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The establishment of a secondary forest in a degraded pasture to improve hydraulic properties of the soil

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ABSTRACT

The recovery of soil hydraulic properties after the conversion of pasture areas into forests is still poorly studied. The aim of this research was to evaluate the effect the vegetation has on the hydraulic properties of soil, as well as the physical and chemical properties of the soil in pasture and secondary forest areas, located in a hill with east and west sun exposed faces. The study was carried out in two 15-year-old secondary forest areas and two pasture areas. Undeformed soil samples were collected in the upper third of each slope using steel rings at depths of 0–10 cm, for laboratory analyses of the physical properties and the saturated hydraulic conductivity of the soil. Additional samples were collected to evaluate the total organic carbon, the carbon storage and the chemical characteristics of the soil. A tension infiltrometer was used to determine the hydraulic properties and the contribution of the macropores to the infiltration of water into the soil. The use of a unmanned aerial vehicle helped to identify the soil cover at different locations and different faces of sun exposure. Secondary forests showed the higher values of macroporosity, soil water infiltration, and carbon storage than pasture areas. Macropores had greatest contribution to soil water infiltration in the secondary forests, whereas the mesopores and micropores had greatest effect in the pasture areas. The high content of organic matter found in the forests resulted in soils with better chemical quality. The saturated hydraulic conductivity and the carbon storage of the soil were smaller in the western forest than eastern forest. These results indicate that in order to increase water flow and water quality it is required to encourage the use of vegetative practices such as silvopastoral systems in pastures and the revegetation of the upper third of the hills.

1. Introduction

Half of the world´s tropical rainforests have been reduced to less than 50 % (Asner et al., 2009), resulting in an extensive loss of biodiversity and changes to the soil hydrologic processes (Liu et al., 2018; Ouyang et al., 2018). The reduction of biomass leads to soil exposure (Savadogo et al., 2007), which changes the structure and volume of the pores as well as the infiltration and hydraulic conductivity of the soil. Several studies have shown big reductions in the infiltration capacity and hydraulic conductivity of the soil (Zimmermann and Elsenbeer, 2009; Sun et al., 2017) after the conversion of forest into agricultural land (Price et al., 2010) and pastures (Bustamante et al., 2018; Owuor et al., 2018; Ouyang et al., 2018).

The reductions in the infiltration and hydraulic conductivity resulted in increasing surface runoff, bulk density, erosion and frequent flooding (Owuor et al., 2018; Ouyang et al., 2018; Harden, 2006; Price et al., 2010). Pastures lead to higher degradation of the soil, due to overgrazing and trampling by animals (Shang et al., 2014).

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In Brazil, pastures account for approximately 20 % of Brazilian territory, the largest of any land usage, especially in the central region of the country, which is mostly composed of the Cerrado Biome (Parente et al., 2017). In the Cerrado, at least 50 % of the pastures present some level of degradation (MAPA, 2014). In the Mata Mineira Zone, part of the Atlantic Forest Biome, the pastures were implanted in soils degraded by coffee plantations, which replaced the forest (Souza et al., 2012). Currently, around 45 % of the pastures in this region present high levels of degradation (MAPA, 2015).

As a consequence of these degradation processes, many efforts are focused on restoring ecosystems and agroecosystems, so they can provide ecosystem services once again (Holl and Aide, 2011). It is possible for some degraded agroecosystems to be restored to their former forest state, resulting in a beneficial effect on the climate, biodiversity, and also improvements in the quality and quantity of water and soil (Bright et al., 2017) among other ecosystem services (Houghton and Nassikas, 2018).

Over the past 20 years there has been a substantial increase in the amount of secondary forests (Wright and Muller-Landau, 2006; Chazdon, 2008). Nowadays, more than 50 % of the forest area results in second growth forests (Chazdon et al., 2016). These forests affect climate, soils and hydrology differently, when compared to primary forests or agricultural areas (Godsey and Elsenbeer, 2002; Hassler et al., 2011). However, the benefits of the secondary forest in recovering hydrologic properties from the degraded soil, for example by the pastures, is still poorly understood (Hassler et al., 2011) and needs to be further analysed.

The restoration will provide benefits for the forest, but how quickly they will occur will strongly depend on the levels of forest degradation, and soil and residual vegetation (Chazdon, 2008). In mountain soils, the solar exposure also influences the recovery processes. The differences between the sun exposed faces are due to multiple factors, such as the effects of the interception of the solar rays that depend on the orientation of the slopes, and also on the earth´s translation and rotation movements (Passos et al., 2017). The sun exposed faces influence the soil temperature, energy balance and water evaporation, and consequently the physical, chemical and biological properties of the soil (Passos et al., 2017; Owuor et al., 2018). However, no study to the authors' knowledge, has related these effects in areas of forest recovery after the soil degradation processes to the pastures.

The aim of this study was to evaluate the effects secondary forests have when established in a degraded pasture area, regarding the hydraulic properties of soils in relation to the faces of sun exposed. Specifically, the aim was to: i) evaluate soil cover in different areas using a unmanned aerial vehicle; ii) evaluate the physical and chemical properties of the soil in pasture and secondary forest areas; iii) evaluate the contribution of macropores to the infiltration of water into the soil.

2. Materials and methods

2.1. Study area

This study was carried out at the Isa Viçosa property (20° 50′33.403″S, 42° 52′ 9.742″ W) in the São Bartolomeu watershed, Viçosa, Minas Gerais, located in the southeast region of Brazil inside Atlantic Forest biome. The average annual temperature of the region is 20.6 °C and the average annual rainfall is 1229 mm. The amount of rain from January to March was 510 mm, and in the period evaluated it was 87.8 mm (Fig. 1).

