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Surface Infiltration on Tropical Plinthosols in Maranhão, Brazil

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1. Introduction

Plinthosols are soils that have inherent limitations such as the formation of highly condensed layers, surface crust formation and restricted water percolation, thereby hampering their management for agricultural production. According to Embrapa (2006), this kind of soil when subjected to the continual process of wetting and drying encourages the development of a plinthic horizon, which means that the soil remains saturated and is subject to water table level fluctuations.

In order to reduce the impact of the limitations of these soils, proper conservative management systems have to be applied. These systems shall have to take into account the soil quality, improving water retention, reducing soil's lost, increasing soil's biological activity, improving exchanging of heat and gases between soil and atmosphere as well as the availability of air, water and nutrients to plants. Thus, understanding the relationship between infiltration and physical attributes in this soil is important for ensuring adequate soil and crop management.

Water infiltration into the soil is one of the basic factors for estimating irrigation intensity according to the plants' requirements; with the aim of avoiding problems of run-off and surface degradation. Ascertaining the infiltration rate and accumulated water quantity is of great importance due to their application in the agriculture and environment, allowing for estimating surface run-off, suspended particle transport, sediment availability, and aquifers capacity to be recharged, defining irrigation systems and studying the effects of different soil management practices (Machiwal et al., 2006; Strudley et al., 2008).

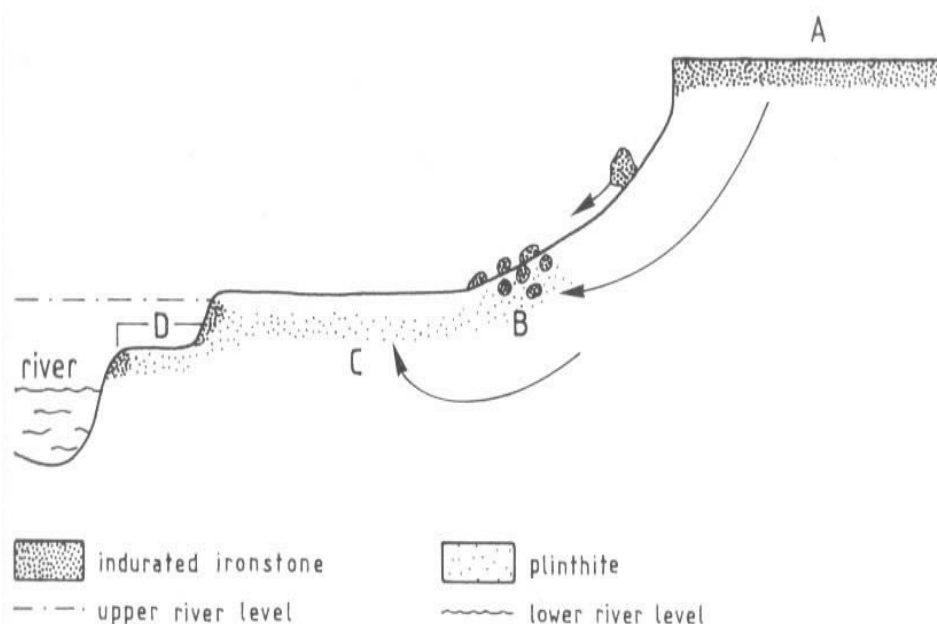
This chapter presents a characterization of that soil and of a conservative management system in a research that evaluated the variability of water infiltration and its relation to soil's physical attributes.

2. Description of Plinthosols

Plinthosols are soils with plinthite, petroplinthite or pisoliths. Plinthite is a Fe-rich, in some cases also Mn-rich, humus-poor mixture of kaolinitic clay (and other products of strong

weathering such as gibbsite) with quartz and other constituents that change irreversibly to a layer with hard nodules, a hardpan or irregular aggregates on exposure to repeated wetting and drying. Petroplinthite is a continuous, fractured or broken sheet of connected, strongly cemented to indurated nodules or mottles. Pisoliths are discrete strongly cemented to indurated nodules. Both petroplinthite and pisoliths develop from plinthite by hardening (FAO, 2006).

Formation of Plinthite involves the following processes: (1) accumulation of sesquioxides, through: (a) relative accumulation as consequence of the removal of silica and bases by ferralitization, and/or (b) absolute accumulation through enrichment with sesquioxides from outside (vertical or lateral, see Figure 1). (2) segregation of iron mottles, caused by alternating reduction and oxidation. In times of water saturation, much of the iron is in the ferrous form, has high mobility and is easily redistributed. When the water table falls, this iron precipitates as ferric oxides that will not, or only partially, redissolve in the next wet season (Driessen & Dudal, 1989).



