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Research paper

Assessing soil compaction in sites subjected to different management systems

Avaliação da compactação do solo em áreas com diferentes sistemas de manejo

Emilly Giacobbo[1]; Jessica Chiafitella[2]; Robert William Florentino[3]; João Anésio Bednarz[4]; Valdemir Antoneli[5]

[1] Student in the Master's Program in Sanitary and Environmental Engineering, Universidade Estadual do Centro-Oeste, Paraná, Brazil. Orcid: 0009-0000-3166-9530. E-mail: emillygiacobbo26@gmail.com

[2] Master's in Sanitary and Environmental Engineering, Universidade Estadual do Centro-Oeste, Irati, Paraná, Brazil. Orcid: 0009-0002-7058-1616. E-mail: jehchifitela@yahoo.com.br

[3] Student in the Postgraduate Program in Sanitary and Environmental Engineering, Universidade Estadual do Centro-Oeste, Irati, Paraná, Brazil. Orcid: 0009-0004-3261-8785. E-mail: robertwilliam1517@gmail.com

[4] Professor of Environmental Engineering and Geography, Universidade Estadual do Centro-Oeste, Irati, Paraná, Brazil. Orcid: 0000-0003-0328-1699 E-mail: joaogeo2013@gmail.com

[5] Professor, Department of Geography, Universidade Estadual do Centro-Oeste, Paraná, Brazil. Orcid: 0000-0002-5942-8330 E-mail: vaantoneli@gmail.com

ABSTRACT: Soil physical, chemical and biological quality is under constant change in rural areas, mainly in small farms where family farming prevails. Land use in these properties is maximized to ensure profitability. The aim of the current study is to investigate how different land-use types affect soil compaction in a small farm in Southeastern Paraná State. The herein investigated land-use types comprised forest, pasture, yerba mate cultivation, eucalyptus reforestation, no-till and conventional tillage. Soil density, resistance, porosity and moisture were the analyzed variables. The current findings enabled concluding that pressure deriving from different land uses affected soil compaction. Pasture recorded the highest soil compaction indices, whereas forest recorded the best indices for this variable. On the other hand, different soil management practices did not significantly affect soil density and porosity in agriculture. However, there were significant variations in soil moisture and resistance.

Keywords: land use, bulk density, soil porosity, soil resistance, family farming.

RESUMO: *A qualidade física, química e biológica do solo, vem sofrem constantes alterações nas áreas rurais, principalmente nas pequenas propriedades rurais com predomínio da agricultura familiar. O uso do solo nessas propriedades é explorado ao máximo para que esta se torne rentável. O objetivo desta pesquisa foi avaliar como os diferentes tipos de uso do solo interferem na compactação do solo em uma pequena propriedade na Região Sudeste do estado do Paraná. Os usos utilizados por esta pesquisa foram: floresta, pastagem, cultivo de erva-mate, reflorestamento de eucalipto, agricultura com plantio direto e plantio convencional. As variáveis analisadas foram a densidade do solo, resistência do solo, porosidade e umidade do solo. Ao término da pesquisa concluiu-se que a pressão sobre os diferentes usos do solo interferiu na compactação do solo. A pastagem indicou os piores índices de compactação do solo e a floresta indicou os melhores índices. Foi observado na agricultura que os diferentes tipos de manejo do solo não indicaram variação significativa na densidade e porosidade do solo. No entanto houve variação significativa na umidade e resistência do solo.*

Palavras-chave*: uso do solo, densidade, porosidade, resistência, agricultura familiar.*

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INTRODUCTION

Agricultural frontier expansion and mechanized production processes have taken on new forms worldwide (Girlanda *et al*., 2001), since they lead to constant changes in agricultural landscapes and make them increasingly homogeneous (Llausàs *et al*., 2009; Katayama *et al*., 2015). However, this progress has not been fully absorbed by smallholdings, which remain out of step with modernized units (Silva *et al*., 1983). Consequently, smallholdings can only count on family labor to develop their agricultural crops by adopting little conservation practices.

Currently, there is some concern about environmental issues in rural areas around the globe, where a set of conservation techniques has been gaining room and promoted by several scientists and institutions (Hobbs *et al*., 2008). These techniques are expected to help improving soil quality (Thierfelder; Wall, 2012), increasing agricultural yield (Gathala *et al*., 2013), reducing soil and water resources' contamination (Semple *et al*., 2001; Maillard *et al*., 2011) and conserving riparian zones, among others.

