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POROSIDADE DE AERAÇÃO E PRODUTIVIDADE DO CAFEEIRO IRRIGADO EM LATOSSOLO VERMELHO EUTROFÉRRICO

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1 RESUMO

A porosidade de aeração (β) do solo está diretamente relacionada com o desenvolvimento e produtividade das plantas. Portanto, o objetivo deste estudo foi avaliar como a porosidade de aeração (β) horária afeta a produtividade do cafeeiro irrigado em Latossolo cultivado na região de Lavras, sudeste do Brasil, e determinar sua faixa ideal. O experimento foi conduzido com a cultivar Rubi MG-1192, com espaçamento 3,5 x 0,8 metros, em blocos casualizados com seis tratamentos e três repetições. Os tratamentos consistiram na aplicação de porcentagens da lâmina bruta de irrigação necessária (*Li*), sendo: não irrigado e 60, 80, 100, 120 e 140% da *Li*. O potencial matricial do solo (ψ_m) em cada tratamento foi medido com sensores, realizando leituras horárias em três profundidades (0,25; 0,50 e 0,75 m). As lâminas crescentes de irrigação proporcionam redução linear da porosidade de aeração média do solo cultivado com café. O tratamento com T100 mostrou um aumento significativo da produtividade e, a partir desse valor a lâmina bruta da irrigação mostrou tendência a reduzir a produtividade do café e porosidade do solo. A faixa ideal de β entre 0,152 e 0,163 $m^3\ m^{-3}$ proporcionou condições adequadas de aeração e maiores produtividades para o cafeeiro.

Palavras-chave: agricultura irrigada, produção, atributos do solo.

SOUZA, J. L. M.; ROSA, S. L. K.; EVANGELISTA, A. W. P.; GURSKI, B. C. AIR-FILLED POROSITY AND YIELD OF IRRIGATED COFFEE IN A EUTROPHIC RED OXISOL

2 ABSTRACT

Soil air-filled porosity (β) is directly related to the plant development and yield. Thus, this study aimed to evaluate how hourly aeration porosity (β) affects the productivity of irrigated coffee cultivated in an Oxisol in the region of Lavras, southeastern Brazil, to determine its ideal range. The experiment was conducted with the Rubi MG-1192 cultivar, spaced at 3.5 x 0.8 meters, in randomized blocks with six treatments and three replicates. The treatments

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consisted of applying percentages of the gross irrigation depth required (*Li*), being non-irrigated, 60, 80, 100, 120, and 140% of *Li*. The soil matric potential (ψ_m) in each treatment was measured using sensors, performing hourly readings at three depths (0.25, 0.50 and 0.75 m). The increase in gross irrigation depths provides a linear reduction of the average air-filled porosity in the soil cultivated with coffee. The T100 treatment showed a significant productivity increase, and from this value the gross irrigation depth showed a tendency to reduce coffee productivity and soil air-filled porosity. The ideal range of β between 0.152 and 0.163 $m^3\ m^{-3}$ provided adequate aeration conditions and a higher yield for coffee.

Keywords: irrigated agriculture, productivity, soil properties.

3 INTRODUCTION

The cultivation of coffee beans has developed in regions considered suitable for crops in terms of water requirements. With the expansion of coffee production, new cropping and management technologies, such as irrigation, have become necessary since the major environmental stress that affects coffee production is hydric stress (SCHEEL et al., 2019). Irrigation criteria have been established considering the crop response to the soil water content. However, with no water limitations, oxygen diffusion (O_2) in the soil is the limiting factor for plant growth and production since the gas diffusivity of the soil depends on the air-filled porosity (β), which controls the movement of gases to and from the atmosphere (SMITH et al., 2003; JABRO et al., 2012; NEIRA et al., 2015).

An increase in the soil water content reduces β by preventing soil O2 diffusion. In contrast, with the constant consumption of O2 by edaphic fauna and roots, plants can be exposed to hypoxic conditions or low oxygen concentrations, affecting energy production via oxidative phosphorylation, limiting root growth and reducing productivity (WEITS; VAN DONGEN; LICAUSI, 2020). β seems to be a problem that has already been overcome in Brazil since the predominant soils (Oxisols and Ultisols) in the country are well drained (EMBRAPA, 2018). However, β can be a problem when irrigation is used since inadequate management can lead to excess water in the soil, causing a reduction in β. Therefore, a β minimum (β_{min}) was adopted, which indicates the ideal air-filled porosity so that the O2 diffusion rate in the soil is equal to its consumption, avoiding plant stress and improving productivity in irrigated systems. Thus, with no aeration limitation, the water availability for plants will be as high as possible.

There is no concordance in the literature as to the ideal β_{min} value, since there are uncountable edaphic and physiological factors that affect it. However, $\beta_{min} \geq 0.1\ m^3\ m^{-3}$ was adopted as a limiting value for crop development (GRABLE; SIEMER, 1968; PÄIVÄNEN, 1973; THEODOROU; CAMERON; BOWEN, 1991; TORMENA; SILVA; LIBARDI, 1998). The limit value of β_{min} is only a reference, since the O2 diffusion rate in the soil depends on the differences in root density, activity, chemistry, and structure among the different crops (BEN-NOAH; FRIEDMAN, 2018). The determination of β_{min} is complex, and no consistent values for coffee are available in the literature. Therefore, other crops are used as references, which is not ideal, given the particularity and importance of coffee as an agricultural crop. Zou et al. (2001) reported that the root elongation rate increased rapidly when the air-filled porosity was between 0.05 and 0.15 $m3^{-3}$ for radiata pine. Silva, Imhoff and Kay (2004), evaluating a soil in Canada with a maize crop, reported a relationship between plant growth and air-filled porosity for no-tillage and conventional-tillage systems between 0.05 and 0.27 $m^3\ m^{-3}$. Klein et al. (2008) reported values between 0.07 and 0.24 $m^3\ m^{-3}$ under a no-tillage system and 0.17 and 0.27 $m^3\ m^{-3}$ under no-tillage with mechanical scarification for wheat, and Wall; Heiskanen (2003) reported values between 0.20 and 0.40 $m^3\ m^{-3}$ for pine crops. Therefore, high variation in β_{min} in different plant species and soils has been reported.

Owing to the direct influence of β_{min} on crop productivity and the cost involved in irrigation activity, β_{min} determination is essential as a yield parameter, especially for crops with high economic value, such as coffee in Brazil. In this context, the objective of this study was to evaluate how the hourly air-filled porosity (β) affects the productivity of coffee plants irrigated with a eutrophic red Oxisol and to determine its ideal range in Lavras, southeastern Brazil.

