PRODUCTION FUNCTIONS OF IRRIGATED COFFEE UNDER DIFFERENT PLANTING DENSITIES

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ABSTRACT: The aim of this study was to evaluate criteria for irrigation and planting densities best suited to coffee growing to maximize yield. The experiment was conducted in an area of the Department of Agriculture, Federal University of Lavras, Minas Gerais, Brazil, in a randomized complete block design with split-plots and four replications. Planting was carried out using healthy coffee seedlings of the Ruby MG-1192 cultivar. It was observed that the use of irrigation provided for significant increases in processed coffee yield in high density planting from 10,000 to 20,000 plants ha^{-1}. Irrigations based on tensions from 60 kPa to 100 kPa are sufficient to meet the water requirements of coffee in dense plantings, but the increase in the number of plants from 10,000 to 20,000 compromises the sustainability of the crop through the disproportionate increase in water consumption for irrigation, with small increases in yield. For the irrigation tension of 60 kPa, the relative increase in yield outweighs the other criteria for irrigation, with 13,750 plants ha^{-1} being the number of plants indicated.

Index terms: *Coffea arabica* L., sustainability, high density planting.

FUNÇÕES DE PRODUÇÃO DO CAFEEIRO IRRIGADO EM DIFERENTES DENSIDADES DE PLANTIO

RESUMO: *Objetivou-se, neste trabalho, avaliar critérios de irrigação e densidades de plantio mais adequados ao cultivo do cafeeiro que maximizem a produtividade das lavouras. O experimento foi conduzido em área do Departamento de Agricultura da Universidade Federal de Lavras/MG, em delineamento de blocos casualizados com esquema de parcelas subdivididas (densidades de plantio nas parcelas e irrigações nas subparcelas), com quatro repetições. O plantio foi realizado utilizando-se mudas sadias de cafeeiro, cultivar Rubi MG-1192. Observou-se que o uso da irrigação proporcionou aumentos expressivos de produtividade de café beneficiado em cultivos adensados de 10.000 a 20.000 plantas ha*$^{-1}$*. Irrigações baseadas entre tensões de 60 kPa a 100 kPa são suficientes para atender a demanda hídrica do cafeeiro em plantios adensados, porém o aumento no número de plantas de 10.000 para 20.000 compromete a sustentabilidade do cultivo pelo aumento desproporcional do consumo de água para irrigação com pequenos incrementos de produtividade. Para a tensão de irrigação de 60 kPa o aumento relativo de produtividade supera os dos demais critérios de irrigação, sendo o número de plantas indicado de 13750 plantas ha*$^{-1}$.

Termos para indexação: *Coffea arabica L., sustentabilidade, plantio adensado.*

1 INTRODUCTION

Coffee culture is one of the five most important agricultural activities in Brazil and the most important in Minas Gerais state. With all this importance, productivities from Brazil as well as from Minas Gerais are still low to maintain sustainability of the activity when facing the price variations in international market.

One of the forms to increase productivity is to reduce spacing, which enables increase in the number of plants per hectare and the use of irrigation with criteria that meet the plants' demand for water without increasing drastically production costs, keeping also the environmental sustainability by saving water.

In the first case, the use of densed system can also improve productive capacity of the soil by increasing pH, Ca, Mg, K, P and organic C, aggregates stability, water retention and lowering toxic A1, since it enables higher water and nutrients use, lowering losses and increasing efficiency of fertilizer use (AUGUSTO et al., 2007), possibly leading to a productivity increase when compared to the traditional crops systems (PEREIRA et al., 2007). Spacing can act over production per area unit and thus it is aimed to suit planting densities that enable higher productivities and, at the same time, allow space for conducting cultural practices (BRACCINI et al., 2005, 2008). In the second case, the irrigation technique use has

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lowered drought effects and is one of the forms to mitigate hydric deficiency problems generating production income (ARRUDA; GRANDE, 2003). Coffee culture irrigation has expanded even in producing regions such as Southern Minas Gerais, considered fit to coffee cultivation. Especially by the use of systems that apply water in a located manner and characterized by the small use of labor, through automation, maintaining high water levels to improve cultures1 development, capacity to fit rocky soil conditions, shallow or rugged, possibility to apply chemicals in irrigation water solution and reduction of culture contamination. All of these reasons contribute to the growth of such process in Brazil (MARTINS et al., 2007). Amongst the local irrigation methods, one of the mostly used systems in coffee culture is dripping.

