# Spatial variability in the physical properties of an Oxisol under coffee cultivation in the Brazilian Cerrado

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## Abstract

The physical properties of the soil are limiting factors for coffee cultivation and yields. Therefore, we analyzed spatial variability in the physical properties of a clayey Oxisol under coffee cultivation. The experiment was carried out on 14-hectares of a coffee (*Coffea arabica*) plantation in the city of Monte Carmelo, in the Brazilian state of Minas Gerais. Soil samples were collected from two layers (0 - 0.1 m and 0.1 - 0.2 m) at 61 grid-points spaced at 50 x 50 meters. These samples were saturated to determine total porosity and soil bulk density. Soil resistance readings were also taken from the same grid points and layers using an impact penetrometer. Descriptive statistics were used to evaluate all variables. Additionally, geostatistics were used to model spatial variability within the soil physical properties. Variographic analysis was performed using semivariograms. We found that density, total porosity and soil resistance to penetration varied throughout the study area, which demonstrates that management type can alter soil physical properties and that maps generated by geostatistics can help coffee growers make decisions related to soil management.

**Keywords:***Coffea arabica*, soil physical quality, geostatistics.

## 1. Introduction

Coffee production plays a significant role in the agribusiness sector and overall economy of Brazil. In 2016, Brazil produced over 51 million bags of coffee and was the largest exporter in the world (Conab 2016). The Cerrado region in the Brazilian state of Minas Gerais has great potential for coffee production and possesses the soils and climatic conditions needed to produce high-quality coffees (Alves *et al.* 2011) that are certified and economically competitive.

Spatial and temporal variations in the soil result from processes that are controlled by various interrelationships among physical, chemical, and biological properties. Thus, changes to the soil can directly alter the structure and biological activity of the soil, affecting fertility, the agroecosystem (Brookes 1995) and crop yields.

Thus, intensive agriculture and inappropriate management practices can degrade soil physical properties and favor processes that reduce porosity and increase soil density, which, in turn, hinder root development and may reduce crop yields.

Soil resistance to penetration, as measured by a penetrometer, is the relationship between the force exerted to penetrate the ground by a rod with a metallic cone at one end, and its basal area, which is constant and known. This method is quick, simple and well correlated with root development (Bengough *et al.* 2001). Soil resistance to penetration has also been used to identify compacted layers and changes in soil physical properties within horizons (Reichert *et al.* 2010).

Soil density is defined as mass per unit volume of dry soil. This volume includes both solid particles and porous space (Brady and Weil 2013). Therefore, conditions that influence the arrangement of soil particles will directly affect soil density values (Ferreira 2010). These conditions include organic matter content, soil structure (mineralogical composition), soil depth and conservation practices.

Total porosity encompasses both macropores and micropores. These pores are essential for plant development because they contain water and air that can be absorbed by roots for plant hydration and respiration. Soil is a three-phase system. Thus, determining total porosity is essential for optimizing management practices, since the system is closely linked to the dynamics of solute storage and transport and gas circulation, which are, in turn, essential to biochemical processes, especially those related to plant productivity (Epstein and Bloom 2006).

Soil physical properties may vary within a cultivated area because of several factors that include management practices (Silva *et al.* 2010), especially those practices related to soil compaction.

Understanding variations in physical properties within a cultivated area is important for soil surveying, soil management, soil sampling and managing agricultural practices (Silva *et al.* 2010). Thus, it is important to determine the extent and intensity of spatial variations, either alone or in conjunction with other variables (Gandah *et al.* 2000) such as soil density, structure, resistance to penetration and porosity.

These properties determine whether the soil is adequate for plant development and the maintenance of a diverse population of soil organisms (Doran and Parkin 1994) that directly affect crop yield. Precision agriculture can also contribute to the long-term sustainability of agriculture (Bongiovanni and LowenbergDeboer 2004). Consequently, the objective of this study was to analyze the spatial variability of the physical properties of a clayey Oxisol under coffee cultivation.

## 2. Material and methods

The experiment was conducted at a coffee plantation (18 ° 42'28.9 "S 47 ° 33'27.0" W) with a clayey Oxisol (Embrapa 2013). The area had been cultivated with *Coffea arabica* for several years and was replanted in January 2012 at a spacing of 3.8 x 0.7 m. Starting in March 2015, a 14-ha area was sampled at 61 grid points, spaced at 50 x 50 m (Figure 1).

