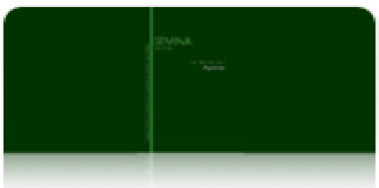

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Study of soil physical properties and water infiltration rates in different types of land use

Estudo dos atributos físicos do solo e taxas de infiltração de água em diferentes modalidades de uso da terra

Kristiana Fiorentin dos Santos[1*]; Fabrício Tondello Barbosa[2]; Ildegardis Bertol[3]; Romeu de Souza Werner[4]; Neuro Hilton Wolschick[4]; Josie Moraes Mota[5]

Abstract

Studying the changes in soil properties caused by different land uses allows measures to be adopted that will reduce the risk of future negative effects. The aim of this study was to evaluate soil physical properties and quantify water infiltration for different types of land use in the Santa Catarina Plateau of southern Brazil. The research was conducted on a 1,200 ha rural property. The land use types selected were natural forest (NF), planted pine (PP), crop-livestock integration (CLI), and burned natural rangeland (BR). A sample survey was carried out in nine different areas for each land use. Samples were collected from four soil layers and the soil bulk density (Bd), total porosity (Tp), and macropore (Ma), micropore (Mi), and biopore (Bio) volumes were measured. Water infiltration tests were performed to obtain the initial (*ii*) and final (*fi*) water infiltration rates into the soil, and the total amount of water that had infiltrated the soil (*Ti*). In NF, Bd was lower and Tp was higher than in other types of land use. The forest vegetation (NF and PP) had higher Ma and Bio volumes in the superficial layers of the soil. Water infiltration was markedly different between land use types. The NF had the highest *ii*, *fi*, and *Ti* values followed by PP, whereas the CLI and BR areas had drastically lower infiltration parameters with BR having the lowest values. The variables *ii*, *fi*, and *Ti* correlated positively with Tp, Ma, and Bio, but negatively with Bd.
Key words: Soil quality. Crop, livestock, and forest. Soil permeability.

Resumo

O estudo das modificações nos atributos do solo provocadas pela forma de utilização das terras possibilita a adoção de medidas que reduzam riscos de futuros impactos. A pesquisa teve por objetivos quantificar atributos físicos do solo e a infiltração de água em diferentes modalidades de uso da terra no Planalto Sul Catarinense. O estudo foi conduzido em propriedade rural de 1.200 ha, onde foram selecionadas áreas sob floresta natural (FN), plantio de pinus (PP), integração lavoura-pecuária (ILP) e campo natural pastejado e submetido à queima (CN). Para isso, realizou-se levantamento amostral em nove glebas distintas para cada tipo de uso. Foram coletadas amostras de solo em quatro camadas para determinação da densidade do solo (Ds), porosidade total (Pt), macroporos (Ma), microporos (Mi) e bioporos (Bio).

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Testes de infiltração de água no solo foram realizados para obtenção das taxas de infiltração inicial (ii) e final (if) e da lâmina total infiltrada (It). Na FN a Ds é menor e a Pt maior do que nos demais tipos de uso da terra. A vegetação florestal (FN e PP) se destaca com maiores volumes de Ma e Bio nas camadas superficiais do solo. A infiltração de água apresenta diferenças acentuadas entre os tipos de uso. A FN tem maiores valores de ii, if e It, seguida pelo PP, enquanto CN e ILP tem redução drástica nos parâmetros de infiltração, com menores valores no CN. As variáveis ii, if e It correlacionam-se positivamente com Pt, Ma e Bio e negativamente com Ds.
Palavras-chave: Qualidade do solo. Lavoura, pecuária e floresta. Permeabilidade do solo.

Introduction

Humans interact in a complex way with the biosphere. They modify the natural habitat and cause environmental imbalances across many regions of the planet (PACHÊCO et al., 2006). Changes in usage patterns and ground cover have aroused concern. These changes need to be better planned if negative effects, such as loss of biodiversity, and the erosion and contamination of water resources, are to be avoided. Therefore, it is important to measure the magnitude of these changes (GALHARTE et al., 2014).

