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Drip irrigation in coffee crop under different planting densities: Growth and yield in southeastern Brazil

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irrigated coffee cropping
Coffea arabica L.
plant spacing

ABSTRACT

Irrigation associated to reduction on planting spaces between rows and between coffee plants has been a featured practice in coffee cultivation. The objective of the present study was to assess, over a period of five consecutive years, influence of different irrigation management regimes and planting densities on growth and bean yield of *Coffea arabica* L.. The treatments consisted of four irrigation regimes: climatologic water balance, irrigation when the soil water tension reached values close to 20 and 60 kPa; and a control that was not irrigated. The treatments were distributed randomly in five planting densities: 2,500, 3,333, 5,000, 10,000 and 20,000 plants ha^{-1}. A split-plot in randomized block design was used with four replications. Irrigation promoted better growth of coffee plants and increased yield that varied in function of the plant density per area. For densities from 10,000 to 20,000 plants ha^{-1}, regardless of the used irrigation management, mean yield increases were over 49.6% compared to the non-irrigated crop.

Palavras-chave:
cafeicultura irrigada
Coffea arabica L.
espaçamento de plantio

Irrigação por gotejamento em cafeeiros sob diferentes densidades de plantio: Crescimento e produtividade no Sudeste do Brasil

RESUMO

Associada ao adensamento da lavoura, a irrigação tem sido prática de destaque na cafeicultura. Objetivou-se, neste trabalho, avaliar a influência de diferentes regimes de irrigação e densidades de plantio sobre o crescimento vegetativo e a produtividade média de cafeeiros *Coffea arabica* L, ao longo de cinco anos. Os tratamentos constaram de quatro regimes de irrigação: balanço hídrico climatológico; irrigações com base nas tensões de 20 e 60 kPa, além de uma testemunha não irrigada, os quais foram distribuídos aleatoriamente em cinco densidades de plantio 2.500; 3.333; 5.000; 10.000 e 20.000 plantas ha^{-1}. O delineamento experimental em blocos casualizados em esquema de parcelas subdivididas foi utilizado com quatro repetições; verificou-se que a irrigação promove maior crescimento das plantas de cafeeiro e aumenta a produtividade, que varia em função da densidade de plantas por área. Obtiveram-se, para as densidades de 10.000 e 20.000 plantas ha^{-1}, independente do manejo da irrigação utilizado, aumentos médios de produtividade acima de 49,6% em relação ao cultivo não irrigado.

Introduction

Coffee irrigation is a promising technique that may provide both yield increase and expansion of coffee plantations in areas considered unsuitable due to the occurrence of water shortage (Silva et al., 2008). The main advantage of drip irrigation is its capability of applying small amounts of water with a high degree of uniformity, making this method potentially more efficient than others irrigation methods. For coffee producers, a further advantage attributed to the irrigation method is the possibility of implementing fertigation, a practice which may result in substantial fertilizer savings (Guimarães et al., 2010).

Serra et al. (2013) found in a coffee growing area in southern Minas Gerais that the increase in the number of plants from 14,000 to 15,125 plants ha^{-1} and the reduction of irrigation water applied by the adoption of higher value of soil water tension (20 to 100 kPa) can provide increments of the order of 27% in productivity (equivalent of 21.5 60 kg bags of processed coffee). Brazil's irrigated coffee area occupies 10% of its total planted area and provides 22% of the total amount of coffee bean produced in Brazil (Saturnino, 2007). Irrigation has increased productivity in regions where water shortage periods coincide with the frutification stage (Silva et al., 2008). In the southern region of the state of Minas Gerais, a 119% increase in yield was obtained in the first five harvests of the coffee cultivar Rubi MG-1192 by applying irrigation water levels corresponding to 60% of the evaporation from the Class A Pan (Epan) compared to the non-irrigated coffee trees (Gomes et al., 2007).

Another technique that has been used in coffee plantations in order to increase yield is higher density of planting. Several studies (Paulo et al., 2005; Braccini et al., 2005; Pereira et al., 2007) have shown that increased population density results in lower coffee bean production per plant. Paulo et al. (2005) observed a reduction of 93.5 g of processed coffee per plant (equivalent to 45%) with increasing number of plants from 2,500 to 5,000 plants ha^{-1}. However, because coffee bean weight remains fairly constant (Carr, 2001), greater yields per unit area are achieved due to the increase in the number of plants per area. Reduced spacing also alters plant growth, because the self-shading alters the balance of growth regulators that stimulate tip meristem development, such as auxins, gibberellins, and cytokinin (Taiz & Zeiger, 2004). Under reduced spacing conditions, plants produce thinner stems and smaller canopy diameters when compared to plants grown on a wider spacing (Martinez et al., 2007). Consequently, planting density may also affect water relations of coffee crop (Carr, 2001).

In Brazil and abroad there are few studies associating irrigation management criteria and coffee crop planting densities. Thus the objective of the present study was to assess, over a period of five consecutive years, the influence of different irrigation management regimes and planting densities on *Coffea arabica* L. cv Rubi MG-1192 growth and coffee bean yield.