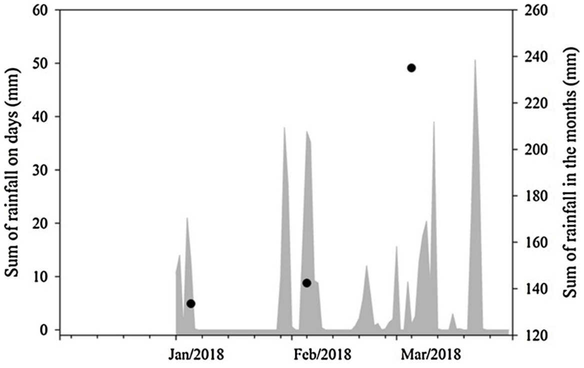

Fig. 1. The peaks indicate the amount of rainfall per days and the black circles indicate the amount of rainfall per months in Viçosa, Minas Gerais, Brazil.

The study area is located around 810 m above sea level and contains two types of vegetation and two faces of sun exposure (Fig. 2): secondary forest-east (SF-E), secondary forest-west (SF-W), eastern pasture (EP), and western pasture (WP). All the areas presented similar slope values (± 19 %), except the SF-E area (± 14 %).

The SF-E and SF-W areas were established in pasture areas where the molasses grass (*Melinis minutiflora*) and donkey-tail grass (*Andropogon bicornis*) were predominant. The recovery process of these areas started in 2005, using a terracing procedure to control the erosion in the pasture from the western exposed face. Some native and fruit trees were planted on the east and west exposed faces, after the application of manure and limestone as natural fertilizers. Some species survived an ant attack and grew naturally in these areas, such as: *Ceiba speciosa*, *Cupressus lusitanica*, *Anadenanthera colubrina*, *Anadenanthera macrocarpa*, *Cecropia pachystachya*, *Mangifera indica* (Mango), *Cedrus* (Cedar), *Tabebuia*, *Bauhinia forficate, Acacia mangium*, *Elaeocarpus serratus, Cariniana legalis*, *Sclerolobium paniculatum*, *Lecythis pisonis*, *Miconia candolleana Train, Bombacopsis glabra* (Chestnut), *Caesalpinia pluviosa*, *Psidium guajava*, *Ocotea divaricata* (Cinnamon), *Artocarpus altilis*, *Piptadenia Gonoacantha*, *Mollinedia schottiana*, *Myracrodruon urundeuva*, *Eugenia fusca* and *Campomanesia xanthocarpa*.

The pasture areas are older than the forest areas. In these areas, brachiaria grass (*Brachiaria* spp.) and bahiagrass (*Paspalum notatum*), dominate the east face and west face, respectively. The western pasture presented a higher level of degradation than the eastern pasture, with the occurrence of furrow erosions. The cattle (15 units) are free to roam as they wish, and according to the owner of the land, the only management carried out in these areas for many years was liming. The soil from these areas was classified as Red-Yellow Oxisol.

2.2. Soil cover

The unmanned aerial vehicle (DJI Phantom 4 Pro drone, DJI Shenzhen Daijiang Baiwang Technology Co., Ltd, Shenzhen, China) with Drone Deploy software was used to capture images from the soil of the studied area.

Topographic GPS was used to demarcate strategic points in the study area in order to remove the error from the GNSS (Global Navigation Satellite System). The images were processed and georeferenced to create an orthomosaic image of the area. These processes were performed using the Agisoft Photoscan version 1.3 (Degtyarniy per., St. Peterbug, Russia).

2.3. Soil sampling

At each study location (SF-E, SF-W, EP, and WP) an area of approximately 400 m^2 was selected in the upper third of the slopes for the evaluation of the physical and chemical properties, and to determine the total organic carbon in the soil. Within each area, 15 samples of the soil were collected, in a total of 60 samplings.

2.4. Physical and chemical characteristics and determination of total organic carbon

Undisturbed soil samples were collected using steel rings at 5.3 cm in height, 4.8 cm in diameter, and at 0 − 10 cm of depth, to determine

