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Chapter

Soil Management and Water-Use Efficiency in Brazilian Coffee Crops

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Abstract

Brazil is a world leader in coffee production. However, currently, it coexists with recurrent and severe droughts, accompanied by intense heat, strong insolation and low relative humidity. As the cultivation is carried out primarily in the rainy season, these world climate variations have affected crops yields and fruits quality, requiring innovative actions that promote efficient use of water stored in the soil. Among several soil management practices that promote a more rational use of water, deep tillage combined with liming, gypsum and fertilizer amendments lead to an increase in effective depth of coffee roots, therefore reducing water stress. Moreover, intercropping with *Urochloa* sp. is highly efficient in enhancing soil structure, water infiltration and plant available water capacity. Additionally, other innovative techniques and practices are also introduced in this chapter.

Keywords: soil water, soil structure, deep rooting, soil amendments, deep tillage, intercropping

1. Introduction

Adequate soil physical and hydrological conditions are key conditions for full plant development, which is a premise for coffee quality exportation due to requirements for grain quality and crop uniformity [1]. However, in the main coffee producing region of Brazil, there have been severe droughts. Although soils are mostly deep and able to store a large volume of water, they present small effective depth for the development of the root system, resulting in the edaphic drought, which has brought many losses to coffee farmers. This situation is aggravated in soils of oxide mineralogy and with very small granular structure, which condition the formation

of pores with extreme diameters [2]. Thus, it leads to very rapid loss of water stored in very large pores, or to its strong retention in extremely small pores.

A number of measures have been sought by Brazilian researchers to solve the problems, such as selecting drought tolerant plants [3, 4]. However, a measure that has attracted the attention of most producers is the adoption of soil management systems that provide the best development of the root system of coffee crops and physical-hydrological adequacy of the soil.

Therefore, this chapter will discuss the main limitations of soils used in the main coffee growing area of Brazil and the mitigation techniques for soil suitability based on research that have been developed for over a decade.

2. Soil adequacy

2.1 Preparation, planting corrections and rooting

In the past, coffee cultivation was traditionally performed in grooves of 0.40 m × 0.40 m × 0.40 m. From the 1970s, the use of furrows for planting coffee was introduced in large scale. These furrows, open with tractors and with small furrowers, were shallow at 0.30–0.40 m deep and V-shaped, with small width at the bottom. For these reasons, and also due to the fact that under conventional coffee growing conditions soil fertilization was performed on the surface layers, much of the root system was limited to the first 0.40 m depth [5].

With the advancement of knowledge and technologies, it has been found that coffee roots can reach depths well above 1 m when in the absence of physical limitations and when adequate chemical conditions [6–8], such as sufficient calcium, phosphorus and boron contents, are provided [9].

With the development of new soil preparation tools, coffee farmers have been adopting deep furrow associated with soil correction and/or fertilization [10]. In the south and southwest regions of the state of Minas Gerais, deep tillage has often been carried out, allowing the incorporation of phosphate or limestone to a depth of 0.90 m. Due to higher soil turnover, larger amounts of fertilizer can be added in the furrow, correcting the soil in deeper layers and providing a better environment for coffee root development [6, 7, 10, 11].

Coffee cultivation using deep tillage system associated with surface application of additional doses of gypsum presents better drought resistance when compared with crops planted using conventional system, which conditions the permanence of the root system on the soil surface. Regarding the additional operation costs, the practice of deep tillage is compensated by the high crop yields in the first harvest [12]. Nevertheless, there are large variations in production costs, especially considering the price of the product.

Gypsum ($CaSO_4.2H_2O$) is considered a good soil conditioner due to its high mobility in the soil profile, providing calcium and sulfur to the plants, as well as acting as a deep corrective for toxic aluminum (**Figure 1**) [13].

The ability of gypsum to increase Ca^{2+} levels in the deepest soil layers is important for the proper development of the crop root system, especially because Ca^{2+} is the main component of the cell wall, being responsible for root elongation and growth [6–8].

The increase in effective CEC of the subsurface layers in management systems in which gypsum is applied is due to the increase in soil organic matter (SOM) (**Figure 2**). Coffee is mostly grown intercropped with Brachiaria between rows [10]. This grass is periodically mowed and its residues remain in the coffee line, representing continuous input of organic matter to the soil [8]. Thus, SOM contributes to

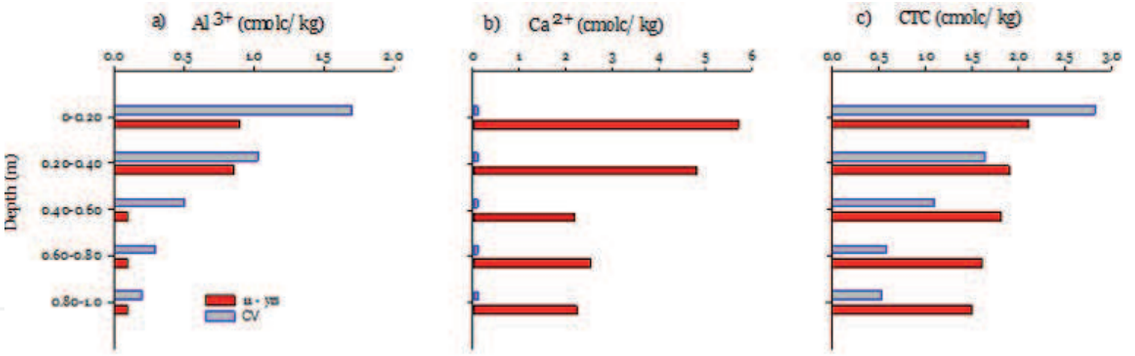


Figure 1.
Contents of Al^{3+} (a), Ca^{2+} (b) and effective CEC (c) in red Latosol under conventional management and after 11 years of deep preparation conservation system and application of 28 Mg ha^{-1} of gypsum. Source: From authors.

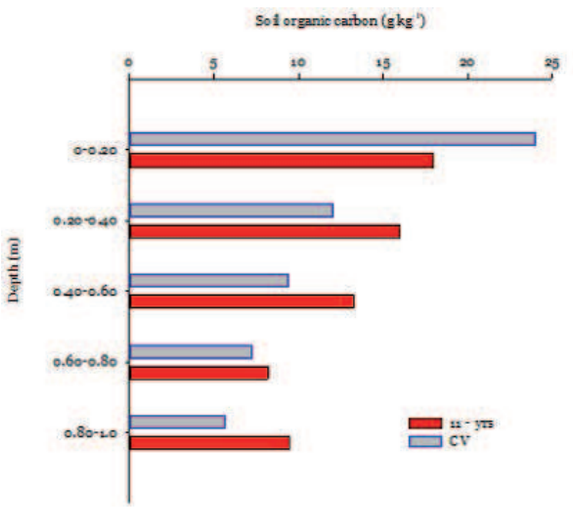


Figure 2.
Average values of organic carbon contents (g kg^{-1}) in red Latosol under conventional management and after 11 years in deep preparation conservation system and application of 28 Mg ha^{-1} of gypsum. Source: From authors.

increased CEC and improved nutrient utilization efficiency by providing a significant number of binding sites for essential elements present in the soil [14].