Material and Methods

This experiment was carried out in an experimental area of the Federal University of Lavras, Minas Gerais, Brazil (21° 14' S, 45° 00' W, and 910 m above sea level) from January 2001 to August 2007. According to the Koppen classification, the local climate is the Cwa type. Annual means for temperature, rainfall, and relative air humidity are, respectively, 19.4 °C, 1,529.7 mm, and 76.2% (Figure 1). The soil at the experimental area is classified as Rhodic Hapludox.

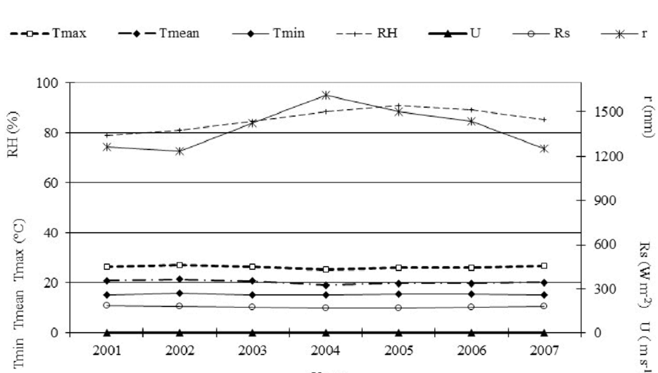


Figure 1. Meteorological data (maximum, mean and minimum temperatures (Tmax, Tmean and Tmin), wind speed (U), relative humidity (RH), solar radiation (Rs) and rainfall (r) recorded from 2001 to 2007 in the experimental area

Planting of *Coffea arabica* L. cv Rubi MG-1192 seedlings was set up in January 2001. Coffee seedlings were obtained from seeds and grown in polyethylene bags. In order to produce them, the substrate consisted of sieved soil and well decomposed manure in 7:3 volume/volume. Liming and fertilization were carried out according to soil and leaf analysis (Table 1), based on the recommendations for use of correctives and fertilizers in Minas Gerais, Brazil (Guimarães et al., 1999). Liming was performed three months before planting the crop, using 1.5 t ha^{-1} of dolomitic limestone. The fertilization was applied annually, and splitted in the period from October to January. The amounts of fertilizer applied were increased by 30%, as recommended by Santinato & Fernandes (2002) in the case of irrigated coffee plantations. Monoammonium phosphate was spread under the canopy area of the plants. A mixture of potassium nitrate and urea was applied in fertigation.

A split-plot randomized block design with 20 treatments was used. Four replications of four irrigation regimes were randomly distributed along each one of five main blocks. Each main block was set up in a different planting density: (D1) 2,500 plants ha^{-1} (4.0 m between rows and 1.0 m in the row), (D2) 3,333 plants ha^{-1} (3.0 m between rows and 1.0 m in the row), (D3) 5,000 plants ha^{-1} (2.0 m between rows and 1.0 m in the row), (D4) 10,000 plants ha^{-1} (2.0 m between rows and 0.5 m in the row), and (D5) 20,000 plants ha^{-1} (1.0 m between rows and 0.5 m in the row). These planting densities were submitted to four irrigation regimes: (i) irrigation every Monday, Wednesday, and Friday with amounts of water applied determined by a climatologic water balance; (ii) irrigation when the soil water tension reached values close to 20 kPa at the depth of 0.25 m; (iii) irrigation when the soil water tension reached values close to 60 kPa at 0.25 m depth; and (iv) a control that was not irrigated.

Each block was composed by the same number of coffee plants uniformly distributed along the same number of planting rows. Each one of these plots was composed by 10 consecutive plants along a continuous plant row segment. The first and the

Table 1. Chemical analysis of the soil at the beginning of differentiation of treatments

Attribute	Layer (cm)		
	0-20	20-40	40-60
Potential hydrogen (pH)	5,8	5,2	4,9
Phosphorus (mg dm^{-3})	41,0	33,0	5,0
Potassium (mg dm^{-3})	62,0	42,0	33,0
Calcium (cmml$_c$ dm^{-3})	4,9	2,3	1,5
Magnesium (cmol$_c$ dm^{-3})	2,1	1,1	0,7
Aluminum (cmol$_c$ dm^{-3})	0,0	0,3	0,6
H + Al (cmol$_c$ dm^{-3})	4,0	6,3	6,3
Sulfate (mg dm^{-3})	97,3	161,8	201,0
Boron (mg dm^{-3})	0,4	0,4	0,3
Zinc (mg dm^{-3})	1,3	0,7	0,3
Cobre (mg dm^{-3})	2,7	2,0	2,2
Manganese (mg dm^{-3})	2,2	1,5	1,0
Ferro (mg dm^{-3})	36,9	35,3	20,8
Cation exchange capacity Effectivet (cmol$_c$ dm^{-3})	7,2	3,8	2,9
Cation exchange capacity potential (cmol$_c$ dm^{-3})	11,2	9,8	8,6
Aluminum saturation (%)	0,0	7,9	20,8
Base saturation (%)	64,2	35,5	26,6
Organic matter (dag kg^{-1})	3,5	2,7	2,2

last plant of each segment were not considered for measurement purposes.