A Global Navigation Satellite System (GNSS) receiver (Hipper double-frequency L1 / L2) was used to determine the coordinates of the grid points. One of the receivers was used as a basis for GNSS screening, providing relative static positioning. The data were then evaluated using Topcon Tools 8.2.3 software and two reference stations from the Brazilian continuous-monitoring network (*Rede Brasileira de Monitoramento Contínuo* - RBMC) located in Uberlandia and Rio Paranaiba in the state of Minas Gerais. Given the varying relief of the site, soil samples were taken from two layers (0 - 0.1 m and 0.1 - 0.2 m) at all grid points. These samples were used to determine the soil physical properties.

Soil resistance to penetration was determined at both layers (0-0.1 and 0.1-0.2 m) using an impact penetrometer (Stolf 1991). Simultaneously, soil gravimetric water content was also evaluated (Embrapa 2011).

Undisturbed soil samples were also collected using cylinders (length = 0.03 m, diameter = 0.048 m, volume = 53.16 $10^{-6}$ $m^3$) at the 0 to 0.1 m and 0.1 to 0.2 m layers. These samples were then saturated to determine total porosity and soil density (Embrapa 2011).

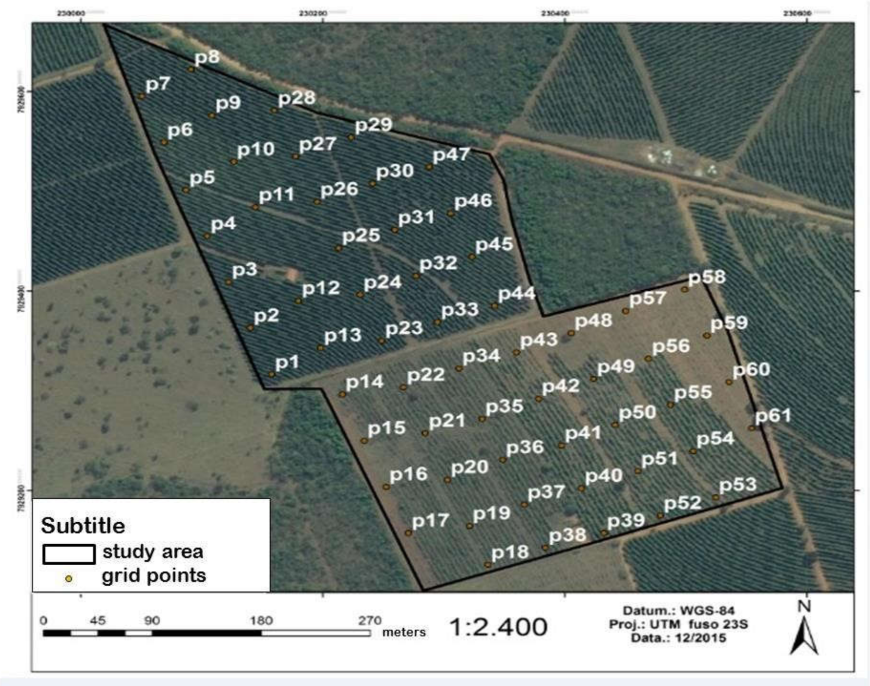

Figure 1. Study area - Monte Carmelo, Minas Gerais, Brazil

Descriptive statistics (mean, variance, coefficient of variation, asymmetry coefficient, and kurtosis coefficient) were obtained for each variable to determine the distribution and variation of the data. Minimum, maximum and amplitude values of the data were also analyzed.

Geostatistics were used to define the spatial variability model of the soil physical properties. Radiographic analysis was performed using semivariograms and semivariance was determined for each variable. Afterwards, semivariance □(h) versus distance (h) was graphed and used to adjust the semivariogram model to the experimental data. Semivariance and the semivariogram model were calculated using GS+ geostatistics software (Robertson 1998).

After defining the semivariogram model, spatial distribution maps were generated for each of the variables using interpolation via the kriging method. A cross-semivariogram was also used to determine spatial correlation among properties.

The mathematical models were fit to semivariograms using the"*Jack-knifing*" validation method, where the mean and variance of the reduced errors were evaluated (Souza *et al.* 1997) considering spherical, exponential, linear and Gaussian models.

## 3. Results and discussion

### *3.1 Analysis of statistical variability*

We classified variation (CV) in our descriptive statistics using the system proposed by Warrick and Nielsen (1980), where CV < 12% is considered low, 12% < CV < 60% is average and CV > 60% is high. Thus, Table 1 shows that the soil density, total porosity and soil water content variables presented low CV in both layers, and could be considered homogeneous, while the CV of soil resistance to penetration was average in both layers. Note that the soil resistance variable was more heterogenous than the other variables.

