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Hydropedology of a High Tableland with Cerrado, Brazilian Central Plateau: the Frutal Catchment Case Study

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ABSTRACT: Currently, the Brazilian savanna (Cerrado) represents the main agricultural area of the country, comprising a great variety of landscapes and soils, geological formations and vegetation patterns, as well as the major watershed. We studied the hydropedology and morphometry of a representative catchment (Frutal river), on a high tableland (*Chapada*) in the Triângulo Mineiro region, Brazil, describing the soil-water-landscape relationships to understand land use and water resources. To this end, we applied physical, chemical, micromorphological, and morphometric methods. When dry, compaction was observed in well-structured Ferralsols (*Latossolos*) with medium texture under intensive agriculture, reducing the water recharge capacity. The soil carbon stock was highest in hydromorphic savannas (*veredas*), reaching an organic matter content of 316.8 g kg^{-1} in the studied Umbric Gleysols, representing poorly drained lowlands. Physical and micromorphological properties were relevant parameters to understand the water recharge in soil; in agricultural fields, bulk density tended to increase and hydraulic conductivity to decrease, particularly under long-term sugarcane; morphometric parameters in the Frutal catchment indicated a low flooding risk and high flow capacity. This reinforces the need for soil conservation strategies to enhance water infiltration and groundwater recharge, with a view to maintain the water longer in the catchment. For surface water dynamics, slope morphology is an important property, affecting soil erosion, water retention and crop productivity.

Keywords: Rhodic Ferralsols, Gleysols, hydromorphic savannas, *veredas*.

INTRODUCTION

Brazil has a great variety of landscapes and vegetation types and the greatest agricultural potential of all tropical areas worldwide. The need to produce more food has to be reconciled with the conservation of natural resources, with scientific support methods to reach the main goals of the twenty-first century, of combining food production and environmental quality, especially with regard to water, soils, and biodiversity (Turetta et al., 2010; FAO, 2015).

After the "Green Revolution", the Brazilian savanna (Cerrado) became the area most affected worldwide by the wide-reaching land-use changes, associated with rural credit policies subsidized by government programs since the 1970s, especially the Polocentro (Cerrado Development Program).

Thus, the Cerrado became the major agricultural frontier in the tropics (Costa et al., 2002), with rapid replacement of native vegetation by pasture and crops at a large scale. As a result, the deforestation rate in the Cerrado became the second highest in the history of humanity, considering a 40-year period (1970-2010), only behind deforestation in the Amazon region. This anthropogenic pressure, accompanied by land degradation, created serious problems in terms of erosion and soil compaction, increasing production costs (Canillas and Salokhe, 2002), and promoting new phenomena such as "savannization" in Amazônia and "aridification" of the Cerrado, arising from predatory human actions. These phenomena result in deleterious effects on the biodiversity and on soil and water availability for agriculture.

Of the originally around 1.8 million km^2 occupied by the Cerrado biome (Pinto, 2002), currently only 47 % remain, with annual loss rates of the natural vegetation cover between -0.79 % per year and -0.44 % per year from the 1990s to the 2010s (Beuchle et al., 2015), estimated at a mean conversion rate of 1.1 % per year by Machado et al. (2004). The Cerrado is one of the 25 priority ecosystems for conservation (biodiversity hotspots) on the planet and home to a high number of endemic species (Myers et al., 2000), being the richest savanna in terms of biodiversity worldwide (Klink and Machado, 2005).

Conditions such as flat relief, ease large-scale mechanization, suitable climatic conditions, modern techniques of soil cultivation, and genetic advancements have all contributed to optimize agricultural productivity. The dominant Ferralsols (*Latossolos*) cover on extensive tablelands, the absence of rocky or gravelly pavements, and good drainage conditions make the Cerrado the most suitable tropical area for intensive farming (Resende, 2002).

For many years, the Cerrado was considered a resilient environment, compared to the other areas of agricultural frontier expansion in Brazil, such as the Amazon. On the other hand, this apparent resilience was questioned by Ab'Saber (1970) who described the Cerrado as a vulnerable area, threatened by a rapid loss of its natural resources. The strategic position of the Cerrado as the main watershed in Brazil allows understanding the current model of agricultural occupation, raising the question whether the prominent hydrological role of the Cerrado can be maintained in this model.

Some observations suggest a possible hydrological imbalance: the need to introduce more drought-resistant crop varieties and pastures, the increasing demand of water for irrigation, predatory elimination of native vegetation, decreasing water flow in most rivers, decreasing water table, among others (Arantes et al., 2016; Spera et al., 2016).

Thus, the concern for natural resources is a key element to understand the balance between agricultural expansion and environmental sustainability. In this regard, hydropedology is a multidisciplinary science, to contribute positively to a better understanding of the interaction of soil-water systems in a given scenario (Mello and Curi, 2012). Its pillar is the interaction between pedology and hydrology, integrating phenomena at the micro-scale (pores and aggregates), meso-scale (toposequence), and macroscale (watershed). Therefore, hydropedology allows the understanding of processes of soil structure formation, as influenced by mineralogy and land use (Resende et al., 2011), to characterize soil horizons along a toposequence, and to analyze the watershed landscape, with its respective hydrological processes. Thus, landscape research methods, especially the morphometric analysis of the watershed, allow studies related to hydric resources (Horton, 1945; Christofoletti, 1978; Pissarra et al., 2004), underlying further interpretations of soil data, valuable for watershed modeling (Mello and Curi, 2012).

Hydropedology has an unquestionable potential for enhancing knowledge on water production and groundwater recharge. Recent hydropedological studies in Brazil clearly demonstrated the promising potential for a renewed view of environmental sustainability (Alvarenga, 2010; Menezes, 2011; Mello and Curi, 2012).

One area of the Cerrado biome, the Triângulo Mineiro, represents an economically important region of the Minas Gerais State of intense agriculture. However, soil degradation and decreasing productivity caused by land-use pressures have been observed in recent years (Batlle-Bayer et al., 2010). These warning signs highlight the need for integrated research to prevent this trend. Thus, research based on principles of hydropedology and morphometric analysis of a watershed can be key tools underlying measures to balance the maintenance of ecosystem services and agricultural production.

We hypothesized that the land use changes the hydropedological characteristics and soil quality under Cerrado. Therefore, we studied the hydropedology and morphometry of the Frutal watershed in the Triângulo Mineiro region, describing the soil-water-landscape relationships under intensive land use.

MATERIALS AND METHODS

Study area

The watershed of the Frutal stream has an area of 3,478 ha and lies in the municipality of Frutal (Figure 1), in the Triângulo Mineiro. At the higher hierarchical level, it is part of the watersheds of the Grande and Paraná rivers. Currently, the Frutal catchment is used for urban water supply by the municipality. For this study, the Frutal catchment was chosen in view of the ease of access, intensive agricultural land use, flat topography, and regionally representative drainage patterns.

The region has a tropical climate with a well-defined dry season. The mean annual rainfall varies between 1,200 and 1,400 mm, concentrated between October and March. The dry season lasts from 4 to 5 months, coinciding with cooler temperatures. The mean annual temperature is 25 °C, with a maximum monthly average of 31 °C (Inmet, 2009).

The landforms of the area are those of the plateau of the Paraná Sedimentary Basin, in which sedimentary sandstone layers are interbedded between dominant basalt flows (CPRM, 2003). Thus, the stratigraphic sequence in the Frutal basin is composed of basalts of the Serra Geral Formation (± 120 million years ago), overlayered by sandstones of the Vale do Rio do Peixe Formation (± 80 million years ago) and sandstones and conglomerates of the Marília Formation (± 70 million years ago) (CPRM, 2003).

The main soil type in the Frutal catchment are Dystric Rhodic Ferralsols (Typical) (*Latossolo Vermelho distrófico típico*) with medium texture, which are deep, well-drained soils with high aluminum content, covered by Cerrado vegetation. Currently, these soils are widely used for crops (sugarcane, corn, sorghum, soybean, irrigated pineapple), grazing, rubber tree, mostly.