On all blocks, four different lateral lines were laid out along each irrigated row of coffee plant. Two laterals were laid out on each side of the rows. Along the length corresponding to each experimental plot, that was composed by a continuous planting row segment containing 10 coffee plants, dripper/emitter were only installed on one of these four lateral lines, the one that was managed according to the plot's irrigation regime. On these lateral line segments, on-line pressure compensating dripper/emitters, with a 3.78 L h^{-1} discharge, were uniformly installed spaced at 0.4 m. Within each block, each group of lateral lines submitted to the same irrigation regime was independently managed.

The water used to meet the required quality of the drip system presented the following characteristics: 0.11 dS m^{-1} electrical conductivity, 6.5 pH and concentrations of 4.3, 14.4 and 3.336 $cmol_c$ L^{-1} HCO_3, Ca and Mg, respectively. The salinity of this water was considered low by the Thorne and Peterson classification (Class C1) and could be used for irrigation in most crops and most soils, with little probability of causing salinity.

On the plots receiving irrigation based on the soil water potential value (20 or 60 kPa), soil moisture content inside the wetted soil volume was indirectly monitored with tensiometers and an electronic tensiometer with hypodermic needle. Tensiometers were installed along the central part of the wetted volume of soil below the line sources, as determined by the position of the irrigation lateral lines that were laid out on the same alignment determined by planting rows, at depths of 0.10, 0.25, 0.40, and 0.60 m. Irrigation was applied whenever the soil water tension reading at the 0.25 m depth approached the treatment pre-defined value (20 or 60 kPa). Applied irrigation water amounts were computed based on the water volume required to bring the soil moisture content of the entire plot wetted soil volume to the field capacity value. On these treatments, the wetted soil volume was computed as a 0.6 m wide rectangular block having the same plots length and a depth equal to the coffee crop effective root depth. During the first three years after planting, effective root depth was assumed to uniformly increase from 0.25 m up to a maximum value of 0.6 m.

On the plots receiving irrigation every Monday, Wednesday, and Friday, irrigation water amounts applied were computed by a soil water balance in which daily values of evapotranspiration of coffee crop were estimated by the product of daily reference evapotranspiration and crop coefficient values. Daily reference evapotranspiration values were computed according to the Penman Monteith method, as described in the FAO 56 Bulletin (Allen et al., 1998). Meteorological data required for reference evapotranspiration computation (daily values of mean temperatures (°C), maximum and minimum relative humidity (%), solar radiation (W m^{-2}), and wind speed (m s^{-1}) at a 2 m height) were monitored by an automatic metereological station (μmetos®) installed in the experimental area. Daily precipitation (mm) values were also monitored by the same μmetos ® metereological station. Crop coefficient (Kc) values were selected according to Santinato & Fernandes (2002).

The following characteristics were assessed every three months to evaluate the effect of different irrigation regimes and planting densities on the vegetative growth of coffee plants: plant height (cm), using a graduated ruler and the number of primary plagiotropic branches of coffee plants.

The mean processed coffee yield (bags ha^{-1}) was also assessed in five harvests during 2003-2007.

In order to assess coffee yield, fruits were harvested during June and July when the fraction of green fruit achieved a value lower than 15%. At this stage, all fruits of the eight plants of each treatment were stripped and collected. The mass of a 10 L sample of fruit of each treatment was determined and recorded. These samples were air dried until reached moisture content around 12%. At this point, experimentally determined conversion factors of fresh fruit mass to dry fruit mass were calculated for each treatment. Further, these samples were processed and total mass of green coffee per plant was computed and converted to the corresponding value of green coffee yield expressed as 60 kg bags ha^{-1}.

All variables that describe the plant growth of the coffee crop were analysed according to the scheme adopted of split plots (Steel et al., 1997). For the mean coffee yield in five harvests and plant growth, regression analysis were carried out for the quantitative factor (planting density) and the Scott-Knott test at the level of 0,05 significance for the qualitative factor (irrigation regime).

Results and Discussion

Analysis of the average irrigation water depth (mm) applied between harvests to irrigated coffee under different regimes for each planting density from 2001 to 2007 (Table 2) showed that irrigation requirements were highest when irrigation was managed by the climatologic water balance that is, in a fixed schedule and consequently with more frequent applications compared to the other regimes adopted. Under this condition, the soil moisture was continuously at a tension closer to field capacity (10 kPa). Lower water depths were applied in the irrigation at tensions close to 20 kPa (0.25 m depth) than those applied by the climatologic water balance and higher than

Table 2. Mean irrigation water depth (mm) applied between harvests to irrigated coffee crop under different regimes at each planting density from 2001 to 2007