Accordingly, small farms end up using the most of their potential to increase profitability. This process allows farmers to transform land-use restriction areas into arable and pasture areas, a fact that can lead to high soil degradation levels.

Soil degradation refers to processes, mainly human-induced processes, capable of changing soil physical, chemical and biological quality. These changes can affect crop yield (Fao, 2011). Erosion, compaction, salinization, nutrient depletion, contamination and sealing stand out among the main causes of soil degradation.

Soil degradation rate estimates, the extent to which areas are affected by it, costs resulting from declining yield and other economic losses, and how these issues affect food security are extremely varying and uncertain factors.

Soil compaction involves changes in soil physical properties (soil density, strength and porosity) capable of changing soil structure. Changes in soil physical conditions such as increased density and reduced porosity can interfere with agricultural yield (Mueller *et al*., 2013), root growth (Correia *et al*., 2019), as well as reduce soil hydraulic conductivity and air permeability.

Soil density is the parameter most often used to feature soil compaction (Håkansson; Lipiec, 2000). It is worth emphasizing that soil density is inversely related to soil porosity, which, in its turn, refers to the space left in the soil for air and water movement purposes.

However, variations in soil density depend on land-use type and on the adopted agricultural practice. Panagos *et al*. (2024) conducted a soil density survey with 600 samples of different land-use types. According to them, arable land recorded the highest mean soil density (1.26 g cm^{-3}); it was followed by permanent crops (1.23 g cm^{-3}), heterogeneous agricultural areas (1.14 g cm^{-3}), pastures (1.08 g cm^{-3}) and woodlands (0.84 g cm^{-3}).

Variations in soil resistance, density and porosity are mostly evident in agricultural areas subjected to different cultivation practices. Antoneli e Thomaz (2010; 2014) observed significant changes in soil density and porosity levels in surface layer samples of soil subjected to two different management types (conventional tillage and no-till). It is worth highlighting that conservation techniques can help improving soil structure (Yang *et al*., 2018), reducing soil compaction, decreasing soil density, as well as increasing water storage and saturation in the soil profile.

Despite the wide range of research focused on investigating changes in soil compaction in rural areas, few studies focus on investigating these changes in small farms.

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It mainly happens because small farms experience higher pressure on natural resources. It is also worth emphasizing the land-use diversity observed in small farms, which mostly comprise agricultural areas, pastures and soils.

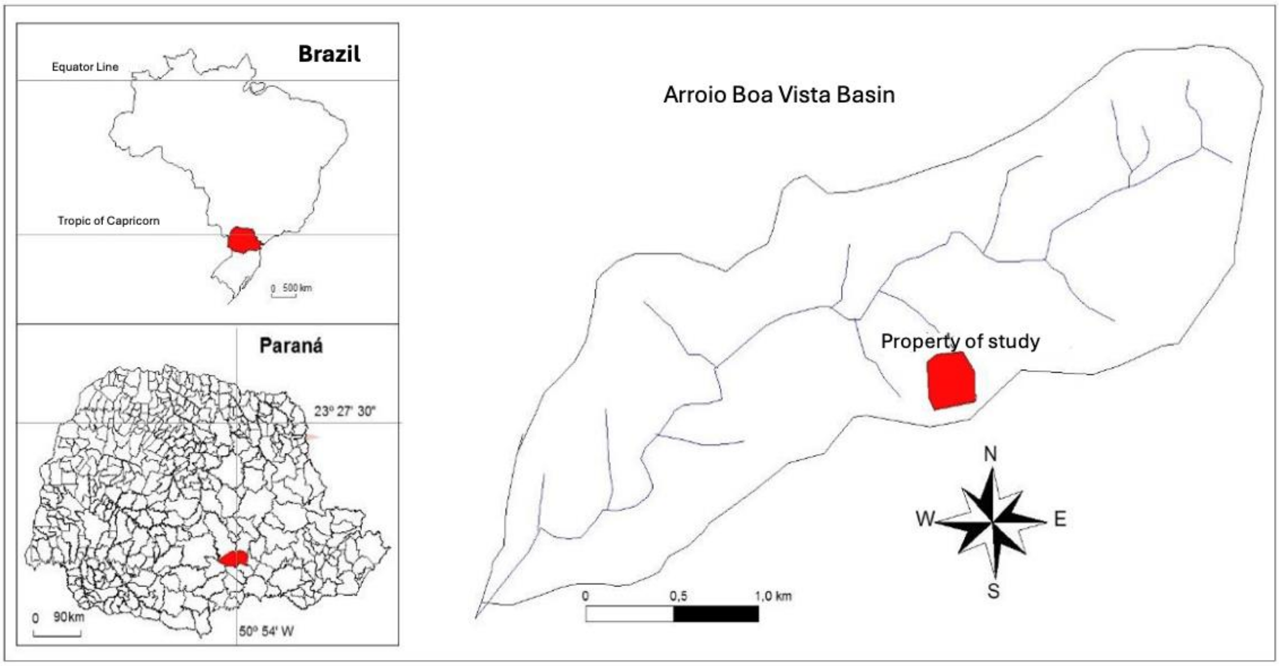
The aim of the current study was to assess soil compaction level in a small rural property in Arroio Boa Vista Basin, Southeastern Paraná State, based on different land-use types. Soil density, total porosity, resistance to penetration and moisture content were herein measured.

