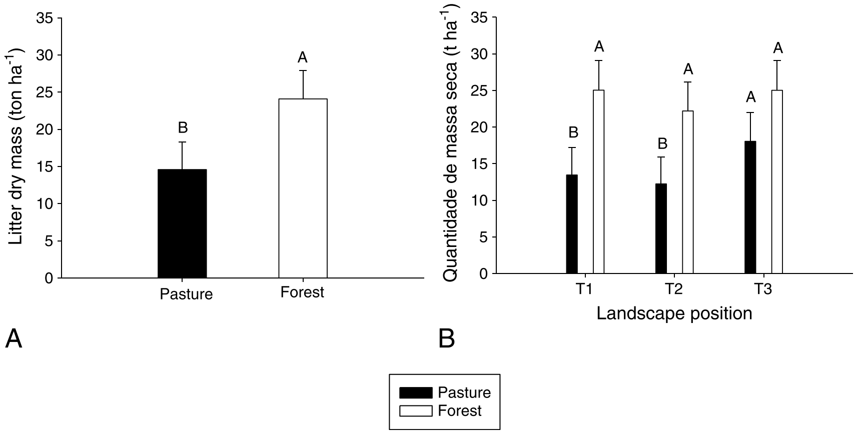

FIGURE 11. A, Litter dry mass in each land use. B, Litter dry mass in different landscape positions for both land uses. All data were obtained by mean of five replicates in three landscape positions and sampling periods. Different capital letters show 5% difference by DGC test. Bars show mean S.E.

Although there were no significant differences of BD between land uses, there was an increase in BD with depth, which results from natural changes in OM and clay contents and changes in soil structure (Laurindo et al., 2009; Pequeno et al., 2011; Oliveira, 2014).

Regardless of the low differences of BD and TP between land uses, significant changes were found between the size of pores, particularly regarding the macroporosity, which is related to water drainage and soil aeration (Bonini et al., 2013). The forest-pasture conversion causes reduction in macropores to near critical values for soil aeration, 0.1 m^3 m^{-3} as defined by Bonini et al. (2013), and an increase in microporosity for all depths and landscape positions. This tendency corroborates the findings of Torres et al. (2014) and helps to explain the absence of differences in TP.

Consecutively, the classification of macroporosity according to size and shape indicates that the land use change causes a reduction in large round and complex pores (>6,000 μm) and an increase in small round and elongated pores (1,000–4,000 μm) in pasture. This physical behavior suggests that the change in land use is causing a transformation of large pores into smaller ones, which may damage the circulation of air and water in the soil profile (Oliveira, 2014).

Despite the fact that changes in porosity are not reflected in TP and BD, these were identified by *S*, because this index is related to soil particle size distribution, BD, OM, type of microstructure, and root growth (Stefanoski et al., 2013b). Forested areas had, at all depths, higher *S* values than did the pasture areas, exhibiting the high structural quality of forest soils (Dexter, 2004) and evidencing the degradation caused by the land use change to pasture.

Relationship Between Soil Attributes and Earthworms

The higher abundance of earthworms in pasture is mainly explained by the higher amount of OM in this land use. Earthworms, especially in T1 and T2, find in the pasture favorable conditions for their development, increasing in number and sexual maturity, confirming the findings of Decaens et al. (2004) and Amosse et al. (2015), where larger quantities of individuals and adults were found in soils with low food restriction. Although the pasture had higher abundance and number of adults, they belonged to 11 different morphospecies, of which six are exclusives occurring only in this environment, showing high adaptability of these morphospecies to the pasture conditions (Hurisso