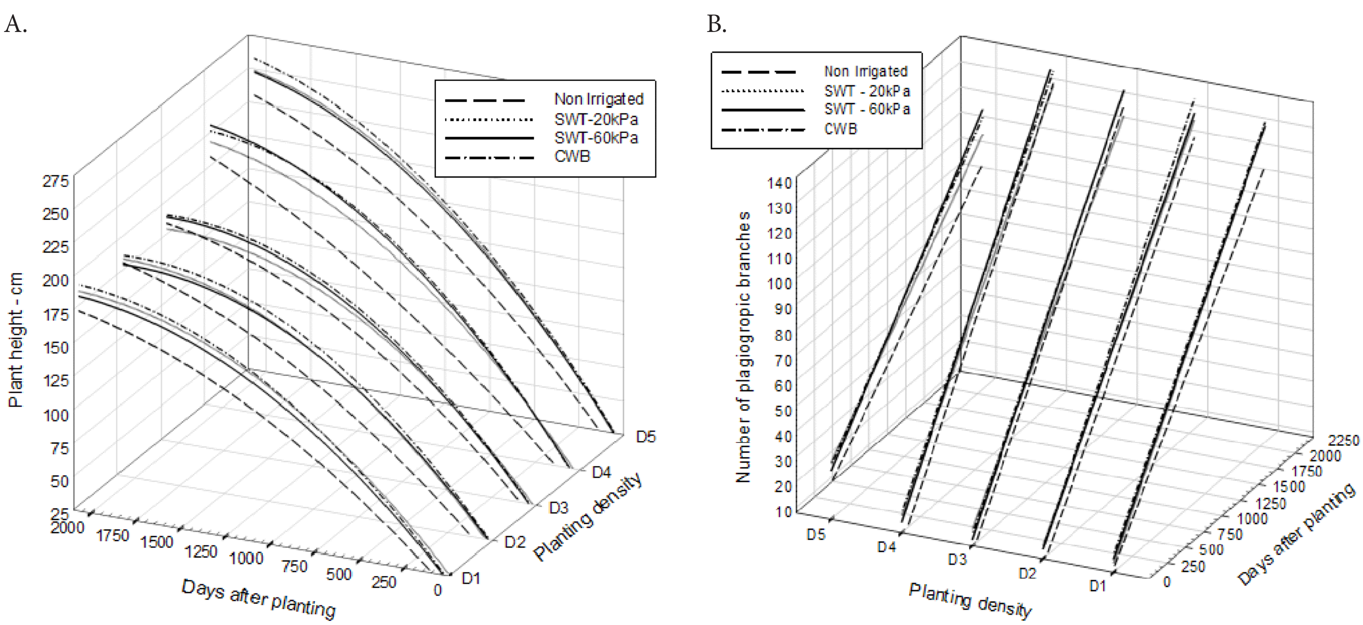
Regime	Irrigation depth - mm				
	Planting density (plants ha^{-1})				
	2,500	3,333	5,000	10,000	20,000
Climatologic Water Balance	390.7	481.7	645.7	797.6	867.6
20 kPa	157.3	220.1	357.4	411.7	737.1
60 kPa	97.4	122.3	164.2	235.7	453.4

Rainfall (mm): 2001/02: 1,681.6 mm; 2002/03: 1,361.9 mm; 2003/04: 1,460.5 mm; 2004/05: 1,527.8 mm; 2005/06: 1,486.7 mm; 2006/07: 1,419.4 mm those applied with irrigation at tension close to 60 kPa. In both regimes regarding the soil water state, the irrigation schedule was variable and irrigation was less frequent compared to the climatologic water balance. A greater water demand (greater values for applied irrigation water levels) was also observed in the most reduced spacing (20,000 plants ha^{-1}) compared to the non-reduced spacing (2,500 plants ha^{-1}) that confirmed the relationship between increase in the plant population and greater water uptake per area unit reported by Kiara & Stolzi (1986) (Table 2).

Time course of plant height and number of primary plagiotropic branches observed at different planting densities and irrigation regimes are shown, respectively, in Figure 2A and B.

For all planting densities and irrigation regimes, time course of plant height was adequately fitted to a quadratic model (Figure 2A and Table 3). A quadratic model was adopted because, as indicated by experimental data, height growth rate of coffee plant is higher during the first years after planting and tends to decrease over time. Plant height time course was affected by both planting density and irrigation.

In all assessed periods, height values of irrigated plants were greater than those of non-irrigated plants. Irrigated coffee plants were able to achieve growth rates larger than that of non-irrigated plants, confirming the fact that restriction in soil water availability negatively affects the metabolic processes for plant growth (Carvalho et al., 2006). However, differences in height



D1, D2, D3, D4 and D5 refer to, respectively, 2,500, 3,333, 5,000, 10,000 and 20,000 plants ha^{-1}; SWT - Soil water tension; CWB - Climatologic water balance.