The fields and natural forests of southern Brazil have suffered from anthropogenic activities, which have been caused by the continuous and rapid replacement and decharacterization of the different environments that the fields and forests are composed of. This, in part, is driven by the increase in size of the agricultural and forest monoculture areas (BOLDRINI, 2009). The removal of the original vegetation cover, the preparation of the soil for the crops, the overgrazing of vegetation, and the use of fire for pasture renewal has contributed to the degradation of the soils in the Santa Catarina Plateau of southern Brazil (WERNER et al., 2016).

The management method currently used in forest monocultures has contributed to soil degradation. It promotes the adoption of uninterrupted crop cycles and non-conservation soil management, especially during forest planting and harvesting (OLIVEIRA et al., 2014). In the case of annual crops, changes in the physical properties are more pronounced in management systems where greater soil mobilization occurs (BERTOL et al., 2004). Furthermore, extensive livestock holding and the burning of fields are common in southern Brazil. These processes modify the soil attributes, eliminate vegetation cover, and leaves soil vulnerable to erosive processes (REDIN et al., 2011).

The degradation of soil physical properties is one of the main processes responsible for the loss of soil quality. The changes are more pronounced in soils that are more intensively used because there is a greater effect on the soil structure. This form of degradation increases compaction and soil resistance to root growth, but decreases the volume and distribution of pores, water infiltration, the stability of aggregates, and plant development (RICHART et al., 2005).

The infiltration of water into the soil is considered to be the best parameter for evaluating soil physical conditions because soil quality and structural stability influence the distribution of pore size, which determines the water infiltration capacity (BERTOL et al., 2000). In forests, soils generally have a greater porosity. This is partly because there are more macropores, which are the main sites for water entry, and its distribution and supply by the water table (CHENG et al., 2002). Forms of land use that promote higher rates of water infiltration are essential if the soil is to be recharged by underground reservoirs, river flow is to be controlled during droughts, and the effects of floods, runoff, and water erosion are to be mitigated (TUCCI; MENDES, 2006).

This study hypothesized that soil subjected to agricultural exploitation, regardless of the type of use, had lower quality physical properties compared to the natural forest, with a consequent reduction in water infiltration into the soil; and that burning natural rangeland results in the greatest deterioration in the physical quality of the soil. The objective was to determine the soil physical properties and water infiltration rates after different types of land use in the Santa Catarina Plateau of southern Brazil.

Materials and Methods

The study was carried out in the municipality of Capão Alto, SC, Brazil (south of the Santa Catarina Plateau), in an area located between 27°55' to 27°57' S and 50°25' to 50°29' W. The Köppen classification system (ALVARES et al., 2013) categorizes the climate as being mesothermal humid subtropical, with warm summers and frequent frosts in the winter (Cfb). The average annual temperature is 14°C and the average altitude is 1,022 m. The predominant soil type is a *Nitossolo Bruno* (EMBRAPA, 2004), a clayey Nitisol according to the IUSS Working Group WRB (2014).

The study site was 1,200 ha in size and four land use types were evaluated. These were a) Natural forest (NF), classified as mixed ombrophilous forest containing *Araucaria angustifolia*. In this treatment, areas that were difficult to access were sampled in order to minimize anthropic and animal interference. b) Planted forest containing *Pinus taeda* (PP) that was 8 to 10 years old. This represents the first cutting cycle. Previously these lands were occupied by natural field pasture and cattle. c) Crop-livestock integration (CLI). These lands were cultivated for 10 years under conventional tillage (1 plow + 2 harrow treatments). They were planted with annual agricultural species in spring-summer and were grazed during autumn-winter. Over the last eight years, a no-tillage system has been adopted for the annual cultivation along with the following crop succession: corn and soybeanin spring-summer, and oats and ryegrass under grazing in autumn-winter. d) Burned natural rangeland (BR). This practice has occurred for 70 years. The land is burnt and then grazed with cattle. With this type of use, the field is burned every two years at the end of the winter season to provoke the renewal of pastures, a common practice in the region.

The research was conducted from September 2012 to April 2013 by sample surveying nine different areas for each type of land use. A preliminary survey was carried out to identify the soil types. Soil sampling points were assigned to areas that were identified as a Nitisol. This meant that variations due to different soil types were avoided. In the CLI areas, the evaluations were carried out when the corn crop began to grow and in the BR areas, the collections were made in the year following the burning of the vegetation. The granulometric characterization and soil organic carbon content in the different soil layers and for the various land uses are shown in Table 1.