4 MATERIALS AND METHODS

The experiment was carried out in Lavras, Minas Gerais State, Brazil, with coordinates of 21°13'43 S, 44°58'59 W and an altitude of 918.8 m. The climate is classified as Cwa (humid subtropical, with dry winters and hot summers), with the warmest temperature of the month above 22°C (ALVARES et al., 2013). The soil is classified as a eutrophic red Oxisol according to Embrapa (2018).

The data used were obtained between 2007 and 2008 from a coffee (*Coffea arabica* L.) crop, variety Rubi, under central pivot irrigation, which was planted in 1999 and has a spacing of 3.5 × 0.80 m. The total area of the experiment was approximately 1.6 hectares and was conducted in a randomized block design with six treatments and three replications. The treatments consisted of applying percentages of the gross irrigation depth required (Li), as follows: T0 (nonirrigated), T60 (60% Li), T80 (80% Li), T100 (100% Li), T120 (120% Li) and T140 (140% Li). The irrigations were carried out at a fixed frequency of two and three days. The gross irrigation depth required was obtained via the following equation:

$$Li_i = \frac{Kc_i \cdot ETo_i - P_i}{E} \quad (1)$$

where Li_i is the gross irrigation depth at each i -period of the crop cycle (mm $period^{-1}$); Kc_i is the crop coefficient used at each i -phenological stage (unitless; Table 1); ETo_i is the reference evapotranspiration at each i -period (mm $period^{-1}$); and E is the efficiency of the center pivot irrigation (%), which is considered equal to 90%.

The dormancy period for irrigated coffee floral induction was considered in the experiment, according to Embrapa (2009) and Lima et al. (2016). Thus, in the period between May 18 and August 1, no irrigation was performed.

The precipitation (P) was measured with a pluviometer installed at a height of 1.5 m from the soil surface. The ETo estimation was performed via the modified Penman–Monteith method, with Cn = 900 K mm $s^3\ Mg^{-1}\ day^{-1}$ and Cd = 0.34 sm^{-1} (ASCE–EWRI, 2005). The daily climate data needed, such as the maximum, minimum and mean air temperatures (°C), mean relative humidity (%), incident solar radiation (MJ $m^{-2}\ day^{-1}$) and wind speed at a height of two meters (ms^{-1}), were measured at the meteorological station of the National Institute of Meteorology (INMET), which is located near the experimental area. The phenological stages and crop coefficients (Table 1) were obtained according to regional data (CAMARGO; CAMARGO, 2001).

Table 1. Coffee phenological stages in 2007 and 2008 crop years, periods and crop coefficients (Kc) used in irrigation management in Lavras, Minas Gerais state, southeastern Brazil.

Stages	Phenological phases	Period Initial	Period End	Kc_i (unitless)
P1	Vegetation and flower bud formation	Mar. 2007	Mar. 2007	1.1
P2	Induction and maturation of floral buds	Apr. 2007	Aug. 2007	0.9
P3	Flowering and beginning of fruit expansion	Sep. 2007	Dec . 2007	1.2
P4	Fruit expansion	Jan . 2008	Mar . 2008	1.1
P5	Fruit ripening	Apr . 2008	Jun . 2008	0.9
P6	Rest and senescence of 3rd and 4th branches	Jul. 2008	Aug. 2008	1.1

The soil p article density (ρ_P) and soil texture were determined from the soil samples at depths of 0.25, 0.50 and 0.75 m according to Teixeira et al. (2017). For the soil physical-water characterization, undisturbed samples were collected at the same depths to determine the soil bulk density (ρ_S) and soil water retention curve. The total soil porosity (α) was considered equal to the volumetric water content at saturation ($\alpha = \theta_{SAT}$). The volumetric soil water content at the field capacity (θ_{CC}) and permanent wilting point (θ_{PMP}) was considered equal to the moisture obtained at potentials of -6 kPa and -1500 kPa, respectively. The macropores ("$\theta_{SAT} - \theta_{CC}$") and micropores ("$\theta_{SAT}$ –macropores") were estimated (EVANGELISTA et al., 2013).

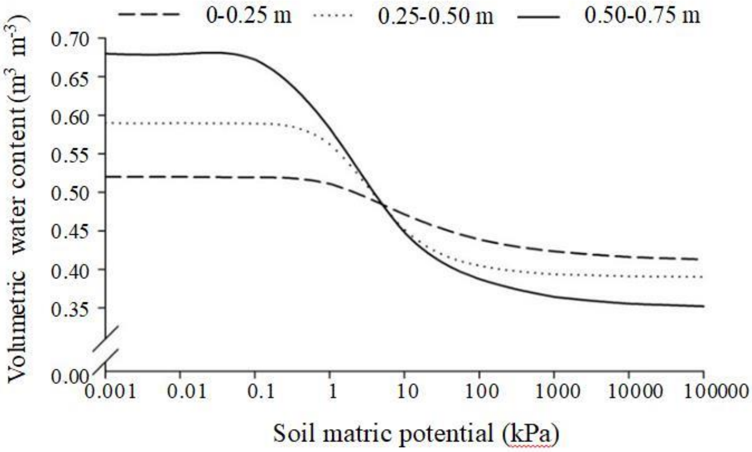
The soil water retention curves were determined on the basis of the volumetric water content retained at 2.0, 4.0, 6.0 and 10.0 kPa tensions in the porous plate funnel and 33, 100, 500 and 1500 kPa in the Richards pressure chamber. An undisturbed soil sample was used for each tension, and the curve was adjusted with the van Genuchten (1980) model, considering the Mualem restriction $m = 1 - \frac{1}{n}$ (Table 2 and Figure 1).

Table 2. Physical-water attributes and average soil water retention curve parameters adjusted with the van Genuchten (1980) model for three layers of a eutrophic red Oxisol irrigated and cultivated with a coffee crop in Lavras, Brazil.

Layer	ρ_P	ρ_S	α	θ_{FC}	θ_{PWP}	θ_r	Macro pores	Micro pores	α	n
(m)	(Mg m $^{-3}$)		----------------- (m ^{3} m $^{-3}$) -----------------						(kPa)	(unitless)
0.00-0.25	2.67	1.29	0.52	0.48	0.42	0.41	0.04	0.38	0.52	1.34
0.25-0.50	2.70	1.10	0.59	0.47	0.39	0.39	0.12	0.27	0.63	1.63
0.50-0.75	2.70	0.86	0.68	0.47	0.36	0.35	0.21	0.15	1.77	1.42

ρ_P – soil particle density; ρ_S – soil bulk density; α – total porosity ($\alpha = \theta_S$); θ_{FC} – volumetric soil water content at field capacity; θ_{PWP} – volumetric soil water content at the permanent wilting point; θ_r – residual water content; α and n – empirical parameters of the van Genuchten (1980) equation.