Coelho and Silva (2005), during three harvests, concluded that irrigation can improve coffee tree average. Coffee tree response to irrigation has been positive in most cases. As for the city of Lavras – MG, Oliveira et al. (2010) comment that irrigation by dripping in coffee culture is economically viable, for the 33,48% real productivity increase obtained with irrigation generates larger profits. Thus, elevation of productivity level by irrigation makes such investment an attractive in coffee production, raising considerably the economic indicators and reducing recovery time of invested capital (ARÊDES; PEREIRA; SANTOS, 2010).

One of the forms to study the effects of water application in cultures is the use of production functions. Production function water/culture describes the relation between the variation of culture production over the variation of applied water amount, being the independent variable “water” transpiration, evapotranspiration, water blade applied during culture cycle, state of ground water, mainly being the applied water blade the one of most interest for the irrigation user (FRIZZONE, 2005). According to Liu et al. (2002), many researchers have demonstrated the use of production function. Aiming to assess the technical and economical implications of different water levels applied to the cultures. In this study, production function will be used also to describe the relation between production variation over the number of plants per area.

The objective of this study is to establish irrigation and planting density strategies more adequate to coffee culture that maximize crop productivity.

2 MATERIALS AND METHODS

The experiment was conducted in an area of the Agricultural Department of the Lavras Federal University (Departamento de Agricultura da Universidade Federal de Lavras/MG), from 2003 to 2007. The geographic coordinates of the area are: latitude 21°15’S, longitude 45°00’W and average altitude 918 m. The weather in the city is Cwa type, according to Köppen (mesothermic with mild summers and drought during winter). Year average rainfall and temperature are 1.460 mm and 20,4°C, respectively (DANTAS; CARVALHO; FERREIRA, 2007).

Planting was performed in January 3rd 2001, using healthy seedlings of Rubi MG-1192 coffee trees. Soil (Rhodic Ferralsol) was analysed during planting for its physicohidric and chemical features (Table 1) for the instalation of field culture.

Cultural treats and phytossanitary treatments were performed when needed during culture development, however no pruning until the performing of this work, being the crop kept free of weed by management association methods during the different stages of culture. Soil corrections and fertilizations were performed according to soil and plant analyses (yearly), following the recommendations of Guimarães et al. (1999) and Santinato and Fernandes (2002), the last two making recommendations for irrigated culture. Micronutrients were daily monitored by foliar fertilization. Weather data were monitored daily through the local weather station (µMetos®).

Experimental lining used was random blocks in subdivided parcels with four repetitions. The five planting densities located in the parcels and the four irrigation criteria plus non irrigated control in the subparcels, totaling 25 treatments. The number of plants per subparcel was 10 and for each parcel 200. The total of plants in the experimental area was of 1000 plants, the number of useful plant in each subparcel being eight..

Four different determining criteria were studied by the moment of irrigation in five densities of coffee tree planting, being those: irrigation when water tension in the soil reached values close to 20 kPa (T1), 60 kPa (T2), 100 kPa (T3) and 140 kPa (T4), non irrigated control (T0) studied in planting densities of (D1) 2500 plants ha^{-1} (4,0 x 1,0 m); (D2) 3.333 plants ha^{-1} (3,0 x 1,0 m); (D3) 5.000 plants ha^{-1} (2,0 x 1,0 m); (D4) 10.000 plants ha^{-1} (2,0 x 0,5 m) and (D5) 20.000 plants ha^{-1} (1,0 x 0,5 m).

TABLE 1 - Result of physical analysis of the soil for experimental area (1).

Layer	*Texture Analysis*			*DS*	*MAC*	*MIC*
	Sand	Silt	Clay			
(cm)	(%)	(%)	(%)	g/cm^3	(%)	(%)
0-20	27	20	53	1,2	7,5	44,7
20-40	23	9	68	1,1	33,6	39,1
40-60	23	9	68	0,9	31,3	33,6

DS = soil density, MAC = machroporosity, MIC = Microporosity.

Irrigation system had a central control unit (pumping system, screen and sand filter, fertilizer injector, manometer and connections), main line of PVC tubes, PN80, PVC deriving lines, PN40, side lines with polyethylene flexible tubes, PN40, valves and drippers with output of 3,75 L h^{-1} spaced 0,3m in lines. The system was periodically assessed for uniformity of water distribution.