MATERIAL AND METHODS

Featuring the study site

The study was carried out in a rural property located in Arroio Boa Vista Basin, Northwestern Guamiranga municipality – Paraná State, at geographical coordinates 25º 09'21" and 25º 07'45" South (latitude) and 50º 54' 44" and 50º 52' 25" West (longitude), at altitude ranging from 720 m to 840 m (**Figure 1**).

Figure 1. Location of the study area.



The study site is located to the Western edge of the Second Paraná Plateau, in the transition area between sedimentary deposits and Serra Geral Formation (Antoneli; Thomaz, 2014). This location allows the emergence of diabase dykes between sedimentary rock areas.

Climate in the study site is classified as Cfb (humid subtropical), according to Köppen's classification. Mean annual temperature in it ranges from 17º C to 19ºC. Historical mean rainfall (1990 to 2020) is 1,957 mm/year; 33% of it happens in spring; 27%, in winter; 24%, in summer; and 16%, in winter.

The region the investigated rural property is located in has some specific features given the prevalence of family farming and the intense land use for tobacco, maize, soybean and bean cultivation purposes. In addition, farmers in this region use low-tech agricultural

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practices, as well as rudimentary implements and tools, mainly because this area mostly comprises small properties, and because 85% of agricultural areas in it are used to grow tobacco.

According to IAPAR classification (1995), Arroio Boa Vista Basin is part of the C13 conglomerate, which defines a region with high share of temporary crops, mainly tobacco, maize and beans, supported by family labor and animal traction. It is also formed by pasture, natural reforested forest and fallow areas associated with remarkably low use of agro-industrial inputs and motor-mechanization.

Climate, terrain and soil conditions in this region enhance land-use types in the herein assessed rural property. The aforementioned property has 21 hectares distributed as follows (**Table 1**).

Table 1. Features of each land-use type found in the study site

Land use	**Area (ha) (%)**	**Features**
Forestry	3.4 (16.3)	Native forest used as legal reserve. Mean slope 14%; Soil type: Haplic Cambisol; Texture: 24% sand, 32% silt, 44% sand. It is used as overnight stay for domestic animals.
Eucalyptus reforestation	2.7(13.0)	Reforestation area planted 15 years Aug. Wood is used to dry tobacco leaves. Slope: 12%. Soil type: Haplic Cambisol. Texture: 26% sand, 30% silt, 44% sand.
Yerba mate	2.0 (9.6)	Yerba mate grown (20 years) with weeding between rows. Slope 8%. Soil type: Haplic Cambisol. Texture: 28% sand, 32% silt, 40% sand.
Pasture	3.2 (15.4)	Native pasture used for extensive animal husbandry (~50 years). Slope 15%. Soil type: Haplic Cambisol. Texture: 30% sand, 24% silt, 46% sand.
Conventional planting	4.5 (21.6)	Agricultural area planted with two crops a year: beans and maize, and oat (in winter). Area cultivated for 25 years. The soil is constantly turned over. Soil exposed throughout cultivation. Slope: 16%. Soil type: Haplic Cambisol. Texture: sand 23%, silt 27%, sand 50%.
No-till farming	5.0 (24.0)	Agricultural area planted with two crops a year: beans and maize; oat is grown in winter and used as mulch for the new crop cycle. Area cultivated for 8 years. No soil disturbance, little soil exposure. Slope: 6%. Soil type: Haplic Cambisol. Texture: 29% sand, 25% silt, 46% sand.

