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Soil moisture in the root zone and its relation to plant vigor assessed by remote sensing at management scale

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ABSTRACT

Vegetation index derived from satellite data can be indirectly utilized for obtaining information on moisture in the soil root zone in cropped areas, considering that the soil profile moisture in many regions of the world is the main factor controlling plant vigor. In this context, the aims of this work were: (i) to verify the relationship between moisture in the soil profile (until 100-cm depth) and the vigor of the plant, as measured by Vegetation Index EVI-2, (ii) to identify which is the plant vigor response time delay for soil moisture at different depths of the profile, (iii) to propose linear equations for estimating soil moisture by EVI-2, and (iv) to test the hypothesis that is possible to identify, with the aid of the EVI-2, which soil depth can be considered the effective depth of water absorption by plants. Data were collected in a coffee crop area at São Roque de Minas, Upper São Francisco River basin, Minas Gerais state, Brazil. The soil moisture was measured with a multi-sensor capacitance (MCP) probe, from March to December, 2010, and the coffee plant vigor was evaluated by Vegetation Index EVI-2. It was verified a correlation between vegetative vigor of coffee plants and soil moisture in the root zone. Linear equations were generated to estimate soil moisture in this zone using vegetation indexes at soil management scale (soil profile explored by the crop). There is a response time delay of coffee vigor to soil moisture, and this time varies according to depth and water content in the soil profile. The highest correlation was obtained at a depth of 60 cm, indicating that this depth is the one that best reflects the plant's water status.

1. Introduction

Water content in soil profiles changes with time as result of rainfall distribution, soil capillarity and drainage, run-off, evapotranspiration, and irrigation (Silva, 2012). It is one of the main factors that affect plant growth and vigor (Magagi and Kerr, 2001; Wang et al., 2007). However, the high spatial and temporal variability of soil moisture influenced by the heterogeneity of soil texture, topography, vegetation, and climate in the natural environment makes soil moisture difficult to measure (Kong et al., 2011).

For coffee trees cultivated in deep soils, such as the main soils in the Cerrado region of Brazil, the main limiting factor is water due to lengthy dry spells during the rainy season (Evangelista et al., 2002). Water sources for irrigation in São Francisco River basin, included in the Cerrado region, are becoming scarce (ANA, 2011); therefore, strategies aiming for the optimization of water use in agricultural systems are crucial (Serafim, 2011; Serafim et al., 2011; Silva, 2012). These soils have low Ca^{2+} contents and high Al^{3+} saturation which prevent the root system from growing deeply into depths where moisture is adequate. Gypsum amendments presumably can mitigate these chemical limitations and stimulate the root system to grow deeper in the soil (Serafim et al., 2011; Silva, 2012; Silva et al., 2012a). However, these field observations need to be confirmed by space-temporal dynamics studies of soil moisture monitoring (Silva, 2012).

Although remote sensing data has been successfully used to estimate the moisture content near the soil surface (Mulder et al., 2011), this information is limited to a few centimeters below the surface (±5 cm) (Crosson et al., 2005) and does not allow access to the whole zone from where water can be absorbed by roots (Liu et al., 2012); besides, the sensors that are used in such studies are less sensitive in vegetated areas (Narayan et al., 2004). Thus, Crow et al. (2008), Liu et al. (2012), Schnur et al. (2010) and Wang et al. (2007) used vegetation indexes, obtained by remote sensing, to measure plant

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Abbreviations: EVI, Enhanced Vegetation Index; NDVI, Normalized Difference Vegetation Index; MCP, multi-sensor capacitance probe; R^2, coefficient of determination; r, Pearson correlation coefficient; CSDT, continuous surface depth versus time; θ, water content ($m^3 m^{-3}$).

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vigor and relate it to the soil moisture in the root zone, in view of that the soil moisture status also influences vegetation growth and thereby changes the spectral characteristics of the vegetation (Wang et al., 2010).

The vegetation indexes combine satellite data at different wavelengths to separate vegetation patterns in a single scene or image (Rouse et al., 1973); this is commonly used for a wide variety of studies involving vegetation (Jiang et al., 2008). Examples of widely used vegetation indexes in environmental studies are NDVI (Normalized Difference Vegetation Index) and EVI (Enhanced Vegetation Index), both available at the Terra/MODIS satellite (Moderate Resolution Imaging Spectroradiometer). The NDVI uses the near infra-red and red bands, and despite the usefulness of that index for vegetation studies, it still shows some limitations, such as the effective influence of the soil conditions and saturation of the index in high biomass areas (Jiang et al., 2008). Due to these limitations, the EVI was developed to increase the signal from the high biomass vegetation and to reduce the atmospheric and soil influences on the index values. Besides the near infra-red and red bands, the EVI also uses the blue band (Méndez-Barroso et al., 2009). Jiang et al. (2008) developed the EVI-2, which produces results very similar to EVI. However, it does not use data in the blue wavelength which is originated from the Terra/MODIS satellite, and it is free of charge at the virtual laboratory of the National Institute of Space Research (INPE) for any geographical coordinate in South America, since the year 2000, in the following site: http://www.dsr.inpe.br/laf/series/. This site was developed within the concept of a remote sensing virtual laboratory (Freitas et al., 2011), aiming to furnish support to studies and analyses involving land use and coverage changes, and it has a friendly interface being easy to handle for different users.