Studies showed that up to 21% of the carbon added by the roots could be incorporated into SOM [15]. Thus, the biomass of the coffee root system itself, favored by calcium, is also a source of organic matter for the soil and certainly contributed to raise the CEC (**Figure 1**).

Moreover, this management system can be considered efficient in the construction of fertility of Latosols, whose mineralogy is dominated by low chemical activity clay minerals (kaolinite and iron and aluminum oxides in the form of goethite, hematite and gibbsite). In these soils, which are typical of the Brazilian Cerrado biome, organic matter can contribute to up to 80% of negative soil loads [16].

Due to intense soil revolving, tillage management systems promote aggregate breakage, leading to significant structural changes [10, 12, 17]. However, by evaluating a Cambisol after 6 months of implantation of the coffee crop, Serafim et al. [17] observed a reduction in soil density and an increase in total porosity due to the benefits conditioned by the structural relief and construction of soil fertility. Serafim et al. [10] described the presence of coffee root system with average depth in the soil profile of 0.80 and 0.60 m at 6 months after planting for Latosol and Cambisol, respectively. After 1 year, the root system reached 1.40 m in Latossol and 1.20 m in Cambisol.

Serafim et al. [18], using the Least Limiting Water Range (LLWR) technique, found that a Cambisol presented no physical-water limitations after 3.5 years of coffee plantation and the crop implanted in this soil reached productivity much higher than the average of the state of Minas Gerais. It evidences the longevity of the positive effects of deep tillage on soil physical properties. Moreover, Serafim et al. [10, 17–19] and Silva [20] observed positive responses in soil physical properties, such as increase in the volume of large macropores (>147 μm), fine macropores (147–73 μm) and large mesopores (73–49 and 49–29 μm), when evaluating the physical quality of this soil after 5 years of tillage implementation. Similarly, Silva et al. [21] observed a significant increase in LLWR and a significant reduction in soil density when evaluating the structural quality of very clayey Latosol after 2 years of coffee cultivation.

Silva et al. [8] found a significant volume of inter-aggregate pores (macropores) after 3 years of coffee cultivation in Latosols, confirming the benefits of the management system using deep preparation associated with surface gypsum application. In the layer between 0.20–0.40 m of the soil, even after 5 years of cultivation, Silva [20] also found that soil management favored the expressive increase of pore volume of classes 9.0–2.9, 2.9–0.6 and 0.6–0.2 μm (mesopores), which is relevant since a good portion of the water retained in the soil will be available to the plants.

Particularly in Latosols under this management system, it was observed that in the absence of chemical and physical limitations of the soil the coffee root system reached depths greater than 1 m at 3 years of age (**Figure 3**), which is of fundamental importance to ensure crop survival in periods of edaphic drought [8].

Serafim et al. [19] evidenced intense water deficit up to 1.60 m in the crop line, when monitoring moisture of a very clayey and oxidic Latosol with 3.5 years of cultivation in a dry year. The authors attributed the results to the presence of roots that used intensely the available water in this depth of soil. Very thin roots were found in the soil layer between 1.50 and 1.70 m, indicating potential for water use in these deeper soil layers.

Similarly, in Cambisol, Serafim et al. [19] also showed more intense drying in the crop line up to 1.6 m caused by the roots of the plants, since active roots were found in this depth. The authors reported that although the crop does not have water availability in the layers closer to the surface in the dry period of the year, the larger volume of soil explored by the roots contributed to reduce the water deficit.

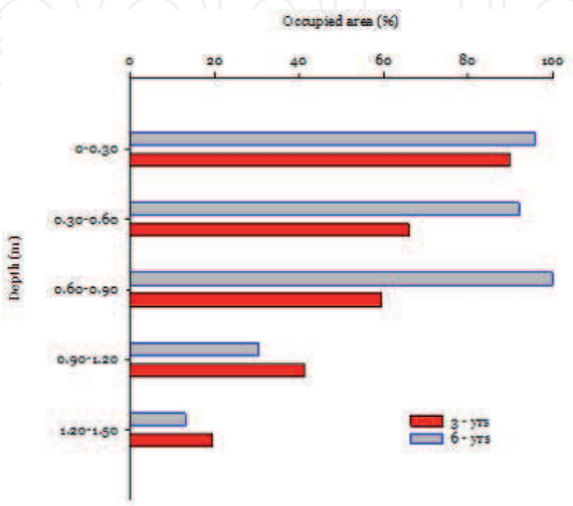


Figure 3.
Area occupied by coffee plant roots along the profile of Rhodic Haplustox. Source: Adapted from Silva et al. [8].

