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

JORGE LUIZ MORETTI DE SOUZA[1]; STEFANIE LAIS KREUTZ ROSA[2]; ADÃO WAGNER PÊGO EVANGELISTA[3] E BRUNO CÉSAR GURSKI[4]

[1] *Departamento de Solos e Engenharia Agrícola, Universidade Federal do Paraná, Rua dos Funcionários, 1540, Bairro Cabral, CEP 80.035-050, Curitiba, Paraná, Brasil. jmoretti@ufpr.br*
[2] *Departamento de Solos e Engenharia Agrícola, Universidade Federal do Paraná, Rua dos Funcionários, 1540, Bairro Cabral, CEP 80.035-050, Curitiba, Paraná, Brasil. skreutzrosa@gmail.com*
[3] *Departamento de Engenharia de Biossistemas, Universidade Federal de Goiás, Campus Samambaia, Avenida Esperança s/n, Caixa postal 131, CEP 74.690-900, Goiânia, Goiás, Brasil. awpego@bol.com.br*
[4] *Departamento de Solos e Engenharia Agrícola, Universidade Federal do Paraná, Rua dos Funcionários, 1540, Bairro Cabral, CEP 80.035-050, Curitiba, Paraná, Brasil. brunocep@gmail.com*

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

The increase of soil water content reduces the β by preventing soil O_2 diffusion. In contrast, with the constant consumption of O_2 by the edaphic fauna and roots, the plants can be exposed to the hypoxic condition or low oxygen concentration, affecting energy production via oxidative phosphorylation, limiting root growth and reducing the productivity (WEITS; VAN DONGEN; LICAUSI, 2021). The β seems to be a problem already overcome in Brazil, since the predominant soils (Oxisols and Ultisols) in the country are well-drained (EMBRAPA, 2018). However, the β can be a problem when irrigation is used, since the inadequate management can lead to excess of water in the soil, causing reduction of β. Therefore, it was agreed to adopt a β minimum (β_{min}), which indicates the ideal air-filled porosity so that the O_2 diffusion rate in the soil is equal to its consumption, avoiding plant stress and improving the 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, it was adopted $\beta_{\text{min}} \geq 0.1$ m^3 m^{-3} as a limiting value for the crops 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 O_2 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 reference, which is not ideal, given the particularity and importance of coffee as an agricultural crop. Zou et al. (2001) observed that root elongation rate increased rapidly when the air-filled porosity was between

0.05 and 0.15 m^3 m^{-3} for radiata pine. Silva, Imhoff and Kay (2004) evaluating a soil in Canada, with a maize crop observed a relationship between plant growth and air-filled porosity for no-tillage and conventional-tillage between 0.05 and 0.27 m^3 m^{-3}. Klein et al. (2008) found values between 0.07 and 0.24 m^3 m^{-3} under no-tillage system and 0.17 and 0.27 m^3 m^{-3} under no-tillage with mechanical scarification for wheat; and Wall and Heiskanen (2003) suggest values between 0.20 and 0.40 m^3 m^{-3} for pinus crop. Therefore, a high variation of β_{min} in different plant species and soils is reported.

Due to the direct influence of β_{min} on crop productivity and the cost involved in the 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 in a eutrophic red Oxisol, and determine its ideal range in Lavras, southeastern region of Brazil.

4 MATERIAL AND METHODS

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

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

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

Where: Li_i is the gross irrigation depth at each i-period of 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}); E is the efficiency of the center pivot irrigation (%), considered equal to 90%.

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

The precipitation (P) was measured with a pluviometer, installed at 1.5 m height from the soil surface. The ETo estimation was performed using the modified Penman-Monteith method, with Cn = 900 K mm s^3 Mg^{-1} day^{-1} and Cd = 0.34 s m^{-1} (ASCE-EWRI, 2005). The daily climate data required, such as maximum, minimum and mean air temperature (°C), mean relative humidity (%), incident solar radiation (MJ m^{-2} day^{-1}) and wind speed at two meters height (m s^{-1}), were measured at the meteorological station of the National Institute of Meteorology (INMET), 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 region of Brazil.