The vegetation indexes can quantify the leaf area and the health and vigor of the vegetation, which are influenced, among other factors, by climate and soil moisture content (Liu et al., 2012). This happens because plants adjust their biological processes to match local climate and water availability in the soil (Schnur et al., 2010). However, as observed by Liu et al. (2012), Méndez-Barroso et al. (2009), Schnur et al. (2010) and Wang et al. (2007), plants need time to respond to changes in atmospheric conditions, which is called "response time delay" in the present work. According to Zhang et al. (2011), this delay reduces the relation between the vegetation index and the soil moisture, and this aspect needs to be taken into consideration when the vegetation index is used to estimate soil moisture.

More recently, Bezerra et al. (2013), utilized data from Landsat satellite to estimate soil moisture at root zone for cotton crop in the Brazilian semi-arid; however, they did not use vegetation indexes but an empiric equation proposed by Scott et al. (2003). Chen et al. (2014) utilized NDVI to quantify the impact of soil moisture on vegetation at large spatial and long-term temporal scales in Australia, but they work only at 0–10 cm depth, Similarly, Wang et al. (2010) utilized NDVI and surface temperature in China's Yongding River basin base to estimate soil moisture at 0–20 cm depth. Wang et al. (2007) successfully estimated the soil moisture in the root zone (until 100 cm depth) based on vegetation indexes. The authors found that NDVI is a good tool for mapping soil moisture content in the root zone in large areas under semi-arid and humid climates. It is important that correlation studies between vegetation index and soil moisture be based on field data considering the specificities of crops, soil properties, and climate of a particular region (Wang et al., 2007); these factors were included in the present study.

In this context, the objectives of this work were: (i) to verify the relationship between moisture content in the soil profile (until 100 cm depth) and the vegetative vigor of the plants, measured by the EVI-2; (ii) to identify the response time delay of plant vigor to the soil moisture at different profile depths; (iii) to propose equations to estimate the soil moisture by using EVI-2; and (iv) to test the hypothesis that EVI-2 can identify the depth where water is more available for the plants, which is of paramount importance for the crop management in regions having a well-defined dry season as in the present study.

2. Material and methods

2.1. Study area

This study was conducted in a crop area with two-year-old *Coffea arabica* L. Catucaí cultivar, spaced 2.5 m between rows and 0.65 m between plants. The experimental area is located at São Roque de Minas, Upper São Francisco River Basin, state of Minas Gerais, Brazil, with coordinates of 20°15′ 24″ S and 46°18″ WGr, at an average altitude of 900 m. The climate in this area is Cwa, according to the Köppen classification, with an annual average precipitation of 1344 mm, a well-defined dry season between May and September, an average annual temperature of 20.7 °C, and an average relative humidity of 60% (Menegasse et al., 2002).

The coffee crop was implanted on a typic dystrophic Red Latosol (EMBRAPA, 2013), corresponding to an Anionic Acrustox (Soil Taxonomy, 1999), which is representative of large areas in the Cerrado region and in Brazil. Some soil characterization data are presented in Table 1.

The soil management in the area is described in Serafim et al. (2011) and summarized as follows: The planting furrows, 0.50 m wide and 0.60 m deep, were accordingly limed and fertilized for the coffee crop. After planting the seedlings, high doses of agricultural gypsum were applied on the soil surface. Brachiaria grass was planted between the plant rows to promote soil covering and nutrient cycling (Serafim et al., 2011). Organic material on the soil surface near the gypsum band was scraped and swept towards the plant row.

2.2. Soil moisture data acquisition

The water content in the soil profile was instantly measured with a multi-sensor capacitance probe (MCP) (*Profile probe–Delta T*, Cambridge, UK, ±0.05 $m^3\ m^{-3}$). Since it is a non-destructive method, it is possible to monitor soil moisture at different depths at the same time. Previous calibration of the probe was performed, allowing to obtaining high accuracy measurements (Silva et al., 2012b). The probe was installed in the planting row, between plants, for measuring soil moisture at 10-, 20-, 30-, 40-, 60-, and 100-cm depth, during 276 days, from March 2010 to December 2010, which includes the whole dry season of 2010 plus the beginning of the rainy season of 2010–2011. Soil moisture was recorded all day long at 4 h intervals.

2.3. Plant vigor data acquisition by EVI-2

To evaluate plant vigor, data of three cells (pixels), with a spatial resolution of 250 m, from 17 previously processed and smoothed EVI-2 images (Freitas et al., 2011) were used. Those three cells encompass

Table 1
Soil physical and chemical analyses[a] of the 0–0.2 m layer (Ap horizon) and 0.6–0.8 m layer (Bw horizon) of the soil used in this study.

Variable	Horizon sampled	
	Ap	Bw
Organic matter (g kg^{-1})	38	16
Bulk density (Mg m^{-3})	0.89	0.79
Total porosity ($m^3\ m^{-3}$)	0.67	0.65
Microporosity ($m^3\ m^{-3}$)	0.45	0.41
Macroporosity ($m^3\ m^{-3}$)	0.22	0.24
Clay (g kg^{-1})	763	819
Silt (g kg^{-1})	198	148
Sand (g kg^{-1})	39	33

[a] EMBRAPA (1997).