Structurally preserved soil samples were collected using volumetric rings from four layers (0-5, 5-10, 10-20, and 20-40 cm soil depth). The samples were used to determine the soil bulk density (Bd), the total porosity (Tp), and the macropore (Ma) and micropore (Mi) spaces by measuring the water saturation of the rings, draining them on a tension table under a matric potential of 6 kPa, and drying the samples at 105°C (EMBRAPA, 1997). The biopore volume (Bio) was quantified by withdrawing water from the saturated rings on the tension table under a matric potential of 1 kPa (ANDRADE et al., 2016).

The infiltration of water into the soil was evaluated over two hours using double concentric rings with variable hydraulic loads (FORSYTHE, 1975). This method was used to determine the initial (*ii*) and final (*fi*) infiltration rates, and the total amount of water that had infiltrated the soil (*Ti*).

Table 1. Granulometric characterization and total organic carbon contents (TOC) of the soil samples taken from the different layers and for the different types of land use.

Land use	Layer (cm)	Sand	Silt	Clay	TOC
		----------	---------- g kg^{-1}	----------	----------
NF	0-5	62	572	366	65
	5-10	61	536	403	42
	10-20	50	497	453	32
	20-40	52	464	484	25
PP	0-5	55	411	534	37
	5-10	59	408	533	29
	10-20	45	388	567	30
	20-40	41	334	625	23
CLI	0-5	54	345	601	38
	5-10	46	338	616	29
	10-20	38	331	631	22
	20-40	33	271	696	19
BR	0-5	63	362	575	39
	5-10	65	331	604	30
	10-20	40	387	573	24
	20-40	47	273	680	23

NF: natural forest; PP: pine plantation; CLI: crop-livestock integration; BR: burned natural rangeland. TOC: total organic carbon.

The data were analyzed through descriptive statistics of the means and by the 90% confidence interval ($p \leq 0.1$). Correlations among the variables were made using Pearson's linear model.