- A: Indurated ironstone (massive iron pan or gravel) capping an old erosion surface.
 B: Plinthite and ironstone (gravel and boulders) in a colluvial footslope (subject to iron-rich water seepage).
 C: Plinthite in soils of a low level plain (river terrace) with periods of high groundwater.
 D: Along the banks of rivers where plinthite becomes exposed and hardens to ironstone. Source: Driessen & Dudal (1989).

Fig. 1. Genesis of Plinthosols. Four physiographically distinct landscape positions where plinthite and ironstone occur.

Global extent of Plinthosols is estimated at some 60 million ha. Soft plinthite is most common in the wet tropics, notably in the Eastern Amazon basin, in the Central Congo basin, and parts of Southeast Asia. Extensive areas with pisoliths and petroplinthite occur in the Sudano-Sahelia zone, where petroplinthite forms hard caps on top of uplifted/exposed landscape elements. Similar soils occur in the Southern African savannah, in the Indian subcontinent, and in drier parts of Southeast Asia and Northern Australia (FAO, 2006).

Many of these soils are known as: Groundwater Laterite Soils, Perched Water Laterite Soils and Plintossolos (Brazil); Soils gris latéritiques (France); and Plinthaquox, Plinthaqualfs, Plinthoxeralfs, Plinthustalfs, Plinthaquults, Plinthohumults, Plinthudults and Plinthustults (United States of America).

In Keys to Soil Taxonomy (Soil Survey Staff, 1992) these soils are included in the Alfisol, Inceptisol, Oxisol and Ultisol orders. In that classification system the occurrence of plinthite is considered to be an additional differentiating characteristic, not a diagnostic horizon, and the definition of plinthic subgroups is not complete.

In Brazilian Soil Classification System (Embrapa, 2006) the Plintosols classes were defined as a soil consisting of mineral material, with the plinthic horizon or concretionary/ petroplinthic solodic horizon, or in one of the following conditions:

(1) Starting within 40 cm from the surface, or

(2) Starting within 200 cm from the surface when preceded by gley horizon, or immediately below the horizon A or E, or other horizon that shows pale colors, variegated or mottled in abundance (> 20 % by volume), a matrix of reddish or yellowish hue 5 Y or that have shades 7.5 YR, 10 YR or 2.5 Y, with chroma less than or equal to 4.

In this definition, it is important to consider the depth, what is the plinthic or lithoplinthic/petroplinthic horizon and the amount of plinthite and, or concretions.

Soils with plinthic horizons occur in floodplains, areas with flat relief or gently sloping undulating and less frequently in geomorphic depression areas. They also occur in shoulders or floodplain areas, under presence and oscillation of the water table, either from periodic flooding or waterlogging, restricting effect on water percolation or runoff. Concretionary horizon soils have better drainage and higher positions in relation to soils with plinthic horizon, and are most frequent in the Amazon region of Brazil (Embrapa, 2006).

Soils with plinthite and, or ironstone (petroplinthite) are common in Northeastern Brazil (Anjos et al., 1995, 2007). According to Embrapa (1986), the main areas in Brazil with plinthite or petroplinthite occur in the Amazon region (upper Amazon), Amapá, Marajo Island, Maranhão lowland, Northern of Piauí, Southwest of Tocantins, Northern Goiás, Pantanal and Bananal Island (Figure 2).

A reconnaissance Soil Survey of the State of Maranhão, Brazil (Embrapa, 1986) showed that associations between soils in which Plinthosols are the main component constitute approximately 44,000 km² of the whole state.

In humid tropics in the Northern center of Maranhão, Brazil, Plinthosols from Itapecuru Formation or colluvial sediments are formed from ferruginous sandstone (Anjos et al., 1995), where conditions of high rainfall alternates with prolonged period of high decrease in rainfall and present various problems such as the formation of condensed layers, surface crust and, consequently, poor drainage, limiting the harvest conditions of the farmers.

Plinthosols presents serious management problems. Waterlogging and low natural fertility are their main limitations. If the plinthite layer hardens, for example, because of deep drainage or erosion, ironstone will limit the possibilities for root growth and lower the water storage capacity of the soil. Most petroferric soils are unsuitable for arable farming; they are used for extensive grazing and firewood production (Driessen & Dudal, 1989).