Other soils, such as Haplic Cambisols (*Cambissolos Háplicos*), Haplic Lixisols (*Argissolos*), and Arenosols (*Neossolos Quartzarênicos*), also occur as inclusions in small areas. These soils are directly related to changes in vegetation patterns, and are found under grassland (*campo sujo*) and woodlands (*cerradão*), where *veredas* systems occur in the hydromorphic fluvial plains.

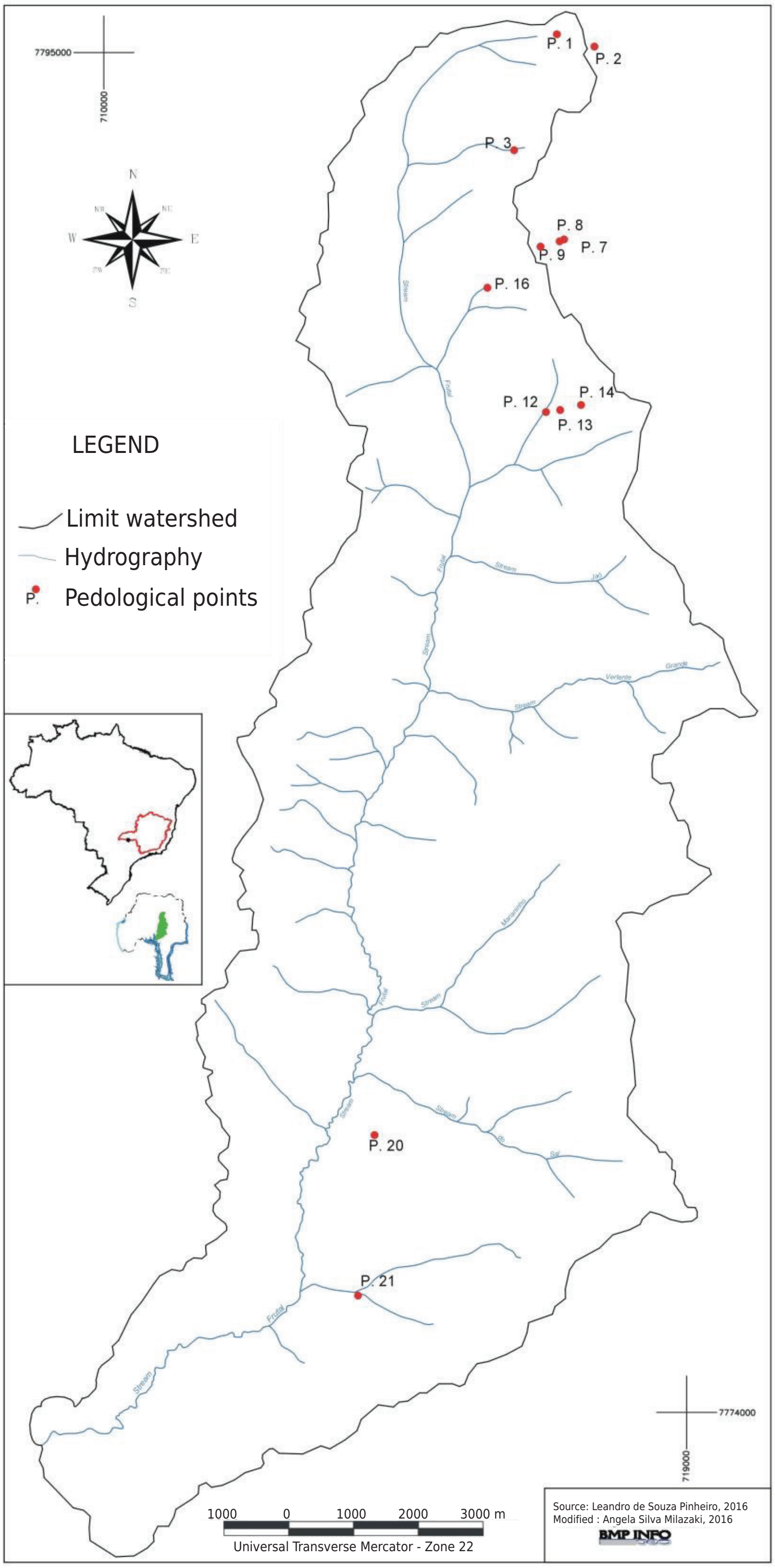

Figure 1. Watershed of the Riberão Frutal, located in the county of Frutal, State of Minas Gerais, Brazil.

Morphological description and soil sampling

Eleven representative pedons were described and sampled as proposed by Santos et al. (2013a). The soil classes were identified based on the current Brazilian System of Soil Classification - SiBCS (Santos et al., 2013b), and adapted according to the World Reference Base for Soil Resources (WRB, 2015) (Table 1). Some soils are located near the catchment border. Pedons P2 and P9 lie in a flat upland area representative of the drainage divide, whereas P7 and P8 are representative of hydromorphic areas under very well-preserved buriti-palm swamps.

Physical characterization

The analysis of the particle composition was performed in air-dried soil samples (<2 mm) (Ruiz, 2005). Soil density (volumetric ring method) and hydraulic conductivity were analyzed according to Donagema et al. (2011).

Chemical characterization

We determined: pH in H_2O and KCl 1 mol L^{-1}; total organic carbon (TOC) (Yeomans and Bremner, 1988); available P, Na^+, and K^+, after extraction with HCl 0.5 mol L^{-1} + H_2SO_4 0.0125 mol L^{-1} (Mehlich-1); Ca^{2+} and Mg^{2+} were determined by atomic absorption spectroscopy and Al^{3+} by titration after extraction with KCl 1 mol L^{-1}; and potential acidity (H+Al) by titration, after extraction with $Ca(CH_3COO_2)$ 0.5 mol L^{-1} at $pH_{7.0}$. All chemical analyses were carried out as described by Donagema et al. (2011).

Morphometric analysis of the catchment

Catchment form

Relief ratio (Rr = Da/L), in which *Da* is altimetric amplitude and *L* is length of the main channel (Schumm, 1956).

Hydrographic density (Hd = n × A), in which *n* is the number of channels and *A* the total catchment area (Freitas, 1952).

Drainage density (Dd = C/A), in which *C* is the total length of channels and *A* the total catchment area (Horton, 1945).

Hydrographic components

Maintenance coefficient [Mc = (1/Dd) × 1000], in which *Dd* is the drainage density (Schumm, 1956).

Channel gradient (Cg = a_{max}/L) (%), in which a_{max} is the maximum altitude and *L* the length of the main channel (Horton, 1945).

Combined parameters

Roundness index (Ri = A/Ac), in which *A* is the total catchment area and *Ac* the circle perimeter area equivalent to the total catchment area (Miller, 1953; Schumm, 1956).

Sinuosity index (Si = L/vd), in which *L* is the length of the main channel and vd the vectorial distance between the upstream and downstream ends of the main channel (Schumm, 1963).

All morphometric data were processed with software ArcGis 10.0 (ESRI, 2010).

Micromorphology

Undisturbed soil samples from the 0.05-0.10 m layer were collected in Kubiena boxes, dried in a forced-air oven at 35 °C. Subsequently, they were impregnated with polyester resin and cut in 1.8 × 30 × 40 mm thin sections (30 µm thick) for subsequent analysis under a petrographic microscope. The microstructural descriptions were based on criteria defined by Stoops (2003) and Stoops et al. (2010). For all descriptions we used a trinocular optical microscope, model Zeiss Axiophot, with integrated digital camera for photographic recording.