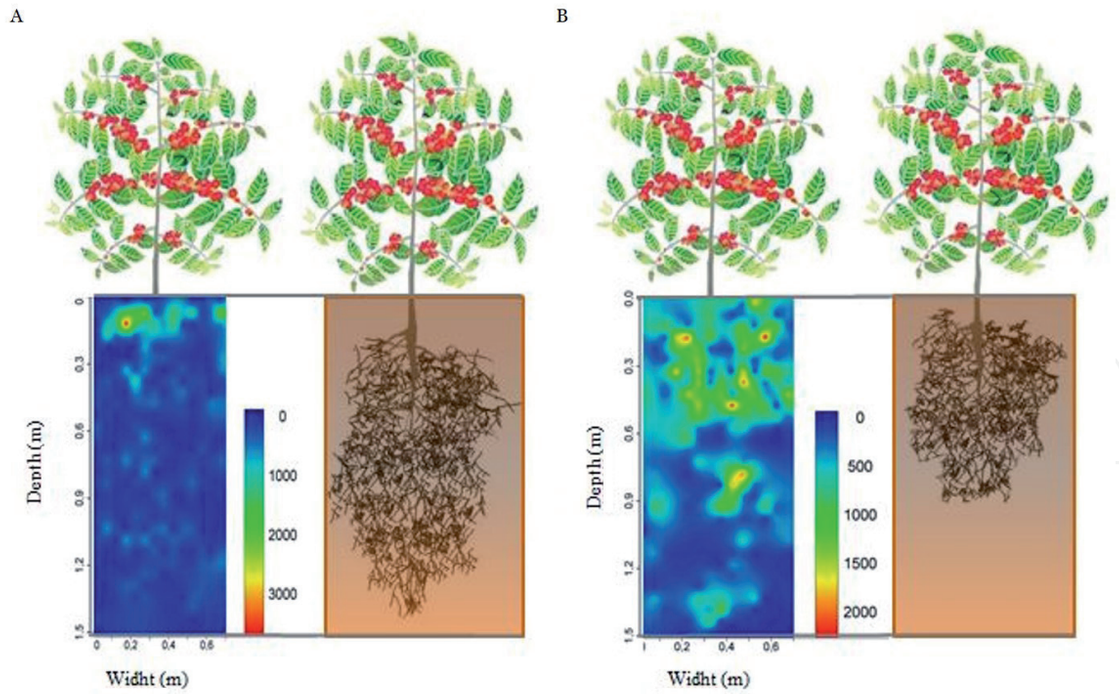


Figure 4.
Root length distribution (mm) in (A) gibbsitic Acrustox and (B) kaolinitic Haplustox both with the multipractice conservation management system for the coffee crop. Source: Adapted from Carducci et al. [7].

Given the above, it is noteworthy that although the benefits of mechanical soil revolving are readily apparent in coffee cultivation after 4 years of management [6, 7, 10, 17–19], studies show that these effects do not last long in some soil classes [22]. In this sense, particularly when soil is revolved, physical improvements to the soil may be temporary, since the durability of the changes depends on the texture and mineralogy of the soil [23].

Silva [20] reported that the deep tillage and gypsum management system was not effective in providing improvements in the physical quality of a Nitisol, since in the 0.0–0.20 m and 0.40–0.60 m layers, management provided a decrease in the volume of large macropores (>145 μm), which may affect the internal drainage of the profile. According to the author, in soils presenting textural B-horizon, the physical conditioning provided by soil preparation is short and the soil tends to reconsolidate. It is possible that clay illuviation may be acting in this process, as observed in Argisol by Marcolan and Anghinoni [24]. When soils are prepared there is a breakdown of aggregates, and an increase in soil clay dispersion [25].

Still regarding the development of the root system in Latosols, the practices employed in the management system described by Serafim et al. [10] also contributed to the coffee root growth, even in young (<3 years) roots [7], which are responsible for rapid water absorption and increased nutrient acquisition [26] (**Figure 4**).

The better distribution of the coffee root system in Latosol with high levels of gibbsite was promoted not only by the employed management system but also by the good distribution of well-connected pore diameters typical of this soil class (**Figures 4** and **9**). In kaolinitic Latosol, the system promoted the relief of the denser original structure, formed by thin and elongated pores promoted by the kaolinite mineral [27, 28], due to deep revolving associated with the addition of organic matter and gypsum, which favored concentrated root growth up to 0.80 m, but with regular root expansion with 500 mm length to 1 m depth (**Figure 4**) [7].

A well-distributed coffee root system along the soil profile, as observed in **Figure 4**, enhances the use of stored water available at greater depths (>0.80 m). Serafim et al. [19] and Silva et al. [29] reported the possibility of more efficient water absorption, minimizing the effects of water stresses to which these plants are subjected when cultivated in soils from the Cerrado biome, without harming crop yields [21]. Thus, knowledge about the distribution of coffee root system, as well as the probable changes in soil structure is the result of the interaction between the management system and the edaphoclimatic conditions that are intrinsic to Latosols.

2.2 Coffee intercropped with Brachiaria

The proper management of soil corrections and conditioning, dose adjustments and phosphorus use by the system, as well as balance in nutrient supply and leaf analysis for monitoring coffee nutrition are the main challenges of modern and competitive coffee cultivation for better use of available water in the soil–plant system [30]. Therefore, it is necessary to build soil fertility for sustainable coffee production in order to obtain increased nutrient use efficiency, increased fertilizer recovery rate, reduced biennial bearing and higher yield.

Coffee cultivation intercropped with *Brachiaria* (*Urochloa* sp.) improves the soil profile fertility. With vegetative intensification, the root system of the main crop naturally tends to deepen, accessing more water and nutrients, incorporating more carbon into the soil and improving its physical and biological quality [31]. In general, Brachiaria species have been considered prominent options for the production of plant residues to be incorporated in the soil or in its surface in no-tillage system, due to the good dry mass production and the high C/N ratio [32, 33]. In the intercropping system with coffee in low fertility soils, this behavior should also contribute to the increase of the soil organic matter (SOM) and consequently its cation exchange capacity (CEC), indirectly increasing the soil nutrients. *Urochloa ruziziensis* stands out among the species of Brachiaria, and is preferred by coffee growers because of its single flowering and well-developed root system with excellent field results [34].

The part of the coffee root system responsible for the absorption of water and nutrients, the thinnest roots, usually deepens to a depth of 40 cm [5] (**Figures 5** and **6**).

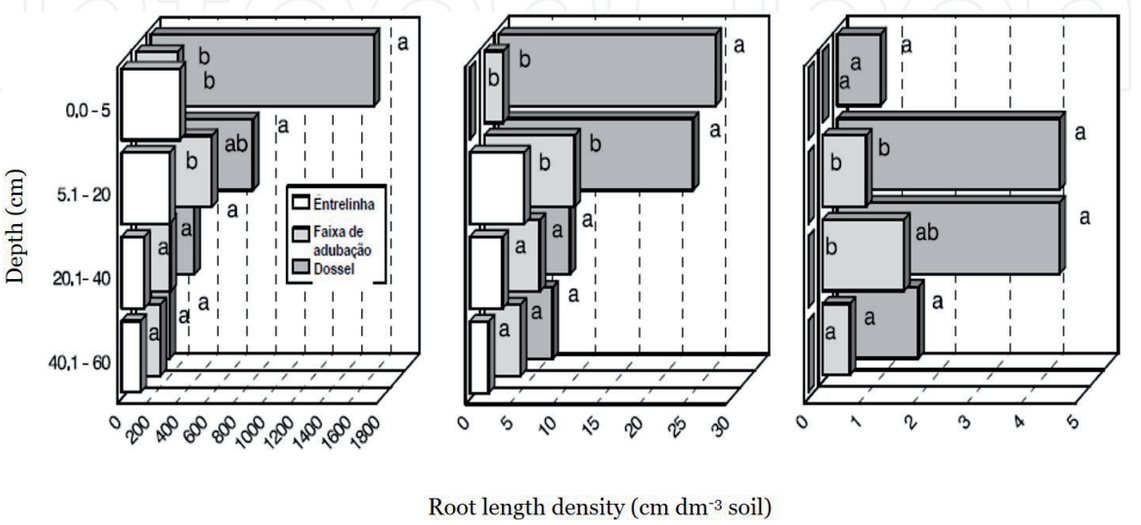


Figure 5.
Density of coffee roots as a function of the sampling site, below the canopy, below the fertilizer range, and in the center of the row. Source: Adapted from Motta et al. [5].