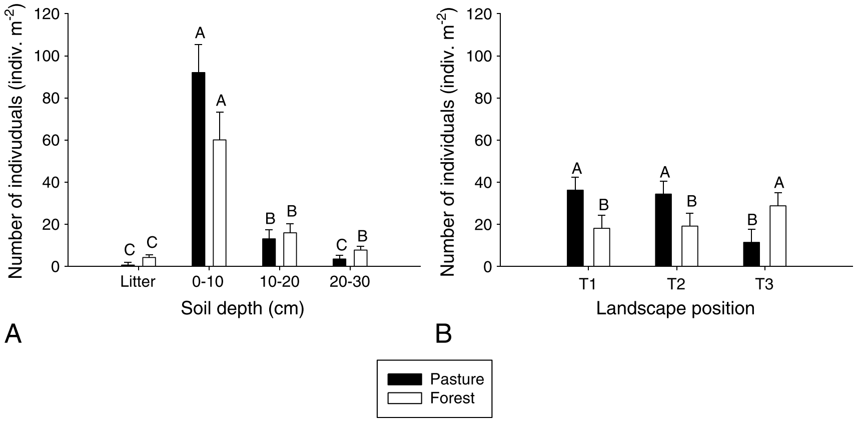

FIGURE 12. A, Earthworm density considering interaction between land use and soil depth. B, Earthworm density considering interaction between land use and landscape position. All data were obtained by mean of five replicates in three landscape positions and sampling periods. Different capital letters show 5% difference by DGC test. Bars show mean S.E.

TABLE 1. Values of Richness (r), Diversity (Shannon and Simpson index) and Dominance (Berger-Parker index) of the Soil Earthworm Community

	Richness		Diversity		Dominance
Use of Soil	**Total species (r)**	**Exclusive Species**	**Shannon**	**Simpson**	**Berger-Parker**
Pasture					
T1	7		1.29	0.39	0.59
T2	7		1.37	0.32	0.46
T3	3		0.32	0.85	0.92
Total	11	6	1.40	0.38	0.59
Forest					
T1	11		1.57	0.34	0.56
T2	9		1.69	0.25	0.46
T3	8		1.31	0.39	0.6
Total	15	10	1.64	0.33	0.54

et al., 2011). On the other hand, in position T3 of the pasture, the soil physical and chemical conditions do not seem to favor the development of earthworms. The higher values of soil BD and lower TP, OM, and U create conditions that reduce the quantity of earthworms at this position (Blouin et al., 2013; Bertrand et al., 2015).

Even with the pasture area having greater abundance of earthworms, the forest area presented greater richness of total (15) and exclusive morphospecies (10) that present larger body widths when compared with the pasture morphospecies. This shows that the change of land use contributes to alter the physical and chemical conditions of the soil and consequently modify the earthworm morphospecies present in it (Amosse et al., 2015). The forest area presented larger quantities of DM and a more heterogeneous litter, resulting in lower pH, Ca, and OM content in the soil (Freitas et al., 2013). The larger DM and its heterogeneity favor the maintenance of U, BD, TP, macroporosity, and large complex pores, resulting in higher values of *S*, which indicates a soil with a good structural quality. These conditions contributed to an ideal environment in the forest for the development of a wide range of earthworm morphospecies, especially those exclusive of this land use, found in slightly higher densities and with larger body sizes, which disappear with the implementation of the pasture (Jouquet, et al. 2014). The area under pasture, especially in the superficial layers, showed high OM, pH, Ca, and U, favoring the development of larger numbers of individuals and adults

TABLE 2. Body Size and Density of Earthworm Morphospecies in Each System and Landscape Position

			Density (Individuals/m^2)					
			Pasture			Forest		
Morphospecies	**Length (cm)**	**Width (mm)**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
1	5.63	3.06	14.00	11.00	2.67	4.89	3.56	4.00
2	3.98	1.90	4.00	5.33	0.00	0.00	0.00	0.00
3	13.50	3.00	0.00	0.00	1.33	0.00	0.00	0.00
4	3.90	1.00	0.00	2.00	0.00	0.00	0.00	0.00
5	3.00	1.00	0.00	0.00	0.00	0.00	1.33	0.00
6	2.40	1.00	0.00	0.00	0.00	1.33	0.00	0.00
7	16.00	6.42	0.00	0.00	0.00	4.00	1.33	1.33
8	1.70	3.00	0.00	0.00	0.00	1.33	0.00	0.00
9	2.66	1.48	0.00	2.67	0.00	0.00	0.00	0.00
10	3.43	2.07	11.33	4.00	0.00	6.67	5.33	10.00
11	7.00	2.00	40.56	23.00	27.73	18.00	13.33	20.67
12	1.97	1.00	0.00	44.00	0.00	1.33	0.00	0.00
13	2.95	1.80	0.00	0.00	0.00	0.00	0.00	1.33
14	5.60	3.00	0.00	0.00	0.00	1.33	5.33	4.00
15	1.75	1.00	0.00	0.00	0.00	2.67	0.00	0.00
16	2.20	2.00	0.00	0.00	0.00	0.00	1.33	1.33
17	2.33	2.00	0.00	0.00	0.00	1.33	0.00	0.00
18	6.93	3.29	5.33	0.00	0.00	0.00	0.00	0.00
19	2.20	2.00	0.00	0.00	0.00	2.67	6.67	0.00
20	2.20	1.56	1.33	0.00	0.00	0.00	0.00	0.00
21	1.90	1.58	6.67	0.00	0.00	0.00	4.00	2.67