RESULTS AND DISCUSSION

Morphological, physical, and micromorphological characterization

The studied soils have structures varying from strong microgranular to massive types (Table 1). According to Resende et al. (2014), soils with *latossólico* Bw horizons (Ferralsols) are important absorbers of water in natural systems. In this case, a better structural development is observed in Ferralsols under native forest. On the other hand, compacted, coalesced structures (hard or very hard, dry consistency) were observed in similar Ferralsols (P9, P14, and P20) under permanent intensive agriculture or pasture. Higher

Table 1. Morphological properties of some selected studied soils

Pedon	Depth	Structure[1]	Boundary	Texture[2]	Consistency[3]			Color
					Dry	Moistd	Wet	
	m							
P1 - Eutric Rhodic Ferralsols (Clayic)/*Latossolo Vermelho eutrófico argissólico*[4] - Semideciduous rainforest. Undulated relief								
A	0.00-0.19	st f/m bl/gr	gradual flat	arenic/medium	s hr	v f	s pl s st	2.5YR 4/3
AB	0.19-0.44	st f/m bl/gr	gradual flat	arenic/medium	s hr	v fr	s pl s st	2.5YR 4/3.5
Bw1	0.44-0.70	st f/m gr	diffuse flat	medium	sf	fr	s pl s st	2.5YR 4/4
Bw2	0.70-1.00^{+}	st f/m gr	-	medium	sf	fr	s pl st	2.5YR 4/6
P2 - Dystric Rhodic Ferralsols (Typical)/*Latossolo Vermelho distrófico típico*[4] - Savanna. Flat relief								
A	0.00-0.20	md f/m bl/gr	gradual flat	arenic/medium	s hr	fr	s pl s st	2.5YR 4/4
Bw1	0.50-0.80	st f/m bl/gr	diffuse flat	medium	s hr	fr	s pl s st	10R 4/6
Bw2	0.80-1.20^{+}	st f/m gr	-	medium	sf	v fr	s pl s st	10R 4/8
P3 - Eutric Haplic Gleysols (Typical)/*Gleissolo Háplico Ta eutrófico típico*[4] - Vereda. Undulated relief								
Ap	0.00-0.20/0.35	md m/b bl/s g	clear wavy	arenic	hr	f	n pl s st	7.5YR 4/3
C1	0.20/0.35-0.50/0.55	ma	clear wavy	medium	-	fr	n pl s st	7.5 YR 5/3
C2	0.50/0.55-0.80^{+}	ma		medium	-	-	s pl s st	10YR 7/2
P7 - Dystric Umbric Gleysols/*Gleissolo Melânico Tb distrófico organossólico*[4] - Vereda. Flat relief								
A	0.00-0.20	ma	clear flat	medium/clayic	-	-	pl st	7.5YR 3/2
C1	0.20-0.40	ma	-	medium	-	-	s pl s st	10YR 7/2
P8 - Dystric Umbric Gleysols (Alic)/*Gleissolo Melânico Tb distrófico organossólico álico*[4] - Vereda. Flat relief[4]								
A	0.00-0.20	ma	abrupt flat	medium	-	v fr	pl s st	10YR 2/1
C	0.20-0.50	ma	-	arenic/medium	-	-	s pl s st	10YR 7/1
P9 - Eutric Rhodic Ferralsols (Typical)/*Latossolo Vermelho eutrófico típico*[4] - Flat relief (sorghum/soybeans crop)								
A	0.00-0.18	md f/m bl	gradual flat	medium	hr	fr	s pl s st	2.5YR 4/4
Bw1	0.40-0.80	st f/m gr	-	medium	s hr	fr	s pl s st	10R 4/6
P12-Dystric Haplic Gleysols (Typical. Alic)/*Gleissolo Háplico Ta distrófico típico álico*[4] - Vereda. Flat relief								
A	0.00-0.20	md m bl	clear flat	medium	s hr	fr	n pl s st	5YR 4/4
C1	0.20-0.60	ma	-	medium	-	-	n pl s st	7.5YR 6/2
P13 - Dystric Xanthic Ferralsols (Typical. Alic)/*Latossolo Amarelo distrófico típico álico*[4] - Semideciduous rainforest. Undulated relief								
A	0.00-0.20	md f/m bl/gr	gradual flat	medium	s hr	fr	s pl s st	7.5YR 4/4
Bw1	0.30-0.50	md f/m bl/gr	diffuse flat	medium	s hr	fr	s pl s st	7.5YR 5/4
Bw2	0.50-0.90	md f/m gr	-	medium	sf	v fr	s pl s st	10YR 5/6
P14 - Dystric Rhodic Ferralsols (Typical)/*Latossolo Vermelho distrófico típico*[4] - Flat relief (sugarcane crop)								
A	0.00-0.20	md m/b bl/gr	diffuse flat	medium	v hr	f	s pl s st	2.5YR 4/6
Bw	0.50-1.20	md m gr	-	medium	s hr	fr	s pl s st	10R 4/7
P20 - Dystric Rhodic Ferralsols (Clayic. Alic)/*Latossolo Vermelho distrófico argissólico álico*[4] - Savanna. Flat relief								
A	0.00-0.20	md f/m bl/gr	gradual flat	medium	hr	f	s pl s st	2.5YR 4/4
Bw1	0.30-0.60	md p/m gr	diffuse flat	medium	s hr	fr	s pl s st	10R 4/5
Bw2	0.60-1.10	st f/m gr	-	medium	sf	fr	s pl st	10R 4/6
P21 - Dystric Umbric Gleysols/*Gleissolo Melânico Tb distrófico organossólico*[4] - Vereda. Undulated relief								
A	0.00-0.20	st f/m gr	clear flat	clayic	s hr	fr	v pl v st	7.5YR 3/1
C1	0.23-0.50	ma	-	heavy clayic	-	-	v pl v st	10YR 7/2

[1] Structure: weak = w, moderate = md, and strong = st; Size: fine = f, medium = m, and big = b; Type: ma = massive, gr = granular, bl = blocky, and single grain = s g. [2] Texture: sandy (<15 % clay), medium (15≤ % clay ≤35), clayey (35< % clay ≤60), and heavy clayey (>60 % clay). [3] Consistency: (a) Dry: loose = ls, soft = sf, slightly hard = s hr, hard = hr, very hard = v hr; (b) Moist: very friable = v f, friable = fr, and firm = f; (c) Wet: not plastic = n pl, slightly plastic = s pl, plastic = pl, very plastic = v pl, not sticky = n st, slightly sticky = s st, sticky = st, and very sticky = v st. [4] Soil classes [FAO (WRB, 2015) and SiBCS (Santos et al., 2013)].

soil density values observed in P9, P14, and P20 (Table 2) resulted from cultivation, reaching 1.77 Mg m^{-3} in a medium texture Ferralsol (P14), confirming studies of Assis and Lanças (2005), which reported higher soil density in cultivation areas than in native rainforest. According to Costa et al. (2002), yield loss due to soil compaction in pasture is common in Brazil and sometimes notorious in the Cerrado region. The soil consistency of the Ferralsols is slightly plastic and sticky, adequate for mechanized agriculture. The soil texture is closely related with the parent material (sandstones - Vale do Rio do Peixe Formation), a reddish hematitic sandstone. All soils had medium texture (15-35 % clay), with exception of P21, which has clayey to very clayey texture in all layers (Table 3).

The dominance of fine sand in these Ferralsols is a direct result of sandstone weathering. These soils with high amounts of fine sand and medium texture are easily compacted under cultivation (Reichert et al., 2003; Severiano et al., 2009; Silva and Castro, 2015), due to inadequate management, heavy machinery at all stages of agricultural cultivation (Pankhurst et al., 2003), especially under sugarcane (Roque et al., 2010). This was ascribed to a close packing of the fine sand under cultivation, as reported by Silva and Castro (2015).

According to Costa et al. (2002), soil compaction has increased in the Cerrado and represents the main constraint for yield maintenance, especially in areas of long-term monoculture, regardless of their texture. Although soil compaction is greater in clayey soils, sandy soils are also prone to compaction and require careful management. One such soil is the medium-texture Ferralsol of this study, found in large areas of the Cerrado with very similar properties. Hence, soil degradation occurs even in the most resilient medium-texture Ferralsols.

Dias Junior and Miranda (2000) postulated that the sand fraction can increase the packing capacity of soil particles when the grains have irregular shapes. In addition, when wet, soil deformation is pronounced (DeJong-Hughes et al., 1987), whereas compaction problems are greater in dry sandy soils (Dias Junior and Miranda, 2000) than in clay soils.