After a few years of planting under sufficient fertilizer application, some soil-moving nutrients such as nitrogen (N), potassium (K), sulfur (S) and boron (B) can leach beyond these absorbing roots. Thus, intercropping with deep-rooted plants practically all year round returns these nutrients to the surface of the soil–plant system. Therefore, managing between rows that collaborate with the proper management of soil fertility will certainly provide higher yields of coffee crop [35] due to the higher nutritional efficiency of the system production.

In addition, Brachiaria presents a root system that complements the efficiency of soil fertility use in the intercropping with the coffee as they explore depths of up to nearly 5 m (**Figure 7**).

In coffee cultivation intercropped with Brachiaria, plant residues are recycled and used as nutrients for coffee nutrition. The amount and regularity of plant residue addition is more important than the synchronization between release and nutrient demand by coffee because the increase in organic matter content over the years.

Brachiaria is more efficient than the coffee tree to extract the phosphorus from the soil, which will be available gradually with the decomposition/mineralization of the straw in the canopy projection. Over the years, the grass also incorporates this nutrient in depth as its root system develops in a larger volume of soil (**Figure 7**).

It is possible to estimate three plant cuts per cycle, with 5 tons of dry matter per hectare in each field based on Brachiaria average productivity data [37] and

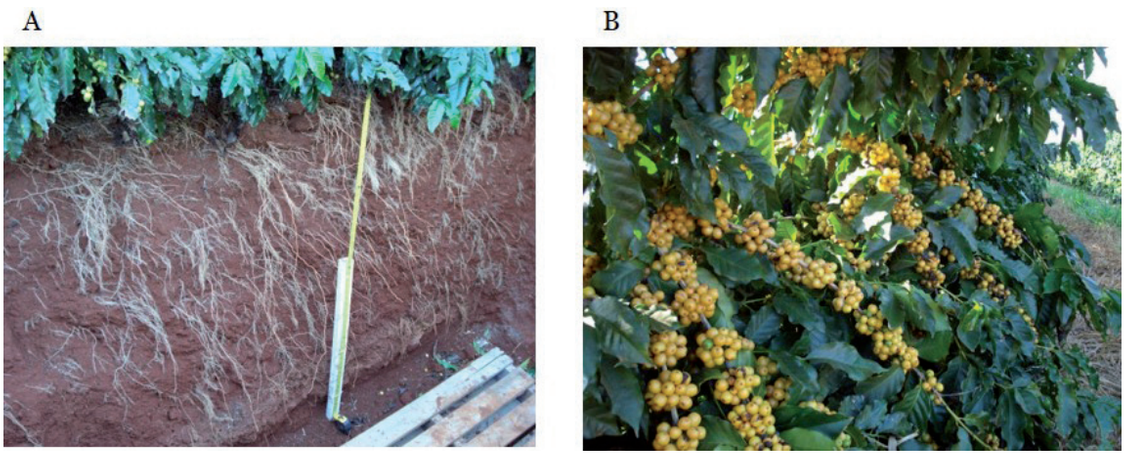


Figure 6.
Root system (A) and aerial part (B) of productive coffee, with good management of soil fertility construction in association with Brachiaria. Photo: Paulo T. G. Guimarães.

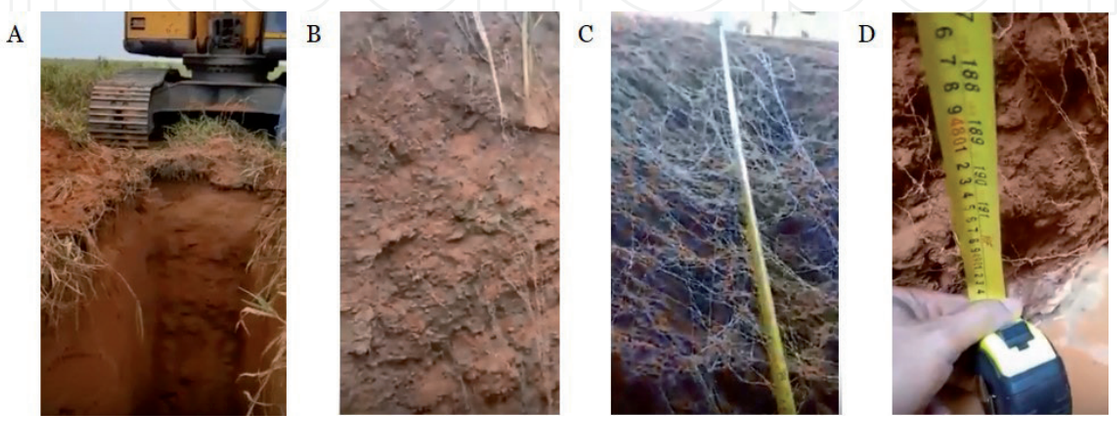


Figure 7.
Root system of Brachiaria (Urochloa ruziziensis) pasture. (A) Detail of trench opening; (B) frontal view of Brachiaria roots; (C) view of Brachiaria roots from within the trench; (D) measurement of Brachiaria root system depth up to 4.9 m soil depth. Source: Revista Cafeicultura [36].

proportional adjustment of its soil exploration area in consortium with the coffee tree (up to 30% of the area). The nutritional contents in dry matter for each coffee brush operation are: 75 kg of N; 20.6 kg P_2O_5; 193 kg of K_2O; 24.4 kg of CaO; 20.8 kg of MgO; 3.5 kg of S-SO_4; 90 g of B; 55 g of Cu; 1 kg of Fe; 475 g of Mn, and 400 g of Zn [34]. For the availability of these nutrients in the crop cycle, it is necessary to mineralize the dry matter, which depends on the presence of water, temperature and microorganisms in the soil, since some nutrients, such as N and P, are partially released over a period of 3 years [38].