Figure 1. Soil water retention curves adjusted with the Van Genuchten (1980) model for three layers of a eutrophic red Oxisol irrigated and cultivated with a coffee crop in Lavras, Brazil.



The soil matrix potential $\psi_m(t_i)$ was estimated with *Watermark* sensors, which were installed at depths of 0.25, 0.50 and 0.75 m and connected to data loggers for hourly readings (t_i) from March 2007 to August 2008. The volumetric water contents $\theta(t_i)$ were obtained from the matrix potentials $\psi_m(t_i)$, and the soil water retention curves were adjusted for each depth. The hourly $\beta(t_i)$ was calculated for each soil depth, considering the following:

$$\beta(t_i) = (\alpha - \theta(t_i)) \quad (2)$$

where $\beta(t_i)$ is the soil air-filled porosity at each i -time ($m^3\ m^{-3}$); α is the total soil porosity ($m^3\ m^{-3}$); and $\theta(t_i)$ is the volumetric water content at each i -time ($m^3\ m^{-3}$).

The harvesting of the coffee plots was carried out manually. For evaluation, 12 coffee plants were chosen randomly from each plot. The beans harvested in the “cherry”, “green”, “raisins” and “dry” stages were mixed and homogenized before beneficiation to estimate yield productivity. The samples were dried to reach 12% humidity, on the basis of weight, and then processed (outer skin removal and weighing). Productivity was expressed in bags of 60 kg of coffee beans processed per hectare.

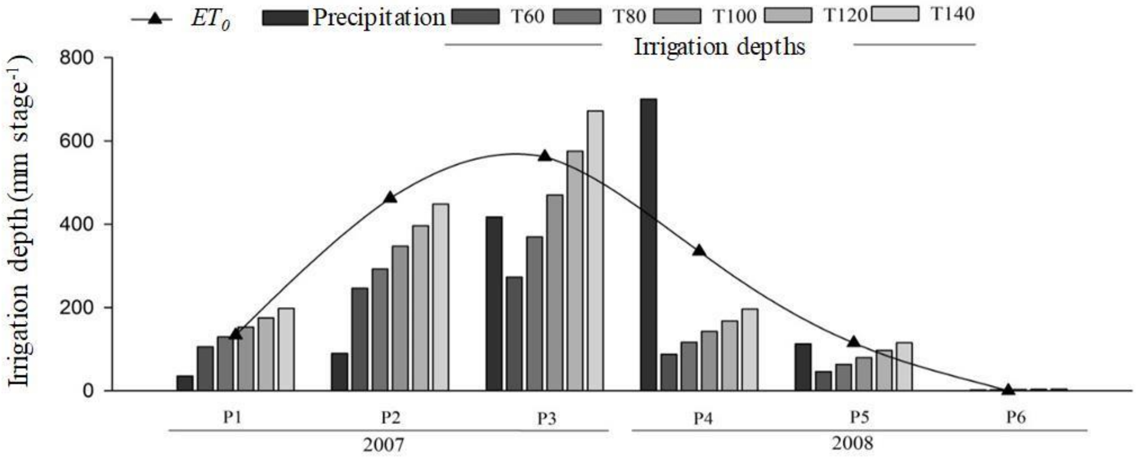
The results of yield and soil air-filled porosity (β) were subjected to statistical analysis of variance (F test), correlation, regression and frequency (MANLY, 2008). The productivity averages were compared with the Tukey test at 5% probability ($p<0.05$).

5 RESULTS AND DISCUSSION

5.1 Water relations and soil air-filled porosity (β)

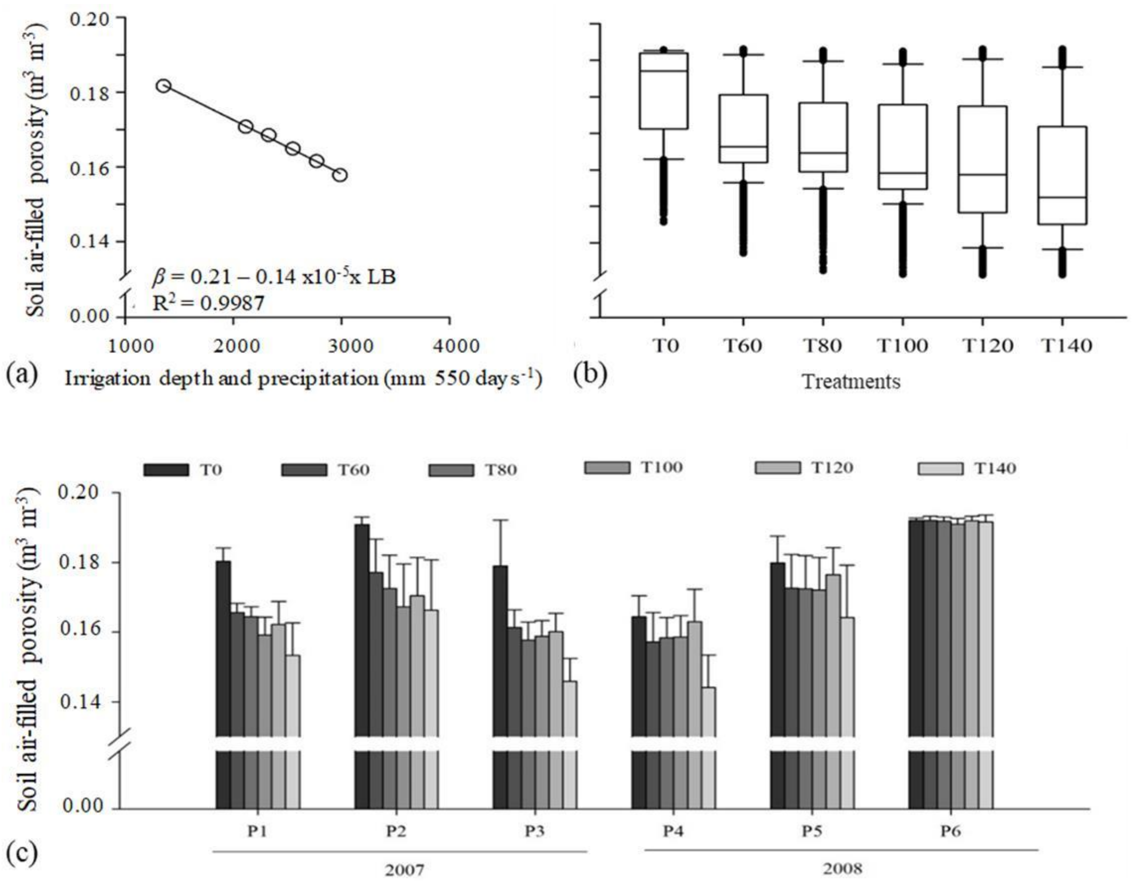
The precipitation was greater than the reference evapotranspiration (*ETo*) only in the P4 stage between January and March 2008 (Figure 2), indicating the importance of coffee irrigation in Lavras during the analyzed period. The gross irrigation depths (60, 80, 100, 120 and 140%) provided increments of 20% of the water applied from T60 to T140.