Soil humidity was indirectly monitored by digital tensiometers and electric resistance blocks (Water Mark-Irrometer□) previously calibrated for the specific soil conditions of the experiment. The tensiometer and the porous blocks were installed at depths of 10, 25, 40, 60, 80 and 100 cm. for tensions of 20 and 60 kPa were used tensiometers while for tensions of 100 and 140 kPa were used WaterMark® porous blocks. Irrigation of each subparcel took place when water tension reading at 25cm depth indicated irrigation tension relative to that treatment. The irrigation blades were calculated considering the reading obtained from the tensiometers and porous blocks in depths of 10, 25 and 40cm until plants reached full vegetative development and from that point there were still being considered the 60cm deep readings.

The correspondence between water tension in the soil and humidity was obtained by soil humidity characteristic curves, determined in laboratory for the different considered depths (Table 2).

Harvest was performed when there were left about 20% of fruits still green, by cloth untwining, in every subparcel, being the swept coffee (separately picked) also quantified in the analysis. At the end the productivity was obtained in sacs ha^{-1} for each irrigation treatment in the different planting densities.

The results obtained were subjected to variance analysis. When meaningful, the averages were adjusted to a non-linear regression model of second order which allowed to obtain the production functions establishing a technic relation between the studied factors: "irrigation blades applied to different criteria" versus "processed coffee productivity (sacs ha^{-1})" and "planting densities" versus "processed coffee productivity (sacs ha^{-1})".

3 RESULTS AND DISCUSSION

The average water blades applied (mm) in five harvest years and corresponding to each irrigation criteria are presented in Table 3.

These values decreased due to the increase of soil water tension adopted for irrigations and due to the reduction of number of plants in area. Although the water volume applied per plant is lower it is necessary to consider (MARIN, 2003) the leaf area differences between planting systems in wide and reduced spacings, since densed crops generate an increase of water consumption per area unit, despite the microweather alterations. On the other hand, although stated that relative humidity within crop tends to increase as density increases, possibly due to canopy's smoother aerodynamics of densed crops there is a decrease of evapotranspiration levels in these systems (SANTOS; DUBEUX JUNIOR; SILVA, 2003). Thus, not necessarily irrigation criteria, in which is applied larger water blade, is the one that brings more development and production of densed crops.

The reductions of applied blades provided by the increasing on soil water tension values within each crop density (Table 3) were expected. In more frequent irrigations (20 and 60 kPa) smaller blades were applied compared to more spaced irrigations (100 and 140 kPa), however when accounted at the end of a cycle they represented a larger water consumption for irrigation. In the densities of 2.500, 5.000 and 20000 plants ha^{-1} it was observed as atypical behavior related to the applied blades in tensions of 60 and 100 kPa.

TABLE 2 - Characteristic curve equations of water retention in the soil, according to the model by Equações da curva característica de retenção da água no solo, segundo o modelo de Genuchten and Nielsen (1985), for 0-20 cm, 20-40 cm and 40-60 cm layers.

Soil layer (cm)	Characteristic curve equation (Y in cm)	R^2
0-20	$\theta = 0{,}223181 + \frac{0{,}340456}{\left[1+\left(0{,}027793\cdot\lvert\psi_m\rvert\right)^{2{,}031813}\right]^{0{,}287954}}$	0,993
20-40	$\theta = 0{,}239476 + \frac{0{,}350076}{\left[1+\left(0{,}035177\cdot\lvert\psi_m\rvert\right)^{1{,}903507}\right]^{0{,}298648}}$	0,991
40-60	$\theta = 0{,}205741 + \frac{0{,}454637}{\left[1+\left(0{,}141522\cdot\lvert\psi_m\rvert\right)^{3{,}3333909}\right]^{0{,}150509}}$	0,988

TABLE 3 - Applied blades (mm) in different irrigation criteria in five planting densities (plants ha^{-1}) and rainfall occurred in between harvest period (from June of one year until June of the following year).