Despite the many advantages presented by the cultivation of Brachiaria between coffee lines, there may be some disadvantages, especially if the coffee grower



Figure 8.
Appropriate management of rows of coffee plants with Brachiaria after mowing. Photo: Geraldo C. Oliveira.

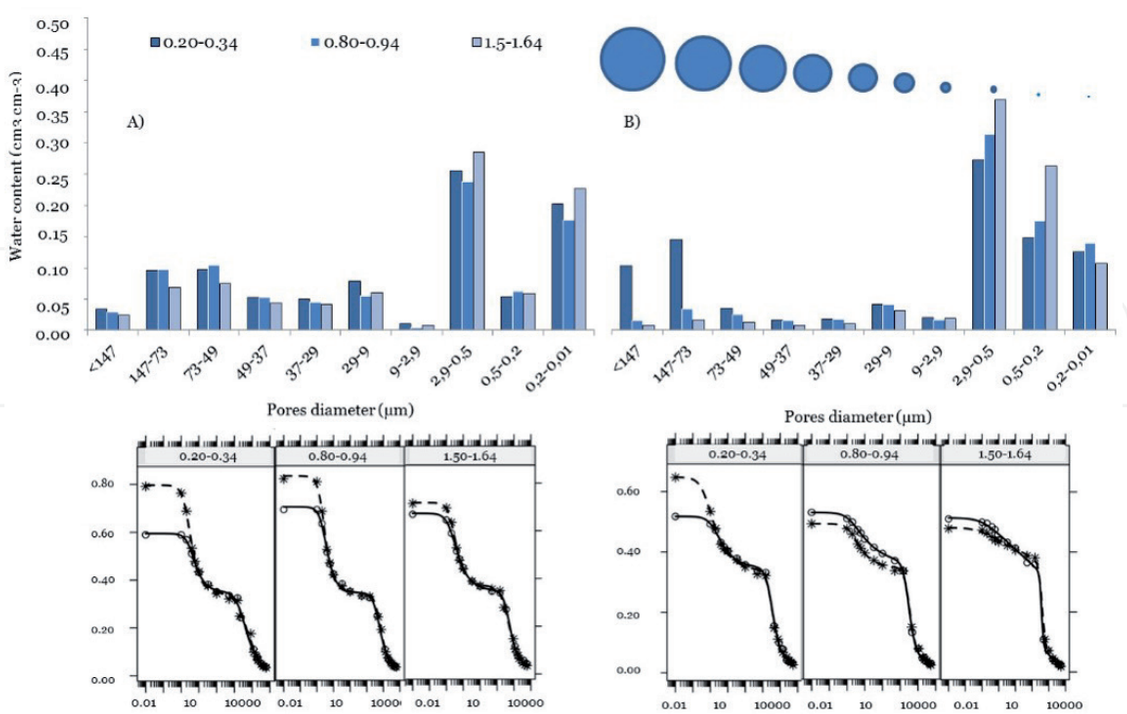


Figure 9.
Pore distribution of (A) gibbsitic Acrustox and (B) kaolinitic Haplustox, both with the multi-practice conservation management system for coffee cultivation at 0.20–0.34, 0.80–0.94 and 1.50–1.64 m depth. The pore diameter was extract of soil water retention curve by double van Genuchten model. Pore size <0.01 µm corresponds to >3500 kPa by WP4-T psychrometer [2]. The blue spheres represent the pore diameters. Source: From authors.

handles it incorrectly. Under conditions of severe water deficit, there may be competition for water and nutrients, harming the crop of commercial interest [39]. There may also be competition for nutrients and light and it is recommended to provide adequate and balanced coffee nutrition, as well as to maintain a strip of about 0.40 m on each side of the coffee trees, free from competing plants, and covered by residues from Brachiaria (**Figure 8**).

Coffee cultivation intercropped with Brachiaria is one of the practices of building soil fertility in profile for greater sustainability of coffee growing. The addition of this grass to the cultivation system is necessary for greater use of water and soil nutrients, which also allows the suppression of other difficult to control weeds, presenting several benefits for better coffee development and productivity and consequently greater profitability.

3. Porosity, water retention and availability in soils cultivated with coffee

The presence of an ideal pore network with a wide range of diameters is one of the key factors for high crop yields, especially those most demanding for water, such as coffee [21, 40]. Soil pore diameter and distribution interfere with drainage ratios, available water content, ion adsorption, root growth, aeration and temperature, acting directly on physical-water phenomena, being an indicator of soil quality [41–43].

Since soil mineral composition influences pore shape, length and connectivity, soils of oxide mineralogy, such as the very weathered Cerrado Latosols, tend to have a very strong, well-connected microgranular structure with large pore formation. There is formation of thinner and elongated pores [2, 27, 28, 43–45], which has implications on the water content available to plants.

When used in some production process such as food, fiber or energy, some structural change must occur, modifying the distribution and connection of their pore networks and, consequently, promoting changes in the soil air-water dynamics. In this sense, conservation agriculture [13] has as its principle the physical and chemical improvements of the root environment, by reducing soil tillage and maintaining living or dead surface cover. Thus, it minimizes the compressive and erosive processes, in addition to the oxidation of organic material, promoting the vertical growth of the root system of crops.

With these simple conservationist measures, coupled with the chemical corrections of acidic Latosols, improvements in the physical environment are expected, favored by the good development of the coffee roots, particularly by the reduction of restrictive impediments to the vertical growth of its roots and access to stored water [6–8, 29] (**Figure 9**).

Thus, the conservationist soil management system described by Serafim et al. [10] promoted changes in water retention in very weathered Latosols. According to Carducci et al. [2], the system was able to alter pore scaling such that it increased in the layer of 0–0.20-0.34 m the volume of large macropores (>147 μm) in kaolinitic Latosol and increased the intermediate diameters (73–2.9 μm), which are pores responsible for the gradual release of water to plants [43, 46]. There was also no limitation to aeration in soils (>147 μm: ≈ 15%), because the values were within the acceptable range for gas exchange maintenance (**Figure 9**).

According to Carducci et al. [2, 47, 48], genetically weathered Latosols present a large amount of interconnected structural pores, which facilitate drainage. Textural pores (including cryptopores) are responsible for water retention of high energy

[2, 43, 46, 49] However, because it was submitted to the conservationist management system, there was a small increase in the intermediate pores when compared to the greater depth evaluated in both soils, especially the one with gibbsite.

There is higher water retention in the cryptopores of gibbsitic Acrustox (pores with diameter < 0.01 μm) due to the high energy (3500 kPa), which makes this water unavailable to the roots of coffee trees [48, 49] (**Figure 9**).