Figure 2. Reference evapotranspiration (*ETo*), precipitation and treatments with increasing gross irrigation depth during the coffee phenological stages (P1 to P6).



The increasing gross irrigation depth caused, on average, a linear reduction in β during the 13200 analyzed hours (Figure 3a). The water applied during irrigation infiltrated the soil, reducing the amount of air-filled porosity; however, it was not enough to saturate the soil, as at this limit, the stabilization of β was expected (Figure 3a). Despite the high variability of air-filled porosity values during the studied period (Figure 3b), no treatment, including T140, was able to reach $\beta < 0.10$, a value considered critical in the literature (GRABLE; SIEMER, 1968; HALL et al., 1977; XU; NIEBER; GUPTA, 1992).

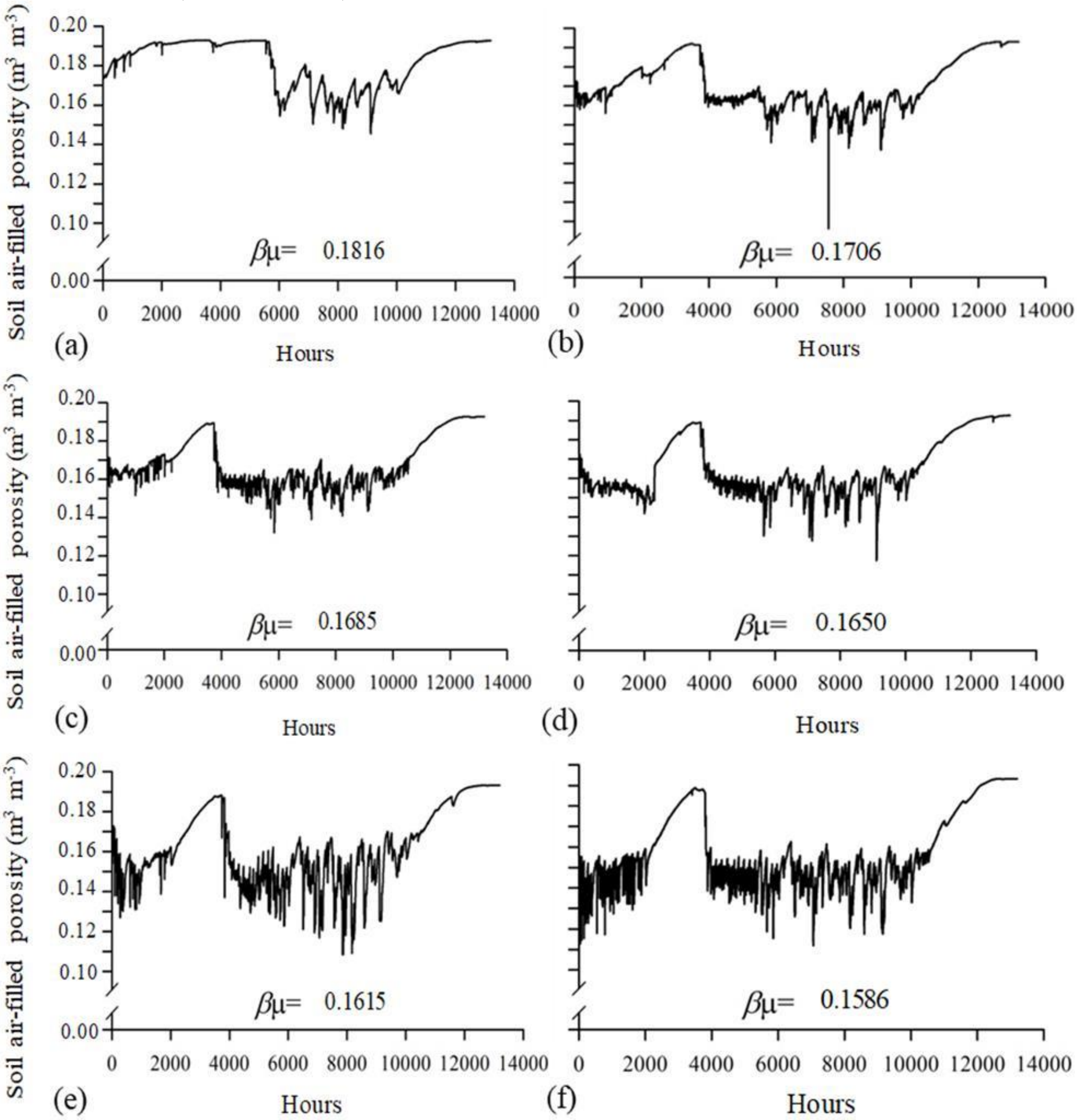
Figure 3. Relationship between gross water depth and mean soil air-filled porosity (β) in the different treatments and periods evaluated: a) linear regression analysis between mean soil air-filled porosity versus gross irrigation depths applied in the treatment (“precipitation + irrigation”); b) β *boxplot* in the different treatments; and c) β average in the different periods.



In the flowering and fruit expansion stage (P3), in addition to the relatively high evaporative demand, the coffee was in the reproductive period; for this reason, it was responsible for the greatest degree of gross irrigation depth applied during this stage (Figure 2). The problem in establishing a β_{min} in phenological phases considered critical is that the maximum water demand of the plant coincides with the highest demand of O_2, and these two attributes are antagonistic in the soil (LICAUSI, 2011; NEIRA et al., 2015). This occurred in the P3 and P4 stages, which are considered critical for coffee yield and presented the lowest values of β (Figure 3c).