Stages	Phenological phases	Period		Kc_i
		Initial	Final	(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 particle density (ρ_P) and soil texture were determined with soil samples at 0.25, 0.50 and 0.75 m depths 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 field capacity (θ_{CC}) and permanent wilting point (θ_{PMP}) was considered equal to the moisture obtained at -6 kPa and -1500 kPa potentials, respectively. The macropores ("$\theta_{SAT} - \theta_{CC}$") and micropores ("$\theta_{SAT}$ – macropores") were estimated (EVANGELISTA et al., 2013).

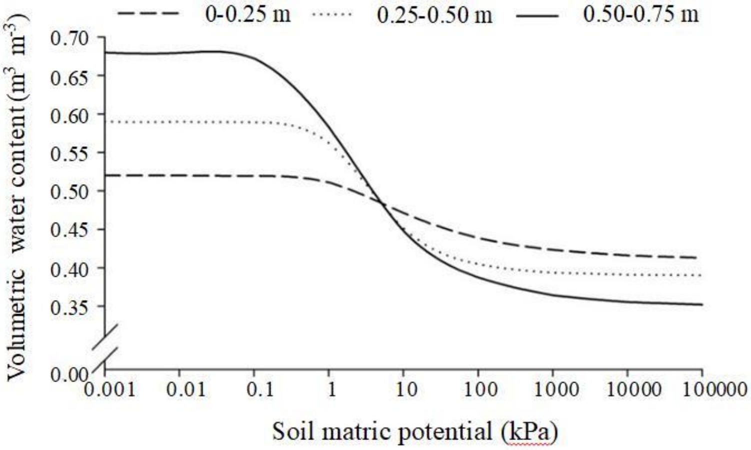
The soil water retention curves were determined based on the volumetric water content retained at 2.0, 4.0, 6.0 and 10.0 kPa tensions, in porous plate funnel, and 33, 100, 500 and 1500 kPa, in Richards pressure chamber. An undisturbed soil sample was used for each tension and the curve was adjusted with 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 curves parameters, adjusted with the Van Genuchten (1980) model for three layers of a eutrophic red Oxisol irrigated and cultivated with 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 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 coffee crop in Lavras, Brazil.



The soil matric potential $\psi_m(t_i)$ was estimated with *Watermark* sensors, installed at 0.25, 0.50 and 0.75 m depths, 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 matric potentials $\psi_m(t_i)$ and soil water retention curves adjusted for each depth. The hourly $\beta(t_i)$ was calculated for each soil depth, considering:

$$\beta(t_i) = (\alpha - \theta(t_i)) \tag{2}$$

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}); $\theta(t_i)$ is the volumetric water contents at each i-time (m^3 m^{-3}).

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

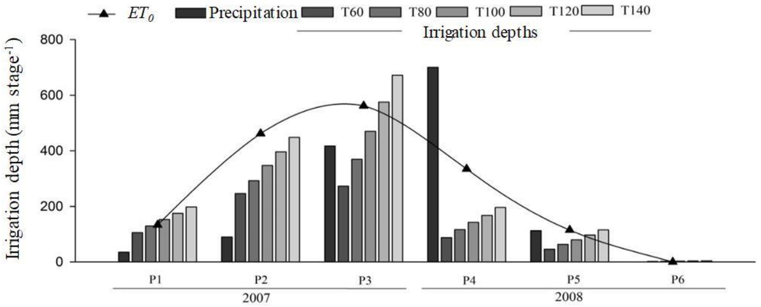
Results of yield and soil air-filled porosity (β) were submitted to statistical analysis of variance (F test), correlation, regression and frequency (MANLY, 2008). The productivity averages were compared with the Tukey test at 5% probability ($p<0.05$).