Figure 2. Height of coffee plant (A) and number of plagiotropic branches (B) in function of the assessment periods in each irrigation regime and planting density

Table 3. Height (cm) of coffee plant in function of the assessment periods in each irrigation regime and planting density

Irrigation regime	Planting density (plants ha^{-1})	Equations	R^2
Non irrigated	2,500	$y = -2.3285 \times 10^{-5} x^2 + 1.2616 \times 10^{-1} x + 13.445$	0.9804
	3,333	$y = -2.4293 \times 10^{-5} x^2 + 1.3485 \times 10^{-1} x + 9.4454$	0.9806
	5,000	$y = -3.0277 \times 10^{-5} x^2 + 1.4743 \times 10^{-1} x + 11.922$	0.9816
	10,000	$y = -1.7835 \times 10^{-5} x^2 + 1.3575 \times 10^{-1} x + 6.5126$	0.9810
	20,000	$y = -2.9809 \times 10^{-5} x^2 + 1.7221 \times 10^{-1} x + 1.8532$	0.9891
SWT-20 kPa	2,500	$y = -3.4188 \times 10^{-5} x^2 + 1.4946 \times 10^{-1} x + 26.687$	0.9740
	3,333	$y = -3.9512 \times 10^{-5} x^2 + 1.6328 \times 10^{-1} x + 18.765$	0.9569
	5,000	$y = -3.9868 \times 10^{-5} x^2 + 1.6042 \times 10^{-1} x + 21.867$	0.9712
	10,000	$y = -3.7041 \times 10^{-5} x^2 + 1.7512 \times 10^{-1} x + 18.455$	0.9594
	20,000	$y = -4.2019 \times 10^{-5} x^2 + 2.0082 \times 10^{-1} x + 13.180$	0.9844
SWT-60 kPa	2,500	$y = -3.3198 \times 10^{-5} x^2 + 1.4853 \times 10^{-1} x + 20.586$	0.9710
	3,333	$y = -4.0303 \times 10^{-5} x^2 + 1.6181 \times 10^{-1} x + 20.781$	0.9809
	5,000	$y = -4.1432 \times 10^{-5} x^2 + 1.6998 \times 10^{-1} x + 17.778$	0.9827
	10,000	$y = -4.0744 \times 10^{-5} x^2 + 1.9090 \times 10^{-1} x + 14.122$	0.9854
	20,000	$y = -3.9411 \times 10^{-5} x^2 + 1.9418 \times 10^{-1} x + 14.623$	0.9764
CWB	2,500	$y = -3.5666 \times 10^{-5} x^2 + 1.5727 \times 10^{-1} x + 21.772$	0.9865
	3,333	$y = -4.2471 \times 10^{-5} x^2 + 1.6909 \times 10^{-1} x + 21.816$	0.9162
	5,000	$y = -4.3556 \times 10^{-5} x^2 + 1.7489 \times 10^{-1} x + 18.269$	0.9581
	10,000	$y = -4.5839 \times 10^{-5} x^2 + 2.0014 \times 10^{-1} x + 12.528$	0.9741
	20,000	$y = -3.9881 \times 10^{-5} x^2 + 1.9972 \times 10^{-1} x + 15.458$	0.9845

D1, D2, D3, D4 and D5 refer to, respectively, 2,500, 3,333, 5,000, 10,000 and 20,000 plants ha^{-1}; SWT - Soil water tension; CWB - Climatologic water balance.

among irrigated and non-irrigated plants decreased over time, because each cultivar has its own characteristics height around which growth tends to stabilize (Carvalho et al., 2006). In the last assessment, 1980 days after planting, the mean height of irrigated plants at the 2,500, 3,333, 5,000, 10,000 and 20,000 plants ha^{-1} were, respectively, 9.8, 3.1, 2.4, 10.6 and 9,9% taller (equivalent to 16.9, 5.5, 4.5, 21.8 and 22.4 cm) than the non-irrigated plants growing at the same planting density. Irrigated coffee plants with height greater than non-irrigated plants were also observed by Moreira et al. (2004) who reported a 10.3% increase (corresponding to 15.4 cm) in the height of irrigated plants.

At the last assessment, 1980 days after planting, the mean height of plants growing at the 20,000 plants ha^{-1} density was, respectively, 31.5, 28.9, 26,5 and 9.6% greater than the mean height of plants growing under the density of 2,500; 3,333; 5,000 and 10,000 plants ha^{-1} (Figure 2A). Changes on the balance of growth regulators that stimulate tip meristem development, such as auxins, gibberellins, and cytocinins (Taiz & Zeiger, 2004), induced by an increase on the degree of self-shading may explain why plants growing under high planting density achieved the highest height values. Similar results were described by Paulo et al. (2005), who reported grater growth rate of the orthotropic branch induced by reduced planting spacing.

Under the same planting density, straight lines fitted to the number of plagiotropic branches were similar for the different irrigation regimes (Figure 2B and Table 4).

At the last assessment, held 1980 days after planting, the mean number of plagiotropic branches of irrigated plants at 2,500, 3,333, 5,000, 10,000, and 20,000 plants ha^{-1} were, respectively, 14.3, 8.5, 2.4, 3.1, and 18.2% greater than the mean number of plagiotropic branches of non-irrigated plants growing at the same planting density (equivalent to 16, 10, 3, 4, and 17 plagiotropic branches). Significant increases in the number of plagiotropic branches of coffee plant irrigated with water depths corresponding to 50 and 100% of the field capacity were also observed by Rodrigues et al. (2010) showing the potential of using irrigation to improve coffee plant growth.