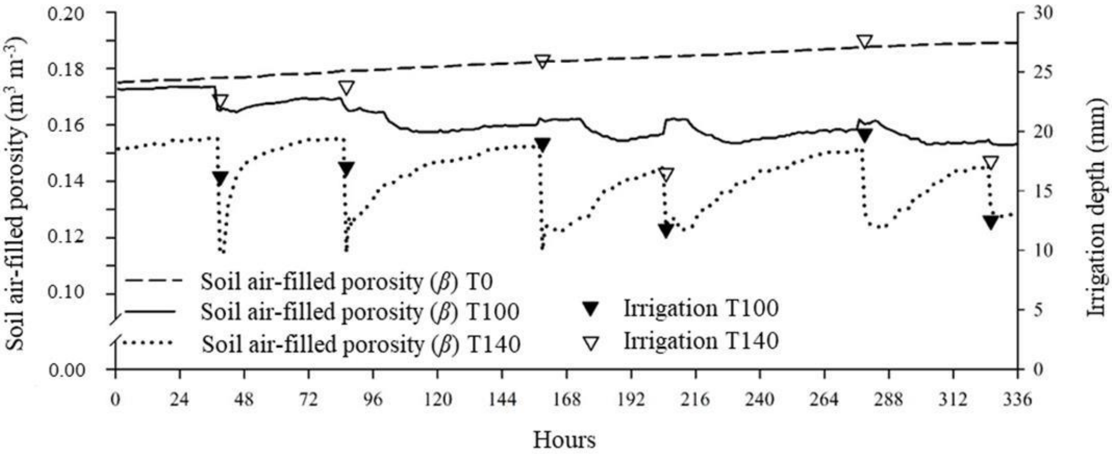
The hourly volumetric water content $\theta(t_i)$ data during the 13200 hours allowed verification of the effects of the irrigation and pluviometric precipitation on the hourly variations in $\beta(t_i)$ (Figure 4). In T0, without irrigation, the mean air-filled porosity β_{μ} = 0.1816 m ^{3} m $^{-3}$ (Figure 4a) was measured. With complementary irrigation, the tendency of β was similar; however, with different amplitudes, the increase in gross irrigation depth changed β_{μ} during the study period (Figure 4). As the irrigation depth increased, there was greater oscillation in the amplitude and a decrease in the aeration porosity, which is expected since more pores were filled with water. During the period between 2000 and 4000 hours, the oscillation was low due to the dormancy period required for the floral induction of irrigated coffee.

Figure 4. Soil air-filled porosity (β) at 13200 hours in a eutrophic red Oxisol cultivated with a coffee crop under irrigation, considering the following treatments: a) T0 (without irrigation); b) T60 (60% of the recommended gross irrigation depth); c) T80; d) T100; e) T120; and f) T140.



The hourly variation in β, specifically over two weeks without rainfall (Figure 5), verified its growth over time in the T0 (nonirrigated) treatment. The application of irrigation reduced the β immediately, especially in T140. Afterwards, the water infiltrating the 0–0.75 m layer is consumed by the coffee plants or drained to deeper layers, increasing β over time. The irrigation applied in the T100 treatment caused variation in the soil water content and consequently less β variation in relation to T140, resulting in lower wetting peaks and allowing more uniform airflow. In the T140 treatment, β decreased rapidly, requiring approximately 24 hours to return to the mean value.

Figure 5. Hourly values of soil air-filled porosity (β) and irrigation depth in the T0, T100 and T140 treatments throughout two weeks without rainfall (March 3--14, 2007) on coffee plants irrigated with a center pivot system in Lavras, Brazil.



Van Lier (2001) suggested that wetting peaks reduce the permeability of soil to air, which requires higher O2 pressure gradients. As a result, the pressure of this gas decreases with increasing soil depth; therefore, part of the root system may experience a lack of O2.

5.2 Soil air-filled porosity (*β*) and yield

The variation in β among the treatments was reflected in the significant differences in coffee yield. Considering the 2006/2007 harvest, the T100 and T120 treatments resulted in relatively high productivity (Table 3), with values of 45.59 and 38.35 bags ha $^{-1}$, respectively, and for the 2007/2008 harvest, the T80, T100, T120 and T140 treatments did not significantly differ. In the two harvests analyzed, there was a significant increase in productivity until the T100 treatment (149 bags ha $^{-1}$), despite the gross water depth being greater in T120 and T140 (Figure 6 and Table 3). There was a significant adjustment between productivity and β (Figure 7), where the "optimum" point for coffee was reached for β_{μ} = 0.163 m ^{3} m $^{-3}$. Below and above this value, there was a decrease in productivity.

Table 3. Average productivity of irrigated coffee yield with the center pivot system in Lavras, Brazil, according to the treatments T0 to T140, in the 2006/2007 and 2007/2008 harvest years.

Treatment	---------------------------- Yield (bags ha $^{-1}$)	----------------------------	
	Harvest 2006/2007	**Harvest 2007/2008**	**Sum of yields**
T140	26.57 bc	94.73 ab	121.30 ab
T120	38.35 ab	89.27 ab	127.63 ab
T100	45.59 a	104.8 a	149.67 a
T80	21.50 c	80.74 abc	102.25 bc
T60	17.56 c	61.46 bc	79.02 cd
T0	15.15 c	43.48 c	58.63 d

Note: Means followed by the same letters do not differ significantly at the level of 5% probability.

Figure 6. Accumulated gross irrigation depth and sum of two years of irrigated coffee yield with a center pivot system in Lavras, Brazil: a) gross irrigation depth (irrigation + precipitation) applied according to treatments T0 to T140; b) sum of yields from the 2006/2007 and 2007/2008 harvest years.

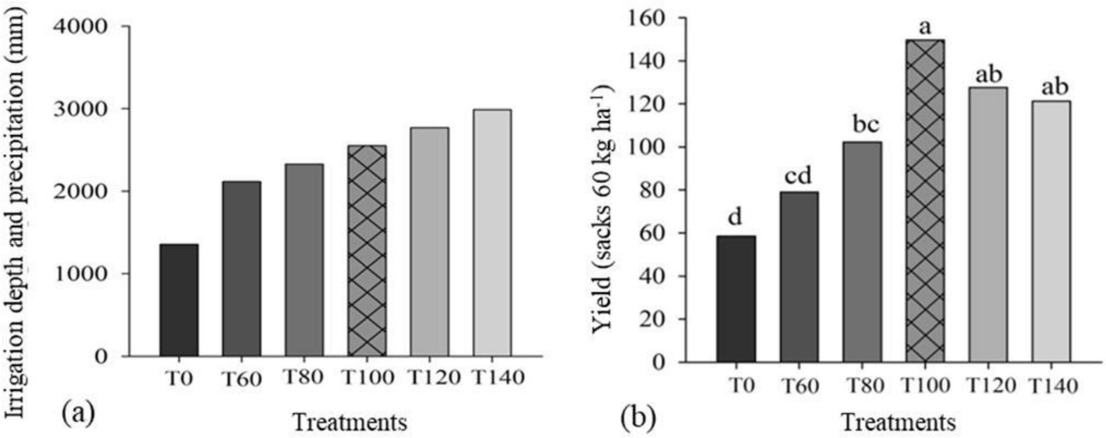
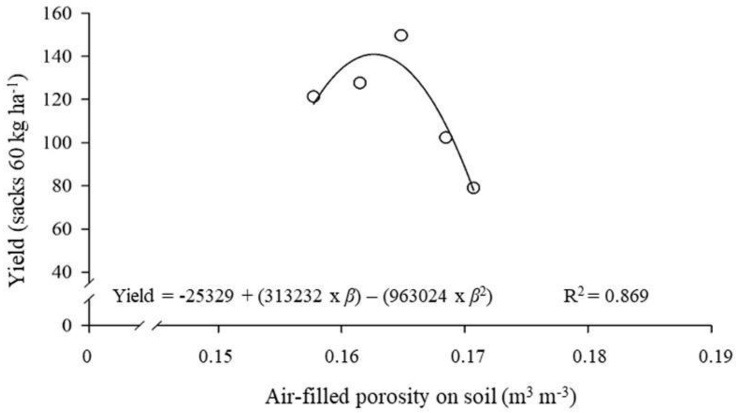