5 RESULTS AND DISCUSSION

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

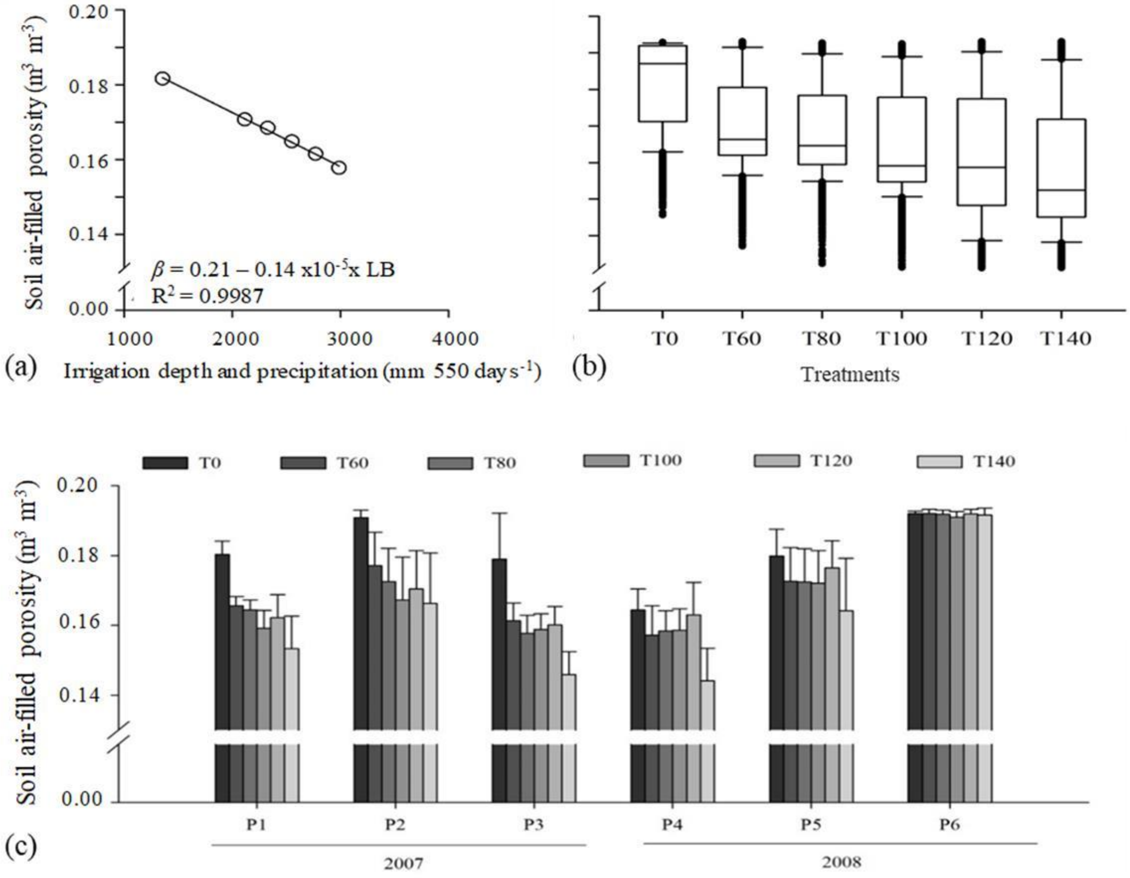
The precipitation was higher than reference evapotranspiration (*ETo*) only in the P4 stage between January and March 2008 (Figure 2), showing the importance of coffee irrigation in Lavras during the analyzed period. The gross irrigation depths (60, 80, 100, 120 and 140%) provided increments of 20% of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

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



The increasing gross irrigation depths caused, on average, a linear reduction of β in the 13200 analyzed hours (Figure 3a). The water applied in the irrigation infiltrated the soil, reducing the amount of air-filled porosity, however, were not enough to saturate the soil, as at this limit the stabilization of β is 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 β < 0.10, value considered critical in the literature (GRABLE; SIEMER, 1968; HALL et al., 1977; XU; NIEBER; GUPTA, 1992).