At the end of the assessment period, an increase in number of plagiotropic branches was observed up to the 10,000 plants ha^{-1} density. At the 20,000 plants ha^{-1} density an expressive decrease was observed on the number of plagiotropic branches in relation to the others planting densities (2,500, 3,333, 5,000 and 10,000 plants ha^{-1}). In the last assessment there were on average 120, 123, 126, 130, and 102 plagiotropic branches per plant at, respectively, 2,500, 3,333, 5,000, 10,000, and 20,000 plants ha^{-1}.

Table 4. Number of plagiotropic branches in function of the assessment periods in each irrigation regime and planting density

Irrigation regime	Planting density plants ha^{-1}	Equations	R^2
Non irrigated	2,500	$y = 5.1908 \times 10^{-2} x + 9.33240$	0.9603
	3,333	$y = 5.6890 \times 10^{-2} x + 5.03610$	0.9715
	5,000	$y = 6.0388 \times 10^{-2} x + 5.01090$	0.9613
	10,000	$y = 6.3093 \times 10^{-2} x + 3.10760$	0.9708
	20,000	$y = 3.6058 \times 10^{-2} x + 2.22010$	0.8107
SWT – 20kPa	2,500	$y = 5.8658 \times 10^{-2} x + 11.1880$	0.9615
	3,333	$y = 5.6267 \times 10^{-2} x + 13.2580$	0.9063
	5,000	$y = 5.3998 \times 10^{-2} x + 14.4140$	0.8767
	10,000	$y = 5.7163 \times 10^{-2} x + 14.3960$	0.9017
	20,000	$y = 3.7595 \times 10^{-2} x + 30.4300$	0.6684
SWT – 60kPa	2,500	$y = 5.7701 \times 10^{-2} x + 13.0410$	0.9684
	3,333	$y = 5.8217 \times 10^{-2} x + 11.7270$	0.9745
	5,000	$y = 6.0823 \times 10^{-2} x + 10.4110$	0.9672
	10,000	$y = 6.3002 \times 10^{-2} x + 12.0050$	0.9264
	20,000	$y = 4.4024 \times 10^{-2} x + 26.9980$	0.7803
CWB	2,500	$y = 5.7564 \times 10^{-2} x + 14.8880$	0.9540
	3,333	$y = 6.0808 \times 10^{-2} x + 12.1830$	0.9531
	5,000	$y = 5.9598 \times 10^{-2} x + 12.5490$	0.9546
	10,000	$y = 5.9313 \times 10^{-2} x + 15.7120$	0.9318
	20,000	$y = 4.1465 \times 10^{-2} x + 29.2720$	0.7307

SWT - Soil water tension; CWB - Climatologic water balance.

This behavior may be explained because up to the 10,000 plants ha^{-1} density, the plantation closed less intensely and there was no significant branch loss induced by self-shading.

Considering the typical coffee biennial yield pattern, the statistical analysis of green coffee yield data shown in Table 5 was performed based only on the five years mean yield value of each treatment.

It is important to point out that when the mean yield of five successive harvests is considered, the influence from both years of high and years of low yield are accounted for.

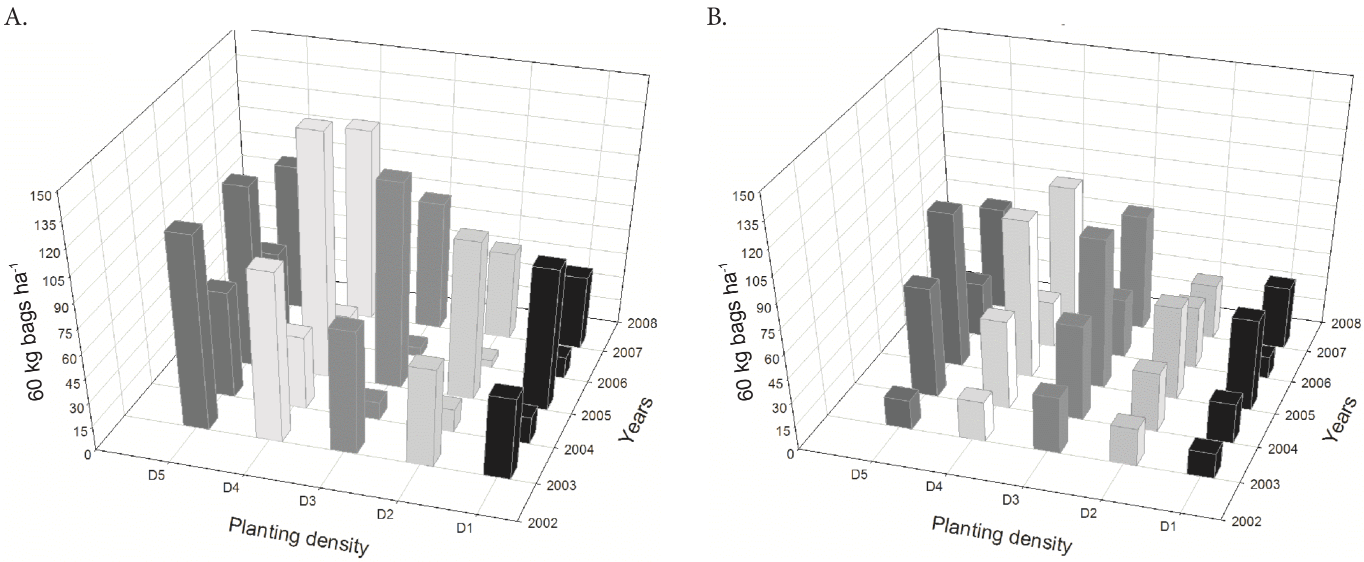
The coffee biennial yield pattern, with a year of high followed by a year of low yield, is clearly depicted on the values shown in Figure 3. It may also be noticed that the biennial cycle crop can occur either in non-irrigated or irrigated coffee plant systems, and in the latter, the fall in yield from one year to another may be greater. Silva et al. (2008) reported similar results, and they attributed the sharp variation of irrigated coffee yield over the years to the fact that irrigation promoted a greater increase in yield in the high years. This biennial characteristic can be explained physiologically by the fact that in a year of great yield,