Figure 7. Regression analysis between yield and average air-filled porosity (β) for the irrigated coffee cultivated in Lavras, Brazil, considering the T0 to T140 treatments.



The soil bulk density (ρ_S) decreased with increasing depth (Table 2). Thus, the total soil porosity (α) was lower in the surface layer, resulting in a lower volume of macropores and a greater volume of micropores. The opposite was observed by Nunes et al. (2010) and Siqueira et al. (2014), who verified that the management of an Oxisol cultivated with coffee increased the ρ_S, modifying the physical-water attributes. The soil water retention curves (Figure 1) also verified a significant increase in the saturation point (θ_S) and a reduction in the residual water content (θ_r) in deeper layers (Table 2).

The Pearson correlations between the soil physical-water attributes (Table 4) and the average air-filled porosity (β_{μ}) throughout the layers analyzed revealed sources of variation. The soil bulk density (ρ_S) was the main variable influencing the decrease in β, with a coefficient of -1.0 ($p < 0.01$), which in turn also reduced the total porosity (α; $p < 0.01$), saturation point (θ_S; $p < 0.01$) and macroporosity ($p < 0.05$). Changes in soil structure modify the pore diameter and distribution, and consequently, the water retention capacity, increasing the moisture at the permanent wilting point (θ_{PWP}; $p < 0.05$) and residual water content (θ_r). File; Carvalho (2009) and Karuma et al. (2014) reported that changes in soil physical properties, such as aggregate stability, consistency, aeration and water retention, promote changes in plant yield. Silva; Lima (2013) reported a decrease in Arabic coffee yield in areas with higher soil density and, consequently, lower total and air-filled porosities.

Table 4. Pearson correlation between the soil physical attributes and average air-filled porosity in all the layers of the analyzed soil.

Source of variation	ρ_P	ρ_S	α	θ_{FC}	θ_{PWP}	θ_S	θ_r	α	n	Macro porosity	Micro porosity
β	0.83 NS	−1.00 **	1.00 **	−0.83 NS	−0.99 *	1.00 **	−0.99 NS	0.93 NS	0.20 NS	1.00*	−0.83 NS

* and ** indicate significance at 5% and 1% probability, respectively; NS is not significant; ρ_P – soil particle density; ρ_S – soil bulk density; α – total porosity (volumetric soil water content at saturation); θ_{FC} – volumetric soil water content at field capacity; θ_{PWP} – volumetric soil water content at the permanent wilting point; θ_r – residual water content; α and n – empirical parameters from the van Genuchten (1980) equation.

On average, when the critical limit of $\beta_{\mu} = 0.163$ m ^{3} m $^{-3}$ was exceeded, the coffee yield decreased (Figure 7). Klein et al. (2008) concluded that a β greater than 0.15 m ^{3} m $^{-3}$ provided greater productivity for wheat in an Oxisol than a β between 0.10 and 0.15 m ^{3} m $^{-3}$. In the same soil type, Primavesi; Melo; Libardi (1988) reported that the mean β_{min} for maximum bean crop yield should be 0.125 m ^{3} m $^{-3}$, with variations ranging from 0.09 to 0.16 m ^{3} m $^{-3}$. All these findings confirm the considerations of Silva; Kay; Perfect (1994), who reported that a reduction in air-filled porosity decreases crop yield. However, the limit of 0.1 m ^{3} m $^{-3}$ established in the literature was not exceeded in the present study in any treatment (Figure 3b, 4 and 7), indicating that coffee needs more β_{min}. According to Van Lier (2001), the deeper the root system is, the greater the β needed, which demands greater pore connectivity for aeration to occur.

The T0 treatment *resulted in β values* in the range of 0.188--0.20 m ^{3} m $^{-3}$, corresponding to a 49% probability in the observed frequency distribution (Table 5). Importantly, at this level of *β,* the soil water content is close to the permanent wilting point (θ_{PMP}). The absence of water in the soil facilitates the flow of air but exposes plants to water stress, causing changes in coffee metabolism, nutritional deficiencies and a reduction in carbon retention, crop yield and coffee bean quality (BATISTA et al., 2010; GRISI et al., 2008; SILVA et al., 2011).

Table 5. Probability of air-filled porosity in soil (13200 hours) on coffee crops in a eutrophic red Oxisol irrigated with a center pivot system from 2007--2008.

Lower limit of the class	**Upper limit of the class**	**------ Observed probability of soil *β* in the treatments (%) -----**											
		----- Absolute frequency -----						**---- Cumulative frequency ----**					
		T0	**T60**	**T80**	**T100**	**T120**	**T140**	**T0**	**T60**	**T80**	**T100**	**T120**	**T140**
0.117	0.122	0.0	0.0	0.0	0.0	2.0	1.0	0	0	0	0	2	1
0.122	0.127	0.0	0.0	0.0	0.0	2.0	1.0	0	0	0	0	4	2
0.127	0.132	0.0	0.0	0.0	0.0	2.0	2.0	0	0	0	0	6	4
0.132	0.137	0.0	0.0	0.0	0.0	3.0	5.0	0	0	0	0	9	9
0.137	0.142	0.0	0.0	0.0	1.0	6.0	10.0	0	0	0	1	15	19
0.142	0.147	0.0	1.0	2.0	3.0	8.0	13.0	0	1	2	4	23	32
0.147	0.152	1.0	4.0	4.0	9.0	9.0	18.0	1	5	6	13	32	50
0.152*	0.158	2.0	7.0	11.0	28.0	13.0	15.0	3	12	17	41	45	65
0.158	0.163*	6.0	16.0	22.0	18.0	12.0	5.0	9	28	39	59	57	70
0.163	0.168	8.0	26.0	21.0	8.0	7.0	2.0	17	54	60	67	64	72
0.168	0.173	10.0	8.0	10.0	4.0	7.0	4.0	27	62	70	71	71	76
0.173	0.178	8.0	7.0	4.0	3.0	3.0	3.0	35	69	74	74	74	79
0.178	0.183	6.0	7.0	5.0	5.0	4.0	5.0	41	76	79	79	78	84
0.183	0.188	10.0	5.0	6.0	7.0	8.0	5.0	51	81	85	86	86	89
0.188	0.200	49.0	18.0	15.0	14.0	12.0	12.0	100	100	100	100	100	100

* Ideal range of air-filled porosity for the development of coffee plants.