The authors mentioned in the previous paragraph point out that deep preparation and maintenance of Brachiaria sp. should be considered as the main factors of this management system. The additional surface applied gypsum (7 kg m^{-1}), act as the supporting factor in the structure of the soils. Carducci et al. [6], when evaluating the same soils in 3D images obtained by X-ray computed tomography, verified that kaolinitic Latosols presented high spatial variability of the soil structure. These pores resulted from the rapid and well-branched growth of the coffee root system [7, 8]. This is extremely relevant information given that the interactions between soil and root have been considered as a key element for the second green revolution aimed at maximizing production [50].

4. Water-use efficiency and plant responses

The water content in the soil profile is one of the main factors of growth and productive vigor of coffee, mainly because it is predominantly implanted in a dry land system. In this sense, the knowledge of soil water dynamics in the root zone in production areas is strategic because it predicts the success of agricultural activity. Management strategies can contribute to the efficient use of stored soil water from rainfall and enable positive responses to the crop.

In order to reduce the effects of water deficit, a plastic film (double-sided, black and white) was used as mulching covering the coffee growing line. Such management provided greater soil water storage up to 0.60 m in an Argisol (Ultisol), with soil moisture above 30% in the dry season, from May to September (**Figure 10**). In the topsoil, the soil moisture also remained higher, especially in warmer seasons, such as in January. These results coincide with the highest growth in stem height and diameter over the first year of coffee development [51, 52], showing that mulching may be an important alternative for keeping water in the root zone at the most critical time for crop development.

In a Cerrado Latosol cultivated with coffee under a conservation system [10], soil moisture was monitored daily during 2010 by means of a capacitance multi-sensor probe to a depth of 1.0 m [53, 54]. Throughout the evaluated period, the lowest moisture values were observed in the 0.50 to 0.75 m layer, indicating that the coffee tree extracted the largest amount of water at this depth (**Figure 11**), coinciding with significant presence of coffee roots [7] (**Figure 4**). In addition, in the months corresponding to the dry season in the region (June to August), it was observed low humidity values in the depth of 1.00 m, and thus deep water absorption, which may have contributed to reduce the water stress suffered by the plant. In this sense, the groove opening and limestone incorporation at 0.60 m associated with the application of additional gypsum may be important for the attenuation of water deficit.

An alternative for soil moisture monitoring is the use of remote sensors, given their repeatability characteristics, access to large areas and easy handling. However, it should be taken into account that coffee is a perennial crop with high root system activity at depth, and the use of remote sensor data to directly measure soil moisture is limited to a few centimeters below the surface (±5 cm) [55], not covering the entire area of water extraction by the roots [56]. Santos et al. [57] used the vegetation index EVI-2 to monitor the vegetative vigor of the coffee tree and to correlate it

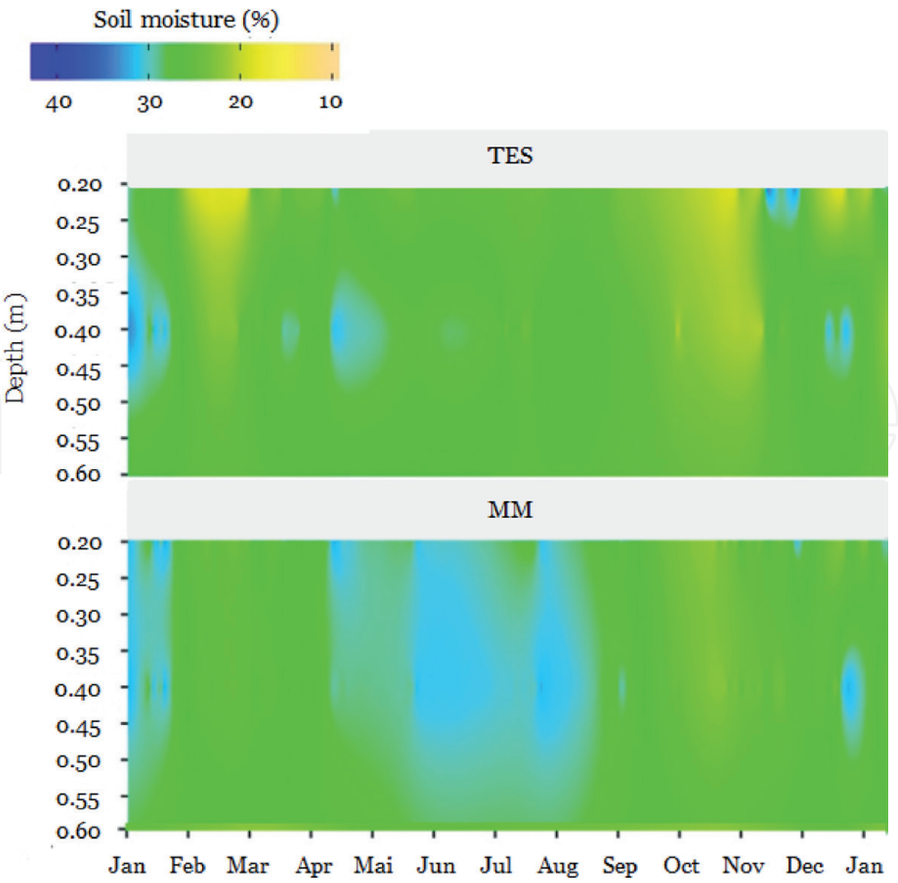


Figure 10.
Continuous variation of soil moisture in 2014 in the 0–0.60 m layer of Argisol as a function of conventional management (TES) and plastic cover (MM) in the first year of coffee cultivation. Source: Adapted from Barbosa [51].