Results and Discussion

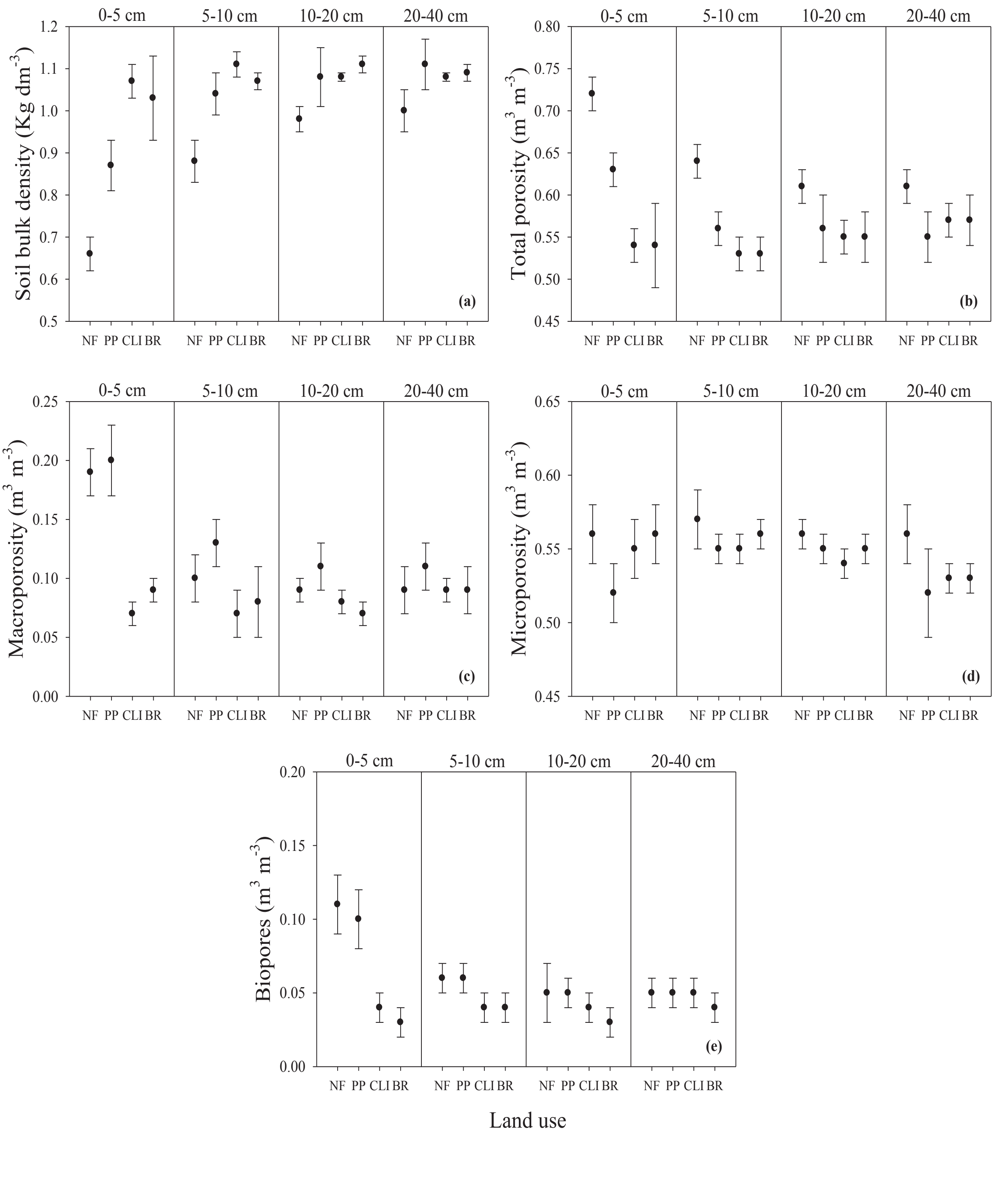
Soil bulk density and porosity

The average values for soil bulk density (Bd) ranged from 0.66 to 1.11 kg dm^{-3} (Figure 1a). The highest values were observed in the cultivated areas compared to the natural state (NF). Although the values for Bd are below those considered critical for clayey soils (1.4 to 1.6 kg dm^{-3}) according to Reichert et al. (2003), the agricultural, livestock and forestry cultivation land uses, independently of the soil management system, promoted changes in soil physical properties.

The natural forest (NF) had a lower Bd in all the soil layers (Figure 1a), which agreed with Matias et al. (2009). This result is because of the preservation of the natural characteristics of the environment through root action effects, forest litter production, and soil fauna (DEMARQUI et al., 2011). In the 0-5 cm layer, the highest values for Bd were found for the crop-livestock integration (CLI) and burned natural rangeland (BR) land use types. Higher densities in the surface layers of the CLI areas are probably because of the machine and animal traffic effects on the soil (KUNZ et al., 2013). For BR, the residual effect of burning may have led to compaction because it causes the mineralization of organic matter in the superficial layer, which has negative effects on soil structure maintenance (REDIN et al., 2011). This is aggravated by the negative effect on soil fauna, which help promote soil aggregation and improve soil physical properties.

Among the cultivated areas, the planted pine reduced the Bd in the 0-5 cm layer compared to CLI and BR (Figure 1a). This effect was restricted to the soil surface because at deeper depths the Bd values in the PP area were similar to the other land-uses when the overlap in the confidence interval limits are taken into consideration.

Figure 1. Soil bulk density, total porosity, macroporosity, microporosity, and biopore volumes in four layers of soil that had been subjected to different types of land use. NF: natural forest; PP: pine plantation; CLI: crop-livestock integration; BR: burned natural rangeland. The dots represent the mean and the vertical bars represent the confidence interval ($p \leq 0.1$). Means where the confidence interval limits overlap are not significantly different.



The total porosity of the soil (Tp) ranged from 0.61-0.72 m^3 m^{-3} in NF, 0.55-0.63 m^3 m^{-3} in PP, and 0.53-0.57 m^3 m^{-3} in CLI and BR. Higher values occurred in NF at all soil depths and in the 0-5 cm layer for PP compared to CLI and BR (Figure 1b). This shows the positive effect of forest use, both natural and planted, compared to non-forest uses. Wendling et al. (2012) found that Tp in the agricultural areas cultivated without soil tillage was lower in the 0-10 cm layer than in the forested areas. The cover given by the aerial part of the trees, the effect of their roots, and litter on the soil surface have important roles in controlling land degradation because they help maintain the structural quality of the soil (BERTONI; LOMBARDI NETO, 2010).

The macropore volume (Ma) ranged from 0.09-0.19 m^3 m^{-3} in NF, 0.11-0.20 m^3 m^{-3} in PP, and 0.07-0.09 m^3 m^{-3} in CLI and BR. In general, higher values were recorded in the forested areas. This difference was more pronounced in the 0-5 cm layer where, on average, the Ma volume was 0.12 m^3 m^{-3} higher than for non-forest uses (Figure 1c). This difference was also apparent in the 5-20 cm layers, although it was less pronounced. In the 20-40 cm layer, the values were similar for the different types of land use.