Photomicrographs of Ferralsols under native vegetation (P1 and P2) illustrate differences in the coalesced microgranular (interconnected) structure, showing greater porosity (Figure 2), greatly decreasing in intensively cultivated soil - P14. In all soils, the groundmass consists of fine quartz grains (coarse material), and a reddish clay micromass, partially coating grains, with a gibbsite-hematite nature. In the same region, Gomes et al. (2004) showed a very similar microstructure with interconnected (coalesced) granules, similar to soils P1 and P2, with zones of loose microaggregates, micromass, appearing mostly as grain coatings, indicating a mixture of quartz grains, and clays in the groundmass. Similar impacts of cultivation/ploughing on Ferralsols' microstructure were described by Marcelino et al. (2010).

Table 2. Bulk density, particle density and hydraulic conductivity of some selected studied soils

Pedon	Soil class	Depth	BD	PD	Ko
		m	Mg m^{-3}		cm h^{-1}
P1	FReuroce	0.05-0.10	1.44	2.67	8.85
P2	FRdyro	0.05-0.10	1.21	2.67	3.46
P9	FReuro	0.05-0.10	1.67	2.67	3.19
P14	FRdyro	0.05-0.10	1.77	2.63	3.08
P16	GLha	0.05-0.10	1.59	2.56	2.27
P20	FRdyroceal	0.05-0.10	1.70	2.74	1.44
P21	GLdyum	0.05-0.10	1.21	2.70	35.27

FReuroce: Eutric Rhodic Ferralsols (Clayic); FRdyro: Dystric Rhodic Ferralsols (Typical); FReuro: Eutric Rhodic Ferralsols (Typical); GLha: Haplic Gleysols (extra sample); FRdyroceal: Dystric Rhodic Ferralsols (Clayic, Alic); GLdyum: Dystric Umbric Gleysols. BD: bulk density (volumetric ring method); PD: particle density (volumetric flask method); Ko: hydraulic conductivity (constant head permeameter).

Pedofeatures such as discrete organic matter fragments and carbon-rich coating were observed. The relative distribution pattern was typically gefuric in P1 and P2, and chitonic/porfiric in P14, probably caused by clay losses and packing under intensive cultivation (soil compaction) (Figure 2, Table 4). Analyzing a comparable Rhodic Ferralsols with medium texture under sugarcane (Cerrado), Silva and Castro (2015) reported very similar results, with a porfiric pattern as a consequence of densified zones, reaching cementation of quartz grains (skeleton) by the compacted micromass. This was also corroborated by Silva et al. (1998) and Soares et al. (2005), who considered the porfiric pattern of Ferralsols as result of severe compaction, particularly in surface horizons of medium-texture soils. This results in a porostriated to granostriated b-fabrics under plane polarized light.

Table 3. Physical properties of some selected studied soils

Pedon	Depth	CS(1)	FS(2)	Silt	Clay	S/C(3)
	m			$g\ kg^{-1}$		
P1 - Eutric Rhodic Ferralsols (Clayic) - Semideciduous rainforest. Undulated relief						
A	0.00-0.19	290	520	70	120	0.6
AB	0.19-0.44	230	540	100	130	0.8
Bw1	0.44-0.70	240	500	110	150	0.7
Bw2	0.70-1.00+	220	490	80	210	0.4
P2 - Dystric Rhodic Ferralsols (Typical) - Savanna. Flat relief						
A	0.00-0.20	180	620	60	140	0.4
Bw1	0.50-0.80	190	610	10	190	0.1
Bw2	0.80-1.20+	190	540	80	190	0.4
P3 - Eutric Haplic Gleysols (Typical) - Vereda. Undulated relief						
Ap	0.00-0.20/0.35	260	540	90	110	0.8
C1	20/35 - 50/55	510	140	100	250	0.4
C2	50/55 - 80+	60	530	190	220	0.9
P7 - Dystric Umbric Gleysols - Vereda. Flat relief						
A	0.00-0.20	400	60	180	360	0.5
C1	0.20-0.40	290	480	10	220	0.0
P8 - Dystric Umbric Gleysols (Alic) - Vereda. Flat relief						
A	0.00-0.20	220	330	170	280	0.6
C	0.20-0.50	220	550	70	160	0.4
P9 - Eutric Rhodic Ferralsols (Typical) - Flat relief (sorghum/soybeans crop)						
A	0.00-0.18	230	520	40	210	0.2
Bw1	0.40-0.80	290	500	60	150	0.4
P12 - Dystric Haplic Gleysols (Typical. Alic) - Vereda. Flat relief						
A	0.00-0.20	100	660	80	160	0.5
C1	0.20-0.60	90	680	70	160	0.4
P13 - Dystric Xanthic Ferralsols (Typical. Alic) - Semideciduous rainforest. Undulated relief						
A	0.00-0.20	140	550	70	240	0.3
Bw1	0.30-0.50	130	540	70	260	0.3
Bw2	0.50-0.90	90	550	90	270	0.3
P14 - Dystric Rhodic Ferralsols (Typical) - Flat relief (sugarcane crop)						
A	0.00-0.20	60	680	60	200	0.3
Bw	0.50-1.20	60	630	70	240	0.3
P20 - Dystric Rhodic Ferralsols (Clayic. Alic) - Savanna. Flat relief						
A	0.00-0.20	240	520	60	180	0.3
Bw1	0.30-0.60	190	500	60	250	0.2
Bw2	0.60-1.10	220	450	70	260	0.3
P21 - Dystric Umbric Gleysols - Vereda. Undulated relief						
A	0.00-0.20	60	60	310	570	0.5
C1	0.23-0.50	20	70	300	610	0.5

(1) Coarse sand. (2) Fine sand. (3) Silt/clay ratio. Coarse sand, fine sand, silt, clay: particle size analysis [pipette method (Claessen, 1997)].

Micromorphological results indicated evidences of compaction by intensive mechanization in patches of sandy soils, and the structural reorganization of P14, leading to coalescing aggregates and closed packing voids with lower macroporosity, becoming similar to clayey Ferralsols, as reported by Gomes et al. (2004) and Silva and Castro (2015). Changes in soil structure due to land use can be detected by micromorphological studies and associated features, when comparing natural with compacted or degraded soil (Bullock et al., 1985). Compacted soils are barriers to natural water infiltration, and may reduce the groundwater recharge capacity, even in medium-texture Ferralsols.

Hydraulic conductivity of saturated soils is considered a very useful property to differentiate the effects of tillage systems and water movement in soils (Assis and Lanças, 2005). In the studied Ferralsols, the hydraulic conductivity values were lowest in cultivated soils (P9, P14, and P20) (Table 2), and highest in P1 (native forest). The high conductivity of the Gleysols (P21), reaching 35.27 cm h^{-1}, may result from biological channels. According to Boone (1988), under no-tillage, a permanent system of biopores and root channels