Table 1. Descriptive statistics for soil bulk density (Ds, in g cm$^{3}$), total porosity (Pt, in m$^{3}$ m$^{-3}$), soil water content (U in kg$^{1}$ kg$^{-1}$) and soil resistance to penetration (RSP, in MPa), in different layers

| Variable | Descriptive statistics | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Min | Max | Amp | M | Var | As | CV | Kurt |
| Ds 0-0.10m | 1.04 | 1.42 | 0.38 | 1.23 | 0.005 | -0.13 | 6.07 | 0.039 |
| Ds 0.10-0.20m | 1.05 | 1.37 | 0.31 | 1.23 | 0.006 | -0.21 | 6.40 | -0.60 |
| Pt 0-0.10m | 0.44 | 0.59 | 0.15 | 0.50 | 0.001 | 0.59 | 7.03 | -0.14 |
| Pt 0.10-0.20m | 0.41 | 0.58 | 0.16 | 0.49 | 0.001 | 0.12 | 6.75 | 0.33 |
| U 0-0.20m | 0.22 | 0.347 | 0.12 | 0.26 | 0.0006 | 0.519 | 0.09 | 0.50 |
| RSP 0-0.10m | 2.63 | 6.87 | 4.24 | 4.14 | 0.57 | 1.07 | 18.29 | 2.02 |
| RSP 0.10-0.20m | 5.47 | 13.08 | 7.60 | 7.74 | 2.21 | 1.39 | 19.23 | 2.28 |

*Min: Minimum value; Max: Maximum value; M: Mean; Var: Variance; As: Asymmetry; CV: coefficient of variation; Kurt: Kurtosis coefficient.

Variation was low (asymmetry values near zero) for of all the soil physical properties (mean values) except soil resistance to penetration.

Mean soil density was the same and total porosity nearly the same in both layers, while soil resistance to penetration was higher in the 0.1-0.2 m layer.

While these conclusions are useful, maps and semivariograms are needed to better understand variations in these physical properties.

### *3.2 Semivariogram analysis*

Geostatistics showed that all the soil indicators were spatially dependent. Thus, none of the variables demonstrated a random distribution within the study area (Table 2).

Table 2. Adjusted semivariogram parameters for soil density (Ds, in g cm$^{-3}$), total porosity (Pt, in m$^{3}$ m$^{-3}$), soil water content (U, in kg$^{1}$ kg$^{-1}$) and soil resistance to penetration (RSP, in MPa)

| Indicator | Parameters | | | | | |
|---|---|---|---|---|---|---|
| | Model | Co | Co+C1 | Co/(Co+C1) | r | R$^{2}$ |
| Ds 0-0.10m | Exponential | 0.00101 | 0.00637 | 15.85 | 43.00 | 0.640 |
| Ds 0,10-0.20m | Spherical | 0.00116 | 0.00641 | 18.10 | 159.10 | 0.969 |
| Pt 0-0.10m | Gaussian | 0.00010 | 0.00126 | 7.936 | 45.70 | 0.431 |
| Pt 0,10-0.20m | Linear | 0.00054 | 0.00108 | 50.00 | 270.35 | 0.942 |
| U 0-0.20m | Exponential | 0.00002 | 0.00067 | 2.985 | 55.20 | 0.781 |
| RSP 0-0.10m | Exponential | 0.351 | 0.898 | 39.08 | 445.60 | 0.677 |
| RSP 0.10-0.20m | Exponential | 0.608 | 2.934 | 20.72 | 142.80 | 0.822 |

*Co: 'pepita' effect; Co+C1: baseline; Co/(Co+C1): Degree of spatial dependence in percentage, being classified in: < 25% = strong; between 25 and 75% = moderate and > 75% = poor (Cambardella *et al*., 1994); r: range.

Soil density (in both layers), total porosity (in the upper layer), soil water content and soil resistance to penetration (in the 0.1-0.2 m layer) showed a high degree of spatial dependence. However, total porosity (0.1-0.2 m layer) and soil resistance to penetration (0-0.1 m layer) showed moderate spatial dependence (Cambardella *et al.* 1994). These results clearly show that properties at a given geo-referenced point are more closely related to the values at neighboring points than to those at other points throughout the site, thus demonstrating the importance of this study.