The critical value for Ma that limits root metabolism and growth, and decreases soil permeability and pore continuity is 0.10 m^3 m^{-3}(XU et al., 1992). This value is used as a reference for annual crops and pastures. The values were below the critical limit in all the CLI and BR layers (Figure 1c), which indicated possible water infiltration and oxygen circulation issues. These problems would detrimentally affect the development of plant roots. The Bd increase and the Ma reduction in the CLI and BR areas are probably due to the compaction caused by machine and agricultural implements traffic, and animal trampling. Werner et al. (2016) emphasized that soil compaction causes a decrease in Tp, but the decrease in Ma is larger.

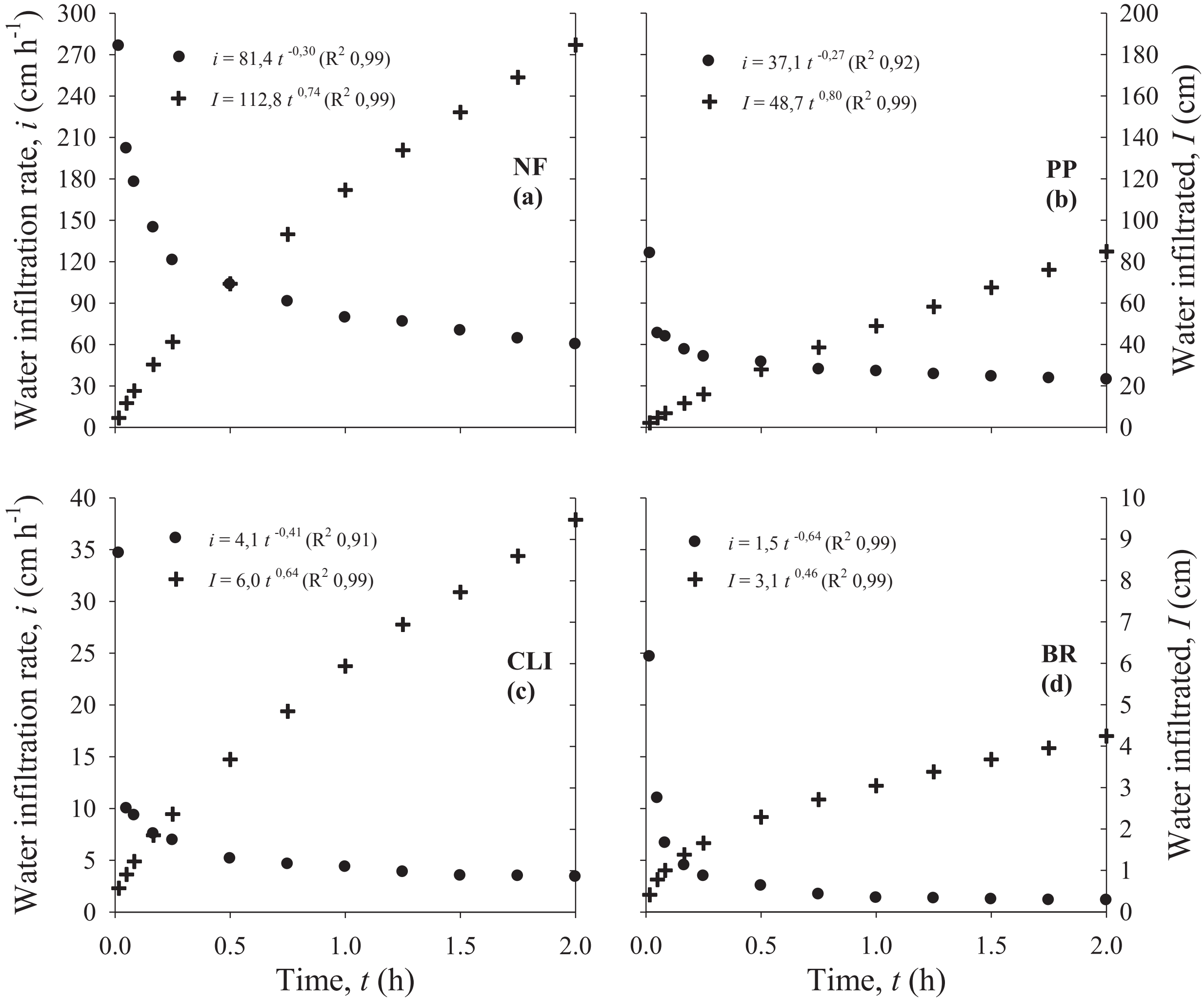
The micropore volume (Mi) was hardly influenced by land-use type (Figure 1d). The values ranged from 0.52-0.57 m^3 m^{-3}, and were slightly higher in NF for all layers, which may represent a greater capacity to retain water in the soil. In comparison to cultivated soils, the natural forest had a higher water storage capacity due to the large volume of smaller pores and the presence of larger pores, which improve the infiltration and the distribution of water in the soil (CHENG et al., 2002).