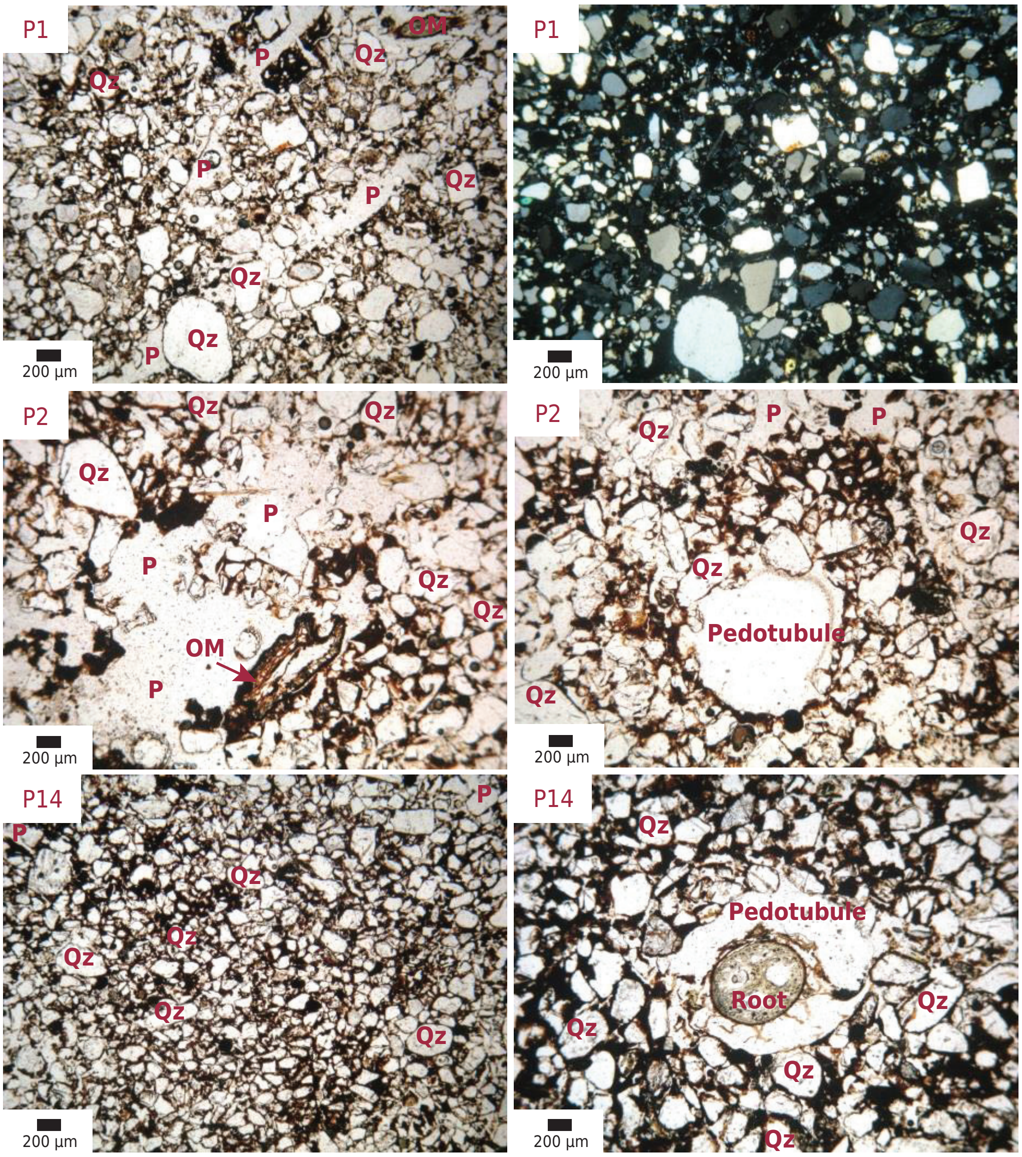

Figure 2. Photomicrographs of some selected soil layers under an optical microscope, in flat light, highlighting different sections with solid microstructure, showing higher porosity (P) in P1 and P2 (planar pores), and lower porosity in P14. The groundmass consists of fine quartz grains (Qz = coarse material) and reddish clay (micromass). Pedofeatures such as organic matter fragments (OM) and coating were observed. Relative distribution showed a gefuric pattern in P1 and P2, and a chitonic/porfiric pattern in P14, due to intensive agricultural use and soil compaction.

allows for better drainage. In a Rhodic Ferralsol under no-tillage, Arzeno (1990) reported hydraulic conductivity values twice as high as under conventional tillage. Also, Assis and Lanças (2005) found a higher saturated hydraulic conductivity in no-tillage than conventional tillage system, and similar to that of native vegetation.

Under conventional tillage, lower infiltration rates lead to increasing runoff and sheet erosion, forming decapitated soils, common in old agricultural areas of the Cerrado (Costa et al., 2002). Aside from erosion, Ferralsols under monoculture (sugarcane and sorghum) are prone to crust formation and hard pan, further reducing water infiltration. According to Håkansson and Medvedev (1995), even under no-tillage cultivation, some soil compaction may occur, caused by the cumulative effect of traffic, although pores are usually better connected (Dick et al., 1989).

Increased clay contents in deeper soil layers of some Ferralsols are usually associated with some clay translocation/illuviation. Although cultivation is known to enhance clay illuviation of Ferralsols, the amount is not enough to induce a textural shift to Lixisols (*Argissolos*) (Chagas, 2004). Increasing soil erodibility of these soils (P1 and P20) is expected, since they would be subjected to both clay elutriation and illuviation.

A low silt/clay ratio in all soils indicates an extreme weathering degree of these Ferralsols, and even of the Gleysols. The Ferralsols developed from basalt (P20) contained consistently higher amounts of clay.

Chemical characterization

The soils are mostly dystrophic (Table 5), as expected for these highly weathered soils, regardless of the parent material (sandstones or basalt). The epi-eutrophic character of Ferralsols (P1) under semideciduous forest is due to its relative shallowness, exposing deeper saprolite, and especially to nutrient cycling at the surface, as observed by Resende (2002) in forest soils. In the case of Ferralsols (P9) (sorghum/soybean rotation) and P14 (sugarcane), the constant fertilizer applications resulted in higher nutrient content in the exchange complex, promoting enrichment both at the surface (application site) and in the deeper soil layers, followed by leaching.

Table 4. Structural and microstructural characteristics of some selected studied pedons

Pedon	Depth	Classification	Vegetation/use	Structure[1]	Microstructure[2]
	m				
P1	0.05-0.10	Rhodic Ferralsols (Clayic)	Semideciduous rainforest	st f/m bl/gr	Type: granular Form: equidimensional Degree of rounding: subrounded/rounded Surface roughness: smooth/wavy Relative distribution: gefuric Degree of aggregate development: moderate Pores: complex/channels
P2	0.05-0.10	Rhodic Ferralsols (Typical)	Savanna (Cerrado)	md f/m bl/gr	Type: granular Form: equidimensional Degree of rounding: subrounded/rounded Surface roughness: smooth/wavy Relative distribution: gefuric Degree of aggregate development: moderate Pores: complex/channels/cavity
P14	0.05-0.10	Rhodic Ferralsols (Typical)	Sugarcane crop	md m/b bl/gr	Type: granular Form: equidimensional Degree of rounding: subrounded/rounded Surface roughness: smooth/wavy Relative distribution: chitonic/porfiric Degree of aggregate development: weak Pores: complex/cavity

[1] Development: md = moderate, and st = strong; Size: f = fine, m = medium, and b = big; Type: gr = granular and bl = blocky. [2] According to Stoops (2003) and Stoops et al. (2010).

All soils have high amounts of exchangeable Al^{3+} and Al saturation levels of >50 % in P2, P8, P12, P13, and P20. The Gleysols P7, P8, and P21 were classified as umbric by the IUSS Working Group WRB (2015), suggesting presence of organo-mineral complexes in these Gleysols, corroborated by higher values of CEC pH 7.0 and organic matter, reaching 316.8 g kg^{-1} in P7 (Table 5). A strong interaction of Al/Fe oxides in the clay fraction with soil organic carbon (SOC) was reported by Zinn et al. (2005), accounting for greater SOC protection in soils of tropical ecosystems. However, even in these regions, significant SOC losses may occur under intensive land use systems (annual tillage) in the 0.00-0.20 m layer and under non-intensive systems on coarse-textured soils in the 0.00-0.40 m layer (Zinn et al., 2005). For soils under