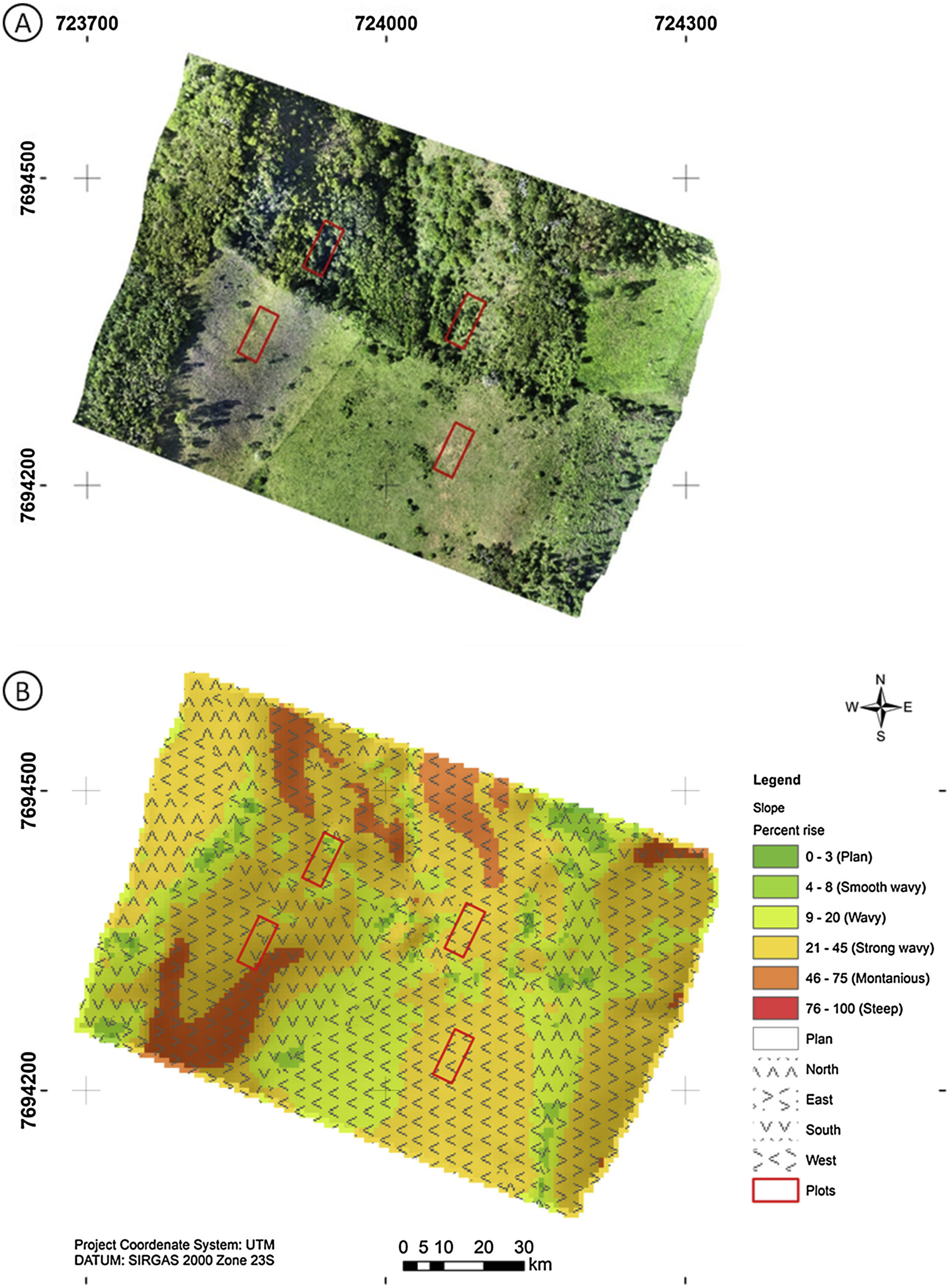

Fig. 2. Orthomosaic of the studied microbasin performed by a unmanned aerial vehicle (A) and slope of study area (B) in Palmital Community, Viçosa, Minas Gerais, Brazil. The arrows show the faces of sun exposure and the polygons in red represent the plots of the study area.

bulk density, particle density and soil porosity. The micro-mesoporosity was determined using the tension table (6 kPa). The total porosity was obtained using the formula: (1- bulk density / particle density), and the macroporosity was calculated by the difference between total porosity and micro- and mesoporosity. The size of the pores filled with water were calculated using the soil moistures, determined by the thermogravimetric method (Embrapa, 2011), bulk density and total porosity according to the formula: (soil moistures x bulk density)/ total porosity). All these analyses followed the soil research standards indicated by Embrapa (2011). The chemical analyses were performed following the procedures according to Lopes and Alvarez (1999). The pH in water was determined in proportion 1:2.5 of soil:solution. The potential acidity (H + Al) was analyzed by the calcium acetate (0.5 mol L^{-1}, pH 7.0) method. The content of calcium, magnesium and exchangeable aluminum (Al-KCl) were determined by atomic absorption spectroscopy. The potassium and available phosphorus were extracted by Mehlich1 and the contents of these elements were determined, respectively, by flame photometric and UV–vis spectrophotometry.

2.5. Analysis of carbon

The total organic carbon was determined by wet oxidation of organic matter using an external heat source (Yeomans and Bremner, 1988). This data was also used to calculate the soil organic matter.

Soil carbon storage (g) was calculated according to bulk density, percentage of carbon and the sampling depth (10 cm) (Guo and Gifford, 2002). In order to calculate the carbon stock in the soil per year, the difference between the carbon storage in secondary forests (considered as a reference) and in the pastures (adapted from Li et al., 2012) was estimated according to the equation 1.

$$\text{Carbon stock (g m}-\text{ 2 year}-\text{ 1)} = \frac{\Delta X}{\Delta t} \quad (1)$$

Where ΔX is the difference of C stocks between the soil from the forest area (considered as a reference) and the pasture area, and Δt represents the years from the start of the conversion of the pasture area to the current forest.

The rate of carbon stock accrual represents the percentage of carbon present in the forest area, in comparison to the carbon present in the pasture area. The relative rate was calculated according to the following Eq. 2.

$$\text{Relative rate of carbon stock (\% year}-\text{ 1)} = \left(\frac{\Delta X}{\text{X cultivation}*\Delta \text{t}}\right)*100 \quad (2)$$

Where: X cultivation is the C stock presented in the soil of the pasture area and Δt represents the years from the start of the conversion of the pasture area to the current forest.

2.6. Saturated hydraulic conductivity

Rings were used for the measurement of saturated hydraulic conductivity. The samples were slowly saturated (from the bottom up) to avoid air retention, over a 48 h period. The constant volume of water used, and its flow was measured through the rings, following the methodology described by Embrapa (2011). After the determination of the constant flow rate, the rate of percolating water was measured and the saturated hydraulic conductivity (K_{sat}) was calculated according to Darcy's Equation for saturated conditions.

2.7. Soil infiltration

The constant water infiltration under tension was determined at different suction rates, -0.5, -2.0 and -6.0 cm of water using the Mini Disk infiltrometer method (Decagon Devices, Pullman, WA; Radius 2.25 cm) during the rainy season. The infiltrometer is composed of an acrylic tube with a semipermeable plastic disc and a rubber stopper. A small tube was installed just above the disc to regulate the suction rate. The infiltrometer disk was randomly placed in the experimental area (SF-E, SF-W, EP, and WP), and in each area 15 repetitions were performed with three different suctions, in a total of 45 measurements per area, amounting to final total of 180 measurements. Prior to the measurement, the surface soil (1–2 cm) was cleaned, to make sure the surface was smooth and level. A fine sand (< 0.25 mm) was then poured onto the surface to ensure a good contact between the soil and the disk of the infiltrometer. The water in the tube of the infiltrometer was then transferred to the soil. The infiltrations were recorded manually at 30 s periods until the values became constant. After the determination of the infiltration, samples of deformed soils were collected near to where the infiltrations were performed, and were stored in sealed recipients for the measurement of soil thermogravimetric moisture (Embrapa, 2011).