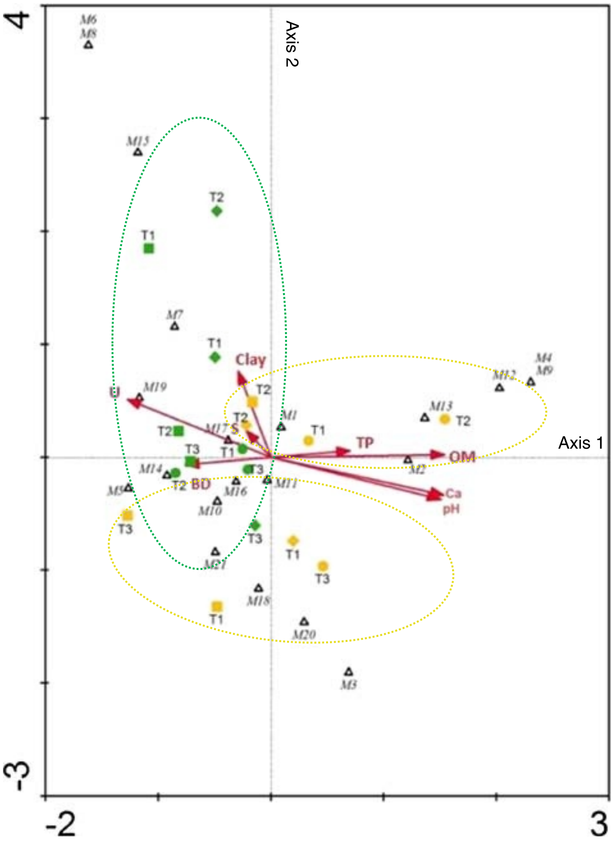

FIGURE 13. Canonical correspondence analysis for earthworm species. Axes 1 and 2 are segregating areas under forest and pasture according with physical and chemical parameters and different earthworm species. Environmental variables are represented by arrows, and physical and chemical variables are abbreviated. S, S index. Soil uses are represented in green for forest and yellow for pasture, and soil depths are represented by circle for 0 to 10 cm, square for 10 to 20 cm, and diamond for 20 to 30 cm. M1 to M21, earthworm morphospecies numbered according external and internal differences. A color version of this figure is available in the online version of this article. full color online

(Marichal et al., 2012), yet belonging to a limited number of morphospecies that are characterized by smaller body sizes.

The sandy loam composition in the surface horizons, associated to the large quantity of grass roots and high OM, favors the maintenance of TP in pasture at similar levels to that found in the forest. Meanwhile, the analyses of the macroporosity and microporosity results show that the soil in the forest area presents more macropores and in the pasture area more micropores.

It is well known that the feeding, burrowing, and casting activities of the earthworms strongly contribute to the formation of macropores, especially rounded ones (Lavelle and Spain, 2001). Several studies also suggest that earthworms have a positive effect on soil physical properties (Marinari et al., 2007). In this study, the strong relation between forest exclusive earthworm morphospecies 14, 16, 17, and 19, whose body widths vary from 2 to 3 mm, and *S* and macroporosity indicates that these morphospecies are essential to macropore formation and maintenance and to the higher soil quality in forested areas. The modification in physical and chemical properties that occur after land use change affects the survival of these key morphospecies, resulting in lower macroporosity formation in pasture.