The biopore volumes (Bio) ranged from 0.05-0.11 m^3 m^{-3} in NF, 0.05-0.10 m^3 m^{-3} in PP, 0.04-0.05 m^3 m^{-3} in CLI, and 0.03-0.04 m^3 m^{-3} in BR. The highest values were recorded for forest land use types (NF and PP) down to a depth of 10 cm. The effect was more pronounced in the 0-5 cm layer, which was three times higher than the agricultural land use types (CLI and BR) (Figure 1e). In the 10-40 cm layers, all treatments had overlapping confidence intervals, although average values for Bio were slightly higher in NF and PP. Lima et al. (2005) reported that the surface compaction caused by agricultural cultivation and machine traffic affected the shape and distribution of the porous space, particularly biopores. According to Costa et al. (2006), biological attributes are more sensitive to changes in soil quality caused by changes in land use and soil management than other variables.

Water infiltration into the soil

The results showed differences in the instantaneous infiltration rate (*i*) and the amount of water infiltrating the soil (*I*), as a function of time (*t*), between the different types of land use (Figure 2). The NF had the highest values, followed by PP. The BR land use type had the lowest values for *i* and *I*, which is related to changes in soil structure caused by management practices. The use of fire and animal trampling accentuated this effect. The CLI land use type also had low values for *i* and *I*, but they were higher than for BR. According to Dalla Rosa (1981), the reduction in water infiltration best explains the increase in the degradation of the soil porous system, which actually occurred in BR and CLI.

Figure 2. Water infiltration rate (*i*) and total amount of water that infiltrated the Nitisol soil (*I*) for four types of land use. (a) NF: natural forest; b) PP: pine plantation; c) CLI: crop-livestock integration; d) BR: burned natural rangeland.



The initial (*ii*) and final (*fi*) water infiltration rates, and the total amount of water infiltrating the soil (*Ti*) were higher in the forest areas (NF and PP) than in the agricultural areas (BR and CLI) (Table 2). The NF land use type resulted in values that were higher than PP. This occurred because NF had a greater diversity of plant species compared to the pine monoculture, which led to greater biological activity and improvements in soil structural quality and the porous system. According to Luciano et al. (2010), water infiltration, both under dry soil conditions and under saturation conditions, is positively affected by the diversity of the plant root system and the galleries present in the soil. The galleries formed by the roots of forest species are deep and facilitate the infiltration of water. However, in crops and pasture, the roots are superficial and smaller in length and diameter. Natural forests also have higher levels of organic carbon in the soil, which also improves infiltration and is fundamental to the formation and stabilization of the aggregates.

Table 2. Initial (*ii*) and final (*fi*) water infiltration rates, and total amount of water infiltrating the soil (*Ti*) for the different types of land use.

Land use	Water infiltration rate		Total amount of infiltrated water
	Initial	Final	
	-------------- $cm\ h^{-1}$ -------------		------------- cm -------------
NF	276,2 ± 55,9	60,2 ± 9,9	184,7 ± 36,4
PP	126,0 ± 29,2	34,5 ± 7,2	84,9 ± 16,6
CLI	34,7 ± 23,0	3,4 ± 1,0	9,5 ± 1,8
BR	24,6 ± 7,6	1,1 ± 0,4	4,2 ± 0,9

NF: natural forest; PP: pine plantation; CLI: crop-livestock integration; BR: burned natural rangeland. Means ± confidence interval ($p \leq 0.1$). Means where the confidence limits overlap, are not significantly different.