The irrigation management in the T100 treatment increased the frequency of air-filled porosity in the range of 0.152 to 0.163 m ^{3} m $^{-3}$, resulting in a 46% observed probability (Table 5). Therefore, the soil water content was maintained close to the field capacity, allowing a constant flow of water and air in the soil. The T120 and T140 treatments had probabilities of 25% and 20%, respectively, for the same class of β. As T100 presented a greater yield than the other treatments did (Figure 6b), the porosity range between 0.152 and 0.163 m ^{3} m $^{-3}$ indicates more adequate environmental conditions for the coffee plants at the studied site.

6 CONCLUSIONS

The increase in gross irrigation depth led to a linear reduction in the average air-filled porosity in the irrigated eutrophic red Oxisol. However, the coffee yield was affected only by irrigation depths lower than the water requirements of the crop in the region.

The 100% gross irrigation depth (T100) treatment resulted in a significant increase in productivity between the two harvests, as analyzed with the eutrophic red Oxisol. This increase in the gross irrigation depth tended to reduce the productivity and soil air-filled porosity of the coffee crop.

The ideal range of soil air-filled porosity (β) between 0.152 and 0.163 m ^{3} m $^{-3}$ provided adequate aeration conditions and relatively high yields for the coffee crop.

7 REFERENCES

ALVARES, CA; STAPE, JL; SENTELHAS, PC; GONÇALVES, JLM; SPAROVEK, G. Koppen's climate classification map for Brazil. **Meteorologische Zeitschrift** , vol. 22, no. 6, p. 711-728. 2013. DOI: 10.1127/0941-2948/2013/0507.

ASCE-EWRI. **The ASCE standardized reference evapotranspiration equation** . Report of the Task Committee on Standardization of Reference Evapotranspiration. Reston: Environmental and Water Resources Institute of the American Society of Civil Engineers, 2005. Available at: https://ascelibrary.org/doi/abs/10.1061/9780784408056. Accessed on: Jun. 03, 2020.

BATISTA, LA; GUIMARÃES, RJ; PEREIRA, FJ; CARVALHO, GR; CASTRO, EM Leaf anatomy and water potential in the tolerance of coffee cultivars to water stress. **Agronomic Science Journal** , v. 41, n. 3, p. 475-481. 2010. DOI: https://doi.org/10.1590/S1806-66902010000300022.

BEN-NOAH, I.; FRIEDMAN, SP Review and Evaluation of Root Respiration and of Natural and Agricultural Processes of Soil Aeration. **Vadose Zone Journal** , vol. 17, p. 1-47, 2018. DOI: https://doi.org/10.2136/vzj2017.06.0119.

CAMARGO, AP; CAMARGO, MBP Definition and schematization of the phenological phases of Arabica coffee under tropical conditions in Brazil. **Bragantia** , Campinas, v. 60, n. 1, p. 65-68, 2001. DOI: https://doi.org/10.1590/S0006-87052001000100008.

EMBRAPA. **Coffee Phenology: Agrometeorological Conditions and Water Balance of the 2004–2005 Agricultural Year** . Documents 5 . Brasília, DF: Embrapa, 2009.

EMBRAPA. **Brazilian Soil Classification System** . 5th ^{ed} ., Brasília, DF: Embrapa, 2018.

EVANGELISTA, AWP; LIMA, LA; SILVA, AC; MARTINS, CP; RIBEIRO, MS Soil water potential during different phenological phases of coffee irrigated by center pivot. **Agricultural Engineering** , Jaboticabal, v. 33, n. 2, p. 269-278, 2013. DOI: https://doi.org/10.1590/S0100-69162013000200006.

GRABLE, AR; SIEMER, EG Effects of bulk density, aggregate size, and soil water suction on oxygen diffusion, redox potential and elongation of corns roots. **Soil Science Society of America Journal** , vol. 32, no. 2, p. 180-186, 1968. DOI: https://doi.org/10.2136/sssaj1968.03615995003200020011x.

GRISI, FA; ALVES, JD; CASTRO, EM; OLIVEIRA, C.; BIAGIOTTI, F.; MELO, LA Leaf anatomical evaluations in “catuaí” and “siriema” coffee seedlings subjected to water stress. **Science and Agrotechnology** , Lavras, v. 32, n. 6, p. 1730-1736, 2008. DOI: https://doi.org/10.1590/S1413-70542008000600008.

HALL, DGM; REEVE, MJ; THOMASSON, A.J.; WRIGHT, VF **Water retention, porosity and density of field soils** . Soil Survey of England and Wales. Harpenden: Hertfordshire, 1977.

JABRO, JD; SAINJU, ONE; STEVENS, WB; EVANS, RE Estimation of CO_2 diffusion coefficient at 0–10 cm depth in undisturbed and tilled soils. **Archives of Agronomy and Soil Science** , vol. 58, no. 1, p. 1-9, 2012. DOI: https://doi.org/10.1080/03650340.2010.506482.

KARUMA, A.; MTAKWA, P.; AMURI, N.; GACHENE, C.K.; GICHERU, P. Tillage effects on selected soil physical properties in a maize-bean intercropping system in Mwala District, Kenya. **International Scholarly Research Notices** , vol. 2014, p. 1-12, 2014. DOI: https://doi.org/10.1155/2014/497205.

KLEIN, VA; VIEIRA, ML; DURIGON, FF; MASSING, JP; FÁVERO, F. Aeration porosity of a Red Latosol and wheat yield under no-tillage scarification. **Ciência Rural** , Santa Maria, v. 38, n. 2, p. 365-371, 2008. DOI: https://doi.org/10.1590/S0103-84782008000200011.

LICAUSI, F. Regulation of the molecular response to oxygen limitations in plants. **New Phytologist** , vol. 190, n. 3, p. 550-555, 2011.

LIMA, LC; GONÇALVES, AC; FERNANDES, ALT; SILVA, RO; LANA, RMQ Growth and productivity of irrigated coffee as a function of different nitrogen sources. **Coffee Science** , Lavras, v. 11, n. 1, p. 97-107, 2016. Available at: http://www.sbicafe.ufv.br:80/handle/123456789/8177. Accessed on: Apr. 21, 2020.