The constant infiltration at each suction (h_0) was determined from the cumulative infiltration measured over time, using the method proposed by Zhang (1997) and calculated using the Eqs 3 and 4. Zhang’s method is a method based on Wooding's equation (Wooding, 1968) and Reynolds and Elrick (1985).

$$K(h\,0) = \frac{\text{C1}}{\text{A}} \quad (3)$$

where "C_1" is the cumulative infiltration curve versus the square root of the time, and "A" is a value of van Genuchten parameters for a given type of soil, suction and disk radius of the infiltrometer (Zhang, 1997), according to the Eq. 4:

$$A = \frac{11.65\,(n^{0.1} - 1)\exp^{(7.50(n-1.9)\,\alpha h0)}, n < 1.9}{(\alpha r)^{0.91}} \quad (4)$$

where n and α are the soil parameters of van Genuchten, r_0 is the radius of the disk and h_0 is the suction on the surface of the disk. The soil parameters of van Genuchten were obtained by Carsel and Parrish (1998), according to the manufacturer’s instructions from the infiltrometer Mini Disk.

In order to evaluate the contribution of macropores to the water infiltration in the soil, the difference in soil water infiltration between suctions -0.5 and -2.0 cm was calculated according to Li et al. (2005).

2.8. Statistical analysis

The experiment was carried out in a completely randomized design with four treatments and 15 replicates. The treatments consisted of: forest facing east, forest facing west, pasture with facing east, and pasture facing west. The obtained data were submitted to analysis of variance and the evaluated characteristics that presented significant difference by the F test had the means compared by Tukey test at a 5 % of probability level. All the analyses were performed using the Genetic and Statistical Analysis System (SAEG) software.

3. Results

3.1. Soil coverings

The photos obtained through using the unmanned aerial vehicle (Fig. 2), made it possible to identify the differences between the types of land use and the variations of faces of sun exposure in the areas of forests and pastures. The soil exposed to the sun from the west (which receives the highest radiation) was more uncovered on the eastern side of the pasture area, which indicates soil degradation. In the same face of exposure, the vegetation in the forest area was less dense than in the east side (Fig. 2).

3.2. Soil properties

The pasture areas presented the highest values of bulk density ($P < 0.05$) and consequently the highest values of micro- and mesoporosity ($p < 0.05$), and lowest values of macroporosity ($P < 0.05$), when compared to the secondary forest areas (Table 1). Regarding the faces of sun exposure, the east face presented the lowest values of bulk density ($P < 0.05$) compared to the west face of the forest area

Table 1
The mean (n = 15) of the physical characteristics and organic matter of the secondary forest and pasture area in the east and west sides.

Physical characteristics and Soil organic matter	Secondary forest		Pasture area	
	East	West	East	West
Bulk density (g cm^{-3})	1.06 ± 0.05c	1.17 ± 0.08b	1.24 ± 0.04a	1.21 ± 0.06ab
Micro-mesoporosity (%)	37.7 ± 0.02b	39.4 ± 0.02b	41.0 ± 0.01a	41.0 ± 0.02a
Macroporosity (%)	17.0 ± 0.05a	13.0 ± 0.05ab	7.00 ± 0.04c	10.0 ± 0.04bc
Moisture (%)	36.0 ± 0.04a	38.0 ± 0.04a	27.0 ± 0.02b	26.0 ± 0.03b
Pores filled with water (%)	70.0 ± 0.08b	85.0 ± 0.12a	69.0 ± 0.08b	62.0 ± 0.14b
Soil organic matter (g Kg^{-1})	82.0 ± 4.23a	57.7 ± 5.35b	39.7 ± 6.08c	33.4 ± 4.18c

The values are mean and plus or minus one standard deviations. Means followed by the same letters in the rows do not differ by Tukey test ($P < 0.05$).

(Table 1).

The moisture was higher ($P < 0.05$) in the secondary forest areas in comparison to the pasture areas. The pores filled with water were bigger ($P < 0.05$) in the western forest when compared to the eastern forest and pastures (Table 1). The values of soil organic matter (Table 1) varied from high (> 4.01 dag Kg^{-1}) in the pasture areas, to very high (> 7.0 dag Kg^{-1}) in the forest areas.

The average particle density in the areas was around 2.43 g cm^{-3}. The moisture was higher in secondary forest-east, followed by secondary forest-west, eastern pasture, and western pasture. The soil texture was clayey in EP and SF-W and more clayey in SF-E and WP (Table 2).

Soils from all areas showed very high acidity (pH < 4.5). The pasture areas presented the highest levels of exchangeable acidity (> 1 $cmol_c\ dm^{-3}$), followed by the eastern forest (> 0.5 cmolc dm^{-3}), and the lowest values were found in the western forest (< 0.5 $cmol_c\ dm^{-3}$). The calcium and magnesium levels were very low in the pasture areas (< 0.4 $cmol_c\ dm^{-3}$ and ≤0.15 cmolc dm^{-3}, respectively). The forest areas presented average levels of calcium and magnesium (> 1.21 $cmol_c\ dm^{-3}$ and > 0.46 $cmol_c\ dm^{-3}$, respectively). The potassium levels were the highest in the forest areas (> 41 mg dm^{-3}), lower in the eastern pasture areas (< 40 mg dm^{-3}) and presented the lowest levels in the western pasture area (≤ 15 mg dm^{-3}). The phosphorus levels were very low in all areas of this study (≤ 8 mg dm^{-3}) (Table 2).