Data collection procedures

Nine (9) trenches were randomly opened at 60-cm depth in each land-use type (forest, eucalyptus reforestation, yerba mate, pasture, conventional planting and no-till) and samples were collected every 10 cm (0-10, 10-20, 20-30, 30-40, 40-50, 50-60 cm). In total, 54 soil samples were collected in each land-use type. Soil density, resistance to penetration, total porosity and moisture content were the analyzed variables. Samples were randomly collected in each land-use type at soil depth of 10 cm.

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Soil density

Soil density was determined based on the volumetric ring method proposed by Embrapa (1997). Samples were collected in soil presenting non-deformed structure based on using steel ring with known volume. Each sample was placed in separate containers, which were sealed, labeled and transferred to the laboratory for analysis purposes.

Each sample was placed in a known-weight container, weighed and taken to oven in order to dry in laboratory environment. Samples were removed from the oven 24 hours later and weighed again. Soil density was calculated by dividing the soil mass by the ring volume. Dried samples were weighed and equation 1, proposed by Embrapa (1997), was used to estimate soil density (equation 1).

$$D_s = \frac{M_s}{V} \quad (1)$$

Wherein:
Ds = Soil density (g cm^{-3})
Ms = Dry mass (g)
V = ring volume (cm^3)

Particle density

Particle density values were found based on the method proposed by EMBRAPA (1997). Deformed soil samples were collected from each layer, as previously described. Samples were dried in oven and loosened. Then, 20 g of soil deriving from each layer was placed in 50-ml volumetric flask filled with ethyl alcohol and left to rest for 24 hours, in laboratory environment. After this period-of-time was over, the flask was topped up with alcohol (whenever necessary) and equation 2 was applied (equation 2)

Dr = P/50-V.Alcohol (2)

Wherein:
Dr = Particle density (g/cm^3)
P = Dry sample weight (g)
V. Alcohol = Alcohol volume inserted in the flask (ml)

Soil porosity

The total porosity method by Embrapa (1997) was also used to find soil porosity. Equation 3 was applied to find soil porosity, based on apparent and real density data (equation 3)

Pt=100*Dr–Da/Dr (3)

Wherein:
Pt = Total Porosity (%)
Da = Apparent Density
Dr = Real Density

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Soil Resistance to Penetration

The dynamic impact penetrometer method, which enables soil penetration by impact (STOLF *et al*., 2014) in soil profile ranging from 0 to 60 cm deep, was used to assess soil resistance to penetration. However, the current study used depth ranging from 0 to 40 cm, since the influence of grazing animals and the action of agricultural implements used in crops are limited to soil surface layers.

Data concerning the number of impacts and the respective depth of each impact were inserted in Microsoft® Excel spreadsheet by using the Microsoft® Visual Basic Application (VBA) as programming language.

Soil moisture

The same density samples were used to identify soil moisture. They were weighed as soon as they came from the field (field moisture). They were placed in oven at 105ºC for 24 hours and, then, weighed. Moisture value was found based on equation 4.

$$U = \frac{Ms - Mu}{Ms} * 100 \quad (4)$$

Wherein:
U = Soil moisture (%)
Ms = Dry mass (g)
Mu = Wet mass (g)

RESULTS

The analysis applied to soil physical features has evidenced significant differences among the herein assessed land-use types. The pastureland extensively farmed for approximately 50 years was the land-use type recording the highest soil density values, which ranged from 1.3 to 1.4 g/cm3. This land-use type was followed by the area subjected to no-till for 8 years, which recorded soil density ranging from 1.1 to 1.3 g/cm3 (**Figure 2**).

Forest recorded lower soil density values ranging from 0.9 g/cm3 (at soil surface) to 1.05 g/cm^3 (at the depth of 60 cm). Eucalyptus reforestation presented significant variation in soil density among the investigated depths. It ranged from 0.99 g/cm3 (at soil surface layer) to 1.2 g/cm^3 (at the depth of 60 cm). The yerba mate crop recorded lesser dense soil at the surface layer than eucalyptus reforestation. However, soil density was higher in layers deeper than 20 cm.

Agricultural areas under no-till and conventional tillage systems presented little density variation in the first soil layers (0 to 20 cm deep), although soil density was higher in no-till areas. Soil density observed for these two cultivation forms recorded higher variation in layers deeper than the aforementioned one. It is worth emphasizing that soil density in agricultural areas subjected to different management forms recorded different values. Soil density in no-till farming was lower in the first layers and higher from 20-cm layer, onwards. Pastureland, on the other hand, recorded the highest soil density among all investigated areas (1.35 g/cm^3, on average).