Planting density (plants ha^{-1})	Blades applied to each criteria (mm)			
	20 kPa	60 kPa	100 kPa	140 kPa
20000 - (1,0 x 0,5 m)	737,6	477,5	566,5	279,6
10000 - (2,0 x 0,5 m)	409,8	250,8	194,1	115,6
5000 - (2,0 x 1,0 m)	347,4	177,4	209,2	91,7
3333 - (3,0 x 1,0 m)	214,9	126,0	124,7	90,0
2500 - (4,0 x 1,0 m)	154,9	97,6	108,3	56,4

	Harvest year				
	2003	2004	2005	2006	2007
Rainfall (mm) Precipitação (mm)	1326	1460	1526	1461	1429

For these densities, larger blades were applied on tensions of 100 kPa in realtion to tensions of 60 kPa. Such behavior can be attributed to the difference between instruments used to measure soil water tension. For tensions of 20 and 60 kPa were used tensiometers while for tensions of 100 and 140 kPa were used porous blocks WaterMark®. The last, even though some researchers indicate for monitoring soil water in a wider portion of soil humidity (HANSON et al., 2000), with values varying from 0-200 kPa and including tension values up to 600 kPa, other studies report that such instrument shows better precision in the same tension portion of the tensiometer (THOMPSON et al., 2005), which means until 80 kPa.

For the technical analysis of irrigation criteria used for managing irrigated coffee crops, besides application blades, which could represent economy in water and energy consumption, it is necessary to analise under the point of view of the maximization of productivity without harm to the qualitative features that are important in the final product's commercialization.

Results analysis indicated significant interaction between irrigation criteria and number of plants per area, indicating that with the increase or reduction of spacing the productivity response can be altered.

Such interaction between the studied factors could be explained by the altering in microweather that occurs in each crop system, and that consequently, interferes in evapotransipration of culture and hidric demand. From that point the changes in vegetative development pattern and production are expected.

Confronted with the influence observed as irrigation criteria went on in each crop density, significance was noticed only for the crops containing 10000 and 20000 plants ha^{-1}. Therefore, for densities of 10000 and 20000 plants ha^{-1} the use of irrigation and the criteria that defines the moment to irrigate that allows differential water applications also defines differential response patterns for coffee production. The increase of irrigation blades from a certain limit can generate reduced productivity increases and not compensating for the coffee producer in a financial way.

The use of production functions allowed to estimate the point of maximum productivity as much as over the increase of water blade as over the increase of the number of plants per area.

Average processed coffee productions over blades applied for densities of 10000 and 20000 plants ha^{-1} (Figures 1 and 2) were adequately adjusted to a second degree equation to obtain the production functions allowing to verify in which blade of portion of applied blades the coffee tree productivity was maximized by the use of irrigation. The determination coefficients were 0,982 and 0,961 for the adjustment of densities of 10000 plants ha^{-1} and 20000 plants ha^{-1}, respectively.

In the production function illustrated in Figure 1 it is shown that average productivity increased in a quadratic way reaching a maximum value of 91,3 sacs ha^{-1} with the application of an average blade of 258,5mm from which the application of larger blades did not promote productivity increases. On the contrary, blades above that value can cause decrease in production besides raising electrical power and water application costs. The blade for which was obtained the maximum productivity corresponds to values close to the average blade applied in the five harvests (250,8mm) for the irrigation criteria based in tensions close to 60kPa. Such results are coherent to those observed by Assis (2010) about the vertical growth and increase of primary plagiotropic branches for which there were not detected significant differences between blades applied based on tensions of 20 and 60kPa.