3.3. Carbon stock and accumulation from the secondary forest in comparison to the pasture

The soil carbon stock ranged from 2857 g m^{-2} to 8976 g m^{-2} with different values in the types of soil usage and the faces of sun exposure (Fig. 3a). The forests showed higher soil carbon stock ($P < 0.05$) when compared to the pasture areas. The soil carbon stocks were higher in secondary forest-east, when compared to the secondary forest-west ($P < 0.05$).

Table 2
Physical and chemical characteristics of the secondary forest and pasture area in the east and west sides.

Physical and Chemical characteristics of the soil	Secondary forest		Pasture area	
	East	West	East	West
Particle density (g cm^{-3})	2.35 ± 0.13	2.47 ± 0.09	2.41 ± 0.13	2.51 ± 0.11
Moisture equivalent (%)	34.0 ± 0.05	31.0 ± 0.04	30.0 ± 0.05	29.0 ± 0.05
Sand (%)	33.0 ± 1.58	36.5 ± 2.51	34.0 ± 1.08	26.4 ± 1.01
Silt (%)	6.6 ± 2.39	9.8 ± 1.82	6.7 ± 1.87	11.4 ± 1.25
Clay (%)	60.4 ± 4.12	53.7 ± 6.50	59.3 ± 2.35	62.3 ± 3.48
pH (H_2O)	4.24 ± 0.01	4.50 ± 0.26	4.16 ± 0.08	4.05 ± 0.19
P (mg dm^{-3})	2.0 ± 0.53	1.2 ± 0.28	1.8 ± 0.33	0.9 ± 0.58
K (mg dm^{-3})	56.0 ± 3.50	49.0 ± 3.50	21.0 ± 3.00	15.0 ± 3.00
Ca ($cmol_c\ dm^{-3}$)	1.92 ± 0.08	2.02 ± 0.09	0.35 ± 0.07	0.12 ± 0.09
Mg ($cmol_c\ dm^{-3}$)	0.73 ± 0.03	0.68 ± 0.03	0.15 ± 0.02	0.05 ± 0.03
Al ($cmol_c\ dm^{-3}$)	0.58 ± 0.02	0.29 ± 0.06	1.36 ± 0.04	1.36 ± 0.04
(H + Al) ($cmol_c\ dm^{-3}$)	8.5 ± 1.23	6.6 ± 0.68	7.9 ± 0.63	6.1 ± 1.18

The values are mean and plus or minus one standard deviations.

The rate of carbon stock accrual was 42 g C m^{-2} a $year^{-1}$ higher in the SF-E than in the SF-W ($P < 0.05$) (Fig. 3b). The variations in soil carbon were also higher in SF-E ($P < 0.05$) than in SF-W, with a rate of 6.9 % per year, which was 2 % higher than in SF-W (Fig. 3c). The forests helped in recovering soil carbon at a higher yearly rate in the east side when compared to the west side (30 %).

3.4. Saturated hydraulic conductivity

The saturated hydraulic conductivity (K_{sat}) was higher ($P < 0.05$) in the SF-E area (110.6 mm h^{-1}) than in the other areas (Fig. 4). Due to the large dispersion of the individual measurements in the SF-W, there was no significant difference when compared to the pasture areas. However, the mean K_{sat} in the forest areas was at least 78 % higher when compared to the pasture areas (Fig. 3).

3.5. Constant infiltration rate at different pressures

The rates of constant infiltration at the four sites and at different pressures (-0.5 hPa, −2 hPa and −6 hPa) are shown in Fig. 5. The stable infiltration rate decreased with the increase in the negative pressure. The lowest infiltration rates were observed at a pressure of −6 hPa (Fig. 5). Most of the water infiltration into the soil occurred at a suction of -0.5 hPa (Fig. 5). At this pressure, secondary forest-east showed the highest values ($P < 0.05$, 20.67 mm h^{-1}), when compared to the other areas. However, as the data dispersion was high, SF-E did not statistically differ from secondary forest-west (12.8 mm h^{-1}). Furthermore, the SF-W did not differ from the infiltrations in the pasture areas. When considering the negative pressure of −2 hPa, a drastic reduction in constant infiltration was observed in all areas (Fig. 5), especially in the forest areas. At this pressure, the western pasture area showed the highest values ($P < 0.05$) (6.6 mm h^{-1}), not differing statistically from the SF-W (4.7 mm h^{-1}). There was no difference between SF-E and eastern pasture ($P < 0.05$). At the pressure of −6 hPa, the constant infiltration was even lower in the forest areas. However, there was a relatively small difference between the rate of constant infiltration at pressures of -2 and −6 hPa. At −6 hPa pressure, the highest ($P < 0.05$) infiltrations occurred in the pasture areas (mean of 2.7 mm h^{-1}) (Fig. 5).