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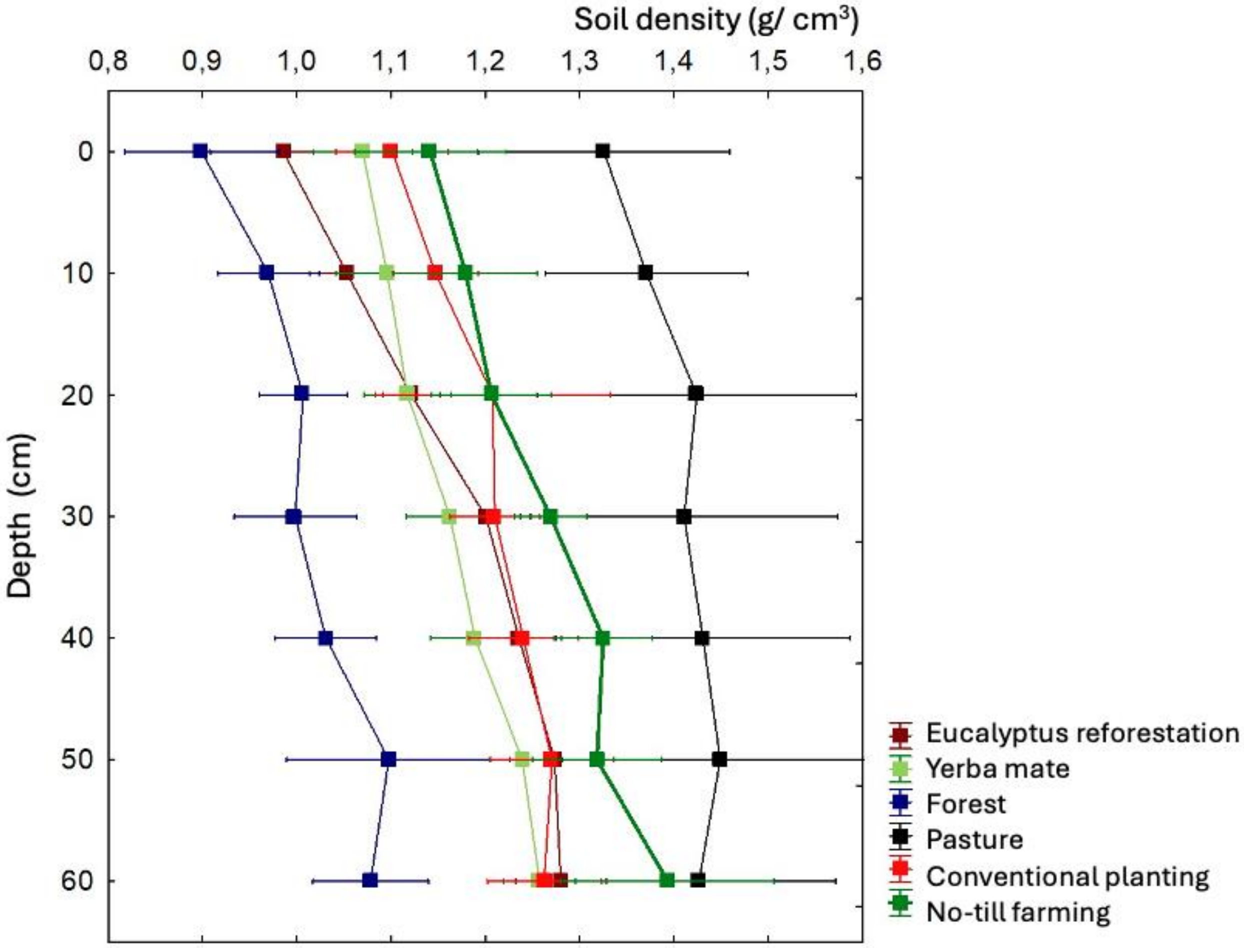
Figure 2. Soil density in different land-use types.



Soil porosity has followed the inverse density pattern, since the highest porosity value was found in forest soil (68%, on average), whereas the lowest value was found in pasture soil (50.5%, on average); increase by 34% (Figure 3).

Figure 3 shows soil porosity extremes between forest (the highest porosity) and pasture (the lowest porosity) soil. Soil porosity values observed for the other investigated land-use types lied between these two types. Yerba mate, eucalyptus reforestation and the two cultivation types recorded similar soil porosity values at all depths.

Both recorded higher values on soil surface than in other layers.

Yerba mate cultivation recorded lower porosity on soil surface than that observed for eucalyptus reforestation and for the two cultivation forms. However, soil porosity was higher between these two land-use types at the depth of 60 cm.