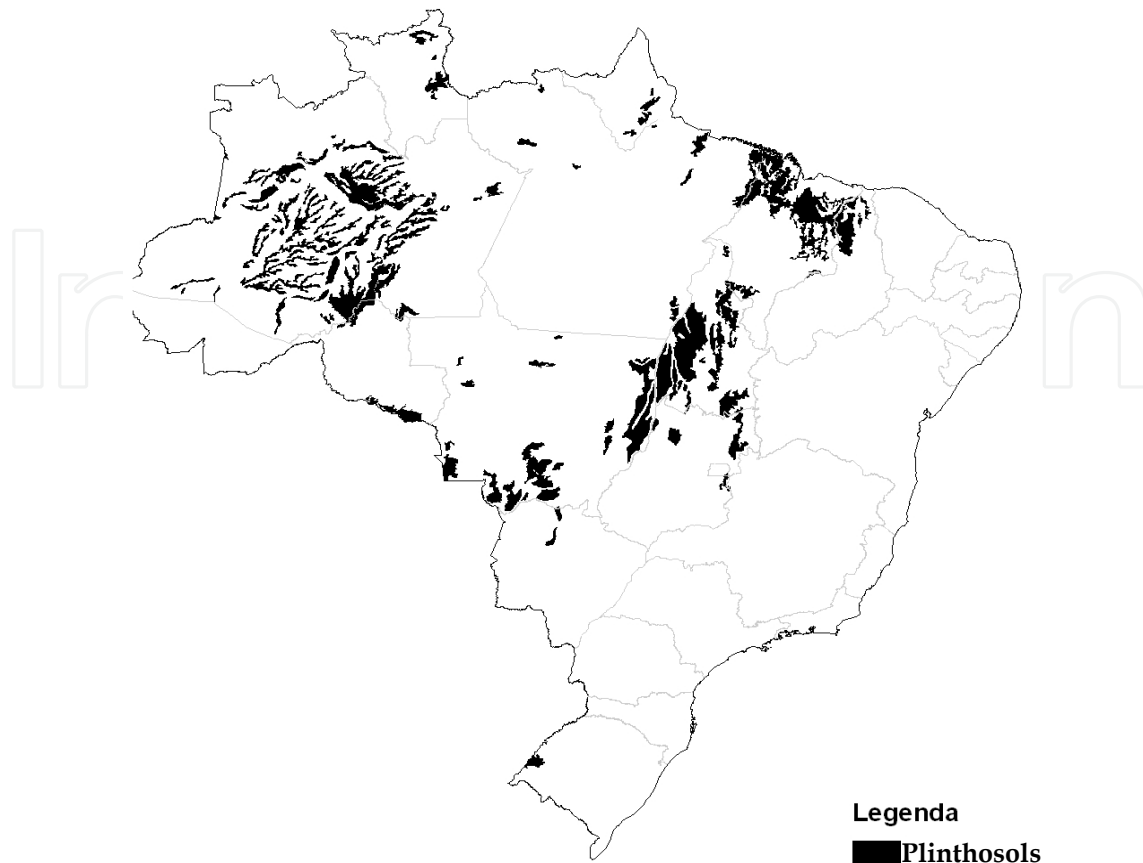


Fig. 2. Occurrence of in Brazil. Source: Embrapa, 2011.

3. Family farming in the humid tropics of Maranhão

Family farmers in the humid tropics in the Northern center of Maranhão, Brazil, practice itinerant agriculture, or slash and burn, over the Plinthosol prevalent in the region. The smallholder farms occupy areas ranging from 1 to 5 hectare, mainly cultivating rice (*Oryza sativa*), corn (*Zea mays L.*), beans (*Phaseolus vulgaris*) and cassava (*Manihot utilissima*).

This shifting cultivation system of the soil, predominantly in the humid tropics, has been practiced for centuries and occupies near 30 % of arable land, holding between 300 and 500 million people among the poorest in the world (Von Uexkul and Mutert, 1990).

After burning, the crops established in the first year produce relatively well, reaching levels of field production higher than those obtained in areas without burning and without fertilizer (Van Reuler and Jansenn, 1993). However, from the second year of cultivation begins a phase of decline in productivity that can be attributed to the chemical fertility reduction, more pronounced in soils of low fertility, and increased weed infestation, more damaging in soils with high natural fertility (Sanchez, 1982 adapted by Ferraz Junior (2004).

The emphasis of this intensification should not be intensive soil tillage and external inputs use. It should promote ways to incorporate management of biological cycles and environmental interactions that determine the sustainable productivity of the agroecosystem (Harwood, 1996). Therefore, this production model has been studied in search of more sustainable alternative proposals.

4. The alley cropping system

The alley cropping system is one of the most simple agroforestry systems, which combines in the same area tree species, preferably legumes and perennial or annual crops of economic interest. Legumes are planted in single or double rows, spaced 2 to 6 m. The branches of the plants are periodically cut at a height from 0.1 to 0.5 m, and lines of crops of economic interest are added, serving as cover plants and green manure (Kang et al, 1990, Szott et al, 1991; Cooper et al 1996).