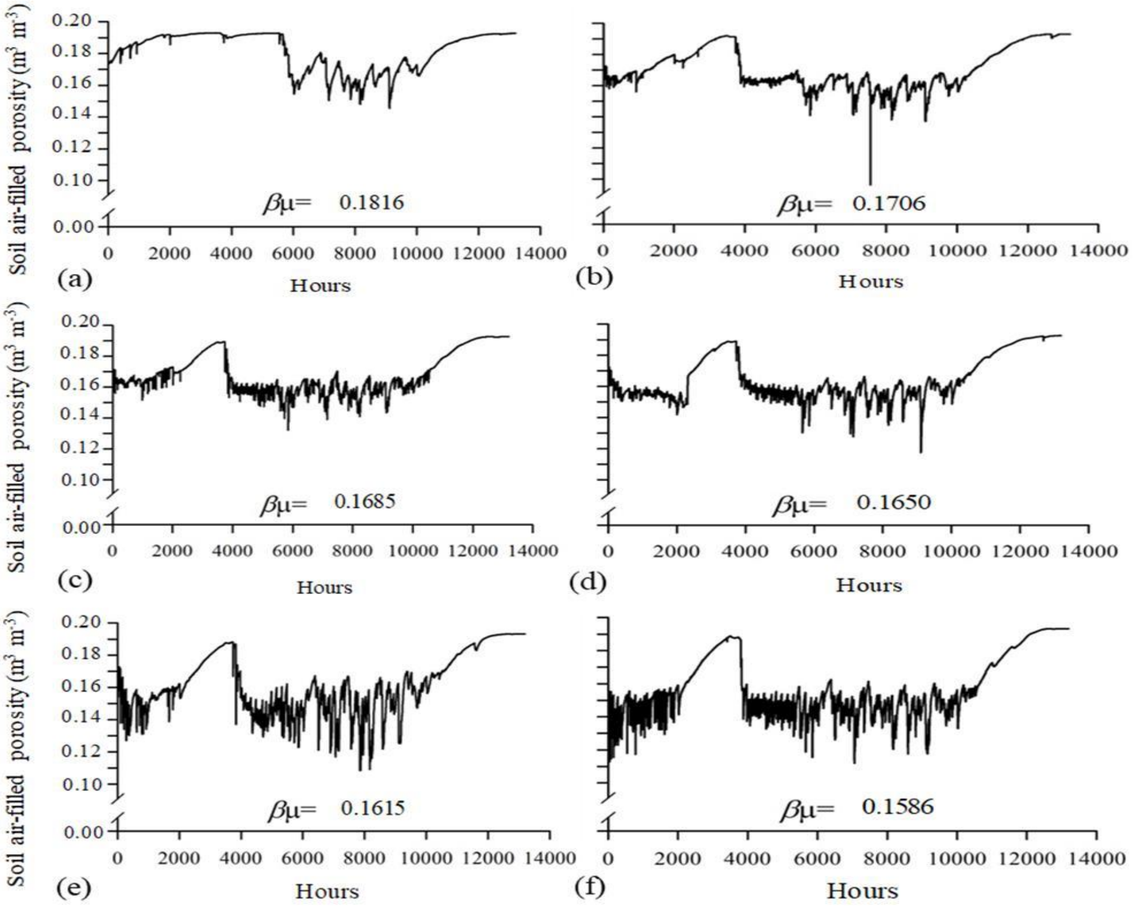
Figure 3. Relationship between gross water depth and mean soil air-filled porosity (β) in the different treatments and periods evaluated: a) linear regression analysis between mean soil air-filled porosity versus gross irrigation depths applied in the treatment ("precipitation + irrigation"); b) β *boxplot*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



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

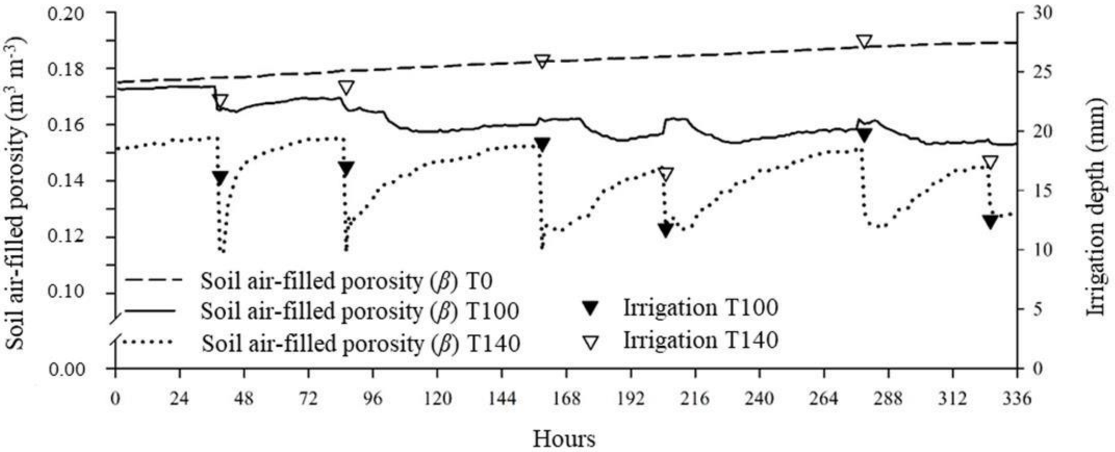
The hourly volumetric water content $\theta(t_i)$ data during the 13200 hours allowed to verifying the effect of the irrigations and pluviometric precipitations in hourly variations of $\beta(t_i)$ (Figure 4). In the T0, without irrigation, a mean air-filled porosity β_μ = 0.1816 m^3 m^{-3} (Figure 4a) was measured. With the complementary irrigation the tendency of β was similar, however with different amplitudes, showing that the increase of gross irrigation depths changed β_μ during the studied period (Figure 4). As the irrigation depth increased, there was a higher oscillation in the amplitude and a decrease in aeration porosity, which is expected since there is a higher amount of pores filled with water. During the period between 2000 and 4000 hours the oscillation was low due to the dormancy period required for irrigated coffee floral induction.