Soil resistance to penetration recorded a sequence of values like those observed for soil density and porosity. The lowest soil resistance to penetration was found in the forest, whereas the highest one was observed in the pasture (Figure 3). It is worth pinpointing that soil moisture is one of the main factors to be taken into consideration to help better understanding soil resistance to penetration. Figure 3 shows the distribution of moisture values observed for each land-use type on the day resistance-to-penetration data were collected.

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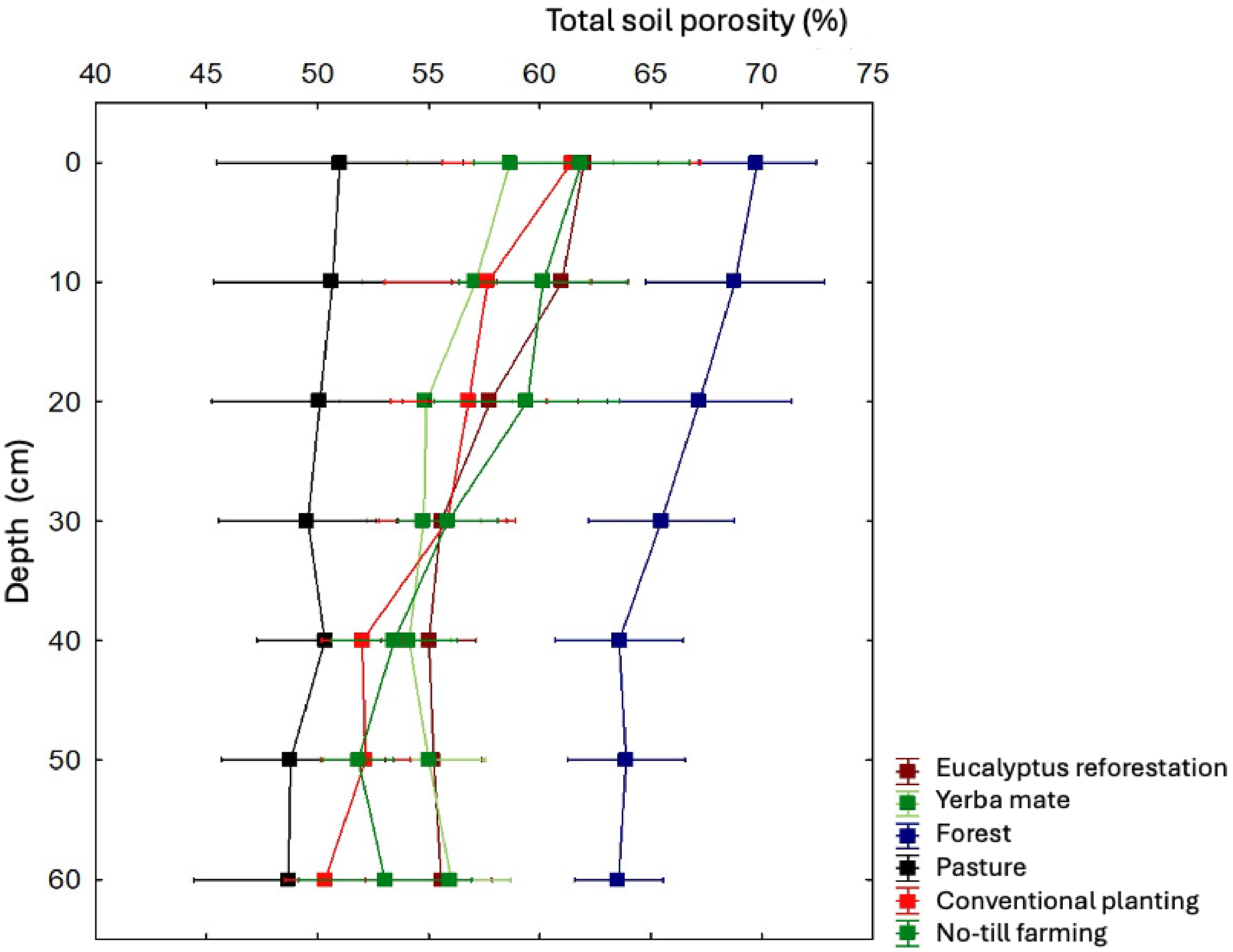
Figure 3. Soil porosity in different land-use types.



The highest variation in soil resistance-to-penetration values was observed at the topsoil layer; pasture recorded 2.55 Mpa (the highest value), on average, whereas forest recorded 1.3 Mpa (the lowest value), on average (variation of approximately 96.2%). However, soil density variation in the last measured layer (60 cm depth) only reached 29.7%.