Analyzing the pore micromorphometric data, it is possible to understand the importance of earthworms in pore formation. Knowing that both areas (forest and pasture) present similar particle-size distributions, good plant cover, and high OM levels and that the pasture does not show compaction by grazing, it can be inferred that the differences found in porosity are associated to activities of roots and earthworms.

The strong association of the forest exclusive morphospecies 6, 7, 8, and 15 with rounded pores of 6,000- to 7,000-μm diameter and the fact that their extinction in pasture pairs up with the disappearance of such pores in this land use may indicate that these morphospecies are responsible for the formation of these pores. This hypothesis is supported by the observed distribution and body size of the forest exclusive earthworms. Morphospecies 7 was probably responsible for the formation of rounded pores of 6,000- to 7,000-μm diameter (Fig. 15), as it was the largest earthworm found in this study site. This morphospecies presented a body width of 6.42 mm and a homogeneous distribution in the three landscape positions. Similarly, the presence of morphospecies 5 strongly related to rounded pores of sizes between 1,000 and 2,000 μm (Fig. 15) and may indicate that their presence in the soil would influence the formation of these smaller rounded pores, confirmed by the body width of this morphospecies of 1 mm. In the pasture toposequence, morphospecies 7 and 5 were missing, and the presence of earthworms with smaller body widths, even with high abundance, was not related to rounded pores. Consequently, the formation of rounded pores in the pasture could be related to other biological activities, such as root growth or other fauna.

Therefore, we can state that the change in land use leads to an increase in OM, pH, and Ca and a reduction in DM, U content with depth, macroporosity, *S*, and large rounded pores in the

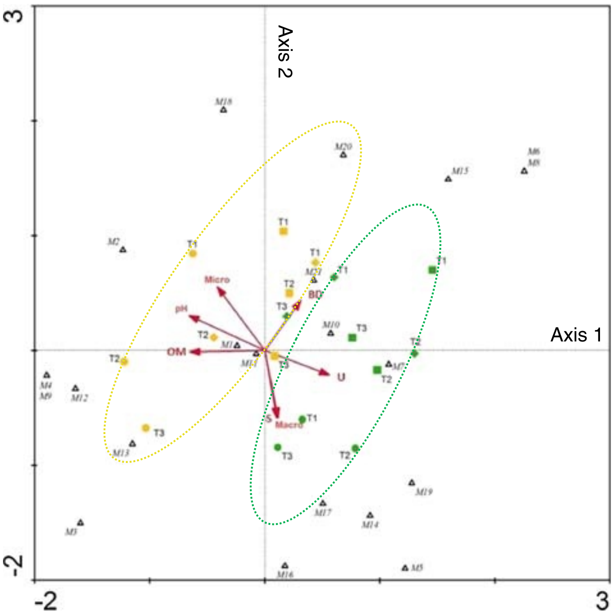

FIGURE 14. Canonical correspondence analysis for earthworm species. Axes 1 and 2 are segregating areas under forest and pasture according to physical and chemical parameters and earthworm species. Environmental variables are represented by arrows, and physical and chemical variables are abbreviated: S, S index; Macro, macropores; Micro, micropores. Soil uses are represented in green for forest and yellow for pasture, and soil depths are represented by circle for 0 to 10 cm, square for 10 to 20 cm, and diamond for 20 to 30 cm. M1 to M21, earthworm morphospecies numbered according external and internal differences. A color version of this figure is available in the online version of this article. full color online