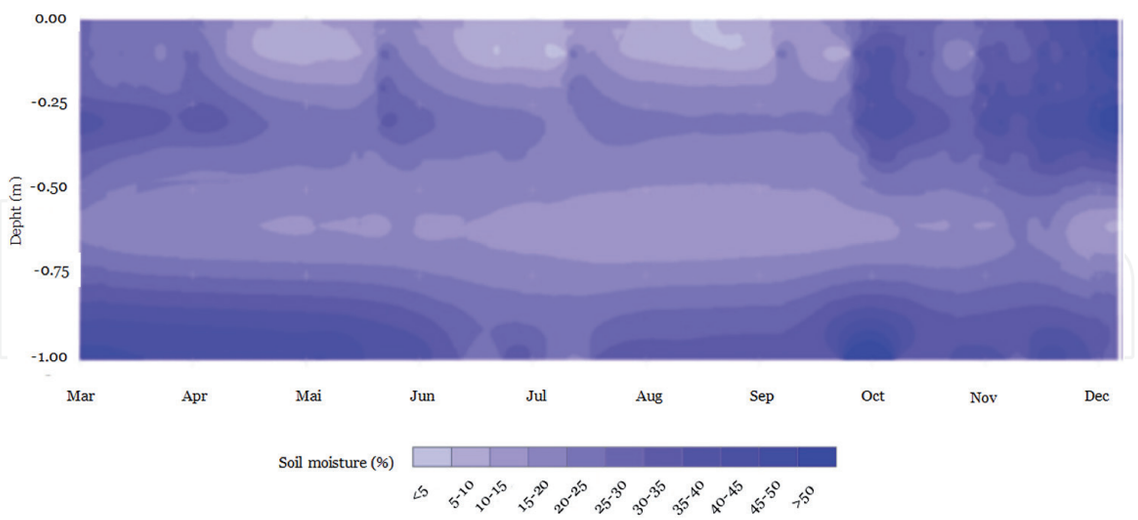


Figure 11.
Continuous variation of soil moisture (% by volume) in the planting line (sensor positioned 0.15 m from the coffee tree trunk) as a function of depth (0–1.00 m) and time (March/2010 to December/2010) in a very clayey gibbsitic-oxidic dystrophic red Latosol with coffee during the 2nd year under management system described in Serafim et al. [10], which includes deep preparation with chemical correction up to 0.60 m, cultivation of Brachiaria between the rows and application of additional gypsum at a dose of 28 Mg ha^{-1}. Source: Adapted from Silva [53].

with moisture data at different depths. The authors concluded that it is possible to estimate the water content in the root zone using EVI-2, and that the humidity at a depth of 0.60 m is the one that most reflects the water situation of the plant.

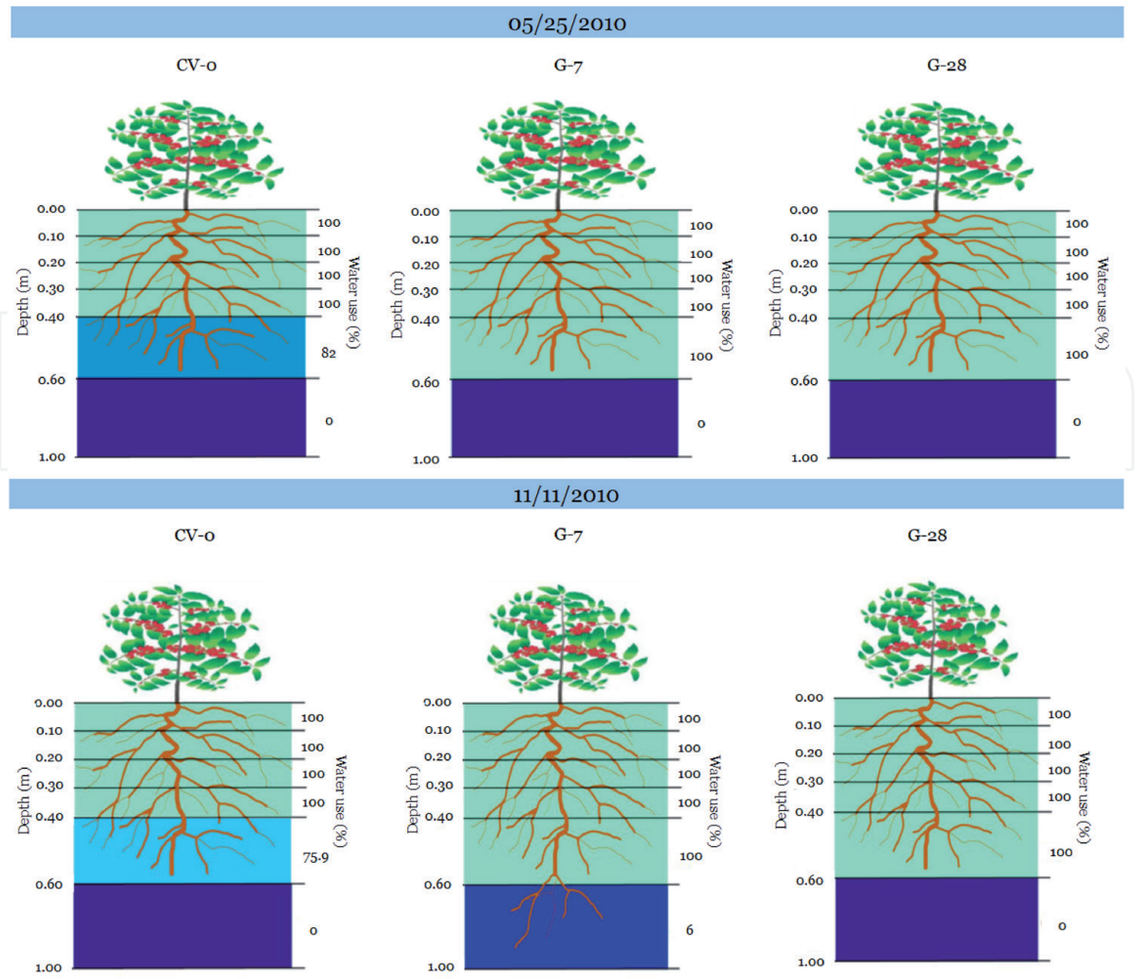


Figure 12.
Water use in layers up to 1.00 m depth during the dry season (May 2010) and in the summer (November 2010) for coffee trees installed in October/2008 due to management with deep soil preparation and limestone incorporation at 0.60 m depth, differing by presenting Brachiaria between the rows and additional application of 7 Mg ha^{-1} of gypsum (G-7) or 28 Mg ha^{-1} of gypsum (G-28), and without application of additional gypsum and uncovered line (CV-0). Source: Ivan Célio Andrade Ribeiro.

To detail the use of additional gypsum practice, water use by the coffee tree in the soil profile was estimated at different time intervals in 2010 (**Figure 12**). The coffee tree consumed water to a depth of 0.60 m in both evaluations performed and for all managements, which corroborates the lower moisture values in this layer (**Figure 11**), confirming the importance of deep tillage and soil correction at 0.60 m. The highest water consumption was observed for treatment G-7, followed by G-28 and lastly for CV-0. The use of additional gypsum allowed the development of thin roots in treatments G-7 and G-28 when compared with CV-0 [11], which may be due to the high levels of exchangeable Ca^{2+}, Mg^{2+} and K^{+} in the soil solution, which remained at adequate values to a depth of 0.85 m in the management with additional gypsum application [58].