The models that best fit the soil density property were exponential and spherical at the 0-0.10m and 0.1-0.2m layers, respectively. The Gaussian and linear models provide the best fit for total porosity in the 00.10 m and 0.1-0.2 m layers, respectively, while the exponential model provided the best fit for soil resistance to penetration in both layers.

This variation shows that there is distance among the results from each soil layer and for each property. Soil resistance to penetration in the upper layer showed the greatest distance (445.6 m) while soil density in the 0-0.10 m layer showed the shortest distance (43 m).

### *3.3 Spatial distribution of soil physical parameters*

Figures 2a and 2b show that the lowest density values were found in the lower left of the map (lowest value = 1.09 Mg m$^{-3}$) while the highest values were found both in the upper sector and in longitudinal bands spanning the center of the map. Carvalho *et al.* (2013) evaluated soil density under coffee cultivation and found similar values that varied between 1.0 and 1.16 Mg m$^{-3}$. Sites with less soil mobilization may have higher soil density values. This circumstance is very common in coffee cultivation since it is a perennial monoculture where weeds are only removed from between rows. Thus, the soil is only exposed during the harvest when traffic from agriculture machinery is high, which increases soil density.

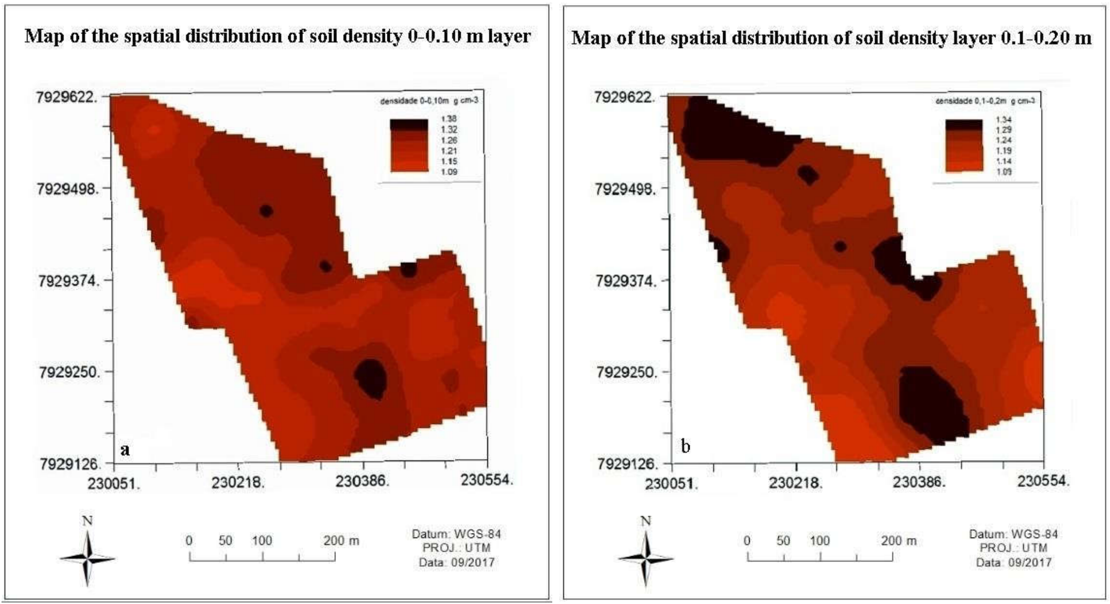

Figure 2. Spatial distribution of density in a clayey Oxisol at 0-0.10 m (2.a) and 0.1-0.20 m (2.b). Monte CarmeloMG-Brazil.

However, soil density also varies due to differences in soil texture, topography and management type. Goedert *et al.* (2002) noted that the research community has not reached a consensus on a specific soil density value that defines whether a given soil is compact or not.

Matiello *et al.* (2005) studied young plants of arabica coffee and found that the roots could penetrate soil layers with densities of up to 1.2 g cm$^{-3}$, whereas root development was quite limited in soil with densities of 1.20 to 1.35 g cm$^{-3}$. The mean values for total porosity (Table 1) were 0.50 and 0.49 m$^3$ m$^{-3}$ for the 0-0.1 and 0.1-0.2 m layers, respectively. The maps produced by ordinary kriging (Figures 3.a and 3.b) show that the values were distributed from 0.59 to 0.44 m$^3$ m$^{-3}$. Porosity was lower in the 0.1-0.2 m layer where soil density was higher. This condition expels air from the pores, which leads to particle rearrangement and denser, more compacted soil (Dias Júnior and Pierce 1996).