This practice, traditionally used in tropical regions of Africa and Asia, has led to improvement in soil chemical attributes (organic carbon and nutrients) in the superficial layer, compared to other practices such as monoculture. The improvement has been attributed to more effective recycling of nutrients, pruning or litter biomass. In addition, the forest species show beneficial effects for their deeper roots that reduce leaching losses and higher soil cover that provides protection against erosion (Mafra et al, 1998).

This agricultural system is based on the following principles: soil fertility regeneration, mulch formation, weeds elimination, nitrogen fixation, nutrient recycling, which consequently provides improved soil quality (Kang 1997).

5. Surface infiltration in Plinthosols

Local research was conducted in 2005 and aimed to determine the spatial variability of surface infiltration in an Argiluvic Plinthosol (Embrapa, 2006) or Plinthic Kandiudult (Soil Survey Staff, 1992). This is presented in detail in the following sections.

5.1 Study area

The study was carried out in Miranda del Norte (Maranhão, State, Brazil), located at 3° 36' South latitude and 44° 34' West longitude (Figure 3) on a 1 hectare plot planted with corn (*Zea mays* L.) using agro-forest system, in an area where family agriculture predominates. The predominant soil is an Argiluvic Plinthosol, with medium texture and over flat relief.

According to Köppen's climatic classification, the region is located in an Aw' - humid tropical climate, having an average temperature of 27° and 1,600 to 2,000 mm year⁻¹ rainfall, concentrated in December and June, with a drier climate predominating in the other months.

5.2 Sampling and laboratory tests

A 113-point mesh (Figure 4) was designed for sampling, having a regular 10 m distance between points in the experimental area, considering the 44 rows of legumes, along the corn rows. Disturbed and undisturbed soil samples were taken at each point at 0 - 0.20 m depth. The disturbed samples were air-dried until they reached an equilibrium point; once being clod, they were passed through a 2 mm mesh for granulometric analysis. Sand, silt and clay content were thus established by means of a 10 g sample subjected to slow agitation for 16 h, in 100 ml solution with NaOH (0.1 mol L⁻¹); clay content was obtained by means of an aliquot drawn out with a pipette (Gee and Bauder, 1986). The undisturbed samples were taken from 100 cm³ volumetric rings to determine bulk density, macroporosity, microporosity and total porosity using a tension table, following the methodology described by Kiehl (1979).