Figure 4. Soil air-filled porosity (β) in 13200 hours, in a eutrophic red Oxisol cultivated with 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 of *β*, specifically over two weeks without rainfall (Figure 5), allowed verifying its growth over time in the T0 (non-irrigated) treatment. The application of irrigation reduced the *β* immediately, mainly in the T140. Afterwards, the water infiltrated in 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 the T140, presenting lower wetting peaks and allowing more uniform airflow. On T140 treatment, *β* decreased rapidly, requiring approximately 24 hours to returns to the mean value.

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



Van Lier (2001) considers that wetting peaks reduce the soil permeability to the air, requiring higher O_2 pressure gradients. As a result, there is a decrease in the pressure of this gas in the soil depth and, therefore, part of the root system may experience a lack of O_2.

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

The variation of *β* in treatments reflected in significant differences in coffee yield. Considering the 2006/2007 harvest, the treatments T100 and T120 obtained higher productivity (Table 3), being 45.59 and 38.35 bags ha^{-1}, respectively, and for 2007/2008 harvest the treatments T80, T100, T120 and T140 did not differ statistically. In the two harvests analyzed there were a significant increase in productivity until the T100 treatment (149 bags ha^{-1}), despite the gross water depth being higher 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 drop in productivity.

Table 3. Average productivity of irrigated coffee yield with 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 to the level of 5% probability.

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

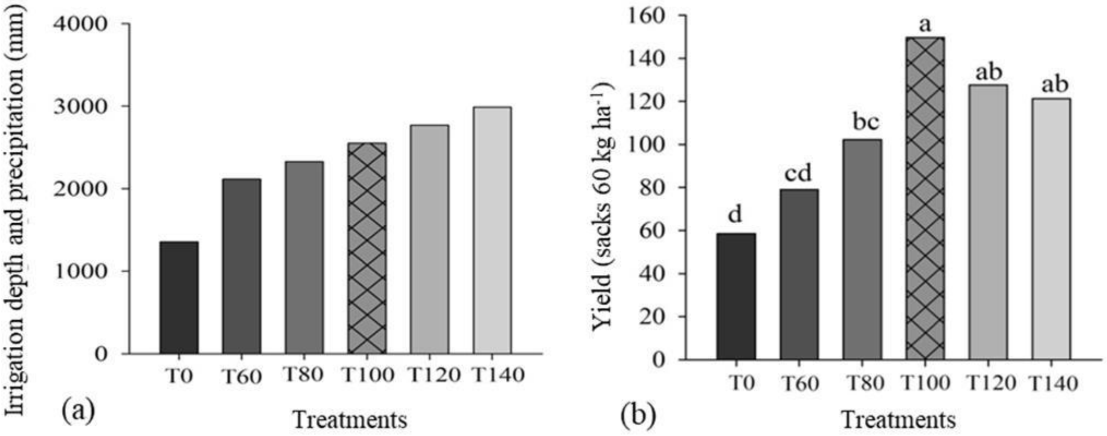
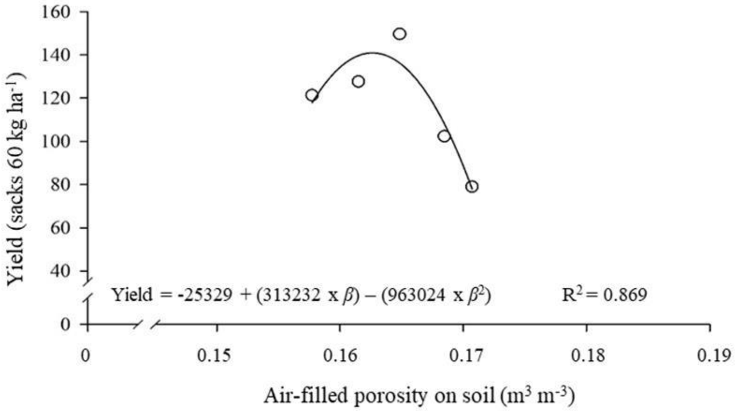