LIMA, CGR; CARVALHO, MP Linear and spatial correlation between corn forage productivity and particle size fractions of a dystrophic Red Latosol. **Bragantia** , Campinas, v. 68, n. 4, p.985- 990, 2009. DOI: https://doi.org/10.1590/S0006-87052009000400019.

MANLY, BFJ **Multivariate statistical methods: an introduction** . 3rd ed. Porto Alegre, RS: Bookman, 2008.

NEIRA, J.; ORTIZ, M., MORALES, L.; ACEVEDO, E. Oxygen diffusion in soils: Understanding the factors and processes needed for modeling. **Chilean Journal of Agricultural Research** , v. 75, p. 35-44, 2015. DOI: http://dx.doi.org/10.4067/S0718-58392015000300005.

NUNES, LAPL: DIAS, LE; JUCKSCH, I.; BARROS, NF Soil physical attributes in a coffee monoculture area in the Zona da Mata region of Minas Gerais. **Bioscience Journal** , Uberlândia, v. 26, n. 1, p. 71-78, 2010. Available at: https://seer.ufu.br/index.php/biosciencejournal/article/view/7040/4666. Accessed on: Jun. 07, 2020.

PÄIVÄNEN, J. Hydraulic conductivity and water retention in peat soils. **Acta Forestalia Fennica** , 129, 1973. Available at: 10.14214/aff.7563. Accessed on: Mar. 11, 2020.

PRIMAVESI, O. MELO, FAF, LIBARDI, PL Soil aeration porosity for maximum common bean production in a greenhouse. **Annals of the Luiz de Queiroz College of Agriculture** , Piracicaba, v. 45(part. 2), p. 381-396, 1988. DOI: https://doi.org/10.1590/S0071-12761988000100024.

SCHEEL, GL; PAULI, ED; RAKOCEVIC, M.; BRUNS, RE; SCARMINIO, IS Environmental stress evaluation of *Coffea arabica* L. leaves from spectrophotometric fingerprints by PCA and OSC–PLS–DA. **Arabian Journal of Chemistry** , vol. 12, no. 8, p. 4251-4257, 2019. DOI: https://doi.org/10.1016/j.arabjc.2016.05.014.

SILVA, AP, KAY, BD, PERFECT, E. Characterization of the least limiting water range. **Soil Science Society of American Journal** , vol. 58, p. 1775-1781, 1994. DOI: https://doi.org/10.2136/sssaj1994.03615995005800060028x.

SILVA, AP, IMHOFF, S., KAY, B. Plant response to mechanical resistance and air-filled porosity of soils under conventional and no-tillage systems. **Scientia Agricola** , Piracicaba, v. 61, no. 4, p. 451-456, 2004. DOI: https://doi.org/10.1590/S0103-90162004000400016.

SILVA, AC; LIMA, LA; EVANGELISTA, AWP; MARTINS, CP Evapotranspiration and crop coefficient of coffee plants irrigated by central pivot. **Brazilian Journal of Agricultural and Environmental Engineering** , Campina Grande, v. 15, n. 12, p. 1215-1221, 2011. DOI: https://doi.org/10.1590/S1415-43662011001200001.

SILVA, AS, LIMA, JSS Soil physical attributes and their spatial relationship with Arabica coffee productivity. **Coffee Science** , Lavras, v. 8, n. 4, p. 395-403, 2013. Available at: http://www.sbicafe.ufv.br:80/handle/123456789/7993. Accessed on: May, 27, 2020.

SIQUEIRA, RHS; FERREIRA, MM; ALCÂNTARA, EN; SILVA, BM; SILVA, RC (2014). Water retention and s index of an oxisol subjected to weed control methods in a coffee crop. **Science and Agrotechnology** , Lavras, v. 38, n. 5, p. 471-479, 2014. DOI: https://doi.org/10.1590/S1413-70542014000500006.

SMITH, K. A.; BALL, T.; CONEN, F.; DOBBIE, K.E.; MASSHEDER, J.; REY, A. Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes. **European Journal of Soil Science** , vol. 54, p. 779-791, 2003. DOI: https://doi.org/10.1111/ejss.12539.

TEIXEIRA, PC; DONAGEMMA, GK; FONTANA, A.; TEIXEIRA, WG **Manual of soil analysis methods** . 3rd ed. rev. and ampl. Brasília, DF: Embrapa, 2017. Available at: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1085209. Accessed on: Apr. 23, 2020.

THEODOROU, C., CAMERON, JN, BOWEN, GD Growth of roots of different Pinus radiata genotypes in soil at different strength and aeration. **Australian Forestry** , vol. 54, no. 1-2, p. 52-59, 1991. DOI: https://doi.org/10.1080/00049158.1991.10674556.

TORMENA, CA, SILVA, AP, LIBARDI, PL Characterization of the optimum water range of a Purple Latosol under no-tillage. **Brazilian Journal of Soil Science** , v. 22, n. 4, p. 573-581, 1998. DOI: https://doi.org/10.1590/S0100-06831998000400002.

VAN GENUCHTEN, MT A closed form equation for predicting the hydraulic conductivity of unsaturated soils. **Soil Science Society of American Journal** , vol. 44, no. 5, p. 892-898, 1980. DOI: https://doi.org/10.2136/sssaj1980.03615995004400050002x.

VAN LIER, JQ Oxygenation of the root system: a physical approach. **Brazilian Journal of Soil Science** , v. 25, n. 1, p. 233-238, 2001 . DOI: https://doi.org/10.1590/S0100-06832001000100025.

XU, X., NIEBER, JL, GUPTA, SC Compaction effect on the gas diffusion coefficient in soils. **Soil Science Society of America Journal** , vol. 56, no. 6, p. 1743-1750, 1992. DOI: https://doi.org/10.2136/sssaj1992.03615995005600060014x.

WALL, A., HEISKANEN, J. Effect of air-filled porosity and organic matter concentration of soil on growth of *Picea abies* seedlings after transplanting. **Scandinavian Journal of Forest Research** , vol. 18, no. 4, p. 344-350, 2003. DOI: https://doi.org/10.1080/02827580310001742.

WEITS, DA, VAN DONGEN, JT, LICAUSI, F. Molecular oxygen as a signaling component in plant development. **New Phytologist** , p.1-12, 2020. DOI: https://doi.org/10.1111/nph.16424.

ZOU, C.; PENFOLD, C.; SANDS, R.; MISRA, RK; HUDSON, I. Effects of soil air-filled porosity, soil matrix potential and soil strength on primary root growth of radiata pine seedlings. **Plant and Soil** , vol. 236, no. 1, p. 105-115, 2001. DOI: 10.1023/A:1011994615014.