The *ii*, *fi*, and *Ti* values for NF were 2.2, 1.7, and 2.2 times higher than PP; 8.0, 17.7, and 19.4 times higher than CLI; and 11.2, 54.7, and 44.0 times higher than BR, respectively. All land use types were different from each other according to their confidence intervals, with the exception of CLI and BR for variable *ii* (Table 2). According to Pinheiro et al. (2009), water infiltration in forest areas tends to be superior to agricultural areas. The removal of natural vegetation and the introduction of cultivated crops or animals for grazing lead to a marked reduction in the water infiltration capacity.

The *ii*, *fi*, and *Ti* values for CLI were 1.4, 3.1, and 2.3 times higher than BR, respectively (Table 2). Bertol et al. (2011) compared different forms of natural field management and found that water infiltration was lower in ground that had been burnt compared to an unburnt field. Therefore, the use of fire and trampling by animals were responsible for the slower water infiltration in the BR area because burning was not carried out on the CLI land and no animals entered the CLI area during the spring-summer period.

In general, the lower values for water infiltration in the BR and CLI areas demonstrate that increasing land use intensity significantly influences this variable. According to Cheng et al. (2002), the natural forests are fundamental to increasing water infiltration in agricultural areas, and their beneficial effect on the quality of water flows has become a key justification for retaining them in strategic locations.

Correlation between variables

The water infiltration variables (*ii*, *fi*, and *Ti*) were significantly correlated with Bd, Tp, Ma, and Bio, but were not correlated with Mi (Table 3). The *ii*, *if*, and *Ti* negative correlations with Bd show that increasing soil compaction alters water flow, reducing both the infiltration rates and the total water absorption capacity of the soil. In this study, the increase in Bd was associated with the increase in the land-use intensity. Hickmann et al. (2012), when assessing the physical-water attributes of soil in cultivated areas and under natural forest, observed a negative Bd effect on hydraulic conductivity.

The variables *ii*, *fi*, and *Ti* were positively correlated with Tp, Ma, and Bio (Table 3), which highlights the important effects of soil structural quality on water infiltration. This is because water infiltration is related to the shape and distribution of the porous space in a soil. The absence of a correlation with Mi shows that water infiltration is dependent on larger pores. The biological pores, created by plant root development and soil fauna, have a greater positive effect on rapid water infiltration because they are more rounded and tubular in shape, and resemble continuous channels (LIMA et al., 2005). Forest vegetation is considered very efficient at creating biological channels, which may be the predominant form of macropores, especially in clay soils (BRADY; WEIL, 2013).

Table 3. Pearson's linear correlations between soil physical properties and the water infiltration parameters.

Variables	*ii*	*if*	*Ti*
Bd	-0,69**	-0,69**	-0,71**
Tp	0,58**	0,56**	0,59**
Ma	0,47**	0,53**	0,51**
Mi	ns	ns	ns
Bio	0,46**	0,50**	0,54**

Bd: soil bulk density (kg dm^{-3}); Tp: total porosity ($m^3\ m^{-3}$); Ma: macroporosity ($m^3\ m^{-3}$); Mi: microporosity ($m^3\ m^{-3}$); Bio: biopore volume ($m^3\ m^{-3}$); *ii*: initial water infiltration rate (cm h^{-1}); *if:* final water infiltration rate (cm h^{-1}); *Ti:* total amount of infiltrated water (cm).**significant correlation at 1%; ns: non-significant correlation.

According to Panachuki et al. (2006), when the soil physical attributes are modified by management practices, the water infiltration rate in the soil also changes, which may cause an increase in runoff and, consequently, increased soil and water losses. This alters the natural hydrological balance of the system.

Conclusion

Under natural forest conditions, the soil bulk density is lower and total porosity is higher than in pine plantations, and under integrated crop-livestock or burned natural rangeland systems. Such effects are more pronounced in the superficial layers of the soil.

Forested areas, composed of natural vegetation or planted pine, produce higher volumes of macropores and biopores in the soil compared to non-forest uses.

The differences in water infiltration are greater between the land-use types than the differences in the density and porosity properties of the soil. The natural forest has the highest initial and final water infiltration rates and total amounts of water infiltrated, followed by pine planting. In contrast, burned natural rangeland and crop-livestock integration drastically reduced the infiltration parameters, with the burned natural rangeland producing the lowest values.

The initial and final infiltration rates and the total amount of water infiltrating the soil correlate positively with total porosity, macropores, and biopores, but negatively with soil bulk density.

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