Table 5. Chemical properties of the studied soils

Pedon	Depth	$pH(H_2O)$	Ca^{2+}	Mg^{2+}	K^+	Al^{3+}	H+Al	S	T	AC	V	m	OM	P	rem-P
	m		$cmol_c\ dm^{-3}$								%		g kg^{-1}	mg dm^{-3}	mg L^{-1}
P1 - Eutric Rhodic Ferralsols (Clayic) - Semideciduous rainforest. Undulated relief															
A	0.00-0.19	5.18	1.67	0.51	0.13	0.68	3.4	2.31	5.71	47.6	40.56	22.7	10.1	0.8	32.2
AB	0.19-0.44	5.16	1.81	0.31	0.08	0.78	2.6	2.21	4.80	36.9	45.81	26.2	6.3	0.4	32.1
Bw1	0.44-0.70	5.29	2.41	0.40	0.07	0.59	2.1	2.88	4.98	33.2	57.82	17.0	7.6	0.3	29.8
Bw2	0.70-1.00+	5.49	3.13	0.55	0.07	0.29	2.1	3.75	5.85	27.9	64.10	7.2	7.6	0.3	23.1
P2 - Dystric Rhodic Ferralsols (Typical) - Savanna. Flat relief															
A	0.00-0.20	4.71	0.52	0.26	0.05	0.39	2.6	0.83	3.43	24.5	24.2	32.0	12.7	0.7	38.0
Bw1	0.50-0.80	4.13	0.09	0.08	0.02	0.39	2.1	0.19	2.29	12.1	8.31	67.2	2.5	0.4	33.1
Bw2	0.80 -120+	5.21	0.04	0.06	0.01	0.29	1.8	0.11	1.91	10.1	5.84	72.5	2.5	0.2	29.2
P3 - Eutric Haplic Gleysols (Typical) - Vereda. Undulated relief															
Ap	0.00-0.20/0.35	5.52	3.94	0.64	0.25	0.00	3.2	4.83	8.03	73.0	60.13	0.0	35.5	2.4	45.9
C1	0.20/0.35-0.50/0.55	5.47	1.25	0.64	0.34	1.85	4.0	2.23	6.23	24.9	35.81	45.3	2.5	1.7	15.4
C2	0.50/0.55-0.80+	5.48	4.94	3.18	0.41	1.56	3.9	8.53	12.43	56.5	68.60	15.5	2.5	4.0	14.0
P7 - Dystric Umbric Gleysols - Vereda. Flat relief															
A	0.00-0.20	5.05	2.01	0.78	0.51	0.39	11.8	3.31	15.11	42.0	21.91	10.5	316.8	1.8	15.6
C1	0.20-0.40	4.87	0.34	0.11	0.09	0.29	1.8	0.53	2.33	10.6	22.71	35.4	8.9	0.6	24.1
P8 - Dystric Umbric Gleysols (Alic) - Vereda. Flat relief															
A	0.00-0.20	4.89	0.36	0.21	0.21	1.27	13.2	0.79	13.99	50.0	5.60	61.7	190.1	2.1	13.4
C	0.20-0.50	5.13	0.12	0.08	0.01	0.78	2.4	0.21	2.61	16.3	8.01	78.8	8.9	0.5	21.6
P9 - Eutric Rhodic Ferralsols (Typical) - Flat relief (sorghum/soybeans crop)															
A	0.00-0.18	4.61	0.30	0.14	0.03	0.21	1.9	0.47	2.37	11.3	19.81	29.9	6.3	0.4	27.2
Bw1	0.40-0.80	5.08	1.69	0.61	0.15	0.00	1.8	2.45	4.25	28.3	57.60	0.0	16.5	8.5	40.3
P12 - Dystric Haplic Gleysols (Typical. Alic) - Vereda. Flat relief															
A	0.00-0.20	4.81	0.33	0.32	0.14	0.88	6.9	0.79	7.69	48.1	10.31	52.7	38.1	1.5	24.3
C1	0.20-0.60	4.86	0.11	0.11	0.07	0.78	4.5	0.29	4.79	29.9	6.12	72.9	21.5	1.1	22.6
P13 - Dystric Xanthic Ferralsols (Typical. Alic) - Semideciduous rainforest. Undulated relief															
A	0.00-0.20	4.69	0.19	0.16	0.13	1.27	5.5	0.48	5.98	24.9	8.01	72.6	31.7	2.1	26.1
Bw1	0.30-0.50	4.69	0.06	0.08	0.04	0.88	2.6	0.18	2.78	10.7	6.50	83.0	11.4	0.3	22.4
Bw2	0.50-0.90	5.04	0.08	0.08	0.02	0.59	2.1	0.18	2.28	8.4	7.91	76.6	7.6	0.3	18.5
P14 - Dystric Rhodic Ferralsols (Typical) - Flat relief (sugarcane crop)															
A	0.00-0.20	6.51	1.82	0.49	0.11	0.00	1.4	2.42	3.82	19.1	63.4	0.0	12.7	1.6	33.1
Bw	0.50-1.20	4.99	0.38	0.16	0.03	0.39	2.3	0.57	2.87	12.0	19.9	40.6	6.3	0.2	20.8
P20 - Dystric Rhodic Ferralsols (Clayic. Alic) - Savanna. Flat relief															
A	0.00-0.20	4.95	0.33	0.23	0.07	0.59	2.9	0.63	3.53	19.6	17.8	48.4	13.9	0.9	35.1
Bw1	0.30-0.60	4.53	0.09	0.07	0.02	0.68	2.4	0.18	2.58	10.3	7.1	79.1	3.8	0.2	19.7
Bw2	0.60-1.10	4.37	0.09	0.07	0.01	0.20	1.8	0.17	1.97	7.6	8.6	54.1	5.1	0.2	18.2
P21 - Dystric Umbric Gleysols - Vereda. Undulated relief															
A	0.00-0.20	4.75	2.82	1.46	0.51	0.59	14.6	4.77	19.37	34.0	24.6	11.2	183.8	8.1	14.5
C1	0.23-0.50	4.44	1.38	0.42	0.19	0.98	12.9	1.99	14.89	24.4	13.4	33.1	82.4	6.1	10.2

Methods: pH in water (1:2.5, soil:water ratio); P, K^+, Na^+ = Mehlich-1 extractor; Ca^{2+}, Mg^{2+}, Al^{3+} = extractor 1 mol L^{-1} KCl; H+Al = acidity potential, calcium acetate 0.5 mol L^{-1}; S = sum of bases; T = cation exchange capacity at pH $_{7,0}$; AC = activity clay (T/clay content × 1000); V = base saturation; m = Al saturation; OM = organic matter (Yeomans and Bremner, 1988); rem-P = remaining phosphorus (Donagema et al., 2011).

native Cerrado, Bayer et al. (2006) reported higher C stocks in clayey than in sandy clay loam soils, suggesting a higher physical stability or organic matter associated with Al/Fe oxy-hydroxides in the clayey Ferralsols. Low rem-P contents in these “umbric” soils show a clearly oxidic nature, with high P sorption, despite the high organic matter content.

The great agricultural expansion into the Cerrado has increased the awareness of the role of this region in the global C cycle and climatic change (Batlle-Bayer et al., 2010). Considering the large area (about 70 million hectares) of the Cerrado that is currently used and potentially available as cropland, the adoption of no-till systems could turn the Cerrado into a major sink for atmospheric C and contribute to the mitigation of global climate change (Bayer et al., 2006). Consequently, the organic matter in Cerrado soils is highly relevant, and its conservation under agricultural use is imperative for a sustainable production. Organic matter is also related with soil compaction, as pointed out by Assouline et al. (1997), as well as soil structure and water infiltration (McBride and Bober, 1989; Zhang et al., 1997). The higher clay contents in the Gleysols of *vereda*s is consistent with their hydromorphic nature, representing the largest carbon sink in the Cerrado region, and according to the current Brazilian environmental law they are permanent preservation areas (*Código Florestal*) that must be fully protected.

Morphometric analysis of the Frutal catchment

The studied catchment is classified as fourth-order watershed, with a perimeter of 56.85 km and total area of 123.52 km^2. The length of the main channel was 26.84 km (Riberão Frutal), with a vectorial distance of 22.95 km. The altimetric amplitude was 146 m and the total length of the 45 tributaries was 96.82 km. The relief ratio (Rr) was 0.0055, indicating the flatness of this high tableland (*chapada*) landform. The hydrographic density (Hd) was 0.36 channels km^{-2}, indicating a low capacity to generate new streams in this catchment. The drainage density (Dd), 0.78 km km^{-2}, indicates low flow and little landscape dissection, typical of the highly permeable nature of the underlying sandstones (*Vale do Rio do Peixe Formation*). According to Resende et al. (1996), Cerrado areas have perennial rivers with a large distance between drainage channels. Hence, the risk of pollution is high, and any pollution hotspot may affect the water quality of extensive areas.