The two analyzed forest areas recorded increasing soil resistance to penetration and moisture values as soil depth increased (Figure 4). Yerba mate cultivation showed lower soil resistance between depths in comparison to the other land-use types. The two analyzed cultivation types recorded increasing soil resistance to penetration and moisture values up to the depth of 40 cm; after that, they recorded decreasing values as soil depth increased. Pasture presented increased soil resistance to penetration from the surface layer to the depth of 10 cm. However, these values decreased from this depth, onwards.

Soil moisture presented similar pattern to that observed for soil resistance to penetration, i.e., it recorded the highest variation at the surface layer and the lowest variation at the depth of 60 cm. Two different moisture groups were observed on soil surface: conventional planting, yerba mate cultivation, eucalyptus reforestation and pasture areas recorded increased moisture content as soil depth increased. Forest and no-till areas, in their turn, recorded reduced moisture content as soil depth increased. The lowest soil moisture content was observed in conventional planting and the highest one, in forest.

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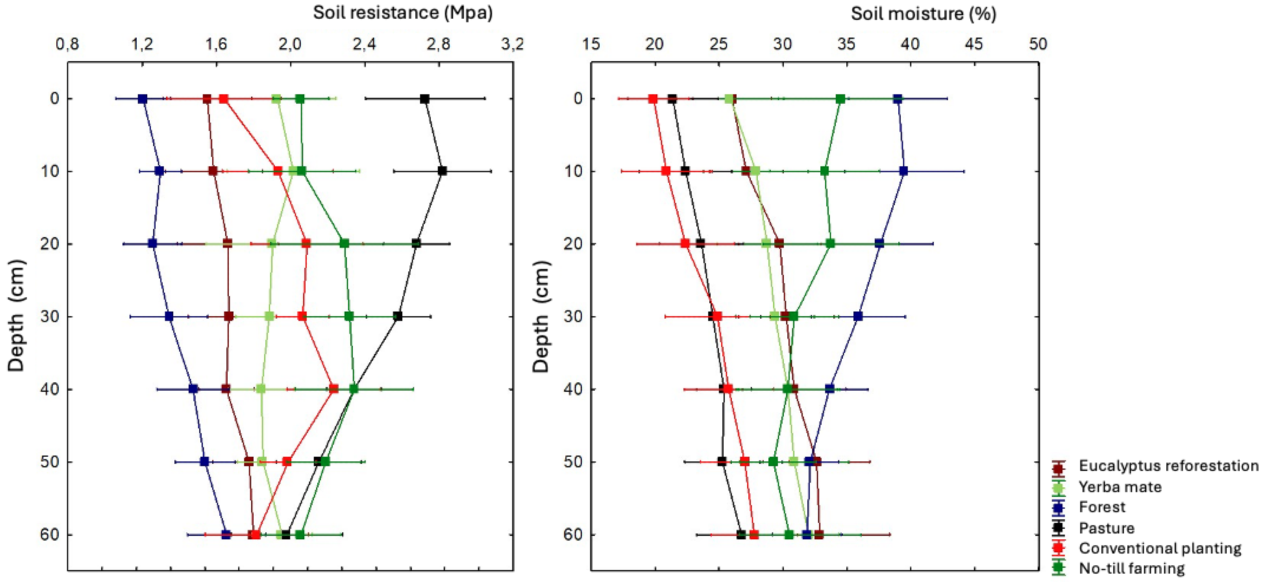
Figure 4. Soil resistance to penetration and moisture values.



DISCUSSION

Small rural properties in Southeastern Paraná State are overall featured by higher land-use diversity, such as agricultural and forest areas interspersed with pasture and reforestation areas. Forest areas are combined to native pasture clearings for extensive animal husbandry purposes. It means that grazing animals use both pasture and forest areas. This is one of the conditions affecting soil compaction in forest areas. Mean values herein recorded for soil density, porosity and resistance to penetration were higher than those observed by Schoenholtz *et al*. (2000); Yu *et al*. (2018); Xia *et al*. (2019); Shao *et al*. (2020). Based on the current findings, implementing extensive animal husbandry without adopting conservation techniques increases soil compaction due to constant trampling.