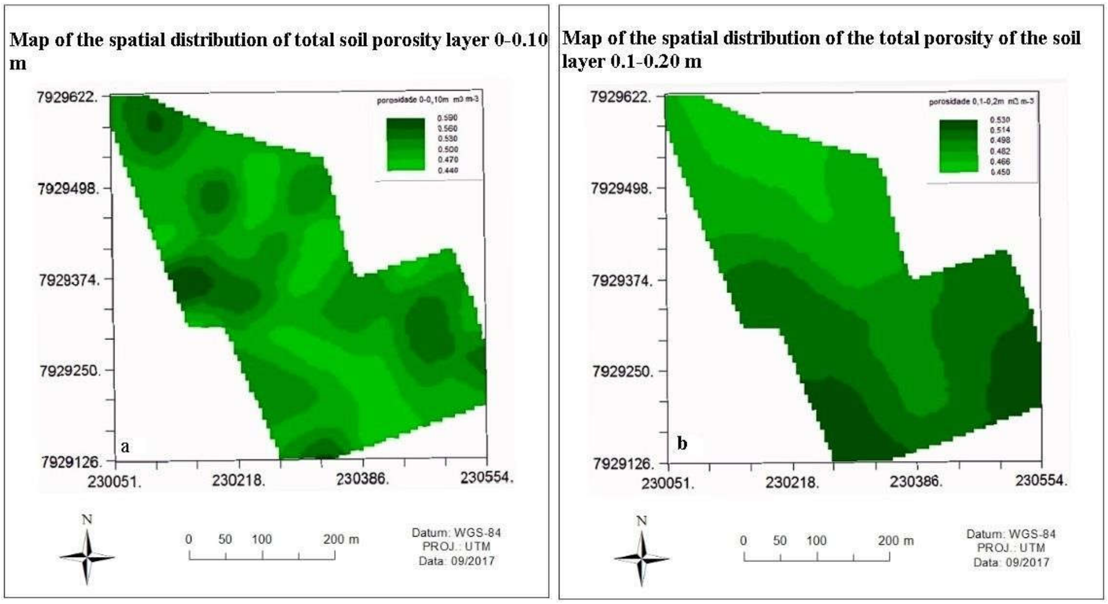

Figure 3. Spatial distribution of the clayey Oxisol total porosity, in the layers 0-0.10 m (3.a) and 0.1-0.20 m (3.b). Monte Carmelo-MG-Brazil.

Camargo and Alleoni (1997) stated that an ideal soil should have 0.5 m$^3$ m$^{-3}$ of total pore volume, but noted that this percentage varies considerably from soil to soil where pedogenetic factors and crop management practices are significant.

Vomocil and Flocker (1996) consider that a macropore volume of 0.1 m$^3$ m$^{-3}$ is the critical limit needed for satisfactory gas exchange and drainage. Thus, based on this criterion, most of our study area is favorable for coffee cultivation.

The roots of coffee plants are extremely sensitive to soil aeration that in turn depends on soil structure and the quantity and ratio of macropores and micropores (Guimarães and Lopes 1986). Matiello *et al.* (2002) stated that exposed, excessively clayey soils hinder the development of coffee roots because raindrops hitting the soil surface tend to disintegrate, remove and translocate particles, which causes pore clogging.

The mean values of soil resistance to penetration (Table 2) were 4.14 and 7.74 MPa, in the 0-0.1 and 0.1-0.2 m layers, respectively. The geostatistical maps in Figures 4a and 4b show that there was no pattern between the layers. In other words, soil resistance at any given grid point differed by layer, map and location.