Table 5. Mean yield of five harvests (2003-2007) in bags ha^{-1} of processed coffee in function of the irrigation regimes and planting densities

Planting densities (plants ha^{-1})	Yield[1] - bags ha^{-1}			
	Irrigation regimes			
	Non irrigated	60 kPa	20 kPa	Climatologic water balance
2.500	29.9 aB	42.0 aC	41.5 aB	44.2 aC
3.333	38.1 aB	43.9 aC	47.4 aB	45.9 aC
5.000	58.7 aA	60.0 aB	50.2 aB	66.8 aB
10.000	57.4 bA	88.6 aA	80.6 aA	88.6 aA
20.000	55.5 bA	88.7 aA	82.1 aA	89.9 aA

[1] 1 bay ≅ 60 kg.

Means followed by the same lowercase letter on the line and uppercase letter in the column do not differ significantly by the Scott-Knott test at the level of 0,05 significance.



D1, D2, D3, D4 and D5 refer to, respectively, 2,500, 3,333, 5,000, 10,000 and 20,000 plants ha^{-1}.

Figure 3. Yield of five harvests (2003-2007) in bags ha^{-1} of processed coffee irrigated (A) and non-irrigated (B) in function of the planting densities

much of the coffee plant photoassimilate reserve is drained for frutification, promoting an imbalance in the leaf/fruit ratio and thus competition between the reproductive and vegetative growth (Matiello et al., 2010). Consequently, branch growth is damaged and the following harvest is reduced.

According to values shown in Table 5, at the 2,500, 3,333, and 5,000 plants ha^{-1} densities, there were no significant differences among mean yield of irrigated and non-irrigated coffee crop. This behavior may be result of the accentuated biennial effect that occurred on these planting densities, as shown in Figure 3. Previous studies (Scalco et al., 2011) carried out in the same experimental area reported that, during high yield years, single plant coffee bean production in conventional planting system (wider spacing) was significantly greater than the one observed at reduced spacing. These studies also demonstrated that, at wider planting spacing, irrigation enhances differences among single plant green coffee induced by differences in planting densities, bringing as a consequence greater variability in yield from one harvest to another. Therefore, at the 2,500, 3,333, and 5,000 plants ha^{-1}, the beneficial effect of the irrigation was masked by the greater effect of the biennial pattern. At these densities, irrigation may have induced a greater exhaustion of photoassimilates of the plants during higher yield years damaging yield in the following year.

For the 10,000 and 20,000 plants ha^{-1} densities (Table 5), there were no significant differences among irrigation treatments (20 kPa, 60 kPa, and CWB) on mean green coffee yield in the five harvests. At the 10,000 plants ha^{-1} density, the mean yield of irrigated coffee, regardless of the irrigation regime used, was 49.7% greater than that obtained in non-irrigated plants (corresponding to an increase of 28.5 bags (60 kg) of green coffee ha^{-1}). At the 20,000 plants ha^{-1} population, this increase was 56.6% (equivalent to 31.4 bags (60 kg) of processed coffee ha^{-1}).

At the 10,000 and 20,000 plants ha^{-1} densities, changes in values of irrigation water depth applied per harvest, associated to changes in considered irrigation treatment (Table 1), did not alter the corresponding five year mean value of coffee yield (Table 5). This result indicted that using the lower irrigation water depths applied corresponding to the irrigation regime when the soil water tension reached values close to 60 kPa, was sufficient to meet the water requirements of coffee crop. At the 10,000 plants ha^{-1} density and irrigation based on the 60 kPa tension, the savings in application were 73.2% (equivalent to 573.1 mm per year) compared to that applied by the climatologic water balance. At the 20,000 plants ha^{-1} density, this reduction was 50.5% corresponding to 427.1 mm per year (Table 4). Correct irrigation management can reflect in water, energy and labor savings that weigh very heavily in coffee production costs (Silva et al., 2013).