The lower soil density and resistance to penetration values recorded at the topsoil in the forest area are explained by the organic matter concentration observed in it due to leaf litter decomposition (Prescott; Vesterdal, 2021). Organic matter may have contributed to increase soil surface porosity in comparison to the other layers (King *et al*., 2019). The current findings suggest that grazing animals use forest fragments for shelter and feeding purposes. This factor led to higher topsoil compaction level in these environments.

Pasture presented the worst soil compaction levels, due to constant animal trampling, which is one of the main causes of soil degradation in pastures (Benevenute *et al*., 2020). The first soil layers in the pasture recorded the highest compaction levels: soil resistance to penetration reached 3.0 MPa, soil density was approximately 1.4 g/cm3 and soil porosity reached approximately 50%, on average. These values hinder plant root development (Drewry *et al*., 2008; Pulido *et al*., 2016; Bécel *et al*., 2012), and it can contribute to increased pasture degradation.

, It was clear that animal trampling has influenced soil density, porosity and resistance to penetration in the first pasture soil layers, since soil compaction recorded similar values up to the depth of 30 cm. Soil layers deeper than the one at presented reduced density, increased porosity and reduced resistance to penetration.

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Increased soil resistance to penetration and reduced soil porosity in the pasture surface layer can lead to reduced water infiltration (COLOMBI *et al*., 2018) and increased surface runoff. The hydrological dynamics of soil surface in pasture areas contribute to reduce soil moisture content. It is worth emphasizing that soil moisture is ally to soil resistance to penetration (Dexter *et al*., 2007). Therefore, there is close correlation between soil moisture and resistance to penetration.

Soil compaction in yerba mate cultivation was like that observed for eucalyptus reforestation. Total porosity at topsoil reached 58.5%, whereas soil density reached 1.09 g/cm3. These values were like those reported by Pezarico *et al*. (2013) who found soil porosity close to 57.0% and soil density of approximately 1.16 g/cm3 in yerba mate plantation.

Eucalyptus reforestation recorded the worst soil compaction values among forested areas; its soil density was approximately 1.07 g/cm^3, total soil porosity reached 60.1% and soil resistance to penetration was close to 1.7 Mpa. These values were following those reported by Alvarenga and Davide (1999) in 15-year-old eucalyptus reforestation area.

Reduced soil quality in eucalyptus areas in comparison to the other forested areas may be explained by the eucalyptus litter decomposition rate, which is slower than that of native species.

The investigated agricultural areas presented similar physical features (Table 1), such as little variation in soil compaction, except for soil resistance to penetration in the 20-40 cm layer, which recorded lower values in no-till farming. The literature comprises a wide range of studies reporting improved soil quality after the implementation of conservation practices.

Different soil management activities were performed in the two planting forms. Soil subjected to conventional planting was constantly turned over, whereas the soil in the no-till system remained undisturbed. This condition enabled the soil in conventional tillage systems to show less compaction from the surface to the depth of 30 cm. The highest soil resistance-to-penetration values observed in both soil management systems were recorded at the depth of 40 cm. This issue can be attributed to the adopted soil management strategy, which increased harrow foot (the most compacted layer) emergence during cultivation, through agricultural activities.

According to some studies, converting soil management from conventional tillage to no-till system often results in higher soil resistance to penetration in the 0-20 cm layer, because the soil is not turned over (Salem *et al*., 2015; Gao *et al*., 2016). Soil moisture in the surface layer of the no-till system appeared not to have reduced soil resistance to penetration, although there was reduced friction between soil particle and equipment cone, as observed by Souza *et al*. (2021).

The highest soil moisture contents in the surface layer of the no-till crop may be explained by the topsoil cover, since oat (*Avena sativa*) is sown during winter and acts as dead layer for the following crop cycle.

CONCLUSIONS

The reduced adoption of conservation practices in different land-use types in small rural properties has led to soil degradation in these areas. Forest areas, for example, were used as fallow land for domestic animals. Native pasture clearings, which were under constant grazing-related pressure, were often interspersed with forest and/or reforestation of exotic species. This condition has increased soil compaction in both forest and pasture

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areas. Soil porosity and density in the yerba mate crop recorded similar values to those observed for eucalyptus reforestation. However, soil surface exposure and lack of topsoil turning may have increased soil resistance to penetration in comparison to that of forested areas. The herein investigated land-use types have shown some similarities at soil compaction level. However, it was clear that adopting conservation practices in agriculture helped improving soil conditions. Therefore, small properties should be further investigated to help better understanding soil compaction issues, given the amount of pressure posed on different land-use and occupation types. Although studies focused on investigating soil physical conditions in small properties remain incipient, the current investigation has contributed to open new research perspectives.

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