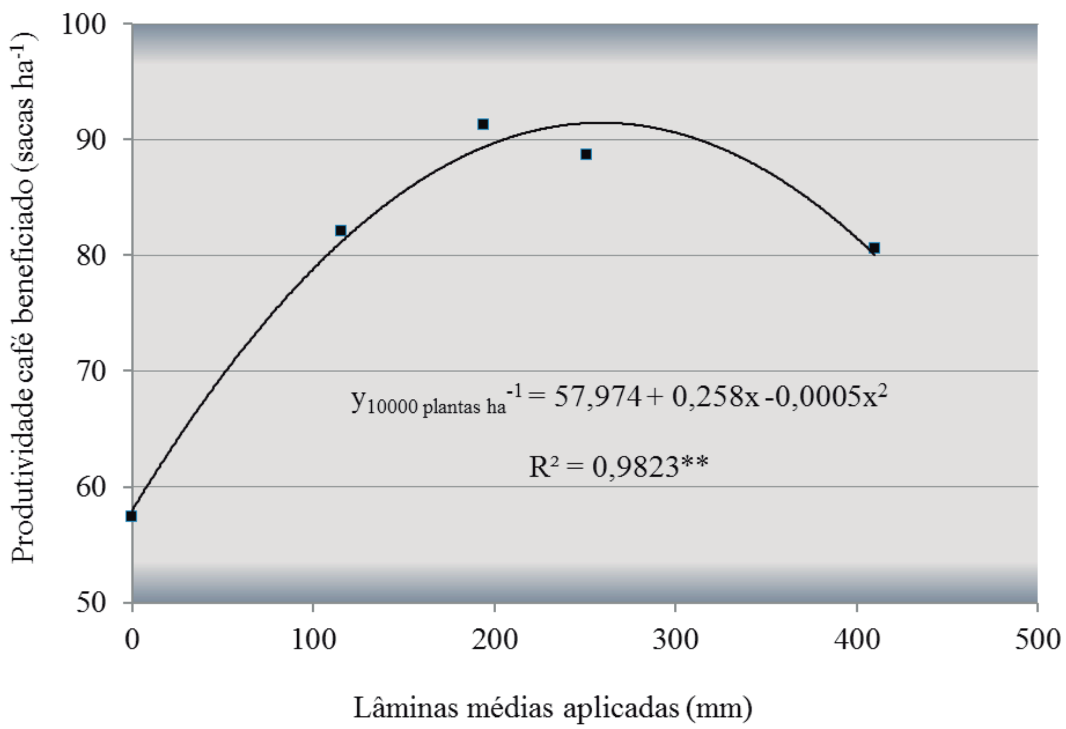


FIGURE 1 - Graphic representation of the production function relative to the increase of applied blades in different irrigation criteria in coffee crops with 10000 plants ha^{-1} .

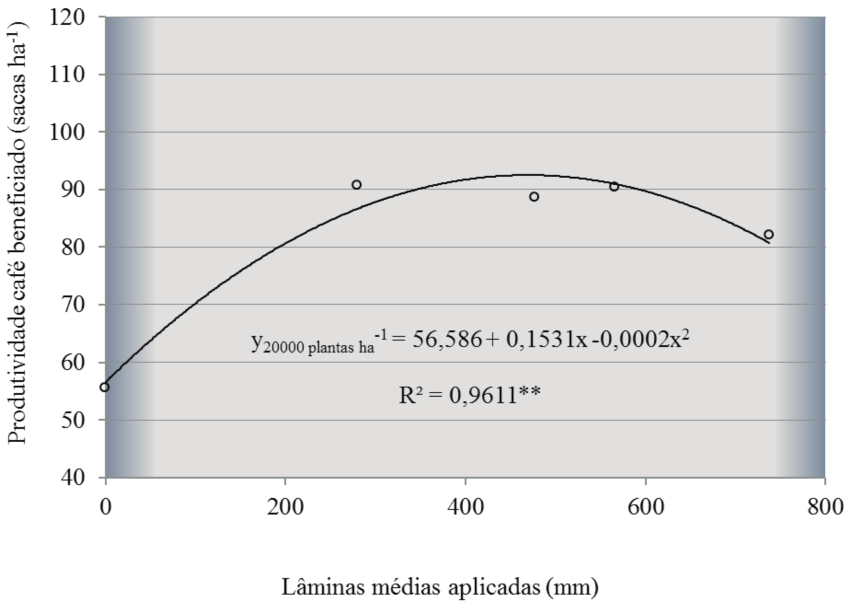


FIGURE 2 - Graphic representation of the production function relative to the increase of applied blades in different irrigation criteria over crops with 20000 plants ha^{-1}.

For the density of 20.000 plants ha-1 also was observed (Figure 2) that productivity increased in a quadratic way applying crescent water blades up to 469,32mm, irrigation blade in which the maximum productivity reached was 92,48 sacs ha-1. From 469,32 mm irrigation blade (close to the one applied in 60kPa tension), productivity reduced, indicating that larger water applications can be harmful to the crops.