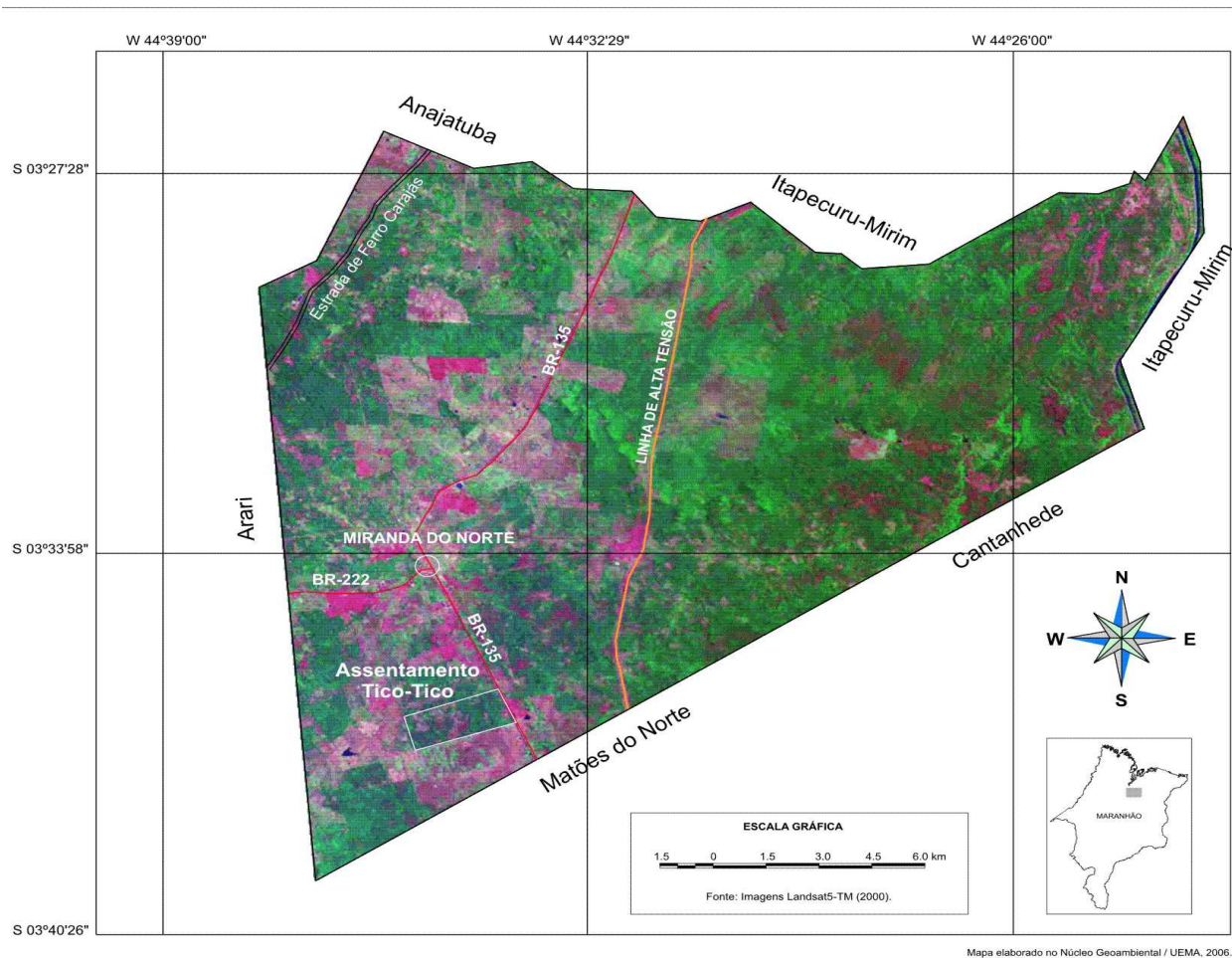


Fig. 3. Localization of the experimental area.

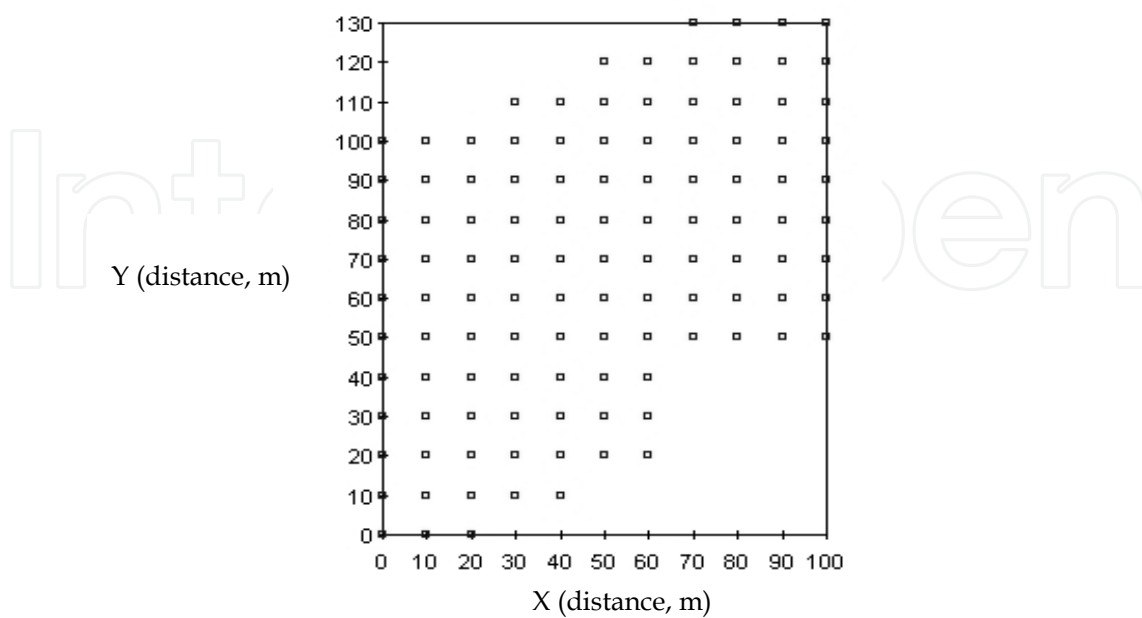


Fig. 4. Regular points mesh in experimental area of Argiluvic Plinthosol.