The maintenance coefficient (Mc) of 1,282.05 m^2 m^{-1} reinforces that the catchment has few drainage channels, whereas the channel gradient (Gc) of the *chapada* slope is 2.12 %, corroborating the low declivity, decreasing the normal erosion. Although the number of narrow channels with low flows is small, they are intensively exploited for irrigation. Hence, a low sustainability of water resources is expected when irrigation demands must be reconciled with water conservation at the catchment scale, of any watershed in the Cerrado region.

The roundness index (Ri) of 0.4802 indicates that the catchment has an elongated shape, with high output capacity and low flooding risk. Also, the extensive flat to slightly undulating relief and high permeability of the sandstone substrate in most Cerrado landscapes results in a high subsurface water recharge capacity. In this respect, Lopes (1983) claimed that the Cerrado region has large water reserves due to the high permeability of sandstones and overlying soils, along with the retention caused by the underlying basalts, which prevent leaching.

These high tablelands have many upland depressions where runoff is concentrated and stored for groundwater recharge, provided that upland erosion is reduced. Consequently, with suitable soil management strategies and an adequate erosion control, intensive agriculture can be reconciled with long-term sustainability, preserving the soil functions.

The sinuosity index (Si) (1.17) indicates that the main channel varies from straight to slightly sinuous, suggesting low sediment deposition (retention), and also low structural control.

CONCLUSIONS

The soil physical and micromorphological properties detected important changes with regard to water recharge.

After cultivation, the microstructure of medium-texture Ferralsols (*Latossolos*) shifted from stable, strong microgranular to compacted, massive types. In the long term, this strongly affects water recharge and intensifies erosion, even where landforms at the landscape scale are flat.

Under cultivation, the soil density of these medium-texture Ferralsols increases and hydraulic conductivity decreases, particularly under sugarcane. Long-term cultivation induced chemical enrichment in the soil surface layer, due to fertilization, with an eutrophic character generated by cultivation.

The morphometric parameters of this typical *chapada* catchment (Frutal) indicated a low flooding risk and high flow capacity. Hence, the need for soil conservation measures to maintain and increase water recharge is emphasized, maintaining the lowland depression free form sedimentary inputs that may prevent water storage and groundwater recharge.

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REFERENCES

Ab'Saber AN. Províncias geológicas e domínios morfoclimáticos do Brasil. São Paulo: Universidade de São Paulo, Instituto de Geografia; 1970. v.20.

Alvarenga CC. Indicadores hidrológicos do solo para identificação de áreas potenciais de recarga subterrânea [dissertação]. Lavras: Universidade Federal de Lavras; 2010.

Arantes AE, Ferreira LG, Coe MT. The seasonal carbon and water balances of the Cerrado environment of Brazil: past, present, and future influences of land cover and land use. ISPRS J Photogramm. 2016;117:66-78. https://doi.org/10.1016/j.isprsjprs.2016.02.008

Arzeno JL. Avaliação física de diferentes manejos de solo em Latossolo Roxo distrófico [tese]. Piracicaba: Escola Superior de Agricultura Luiz de Queiroz; 1990.

Assis RL, Lanças KP. Avaliação dos atributos físicos de um Nitossolo Vermelho distroférrico sob sistema plantio direto, preparo convencional e mata nativa. Rev Bras Cienc Solo. 2005;29:515-22. https://doi.org/10.1590/S0100-06832005000400004

Assouline S, Tessier D, Tavares Filho J. Effects of compaction on soil physical and hydraulic properties: experimental results and modeling. Soil Sci Soc Am J. 1997;61:390-8. https://doi.org/10.2136/sssaj1997.03615995006100020005x

Batlle-Bayer L, Batjes NH, Bindraban, PS. Changes in organic carbon stocks upon land use conversion in the Brazilian Cerrado: a review. Agr Ecosyst Environ. 2010;137:47-58. https://doi.org/10.1016/j.agee.2010.02.003

Bayer C, Martin-Neto L, Mielniczuk J, Pavinato A, Dieckow J. Carbon sequestration in two Brazilian Cerrado soils under no-till. Soil Tillage Res. 2006;86:237-45. https://doi.org/10.1016/j.still.2005.02.023

Beuchle R, Grecchi RC, Shimabukuro YE, Seliger R, Eva HD, Sano E, Achard F. Land cover changes in the Brazilian Cerrado and Caatinga biomes from 1990 to 2010 based on a systematic remote sensing sampling approach. Appl Geogr. 2015;58:116-27. https://doi.org/10.1016/j.apgeog.2015.01.017

Boone FR. Weather and other environmental factors influencing crop responses to tillage and traffic. Soil Till Res. 1988;11:283-324. https://doi.org/10.1016/0167-1987(88)90004-9

Bullock P, Fedoroff N, Jongerius A, Stoops G, Tursina T, Babel U. Handbook for soil thin section description. Wolverhampton: Waine Research Publications; 1985.

Canillas EC, Salokhe, VM. A decision support system for compaction assessment in agricultural soils. Soil Till Res. 2002;65:221-30. https://doi.org/10.1016/S0167-1987(02)00002-8

Chagas AC. Propriedades físicas, mecânicas, químicas e micromorfológicas de um Latossolo Vermelho sob Cerrado e submetido a dois sistemas de manejo em Dom Aquino, MT [dissertação]. Viçosa: Universidade Federal de Viçosa; 2004.

Christofoletti A. Morfologia de bacias de drenagem. Not Geomorfol. 1978;18:130-2.

Companhia de Pesquisa de Recursos Minerais - CPRM. Mapa geológico do estado de Minas Gerais. Escala 1:1.000.000. Belo Horizonte: Serviço Geológico do Brasil; 2003.

Claessen MEC, organizador. Manual de métodos de análise de solo. 2a ed. Rio de Janeiro: Centro Nacional de Pesquisa de Solos; 1997.

Costa LM, Nacif PGS, Costa OV, Olszevski N. Manejo dos solos da região dos cerrados. In: Araujo QR, organizador. 500 anos de uso do solo no Brasil. Ilhéus: Editus; 2002. p. 201-18.

DeJong-Hughes J, Moncrief JF, Voohees WB, Swan JB. Soil compaction: causes, effects, and control. Minnesota: University of Minnesota Extension; 1987. (Agriculture Bulletin, 3115).

Dias Junior MS, Miranda EEV. Comportamento da curva de compactação de cinco solos da região de Lavras (MG). Cienc Agrotec. 2000;24:337-46.

Dick WA, Roseberg RJ, McCoy EL, Haghiri F, Edwards WM. Surface hydrologic response of soils to no-tillage. Soil Sci Soc Am J. 1989;53:1520-6. https://doi.org/10.2136/sssaj1989.03615995005300050037x

Donagema GK, Campos DVB, Calderano SB, Teixeira WG, Viana JHM, organizadores. Manual de métodos de análise do solo. 2a ed. rev. Rio de Janeiro: Embrapa Solos; 2011.

Environmental Systems Research Institute - ESRI. ArcGIS Desktop. Version 10.0. Redlands: 2010.

Food and Agriculture Organization of the United Nations - FAO. The state of food insecurity in the world 2015. Meeting the 2015 international hunger targets: taking stock of uneven progress. Rome: FAO; 2015.

Freitas RO. Textura de drenagem e sua aplicação geomorfológica. Boletim Paulista de Geografia. 1952;11:53-7.

Gomes JBV, Curi N, Schulze DG, Marques JJGSM, Ker JC, Motta PEF. Mineralogia, morfologia e análise microscópica de solos do bioma cerrado. Rev Bras Cienc Solo. 2004;28:679-94. https://doi.org/10.1590/S0100-06832004000400010

Håkansson I, Medvedev VW. Protection of soils from mechanical overloading by establishing limits for stresses caused by heavy vehicles. Soil Till Res. 1995;35:85-97. https://doi.org/10.1016/0167-1987(95)00476-9

Horton RE. Erosional development of streams and their drainage basins; hidrophysical approach to quantitative morphology. Bull Geol Soc Am. 1945;56:275-370. https://doi.org/10.1130/0016-7606(1945)56[275:EDOSAT]2.0.CO;2

Instituto Nacional de Meteorologia - Inmet. Normais climatológicas do Brasil 1961-1990. Brasília, DF: Instituto Nacional de Meteorologia; 2009 [acesso em 30 set 2016]. Disponível em: http://www.inmet.gov.br/portal/index.php?r=clima/normaisClimatologicas.