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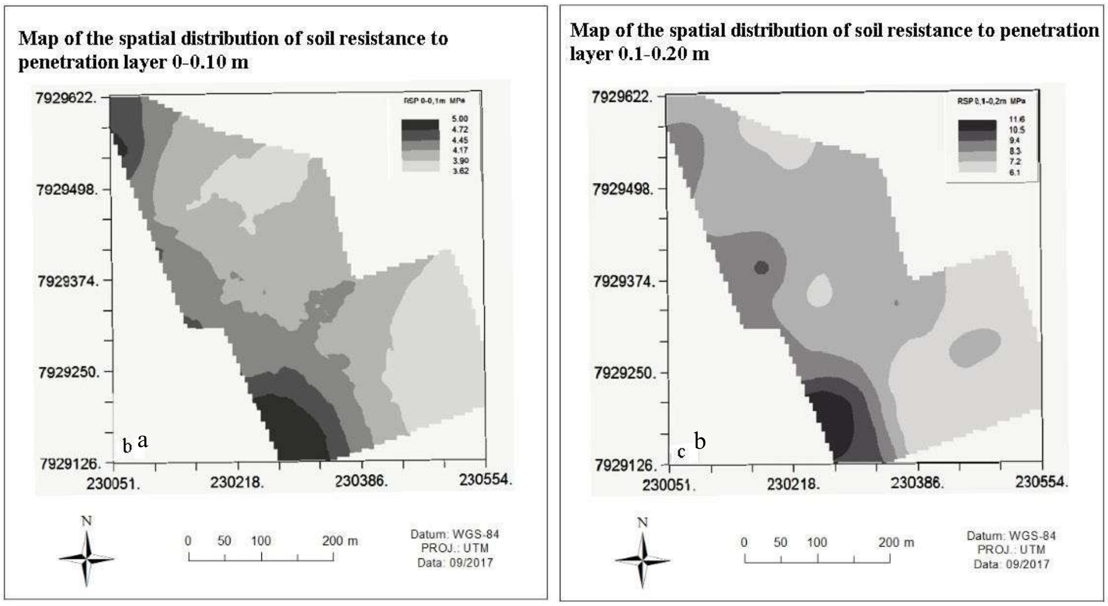

Figure 4. Spatial distribution of soil resistance to penetration in a clayey Oxisol at 0-0.10 m (4.a) and 0.10.20 m (4.b). Monte Carmelo- MG-Brazil.

Carmo *et al.* (2011) found that soil resistance to penetration values were higher between the rows, where agricultural equipment passes, than under the canopy and added that these values were higher under mechanized coffee cultivation than under non-mechanized coffee cultivation or native forest.

In the current study, the highest soil resistance to penetration values (Figures 4a and 4b) were found in areas with the lowest soil water content (Figure 5). According to Almeida *et al.* (2012), soil resistance to penetration is strongly influenced by soil water content at an exponentially decreasing rate (i.e., the lower the soil water content, the exponentially higher the soil resistance to penetration). Bergamin *et al.* (2010) studied a direct sowing system and found differences in soil resistance to penetration down to 0.1 m under mechanized traffic. In the current study, soil resistance to penetration was higher in the 0.1-0.2 m layer.

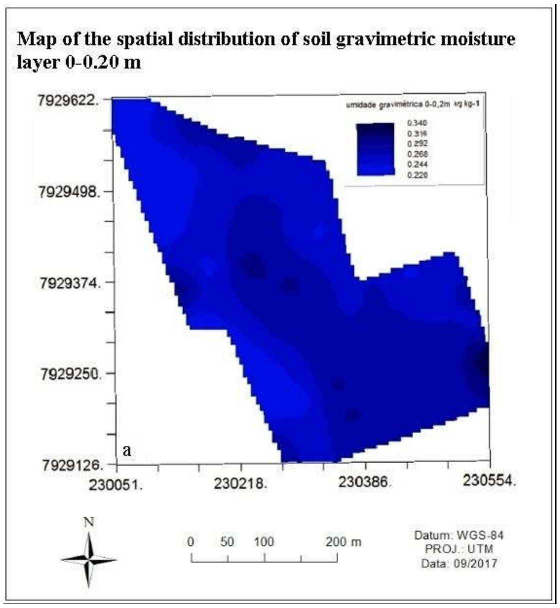

Figure 5. Spatial distribution of soil gravimetric water content in a clayey Oxisol (0-0.20 m layer). Monte Carmelo, MG, Brazil.

The soil just outside of the canopy in coffee plantations is not only where most mechanized traffic occurs but also where most water and nutrient-absorbing roots are located. Given this observation and that all the physical properties measured in the current study presented a degree of dependence, we conclude that geostatistics is an important tool for making decisions related to soil management in coffee plantations, which underlines the need to monitor soil physical properties in this region.

## 4. Conclusions

Our analysis of the spatial variability of physical indicators showed that geostatistics and mapping could be useful in making decisions related to soil management in coffee plantations and especially regarding soil sustainability.

We also found that the evaluated variables showed a strong or moderate degree of spatial dependence, demonstrating that these variables did not behave randomly within the study area.

## 5. Acknowledgement

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