Figure 7. Regression analysis between yield and average air-filled porosity (β) for the irrigated coffee cultivated in Lavras, Brazil, considering the T0 to T140 treatments.



The soil bulk density (ρ_S) decreased with increasing depth (Table 2). Thus, the total soil porosity (α) was lower in the surface layer, presenting a lower volume of macropores and higher 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 made it possible to verify a significant increase in the saturation point (θ_S) and a reduction in the residual water content (θ_r) on deeper layers (Table 2).

Pearson correlations between the soil physical-water attributes (Table 4) and the average air-filled porosity (β_μ) throughout the layers analyzed showed sources of variation. The soil bulk density (ρ_S) was the main variable in the decrease of 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). Lima and Carvalho (2009) and Karuma et al. (2014) state that changes in soil physical properties, such as aggregate stability, consistency, aeration and water retention, promote changes in plant yield. Silva and Lima (2013) verified a decrease in Arabic coffee yield in areas with higher soil density, and consequently lower total and air-filled porosity.

Table 4. Pearson correlation between soil physical attributes and average of air-filled porosity in all 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 ** significant at 5% and 1% probability, respectively; ^{NS} no 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 permanent wilting point; θ_r – residual water content; α e 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, coffee yield decreased (Figure 7). Klein et al. (2008) concluded that β over 0.15 m^3 m^{-3} provided higher productivity for wheat in an Oxisol, compared to β between 0.10 and 0.15 m^3 m^{-3}. In the same soil type, Primavesi, Melo and Libardi (1988) concluded that the mean β_{min} for maximum bean crop yield should be 0.125 m^3 m^{-3}, with variations in range of 0.09 to 0.16 m^3 m^{-3}. All notes confirm the considerations of Silva, Kay and Perfect (1994), in which the reduction of air-filled porosity decreases the 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 higher β_{min}. According to Van Lier (2001), as deeper the root system is, larger is the β required, demanding higher pore connectivity for aeration to occur.

The T0 treatment remained mostly with β in the range of 0.188 to 0.20 m^3 m^{-3}, corresponding to a 49% probability in the observed frequency distribution (Table 5). It is important to highlight that 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 the plants to water stress, causing changes in coffee metabolism, nutritional deficiencies and a reduction in the 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 on soil (13200 hours), observed on coffee crop in a eutrophic red Oxisol irrigated with center pivot system, from 2007 to 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 increased the frequency of air-filled porosity in the range of 0.152 to 0.163 $m^3\ m^{-3}$, obtaining a 46% observed probability (Table 5). Therefore, soil water content was maintained close to the field capacity, allowing a constant flow of water and air in the soil. The treatments T120 and T140 had a probability of 25 and 20%, respectively for the same class of β. As the T100 presented higher yield than the other treatments (Figure 6b), the porosity range between 0.152 and 0.163 $m^3\ m^{-3}$ indicates more adequate environmental conditions for coffee plants in the studied site.

6 CONCLUSIONS

The increase in gross irrigation depths provides a linear reduction of the average air-filled porosity in the irrigated eutrophic red Oxisol. However, the coffee yield was only affected with irrigation depths lower than the water requirement of the crop for the region.

The 100% of the gross irrigation depth (T100) treatment showed a significant productivity increase in the two analyzed harvests with eutrophic red Oxisol. From this value, the increase in the gross irrigation depth resulted in a tendency to reduce 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 higher yields for the coffee crop.

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