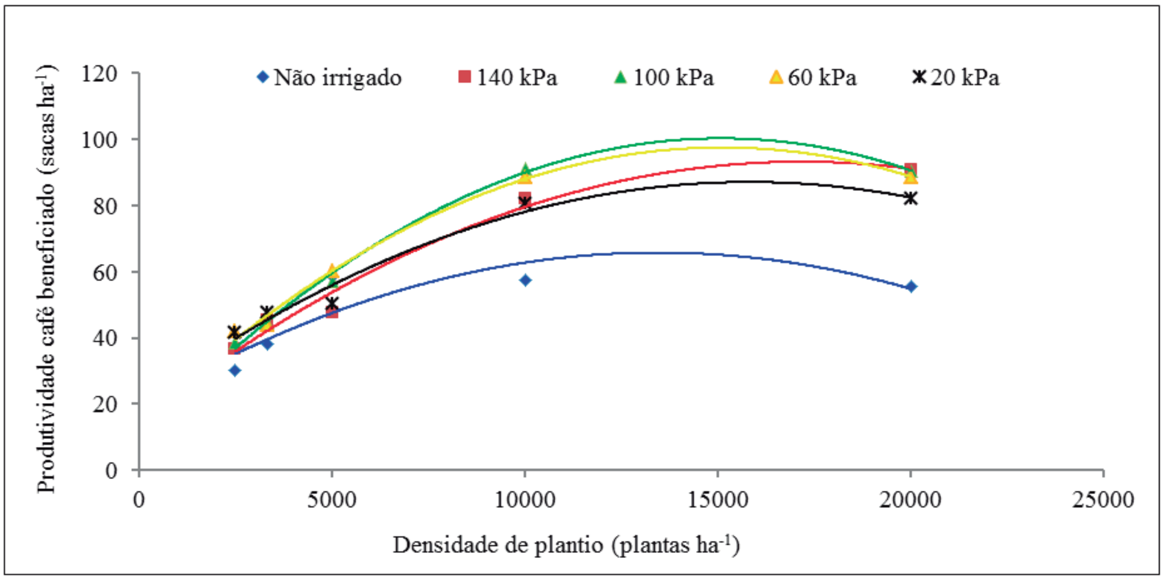
Still based on Figures 1 and 2 it is possible to deduce, as noticed before (Table 3) an increase in water consumption as crop density increased.

Once established relations between applied blades and the correspondent obtained maximum productivities (Table 4) for the three largest crop densities (5000, 10000 and 20000 plants ha-1) it was observed that: the relative increase of applied blade for reaching maximum productivity among the crop densities of 5000 and 10000 was 42,17%, resulting a relative productivity increase of 49%. As for relative water blade increase applied for reaching maximum productivity in density of 20000 compared to the one of 10000 plants ha^{-1} reached 81,5%, resulting an increase of only 1,28% in productivity. Before those results, it is possible to state that the largest applied blade for coffee crops in densities of 20000 could cause environmental damages due to water leaching and nutrients below the region of the coffee trees' root system. In densed systems there is more efficiency when using solar radiation, water and minerals leading to a productivity increase when compared to traditional crops systems (PEREIRA et al., 2007). Therefore, if there is more efficiency in using water in densed coffee systems it can mean that the more frequent use of irrigation does not represent a viable proposition, technically and economically.

The increase in crop density under each criteria of irrigation adjusted itself to a second degree polynomy (Figure 3) indicating that such increase in the number of plants is viable when the population of plants is inferior to 20000 plants ha^{-1}, since in such density there is a strong tendency of production fall. Such fall is easily explained, due to the "enclosement" of the crops and consequent photosynthesis reduction, since with decrease in spacing between lines or between plants there is more intense death ratios of lower third plagiotropic branches, probably due to excessive branch shading (PEREIRA et al., 2011). Such fact may consequently lead to progressive productivity loss and disable the maintenance of this type of coffee crop. On the other hand, researchers (PEREIRA et al., 2007) comment that in densed systems there is more efficiency in using solar radiation, water and minerals leading to a productivity gain when compared to traditional planting systems, besides reduction of biannuality, for self-shading leads to lower flowering per plant and thus a more favorable leaf/fruit ratio, reducing its detrition.

TABLE 4 - Relation between applied water blade (for maximum productivity – LPM) and maximum productivity reached in crop densities of 5000, 10000 and 20000 plantas ha^{-1}, realtive increase in applied blade (AR) and percentual increase of productivity (AP).