4. Discussion

4.1. Physical and chemical characteristics of soil

The porosity and water storage capacity of the soil gradually increases during the plant succession (Zhang et al., 2016; Zhao et al., 2010). This is more noticeable in previous pasture areas (Udawatta and Anderson, 2008). Plant succession promotes an increase in organic

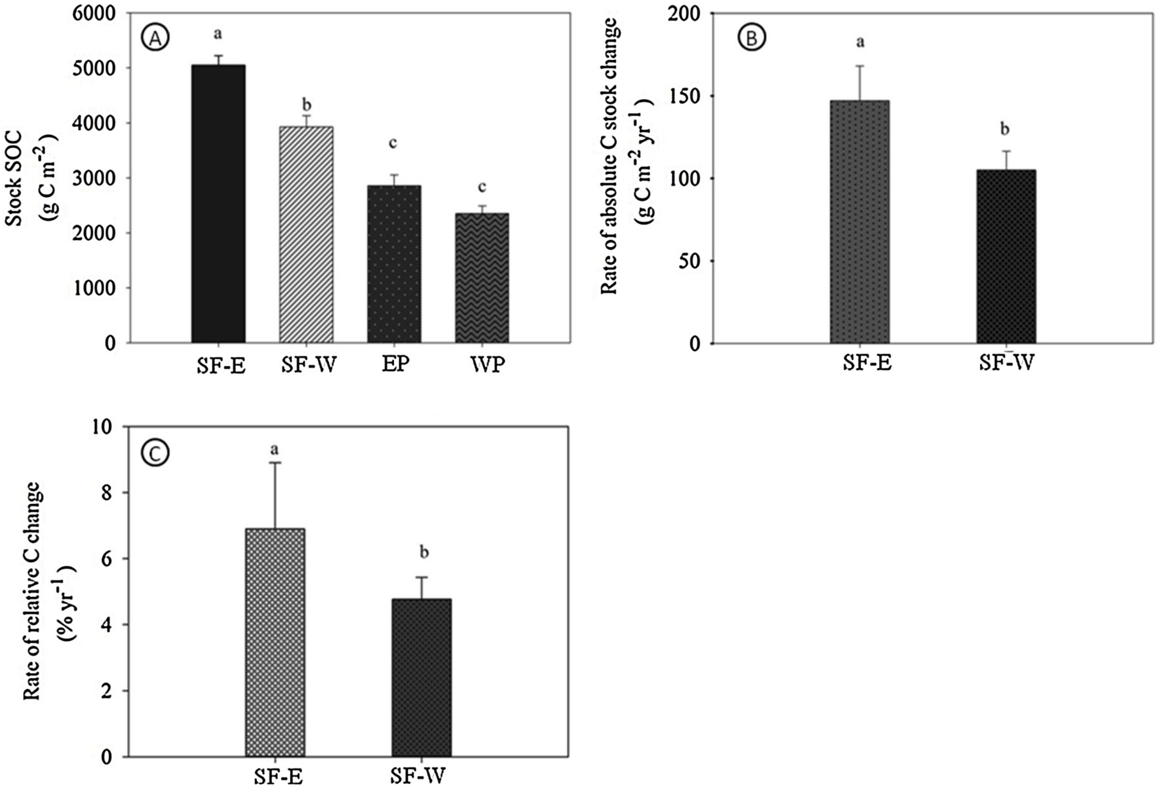

Fig. 3. Soil organic carbon stock (a), rate of carbon stock (b) relative rate of carbon (c) carbon stock in the east (SF-E) and west (SF-W) exposed faces of the secondary forest. The east (EP) and west (WP) exposed faces of the pasture area in Viçosa, Minas Gerais, Brazil. Means followed ($n = 15$) by the same letters in the different uses and faces of sun exposure do not differ among themselves by Tukey test ($P < 0.05$). The bars represent the standard deviations.

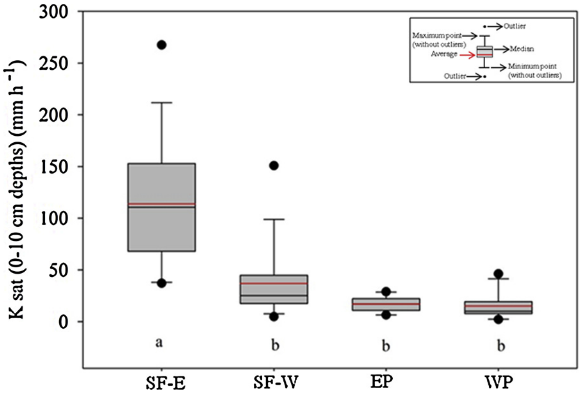

Fig. 4. Saturated hydraulic conductivity (K_{sat}) measured from depths of 0–10 cm in the east (SF-E) and west (SF-W) exposed faces of the secondary forest, and in the east (EP) and west (WP) exposed faces of the pasture area in Viçosa, Minas Gerais, Brazil. Means ($n = 15$) followed by the same letters in the different uses and face of sun exposure do not differ among themselves by Tukey test ($P < 0.05$).

carbon content in the soil (Fischer et al., 2015), mainly occurring in the eastern forest (Table 1 and Fig. 3), which is an area with a lower slope and lower solar incidence (Fig. 2). An increase in the amount of organic carbon changes the structure of the soil, leading to an increase in its macroporosity (Mulumba and Lal, 2008) (Table 1). This causes an increase in the hydraulic conductivity and water infiltration in the soil (Wang et al., 2008; Fischer et al., 2015), and a decrease in the bulk density (Zacharias and Wessolek, 2007) (Table 1, Figs. 4 and 5).

Secondary forests help to stabilize the climate below the canopy, by reducing the temperature (Guariguata and Ostertag, 2001) and soil evaporation (Lin, 2010), which increases the soil moisture (Liu et al., 2014) as observed in both forest areas (Table 1). The occurrence of a rainfall event during the measurement in the western forest explains the higher number of pores filled with water (Table 1), which alter the moisture content in this area.

The litterfall and fine root production of different tree species have a direct effect on the nutrient availability and the soil microbial community (Scheibe et al., 2015). An increase in the exchangeable cations (Ca^{2+}, Mg^{2+} and K^{+}) in forest areas in comparison to the pasture areas (Table 2) may be related to the high recycling rates through litterfall (MC Donald and Healey, 2000), and also to the low nutrient loss due to the lower water runoff and lower soil erosion.