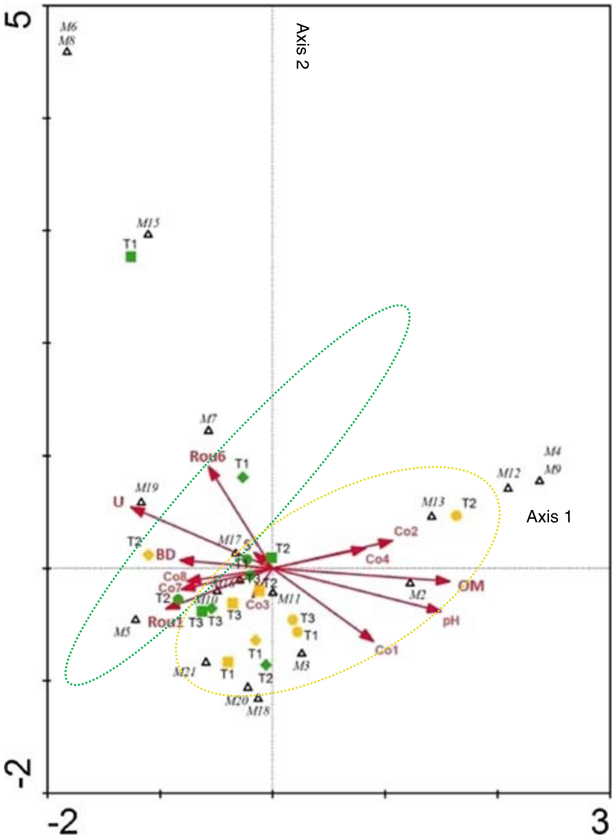

FIGURE 15. Canonical correspondence analysis for different earthworm species. Axes 1 and 2 are segregating areas under forest and pasture according to physical and chemical parameters and different species of earthworms. Environmental variables are represented by arrows and physical and chemical variables are abbreviated: S, S index; U, soil moisture; Rou, rounded pores; Co, complex pores. Numbers near pore definition are referent to pore size being 1 = 1,000 to 2,000 μm, 2 = 2,001 to 3,000 μm, 3 = 3,001 to 4,000 μm, 4 = 4,001 to 5,000 μm 5 = 5,001 to 6,000 μm, 6 = 6,001 to 7,000 μm, 7 = 7,001 to 8,000 μm, and 8 = 8,001 to 9,000 μm. Soil uses are green for forest and yellow for pasture, and soil depths are represented by circle for 0 to 10 cm, square for 10 to 20 cm, and diamond for 20 to 30 cm. M1 to M21, earthworm morphospecies numbered according external and internal differences. A color version of this figure is available in the online version of this article. full color online

pasture, reducing earthworm diversity. This diversity loss causes the extinction of morphospecies highly related to the formation and maintenance of soil macroporosity. Thus, we reaffirm that the diversity loss in earthworm communities can affect the formation of soil macropores, especially by the substitution of larger morphospecies by smaller ones, which contribute less to soil macroporosity.

Exclusive earthworm morphospecies in forest presented a high association with large rounded pores influencing soil macroporosity development, as discussed previously. On the other hand, complex pores, which are the dominant pore shape in practically all the studied soil layers, did not present a clear association with earthworm exclusive and common morphospecies in the forest. In the pasture, a good association of complex pores of 2,000 to 4,000 μm occurred in position T2 with exclusive morphospecies 4 and 9 and common morphospecies 12 that appeared in high densities. This lower association between complex pores with earthworms, especially under forest, could be explained by the fact that the processes involved in forming these pores are more diversified, among which earthworm activity could play a minor or intermediate role (but not dominant) in the formation of these pores (Pituello et al., 2016). In contrast, the formation of large rounded pores is normally more specific and attributed to biological activity, especially root growth and earthworm activity (Oades, 1993).

CONCLUSIONS

The change in land use, replacing forest with pasture, caused changes in the soil structure and porosity. This resulted in changes in soil physical quality, evidenced by the reduction in macropores, large rounded and complex pores, and *S*.

The conversion of forest to pasture in the environmental conditions of this study area favors the increase in earthworm abundance and reduction in richness of morphospecies. The reduction in richness results in the loss of morphospecies highly associated with the formation and maintenance of soil macroporosity, specifically large rounded pores and, secondarily, large complex pores. The loss and replacement of the slightly larger exclusive forest morphospecies by the smaller exclusive pasture morphospecies favor the reduction in macroporosity, resulting in lower soil structural quality.

Detailing soil porosity by dividing it into size and shape classes allowed a more accurate correlation between soil attributes, earthworm diversity, and development, indicating that larger earthworms are better associated with the formation of rounded pores in forest areas.

These results indicate that earthworms are highly sensitive to changes in land use and confirm the close relationship between soil physical quality and earthworm activity. The need for multidisciplinary approaches is essential to study the effects of land use changes on ecosystems.

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