Density (plants ha^{-1})	LPM (mm)	Prod. Max. (sacs ha^{-1})	AR (%)	AP (%)
5000	181,83	61	-	
10000	258,51	91,31	42,17	49
20000	469,32	92,48	81,54	1,28



$Y_{Não\ irrigado} = 19{,}483 + 0{,}0069x - 3E - 07x^2$	R^2=0,7329*
$Y_{140\ kPa} = 14{,}617 + 0{,}092x - 3E - 07x^2$	R^2=0,9762**
$Y_{100\ kPa} = 9{,}185 + 0{,}0121x - 4E - 07x^2$	R^2=0,9958**
$Y_{60kPa} = 14{,}118 + 0{,}011x - 4E - 07x^2$	R^2=0,9926**
$Y_{20kPa} = 20{,}387 + 0{,}0084x - 3E - 07x^2$	R^2=0,9699**

FIGURE 3 - Rgraphic representation of the production functions relative to the planting densities for coffee crops.

Deriving the equations that relate crop density and processed coffee productivity (Figure 3) a maximum number of plants was reached for maximum physical productivity for each criteria of irrigation studied. Maximum productivities could be reached with densities of 13750 and 15125 plants ha^{-1}, corresponding to irrigations done based on tensions of 60 and 100 kPa, respectively.

Based on the relations established between planting densities and maximum productivities for each of the criteria of irrigation used (Table 5) it was observed that the increase in number of plants did not keep a positive relation or even a proportionality with reduction of indicative tension in the moment of irrigation. The planting density in which was obtained the maximum physical productivity resulted in the criteria in which the irrigations were performed in the tension of 100kPa, followed by the tension of 60 kPa. The relative increase in the number of plants between the non irrigated system and the system irrigated in 60kPa tension was 19,6% and productivity increased 51,65%, indicating the benefits of the use of such criteria to establish the irrigation moment. From 20kPa to 100kPa the relative increase in the number of plants was 8% for a productivity increase of 27,15%.

TABLE 5 - Density of planting to reach maximum productivity (DPM), maximum productivity (PM), realtive increase of plants number(ARNP) and realtive productivity increase (ARP) in function of irrigation used criteria.

Irrigation criteria	DPM	PM (sacs ha^{-1})	ARPN (%)	ARP (%)
Non irrigated	11500	59,17		
60 kPa	13750	89,73	19,6	51,65
20 kPa	14000	79,19	1,8	-11,75
100 kPa	15125	100,69	8,0	27,15
140 kPa	15333	85,15	1,4	-15,43

For realtive increases the number of plants of 1,8% for tension of 20kPa when compared to the 60kPa is of 1,4% for 140kPa compared to the 100kPa occurred productivity reductions of 11,75% and 15,43%, respectively.

Those results (Table 5) allow to deduce that: the moment to irrigate may determine differential number of plants intertfering in maximum coffee tree productivity; increase in the number of plants from 14000 to 15125 plants ha^{-1} and reduction of applied blade by adopting the higher value of irrigation tension (from 20 to 100kPa) may lead to increase by 27% in productivity; however, a more expressive increase of 51,56% was reached with an increase from 11500 (non irrigated crop) to 13750 plants ha^{-1} irrigated (19,6%). In this case, the suggestion is irrigations based on tensions of 60kPa that seemed to satisfactory fulfill the coffee trees' hydric demands for the five assessed harvests.

It is important to highlight that both tha number of plants and the different combinations in line and between lines can alter the response pattern of the production functions obtained. Braccini et al. (2002) enphatize that modern agriculture demands efficiency, quality, preservation and environment enhancement and that is inside this standard that should be built the technological models of coffee production, for the models in use nowadays are not adapted to these new conditions. They comment about a small number of plants per area, responsible for low coffee productivities worldwide, and extremely vulnerable to adverse market and weather situations for the thin profit margin, generating instability to the coffee producer and low investment capacity for enhancement of product's quality.

4 CONCLUSIONS

1- Use of irrigation allows processed coffee productivity increases in densed crops being the maximum productivities obtained with densities of 13750 and 15125 plants ha^{-1}, corresponding to irrigations based on tensions of 60 and 100 kPa, respectively.

2- Irrigations based in tensions of 60kPa to 100kPa are enough to fulfill the hidric demand of coffee tree in densed crops.

3- The increase of the number of plants from 10000 to 20000 compromises the sustainability of the harvest by the disproportionate increase of water consumption for little productivity increase.

4- for irrigation tension of 60kPa, the relative productivity increase surpasses the other irrigation criteria being the indicated number of plants 13759 plants ha^{-1}.

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