The high content of organic matter, as a result of the organic residues from the forest, form complexes with Al from the soil solution (Mokolobate and Haynes, 2003), contributing to the low content of Al^{3+} (Table 2). The high acidity of the pasture areas is due to the high content of Al^{3+} in the exchange complex (Table 1), which is related to the low carbon contents in the soil. Tropical ecosystems are characterized by older soils, such as Oxisols from this study, composed of a low nutrient concentration (Camenzind et al., 2018) and a high concentration of phytotoxic aluminum (Kochian et al., 2005). These soils require constant organic matter inputs, that come from forests, to maintain soil life, increase the cycling of nutrients, and form complexes with aluminum, since the organic matter and the organisms from the soil are responsible in guaranteeing the fertility of the soil (Kamau et al., 2019).

The low concentration of phosphorus found in all areas (Table 2) is commonly found in Oxisols and in tropical ecosystems. This phosphorus is adsorbed and fixed by the oxides of Fe and Al, making its absorption by the cultivated plants less possible (Fontes and Weed, 1996). However, this does not have an effect on the native plants because of some strategies developed to deal with this unavailability of phosphorus in the soil (Beck and Sanchez, 1994). According to these authors, when fertilizers are not used, such as in this study, the absorption of phosphorus from the soil is mediated by soil microorganisms. These

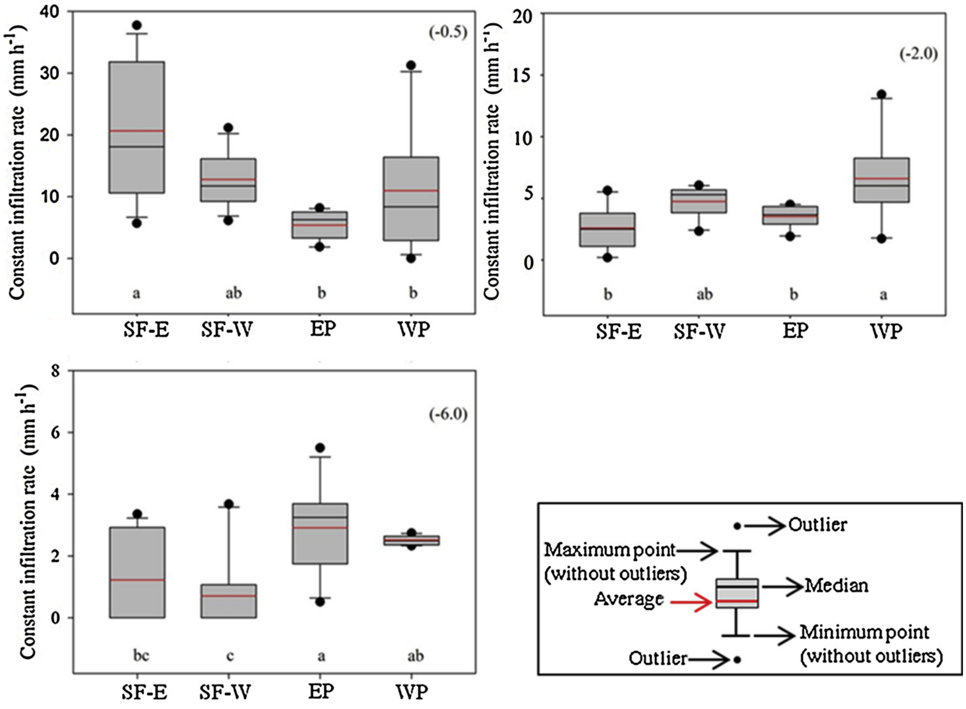

Fig. 5. Mean rate of constant infiltration at different pressures in the east (SF-E) and west (SF-W) exposed faces of the secondary forest, and in the east (EP) and west (WP) exposed faces of the pasture area in Viçosa, Minas Gerais, Brazil. Means ($n = 15$) followed by the same letters in the different uses and faces of sun exposure do not differ among themselves by Tukey test ($P < 0.05$).

microorganisms do not take into account when traditional analyses of phosphorus in the soil are performed.

Thus, in the forest areas containing high and medium levels of organic matter (Table 1), the transformations and availability of phosphorus in soil does not only depend on the chemical characteristics of the soil, but also on the interactions between plants and its associations with microorganisms (Cardoso and Kuyper, 2006, Scheibe et al., 2015, Roth and Paszkowski, 2017). In addition, the roots of the trees found in these soils can help with the acquisition of phosphorus presented in greater depths (Makumba et al., 2006). This highlights the integration between trees and crops in agroforestry systems in the tropics, which is considered as a technology for sustainable management of soils. Thus, the use of silvopastoral systems (an agroforestry system) in the pastures areas should be prioritized.

4.2. *Carbon stock*

Carbon sequestration occurs in trees resulting in a greater retaining of atmospheric carbon in their biomass and soil, than the crops or pastures (Pan et al., 2011). This leads to a higher carbon stock in the forest areas, causing an improvement in the physical chemical quality and hydraulics of the soil, as observed in this study (Table 1, Fig. 3a). The carbon sequestration in the soil depends on the balance between the accumulation of biomass and soil litter, and also on the loss of carbon through respiration and decomposition of the litter and carbon in the soil (Cunningham et al., 2015). The higher amounts of carbon stock in the eastern forest when compared to the western forest (Fig. 3), may be related to the lower solar radiation in the eastern forest (Fig. 2), which leads to a higher humidity and greater plant development. The same may have also occurred with the eastern pasture (higher C content) in comparison to the western pasture (Fig. 3a).