IUSS Working Group WRB. World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. Rome: FAO; 2015. (World Soil Resources Reports, 106).

Klink CA, Machado RB. Conservation of the Brazilian Cerrado. Conserv Biol. 2005;19:707-13. https://doi.org/10.1111/j.1523-1739.2005.00702.x

Lopes AS. Solos sob “Cerrado”: características, propriedades e manejo. Piracicaba: Instituto da Potassa & Fosfato; 1983.

Machado RB, Ramos Neto MB, Pereira PGP, Caldas EF, Gonçalves DA, Santos NS, Tabor K, Steininger M. Estimativas de perda da área do Cerrado brasileiro. Brasília, DF: Conservação Internacional; 2004. (Relatório técnico não publicado).

Marcelino V, Stoops G, Schaefer CEGR. Oxic and related materials. In: Stoops G, Marcelino V, Mees F, editors. Interpretation of micromorphological features of soils and regoliths. Amsterdam: Elsevier Science; 2010. p. 305-327.

McBride RA, Bober ML. A re-examination of alternative test procedures for soil consistency limit determination: I. A compression-based procedure. Soil Sci Soc Am J. 1989;53:178-83. https://doi.org/10.2136/sssaj1989.03615995005300010033x

Mello CR, Curi N. Hydropedology. Cienc Agrotec. 2012;36:137-46. https://doi.org/10.1590/S1413-70542012000200001

Menezes MD. Levantamento pedológico de hortos florestais e mapeamento digital de atributos físicos do solo para estudos hidrológicos [tese]. Lavras: Universidade Federal de Lavras; 2011.

Miller VC. A quantitative geomorphology study of drainage basin characteristic in the Clinch Mountain area, Virginia and Tennessee. New York: Columbia University; 1953.

Myers N, Mittermeier RA, Mittermeier CG, Fonseca GAB, Kent J. Biodiversity hotspots for conservation priorities. Nature. 2000;403:853-8. https://doi.org/10.1038/35002501

Pankhurst CE, Magarey RC, Stirling GR, Blair BL, Bell MJ, Garside AL. Management practices to improve soil health and reduce the effects of detrimental soil biota associated with yield decline of sugarcane in Queensland, Australia. Soil Till Res. 2003;72:125-37. https://doi.org/10.1016/S0167-1987(03)00083-7

Pinto LCG. Uso dos solos nos cerrados. In: Araujo QR, organizador. 500 anos de uso do solo no Brasil. Ilhéus: Editus; 2002. p. 189-99.

Pissarra TCT, Politano W, Ferraudo AS. Avaliação de características morfométricas na relação solo-superfície da Bacia Hidrográfica do Córrego Rico, Jaboticabal (SP). Rev Bras Cienc Solo. 2004;28:297-305. https://doi.org/10.1590/S0100-06832004000200008

Reichert JM, Reinert DJ, Braida JA. Qualidade dos solos e sustentabilidade de sistemas agrícolas. Ciência e Ambiente. 2003;27:29-48.

Resende M. 500 anos de uso do solo no Brasil. In: Araujo QR, organizador. 500 anos de uso do solo no Brasil. Ilhéus: Editus; 2002. p. 1-49.

Resende M, Curi N, Ker JC, Rezende SB. Mineralogia de solos brasileiros: interpretação e aplicações. 2. ed. Lavras: Editora UFLA; 2011.

Resende M, Curi N, Rezende SB, Corrêa GF, Ker JC. Pedologia: base para distinção de ambientes. 6. ed rev ampl. Lavras: Editora UFLA; 2014.

Resende M, Ker JC, Bahia Filho AFC. Desenvolvimento sustentado do cerrado. In: Alvarez V VH, Fontes LEF, Fontes MPF, editores. Os solos nos grandes domínios morfoclimáticos do Brasil e o desenvolvimento sustentado. Viçosa, MG: SBCS; 1996. p. 169-199.

Roque AAO, Souza ZM, Barbosa RS, Souza GS. Controle de tráfego agrícola e atributos físicos do solo em área cultivada com cana-de-açúcar. Pesq Agropec Bras. 2010;45:744-50. https://doi.org/10.1590/S0100-204X2010000700016

Ruiz HA. Incremento da exatidão da análise granulométrica do solo por meio da coleta da suspensão (silte + argila). Rev Bras Cienc Solo. 2005;29:297-300. https://doi.org/10.1590/S0100-06832005000200015

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Oliveira JB, Coelho MR, Lumbreras JF, Cunha TJF. Sistema brasileiro de classificação de solos. 3. ed. Rio de Janeiro: Embrapa Solos; 2013b.

Santos RD, Lemos RC, Santos HG, Ker JC, Anjos LHC, Shimizu SH. Manual de descrição e coleta de solo no campo. 6. ed. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2013a.

Schumm SA. Evolution of drainage systems and slopes in badlands of Perth Amboy, New Jersey. Bull Geol Soc Am. 1956;67:597-646. https://doi.org/10.1130/0016-7606(1956)67[597:EODSAS]2.0.CO;2

Schumm SA. Sinuosity of alluvial rivers on the great plains. Bull Geol Soc Am. 1963;74:1089-100. https://doi.org/10.1130/0016-7606(1963)74[1089:SOAROT]2.0.CO;2

Severiano EC, Oliveira GC, Curi N, Dias Júnior MS. Potencial de uso e qualidade estrutural de dois solos cultivados com a cana-de-açúcar em Goianésia (GO). Rev Bras Cienc Solo. 2009;33:159-68. https://doi.org/10.1590/S0100-06832009000100017

Silva AA, Castro SS. Indicadores macro e micromorfológicos da qualidade física de um Latossolo Vermelho cultivado com cana-de-açúcar. Mercator. 2015;14:169-85. https://doi.org/10.4215/RM2015.1403.0010

Silva AJN, Ribeiro MR, Mermut AR, Benke MB. Influência do cultivo contínuo da cana-de-açúcar em Latossolos Amarelos coesos do estado de Alagoas: propriedades micromorfológicas. Rev Bras Cienc Solo. 1998;22:515-25. https://doi.org/10.1590/S0100-06831998000300018

Soares JLN, Espindola CR, Foloni LL. Alteração física e morfológica em solos cultivados com citros e cana-de-açúcar, sob sistema tradicional de manejo. Cienc Rural. 2005;35:353-9. https://doi.org/10.1590/S0103-84782005000200016

Spera SA, Galford GL, Coe MT, Macedo MN, Mustard JF. Land-use change affects water recycling in Brazil's last agricultural frontier. Global Change Biology. 2016;22:3405-13. https://doi.org/10.1111/gcb.13298

Stoops G. Guidelines for analysis and description of soil and regolith thin sections. Madison: Soil Science Society of America; 2003.

Stoops G, Marcelino V, Mees F. Interpretation of micromorphological features of soils and regoliths. Amsterdam: Elsevier Science; 2010.

Turetta APD, Prado RB, Schuler AR. Serviços ambientais no Brasil: do conceito à prática. In: Prado RB, Turetta APD, Andrade AG, organizadores. Manejo e conservação do solo e da água no contexto das mudanças ambientais. Rio de Janeiro: Embrapa Solos; 2010. p. 239-54.

Yeomans JC, Bremner JM. A rapid and precise method for routine determination of organic carbon in soil. Commun Soil Sci Plan. 1988;19:1467-76. https://doi.org/10.1080/00103628809368027

Zhang H, Hartge KH, Ringe H. Effectiveness of organic matter incorporation in reducing soil compatibility. Soil Sci Soc Am J. 1997;61:239-45. https://doi.org/10.2136/sssaj1997.03615995006100010033x

Zinn YL, Lal R, Resck DVS. Changes in soil organic carbon stocks under agriculture in Brazil. Soil Tillage Res. 2005;84:28-40. https://doi.org/10.1016/j.still.2004.08.007