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Critical soil moisture range for a coffee crop in an oxidic latosol as affected by soil management

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ABSTRACT

Soil management systems affect water availability to plants which is essential for perennial crops such as coffee, especially in initial years of crop establishment. The objective of this study was to investigate the effects of additional gypsum and intercropping on the least limiting water range (LLWR) in an Oxidic Latosol. We also introduced in this study a lower limit of LLWR based on crop evaporation depletion factor (p) and a critical moisture (θ^*) approach. Three management systems were tested: conventional (CV-0), conservation with *Brachiaria decumbens* and additional gypsum [7 Mg ha^{-1} (G-7) and 28 Mg ha^{-1} (G-28)]. Three trenches (1.0 m depth) were dug for each management system for 0–0.05, 0.15–0.20 and 0.65–0.70 m depth sampling. Results showed that LLWR increases with bulk density (Bd) until a first restriction to root growth occured, due to limited aeration. LLWR was always greater than zero, indicating adequate soil quality and water stress was the main plant growth limiting factor. Adoption of θ^* as LLWR lower limit allowed an average reduction of 50.2% in available water. But, this reduction was significantly greater for greater Bd, so this indicates that LLWR modeling is an aid in understanding soil management effects. At 0.15–0.20 m depth, LLWR was greater in G-28 than CV-0. Also at 0.65–0.70-m depth, LLWR in G-28 was the greatest, followed by G-7 and CV-0 treatment. G-28 showed greater LLWR than CV-0 in the interrow position. These results support the hypothesis that the use of *Brachiaria* in interrow and additional gypsum contributes favorably to modify the soil profile conditions for better coffee root development in conservation management systems.

1. Introduction

Clayey Latosols of the Cerrado biome have great potential for grain production when their chemical limitations are overcome by applying soil amendments and fertilizers (Castro and Crusciol, 2013; Goedert, 1983), particularly in management systems with input of organic matter (Lal, 2006). These clayey Oxisols may exhibit a soil bulk density of less than 1.0 kg dm^{-3} in the B horizon; in this condition, the porosity can be greater than 0.70 m^3 m^{-3} due to their oxide-rich mineralogy. Gibbsite can play a fundamental role in the development of granular structure in such soils (Ferreira et al., 1999a; Reatto et al., 2007; Santos et al., 2014; Serafim et al., 2013b). These soils generally have high water retention because of their substantial microporosity. However, they typically have low availability of water to plants because of the abrupt transition from very large pores to very small pores (Carducci et al., 2013; Silva et al., 2014Silva et al., 2014).

Low availability of water is primarily caused by low rainfall or poor rainfall distribution, but also is dependent on the structural quality of the soil, which can induce low water retention in the available range, causing less water intake by plants (Safadoust et al., 2014). A proper soil management system is therefore essential to maintain or increase productivity in agriculture and to avoid soil degradation (Lal, 2000; Verma and Sharma, 2008). Soil structure affects the availability of water, oxygen, and nutrients to

Abbreviations: LLWR, least limiting water range; p, crop evaporation depletion factor; θ^*, critical ou threshold moisture; FC, field capacity; PWP, permanent wilting point; AW, plant available water; Bd, bulk density; PR, penetration resistance; AP, air-filled porosity; Ψ, matric potential; θ, water content (m^3 m^{-3}).

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plants, in addition to penetration by roots (Bronick and Lal, 2005; Guedes Filho et al., 2013).

During cultivation of perennial species such as coffee, the initial soil and water conditions are critical for growth and establishment of a healthy plant in addition to obtaining high yields (Dias et al., 2007; Faria and Siqueira, 2005; Fialho et al., 2010; Serafim et al., 2013a). For instance, when a conventional management system that uses shallow furrows and where the soil is superficially chemically amended, the root system stays shallow in the first 2 years. Growth is limited in the short drought periods in the rainy season because the soil has very little available water in this part of the profile within a few days after rainfall (Santos et al., 2014; Serafim et al., 2013a; Silva, 2012; Silva et al., 2014). Considering that water stress can reduce the productive potential of the coffee crop by up to 80% (DaMatta and Ramalho, 2006), it is necessary to use strategies to improve the physical attributes of the soil profile and promote rooting to greater depths.

To address this issue, farmers from the Cerrado region of Minas Gerais have implemented a set of vegetation and soil conservation techniques i.e., 60-cm-depth furrows, chemical correction and fertilization, cultivation of *Brachiaria* between rows of the coffee crop, and application of additional gypsum to the soil surface. These practices characterize a different management system (Serafim et al., 2011) which maintains adequate physical quality of the soil and increases its chemical quality (Ramos et al., 2013; Serafim et al., 2013b; Silva et al., 2012; Silva et al., 2013). Consequently, there is adequate root development of the coffee tree (Carducci, 2013; Serafim et al., 2013a). However, there is still a lack of information comparing this conservation management system with the conventional system, particularly focusing on the soil water availability for coffee plants.