Infiltration rate was determined during a dry period, at each sampling point, by means of a 15 cm diameter ring, using Guelph permeameter modified by the Agronomical Institute of Campinas (IAC), thus guaranteeing constant water load. Infiltration rate was calculated using Reynolds and Elrick's equation (1985), modified by Vieira (1988):

$$I = 60 \left(\frac{D_p}{D_a} \right)^2 \cdot Q \quad (1)$$

Where I is the infiltration rate of water in saturated soil (mm h^{-1}), D_p is the diameter of the Guelph permeameter (9 cm), D_a is the ring diameter (15 cm) and Q is the estimated water flow in saturated soil (mm min^{-1}).

5.3 Statistical analysis

Descriptive statistics were initially used to analyzing the data, using SPSS 16.0 software for calculating the mean, median, coefficient of variation (CV), minimum, maximum, skewness, kurtosis and Kolmogorov-Smirnov test. Normality was thus verified, a pattern which is not indispensable when related to geostatistical techniques but does give better predictions when data are fit to a normal distribution (Diggle and Ribeiro, 2000). The classification proposed by Warrick and Nielsen (1980) was used for CV analysis: it indicates low CV variability for values below 12 %, average CV variability between 12 % and 60 % and high CV variability when greater than 60 %. Pearson linear correlation was also carried out to identify the correlation between infiltration and the soil's different physical properties.

The physical properties and infiltration's spatial dependence were analyzed by using semivariograms. The theory of regionalized variables was taken into consideration for the fit of theoretical experimental semivariogram models; it has different methods for analyzing spatial variation, one of them being semivariogram (Vieira, 2000) which is estimated by:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_{i+h})]^2 \quad (2)$$

where $Z(x_i)$ and $Z(x_{i+h})$ are observed values of a variable, separated by a distance h , and $N(h)$ is the number of pairs of experimental observations, separated by distance h . The semivariogram is graphically represented by $\gamma(h)$ versus h . The theoretical model's coefficients are estimated from the fit of the model: nugget effect (C0), sill (C0+C1) and range (A).

The degree of spatial dependence (DSP) was also estimated, based on the ratio between the nugget effect and the sill (C/C_0+C_1), being considered strong for DSP when above 75 %, moderate DSP between 25 % and 75 %, and weak for DSP less than 25 % (Cambardella, 1994). GS+ software (Gamma Design Software, 1998) was used to calculating the semivariograms; adopting the largest determination coefficient value (R^2), the lowest value for the sum of the square of the residue (SQR) and crossing a validation coefficient (CVC) close to one as criteria for selecting the model. Once spatial dependence had been determined, infiltration in the nonsampled areas was predicted by kriging, represented on contour map that was drawn up using Surfer software (2000).

5.4 Results and discussions

The average and median values were similar for each one of the studied properties, indicating symmetrical distributions. This was verified by skewness and kurtosis values being close to zero for all properties. They approached normal distribution, except for infiltration (Table 1). These properties' normality pattern has also been reported by Ramírez-López et al. (2008). The Kolmogorov-Smirnov test confirmed normal distribution for most properties, except for infiltration, silt and microporosity.

Property	Mean	Median	CV, %	Minimum	Maximum	Skewness	Kurtosis	K-S
Infiltration, mm h ⁻¹	36,03	30,00	64,15	3,00	90	0,73	-0,38	*
Sand, %	25,63	26,00	12,43	18,00	34,00	0,18	-0,11	
Silt, %	49,35	51,50	19,03	24,00	65,00	-0,66	-0,32	*
Clay, %	24,56	24,00	36,42	7,00	45,00	0,45	-0,65	
Bd, g cm ⁻³	14,13	14,10	4,32	12,60	15,30	-0,42	-0,05	
Map, %	11,85	11,73	19,22	7,23	17,78	0,46	-0,06	
Mip, %	42,91	43,47	7,22	34,82	50,19	-0,34	0,09	*
PT, %	56,73	56,92	7,73	47,55	67,05	0,00	-0,12	
PT, %	56,73	56,92	7,73	47,55	67,05	0,00	-0,12	

Table 1. Descriptive measurements of soil infiltration and physical properties. K-S: Kolmogorov-Smirnov test, *: significant the 5 %; Bd: bulk density, Map: macroporosity, Mip: microporosity, PT: total porosity.

According to Warrick and Nielsen's criteria (1980), it was seen that infiltration had high variability (64.15 % CV). Rodríguez-Vásquez et al. (2008) also found high variability for this property in a high silt content Andisol. Bulk density was the property showing the lowest CV (indicating low variability) together with microporosity and total porosity. Low variability for bulk density and total porosity has also been reported by Ramírez-López et al. (2008). The other properties showed average variability. Clay was the soil particle showing the greatest variability.