Soil carbon changes observed in this study (Fig. 3b) were much higher than those found in all the forest ecosystems, where an average soil carbon change was 2.4 g C m^{-2} $year^{-1}$ (Schlesinger, 1990). As also observed by Martin et al. (2013), the soil carbon levels in these tropical forests (Fig. 3a) can quickly recover after the reconversion of the pastures in forests, on the different faces of sun exposure (Fig. 3b and 3c). However, these results (Fig. 3) were different to what was pointed out by some authors (Poorter et al., 2016; Paul et al., 2002; Li et al., 2012) who believe the rainforests need more time than those found in this study, to accumulate carbon in the soil. The fast recovery of soil carbon indicates the potential these secondary forests have in reducing the effect of climate change (Cunningham et al., 2015, Stocker et al., 2013).

4.3. *Saturated hydraulic conductivity (K_{sat})*

The high variation of K_{sat} presented in this study (Fig. 4) was also observed by other authors (Hassler et al., 2011; Zimmermann and Elsenbeer, 2009), who reported that K_{sat} is affected by several surface properties, even when the measurements are performed at short distances (Leite et al., 2018). Despite the spatial variability, K_{sat} values differed according to different uses of soil (Fig. 4).

The eastern area of the secondary forest, which had the highest organic carbon content in the soil (Table 1), promoted a gradual recovery of the hydraulic properties of the soil, and also increased K_{sat} and water infiltration (Fig. 4 and 5). This was also observed by Agnese et al. (2011). According to Fischer et al. (2015), a high variety of plant species in the forest, improved the soil hydraulic properties, such as the infiltration capacity, caused by an increase in the root biomass and the soil organic carbon, effecting the structure, and therefore, the porosity of the soil.

However, there was no difference between K_{sat} values of pastures and the western forest (Fig. 4). Despite the higher organic matter content of the western forest in comparison to the pasture areas (Table 1), the macroporosity of the western forest soils and pastures (especially eastern pasture) were similar (Table 1), resulting in no differences between the values of hydraulic conductivity (Fig. 4) and infiltration of water into the soil (Fig. 5).

The mean infiltration measured in the eastern forest (114 mm h^{-1}) was similar to the values found by Ziegler et al. (2004) and Hassler et al. (2011). These authors studied the transformation of the tropical grasses in 12-20-year-old secondary forests, and found infiltration values ranging from approximately 65 mm h^{-1} to 160 mm h^{-1}. These values are much higher than those found by Hassler et al. (2011) (varying from 32 to 38 mm h^{-1}) in a forest with 10 years of regeneration, and similar to those from the western forest (37 mm^{-1}). The western forest takes longer to recover, showing the influence the faces of sun exposure have on the forest recovery time.

4.4. Constant infiltration rate

The higher constant infiltration observed at the pressure of -0.5 hPa (Fig. 5) suggests the existence of an extensive macropore network that plays a significant role in the movement of the water into the soil (Holden, 2009), despite being composed of a smaller fraction of total porosity (Moret and Arrúe, 2007). This macropore network is larger in the areas that contain trees (Vetaas, 1992), due to their extensive deep root systems that create biopores after the decomposition of the root (Archer et al., 2016; Zaibon et al., 2017). In addition, the increase of organic matter in these areas (Table 1), results in changes to the structure (Pan et al., 2017), and increases in soil porosity (Zaibon et al., 2017). Therefore, the higher porosity, especially in secondary forest-east (Table 1), led to a greater infiltration (Fig. 5).

As the total organic carbon strongly correlates with the soil water repellency (Goebel et al., 2011; Borja- Lucas et al., 2018), the infiltration measurements in the areas were carried out in moist soil, during the rainy season (Fig. 1). Some studies have shown that the longer the soil stays dry, the greater its resistance to the water from the first rainfall (Goebel et al., 2011), when a high content of organic matter is presented, such as in the forest areas of this study (Table 1). This was observed in the first attempts to measure infiltration in the eastern forest area (data not shown). The initial resistance to wetting is caused by hydrophobic organic compounds derived from vegetation, mainly by the exudation of the roots (Mao et al., 2014). According to Garg and Ng (2015), as the wetting time increases, the occurrence of soil repellency decreases.

It was observed that in the suctions at pressures of −2 hPa and −6 hPa, the gravitational flow of the macropores (predominantly in the forest), has less influence on the water flow, which is then determined by the matrix flow, due to blockage of water flow by air in drained macropores (predominantly in the pastures) (Zwartendijk et al., 2017) (Fig. 5). The suction at −6 hPa causes the water to move through pores with diameters smaller than 0.5 mm (Zhang et al., 2016), which explains the lower rate of constant infiltration of water into the soil in the forest areas (lower micro- mesoporosity), and the higher rate in the pasture areas (higher micro- mesoporosity) (Table 1, Fig. 5). Deforestation for agricultural and livestock purposes leads to long-term reductions in water infiltration due to increased soil compaction (Bruijnzeel, 2004) and consequently the conversion of macropores into micropores (Table 1).

According to Tang et al. (2019), the improvement in the water infiltration capacity is directly related to the increase of the non-capillary porosity of the soil, which highlights the importance of the forests in reducing the surface runoff and supplying the water sources.

5. Conclusion

In relation to the pastures, soils from the secondary forests presented better physical and chemical qualities. Macroporosity, carbon storage, soil water infiltration and exchangeable (alkali) ions were higher, and the exchangeable aluminum was lower in the forest soils. The soil properties measured in this study varied in the different areas. These differences were more prominent in the eastern forest area.

The soil from the eastern forest presented higher values of saturated hydraulic conductivity. In the macropores contributed to the water flows more than the mesopores and micropores, whereas in the pastures the opposite effect was observed.

These results indicate that in order to increase water flow and water quality it is required encourage the use of vegetative practices such as silvopastoral systems in pastures and the revegetation of the upper third of the hills.

Additional assessments are needed to quantify the magnitude of this effect at greater depths, combining surface runoff with infiltration of water into the soil on different faces of sun exposure.

Declaration of Competing Interest

The authors declare that there is no conflict of interest in the manuscript.

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