Soil is the main source of water for crops, and the quantification of water availability can be an indicator of soil physical quality. Plant available water (AW) is classically defined as the moisture range between field capacity (FC) and permanent wilting point (PWP), and water is assumed to be equally available between these limits (Kirkham, 2005; Veihmeyer and Hendrickson, 1927). However, it does not take into consideration possible physical limitations that arise in soil under intensive cultivation conditions. Therefore, AW may not be an adequate indicator of physical quality because compaction (an increase in soil bulk density (Bd)) under intensive management systems can also lead to an increase in both water parameters (FC and PWP) with no substantial change in AW, as was previously shown (Reynolds et al., 2008). On the other hand, Taylor (1952) demonstrated that crop production can be reduced even before moisture in the soil reaches PWP, without soil physical limitations, indicating that water is not equally available to plants between FC and PWP, and, a decrease in water content can decrease plant actual transpiration (Denmead and Shaw, 1962). Attempts to refine the approach of AW were made by Letey (1985), who established the non-limiting water range approach, and later by Silva et al. (1994), who developed the approach of least limiting water range (LLWR). Both approaches included, as physical constraints to plant growth, aeration and mechanical impedance to root elongation, in addition to water restriction. LLWR was defined as the range in soil water content in which those physical constraints to plant growth are minimal (Silva et al., 1994). LLWR has been shown to be highly sensitive to structural changes caused by land-use and management, and it has been validated under different situations (Chen et al., 2014; Guedes Filho et al., 2013; Lapen et al., 2004; Leão et al., 2006; Safadoust et al., 2014; Serafim et al., 2013b; Silva et al., 1994; Silva et al., 1997; Silva et al., 2011; Tormena et al., 1998; Verma and Sharma, 2008; Zou et al., 2000).

However, some studies have shown no correlation between plant growth and LLWR (Benjamin, 2003; Gubiani et al., 2012). In this sense, improvements on LLWR have been proposed associated with calculations of its limits, such as the following examples: (1) test of matric potential associated with FC (Asgarzadeh et al., 2010), which has a significant influence on the water availability, and (2) proposal of a unified calculation of the LLWR upper limit (Mohammadi et al., 2010), which takes into consideration restrictions of root aeration. The latter is more crop-specific because it uses plant physiological parameters. With regard to the lower limit, it has been shown that penetration resistance (PR) is the parameter that most limits LLWR in Brazilian Latosols (Betioli Júnior et al., 2012; Leão et al., 2006; Petean et al., 2010; Tormena et al., 2007, 1999b). However, those soils had low gibbsite content in their clay fraction. When soils are more gibbsitic, the soil is less dense and the hydraulic restriction (PWP) is greater than the mechanical, analysed by LLWR (Serafim et al., 2013a). In this context, in a review of several studies, Håkansson and Lipiec (2000) showed that in low-bulk density soils, during the dry season and despite reduced matric potential, there is no mechanical impedance to the roots. However, hydraulic conductivity is dramatically reduced, limiting the supply of water and nutrients to plant roots. The authors therefore suggested the inclusion of hydraulic conductivity in LLWR to detect water stress.

Accordingly, the LLWR approach has limitations, such as inaccuracy of its lower limit of water availability (PWP), which is associated with the AW concept limitations. In addition to limitations of estimating AW, such as FC and PWP criteria (Asgarzadeh et al., 2010; Silva et al., 2014), there is a conceptual limitation, because AW keeps the plant alive instead of keeping it agriculturally productive (Van Lier, 2000). Because water uptake (transpiration) is severely reduced before PWP is reached (Allen et al., 1998; Denmead and Shaw, 1962; Thornthwaite and Mather, 1955) as a function of the reduction of hydraulic conductivity (Van Lier and Libardi, 1997) and of the actual water content (Metselaar and de Jong van Lier, 2007) production may be limited.

Thus, assuming a value for soil moisture below which there is a reduction in stomata opening and consequently crop growth potential because of a decrease in transpiration rate due to water stress, defined as critical or threshold soil water content (θ^*) (Allen et al., 1998; Berg and Driessen, 2002; Doorenbos and Kassan, 1979; Eitzinger et al., 2004; Thornthwaite and Mather, 1955; Van Lier, 1997), seems to be more appropriate than using PWP. The use of θ^* maintains the practical aspect of the calculation of the lower limit of LLWR, and improves the estimate of modeling of non-limiting soil water range for crop yield. So, the objectives of the present study were as follows: (1) to quantify LLWR on Oxídic Latosol under soil management system for improving the soil quality in the subsurface; (2) to evaluate the hydro-physical conditions for root development in the soil profile up to 0.70 m through LLWR; (3) to check for increasing plant available water with use of intercropping a grass in the interrow; and (4) to introduce into the LLWR estimate the θ^* approach as the lower limit instead of PWP using the available water factor (p) (Allen et al., 1998; Doorenbos and Kassan, 1979). Obtaining θ^* and the p factor is complex because they reflect the evapotranspiration demand, soil hydraulic conductivity, and plant characteristics. However, based on these aspects, we hope to contribute to improving the LLWR estimate for a specific species in a simplified manner. The main hypothesis of this study is that the maintenance of *Brachiaria* in planting interrow and the application of additional gypsum can substantially contribute to alter the soil profile conditions for improving coffee root development.

2. Material and methods

2.1. Site and soil characteristics

The study was performed in an experimental area in the municipality of São Roque de Minas, at the Physiographic Region of