Total porosity was the only property which did not fit a theoretical semivariogram model, indicating lack of spatial autocorrelation, showing a pure nugget effect (Table 2). The spherical model was the predominant model among the properties analyzed; it fits infiltration, silt, clay and microporosity data. Sand, bulk density and macroporosity data fit in exponential models.

Models fit adequately, given the coefficient determination of values which were always above 0.75. Sand and clay were the properties having the best fit for the models. The coefficient of crossed validation was close to 1 for most properties, whereas bulk density had the lowest value (0.81). Infiltration showed the greatest range and was the only property having a range greater than 100 m.

Property	Model	Co	Co+C	A (range,m)	C/Co+C	R2	CVC
Infiltration	Spherical	207,70	415,50	118,90	0,50	0,79	0,96
Sand	Exponential	0,93	11,62	43,80	0,92	0,94	1,05
Silt	Spherical	27,30	84,69	50,80	0,68	0,80	0,98
Clay	Spherical	24,70	85,05	55,80	0,71	0,92	1,00
Bd	Exponential	4,2E-4	38,6E-4	35,10	0,89	0,86	0,81
Map	Exponential	0,28	3,28	29,10	0,91	0,77	0,97
Mip	Spherical	1,10	6,09	24,90	0,82	0,84	0,96
PT	NE	13,69	13,69				

Table 2. Fit in theoretical semivariogram parameters for soil infiltration and physical properties. NE: nugget effect; CVC: coefficient of cross validation, Bd: bulk density, Map: macroporosity, Mip: microporosity, TP: total porosity.

Infiltration did not have a significant correlation with the physical properties (Table 3). It can be observed that infiltration was directly related to silt content and inversely to clay content. The same pattern has been reported by Rodríguez-Vásquez et al. (2008). This relationship between infiltration and silt and clay content is verified on the contour maps (Figure 5) where areas having a greater infiltration rate correspond to areas of greater silt content and lower clay content.

Macroporosity and microporosity were the properties having the least range. Regarding the degree of spatial dependence (DSD), infiltration showed the lowest value, having moderate spatial dependence. Clay and silt also showed a moderate DSD. The other properties showed high DSD, having values greater than 0.80.

A significant and inverse correlation between sand, clay and microporosity was observed. Silt and clay content showed a strong inverse correlation, as can be seen in the contour maps (figure 5) where areas of greater silt content correspond to areas of lower clay content and vice versa.

	Infiltration	Sand	Silt	Clay	Dd	Map	Mip	PT
Infiltration	1							
Sand	0.058	1						
Silt	0.125	-0.127	1					
Clay	-0.198	-0.163*	-0.912**	1				
Dd	-0.098	-0.187	-0.082	0.165	1			
Map	-0.129	-0.211	-0.194	0.223	-0.13	1		
Mip	-0.057	-0.137*	-0.067	0.147	0.144*	0.255	1	
PT	-0.021	-0.197	-0.156	0.226	0.064*	0.698**	0.654**	1

*Correlation was significant at the 0,05 level ; **Correlation was significant at 0,01 level, Bd:bulk density, Map: macroporosity, Mip: microporosity, PT: total porosity.

Table 3. Pearson correlation between soil infiltration rate and physical properties.

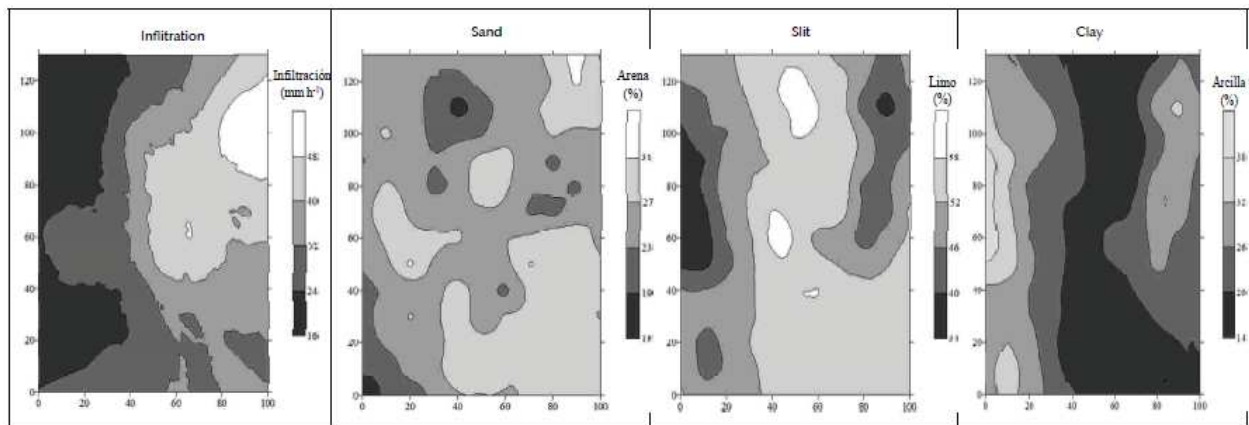


Fig. 5. Contour maps of infiltration and sand, silt and clay contents.