In the considered period, the rainfall values between harvests ranged from 1,361.9 to 1,681.6 mm (Table 2) that in principle can be considered as sufficient to meet the water requirements of the coffee crop in the southern region of Minas Gerais state, Brazil. Consequently, this factor should not be considered alone, because in addition to quantity, the distribution of the rainfall over the year is also an important factor to consider, highlighting the importance of irrigation in this situation. Due to the climatic changes and the frequent occurrence of drought in months considered rainy (Pellegrino et al., 2007) irrigation associated to planting in reduced spacing may alleviate the climatic vulnerability of the plant so that its development and production are not damaged.

The benefits of irrigation of coffee crop in the southern region of Minas Gerais, Brazil, have been reported in many studies (Carvalho et al., 2006; Guimarães et al., 2010; Serra et al., 2013; Silva et al., 2008). In a study of five harvests of coffee crop, Gomes et al. (2007) assessed the effect of various irrigation amounts, computed as fractions of a Class A pan evaporation (Epan), on yield of the Rubi MG-1192 coffee cultivar. They reported that plants irrigated by a center pivot presented a mean yield 63.7% higher (15.3 bags ha^{-1}) than non-irrigated plants. The same authors did not observe significant differences in coffee yield due

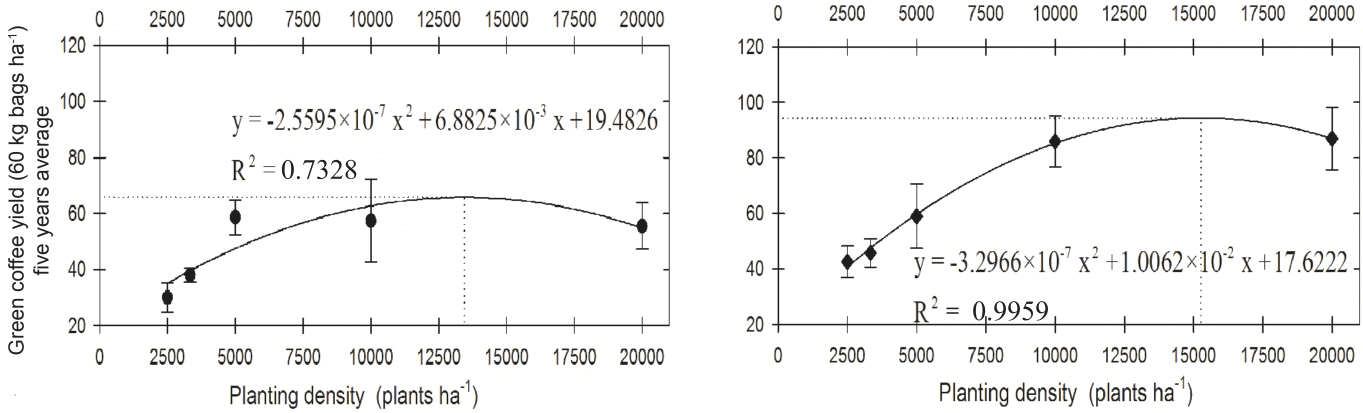


Figure 4. Mean yield of five harvests (2003-2007) in bags ha^{-1} of processed coffee irrigated (A) and non-irrigated (B) in function of the planting densities

to irrigation water depth (60, 80, 100, 120, and 140% Epan). A similar result was also found in the present study, that is, on the average of the five harvests assessed, the lower irrigation water depth used was sufficient to meet the water needs of the coffee crop without damaging its productive potential.

For both irrigated and non-irrigated plants, mean coffee yield (bags ha^{-1}) as function of planting density fitted a quadratic model (Figure 4).

The quadratic model is able to reproduce the accentuated yield reduction observed at the 20,000 plants ha^{-1}. As mentioned before, when analysing time evolution of plagiotropic branches, at the 20,000 plants ha^{-1}, coffee crop gradually lost the productive branches on the lower and mid third. The loss of branches occurs because self-shading of the plantation induces smaller production of photoassimilates in the shaded area of the leaf canopy that culminates in their death (Rena & Maestri, 1987). At this planting density, shading became limiting for production as it may also have inhibited flowering, because light is an important factor in bud induction for this process. The smaller number of plagiotropic branches on the plants in the 20,000 ha^{-1} population (Figure 2B) allied to the greater height (Figure 2A) as consequence of self-shading is shown in a process of etiolating, and only the internodes growth of plants conducted at this density.

According to the fitted equations, maximum correspond to coordinates 13,445 plants ha^{-1} versus 65.7 bags ha^{-1} (non-irrigated) and 15,261 plants ha^{-1} versus 94.4 bags ha^{-1} (irrigated). A similar response to irrigation was reported by Braccini et al. (2005) maximum yield of non-irrigated coffee crop, cv Iapar 59 with a population around 15,000 plants ha^{-1}.

Conclusions

1. Regardless of the planting density, irrigation promoted higher growth of coffee plant.

2. The effect of irrigation on the increase in coffee yield (processed bags) varied in function of the plant density per area.

3. For densities of 10,000 and 20,000 plants ha^{-1}, regardless of the regime used to manage irrigation (20 kPa, 60 kPa and climatologic water balance) mean yield increases can be obtained of over 49.6% compared to non-irrigated cultivation.

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