Water use at a depth of 1.0 m was observed only in the G-7 treatment in November 2010, where the plant consumed about 6% of the stored water. At that time, the coffee tree was 2 years old, showing potential for deep water extraction. Moreover, even in the rainy season there was drought of more than 20 days [29, 53], associated with lower rainfall in the region this year compared to the historical average [59], implying less soil water storage. However, the high soil moisture at a depth of 1.00 m - above the critical moisture content for reducing maximum coffee perspiration in all managements [29] - indicates that this layer is an important water reservoir that can be accessed by plants during the driest or summer periods, reinforcing the importance of deepening the root system through management [29, 59].

Although management with additional gypsum (G-7 and G-28) provided higher water consumption compared to CV-0, it was not possible to differentiate its effects on water stress suffered by plants, evaluated by leaf water potential (ψf) in January, April, and August 2010 (**Figure 13**). It is noteworthy that in CV-0, although no additional gypsum was applied, liming was performed on the surface and in the planting furrow to a depth of 0.60 m, which favored the deepening of the root system [7].

The highest water stress was observed in August (**Figure 13**), coinciding with the peak of the dry season in the region and the lowest soil water content [29, 59]. However, all observed ψf values were below the critical range of water stress that leads to a reduction in coffee crop production, which is between −1.8 and −2.5 MPa [60–62].

Regarding plant growth, lower plant height values were observed in the G-7 and G-28 managements when compared with CV-0 (**Figure 13**), which may be explained by competition for root-shoot photoassimilates [63], since the coffee tree showed denser and deeper root systems for G-7 and G-28 [11]. In addition, the evaluations were carried out shortly after planting and, considering that the main morphological and physiological characteristics of the coffee root system complete its development at 5 years of age [1], it is expected that the investments made in liming, application additional gypsum and fertilization result in greater root development in the G-7 and G-28 managements in subsequent years [21].

Despite the lower initial plant growth, the adoption of the conservation management system provided maintenance of the water state of plants during the dry and summer season (**Figure 13**), resulting in statistically equal yields between CV-0, G-7 and G-28 management system at the first harvest in 2011 [29], highlighting the importance of deep tillage and soil correction. However, in 2012, higher yields were obtained in the managements G-7 and G-28. On average, production was 52.8 bags ha^{-1} in CV-0 (1 bag = 60 kg of coffee grains), 54.5 bags ha^{-1} in G-7 and 58.0 bags ha^{-1} in G-28 [59]. Coffee plants take 2 years to complete their phenological cycle [64]. Thus, soil moisture in 2010 influenced production in 2011 and 2012, demonstrating the positive effect of investments in additional gypsum associated with the

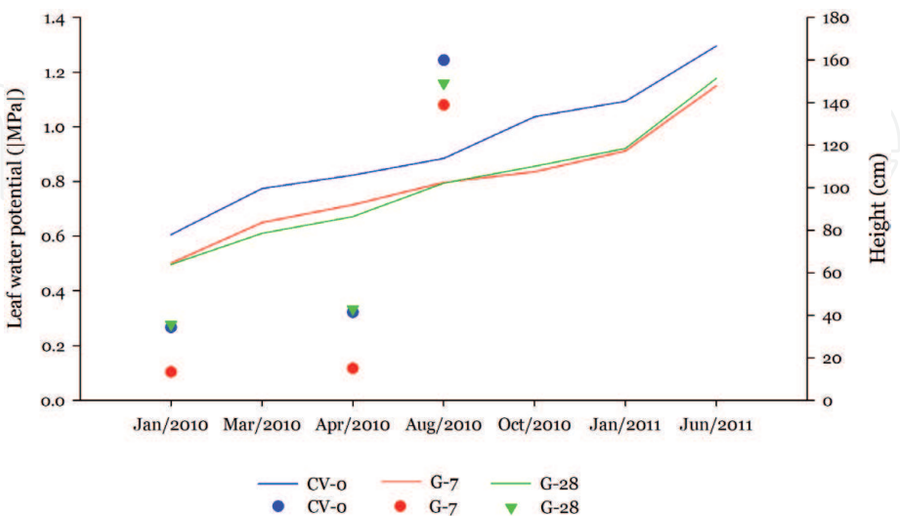


Figure 13.
Water stress assessed by leaf water potential (Ψf) at three times of the year (January 5; January 18 and August 20, 2010), and plant growth at height assessed continuously each month (January 5, 2010 to June 18, 2011) for coffee planted in October 2008 due to management with deep soil preparation and limestone incorporation, differing for presenting Brachiaria between the rows and additional application of 7 Mg ha^{-1} of gypsum (G-7) or 28 Mg ha^{-1} of gypsum (G-28), without application of additional gypsum and uncovered gypsum (CV-0). Source: From authors.

maintenance of Brachiaria in the G-7 and G-28 treatments, which provided higher water consumption by the plant in 2010 (**Figure 12**).

The trend of higher production for management with additional gypsum was confirmed in the 2013 crop, in which 63.0 bags ha^{-1} was produced in CV-0; 75.5 bags ha^{-1} in G-7, and 71.1 bags ha^{-1} in G-28 (data obtained through personal communication with consultants in the area). However, in the 2014 harvest, only the G-28 treatment presented higher yield (87.2 bags ha^{-1}) when compared with CV-0 (85.6 bags ha^{-1}). Management G-7 presented the lowest yield (57.5 bags ha^{-1}). However, when evaluating the general average of the first four seasons, it is observed that there is little difference between the evaluated managements, in which in CV-0 were harvested 63.6 bags ha^{-1}, 60.5 bags ha^{-1} in G-7 and 68.6 bags ha^{-1} in G-28.

5. Final remarks

There have been strong droughts and short-time droughts in rainy season in the main coffee producing regions of Brazil. Although most of the soils used are deep and capable of storing a large volume of water, these soils have a small effective depth for the development of the root system due to severe chemical limitations, therefore causing a yield gap.

Brazilian researchers have studied ways to overcome this problem, such as selecting drought tolerant plants. However, a strategy that has attracted the attention of farmers is the adoption of soil management systems that provide the best development of the coffee root system, with chemical and physical adequacy of soils. Deep tillage, maintenance of intercropped Brachiaria in the coffee plant interrow and additional gypsum play important roles in this management system. This is relevant information given that the interactions between soil and root have been considered as key elements for the maximization of crop production. Therefore, the set of practices previously mentioned in this chapter has alleviated the soil limitations caused by droughts, root growth and, consequently, the development of productive coffee trees.

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