Bulk density also had a positive and significant correlation with microporosity, leading to moderately similar contour maps (Figure 6). Total porosity (a property in which spatial dependence was not found) had an inverse correlation with sand and silt content and a direct correlation with clay content, as well as with bulk density, macroporosity and microporosity.

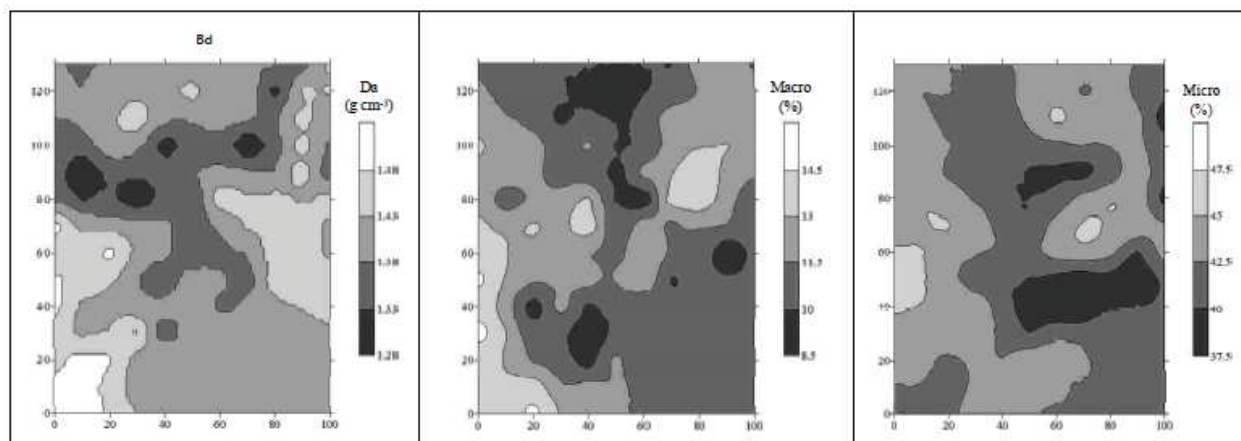


Fig. 6. Contour maps of bulk density, macroporosity and microporosity.

The contour maps confirmed the relationship between the variables analyzed in this study (figure 5 and 6) as well as the spatial variability existing in the soil, indicating the convenience of carrying out localized soil management practices according to the conditions of the area and crop requirements. This could potentially lower production costs and soil degradation which results from conventional management.

6. Conclusions

Surface infiltration and soil properties analyzed by means of descriptive statistics and geostatistics revealed the soil's high variability in its infiltration and physical property patterns, this being an important tool for decision-making since it leads to establishing the soil quality parameters which are directly related to agricultural production.

The linear correlation estimated for the properties led to identifying which ones were most closely related; such relationships were spatially confirmed by means of contour maps obtained by kriging when the properties fit the theoretical semivariogram models.

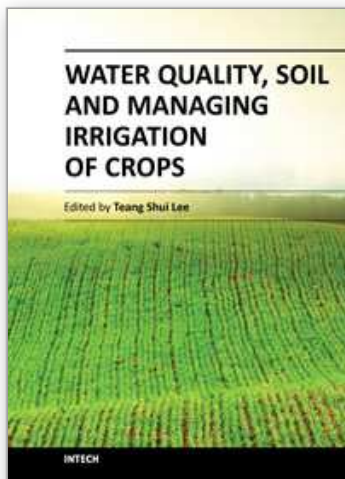
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The book entitled Water Quality, Soil and Managing Irrigation of Crops comprises three sections, specifically: Reuse Water Quality, Soil and Pollution which comprises five technical chapters, Managing Irrigation of Crops with four, and Examples of Irrigation Systems three technical chapters, all presented by the respective authors in their own fields of expertise. This text should be of interest to those who are interested in the safe reuse of water for irrigation purposes in terms of effluent quality and quality of urban drainage basins, as well as to those who are involved with research into the problems of soils in relation to pollution and health, infiltration and effects of irrigation and managing irrigation systems including basin type of irrigation, as well as the subsurface method of irrigation. The many examples are indeed a semblance of real world irrigation practices of general interest to practitioners, more so when the venues of these projects illustrated cover a fair range of climate environments.

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