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Growth, yield, and water-use efficiency of papaya plants in the semi-arid region of Bahia State, Brazil

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Abstract: The papaya is an important crop grown in Bahia State, Brazil and an alternative for semi-arid regions. The aim of this research was to evaluate the plant growth, total yield, weight-fruit distribution, and the water-use efficiency of papaya under five irrigation depths. This study was conducted at an experimental field of the Federal Institute of Education, Science and Technology Baiano - *Campus* Guanambi using the variety 'Havai Gold' irrigated by drip. The experiment was arranged in a randomized block design with five treatments and four replicates. The treatments consisted of five irrigation depths: 55, 70, 85, 100, and 115% of crop evapotranspiration (ETc). The total yield, water-use efficiency, plant height, number of leaves per plant, and crown diameter of 'Havai Gold' papaya plants are not altered by the irrigation depths; however, the yield of the fruit-weight class F linearly increases with irrigation depths. Considering that the irrigation depths above 74.94 and 77.40% of ETc do not increase plant height and stem diameter, respectively, the irrigation management of papaya in this region can be scheduled using 75 to 100% of ETc.

Keywords: *Carica papaya* L., water deficit, irrigation management, 'Havai Gold'.

Crescimento, rendimento e eficiência de uso da água de mamoeiro Papaya na região Semiárida do Estado da Bahia, Brasil

Resumo: O mamoeiro é um cultivo importante cultivada no Estado da Bahia, e é uma das alternativas para a região semiárida. Objetivou-se com este trabalho avaliar o crescimento da planta, a produtividade total e por classe da fruta e a eficiência do uso da água do mamoeiro sob diferentes níveis de reposição de água. O estudo foi realizado no Campo Experimental do Instituto Federal de Educação, Ciência e Tecnologia Baiano, *Campus* Guanambi, utilizando-se a variedade de 'Havaí Ouro', irrigada por gotejamento. O delineamento experimental foi em bloco casualizado com cinco tratamentos e quatro repetições. Os tratamentos consistiram em cinco níveis de irrigação: 55, 70, 85, 100 e 115% da evapotranspiração da cultura (ETc). A produtividade total, a eficiência do uso da água, a altura da planta, o número de folhas por planta e o diâmetro da copa do mamão 'Havaí Ouro' não são alterados pelos níveis de irrigação, no entanto, a produtividade na classe de peso F aumenta linearmente com os níveis de irrigação. Considerando que as lâminas de água acima de 74,94 e 77.40% de ETc não resultam em aumento na altura da planta, diâmetro do caule, respectivamente, o manejo da irrigação do mamoeiro nesta região pode ser programado com 75 a 100% ETc.

Palavras-chave: *Carica papaya* L., déficit hídrico, manejo da irrigação, 'Havaí Ouro'.

Introduction

Based on yield achieved in 2013 of 1,582,638 ton (FAO, 2015, IBGE, 2015), Brazil is the second largest producer of papaya in the world, behind India that had a yield of 5,544,000 ton (FAO, 2015). In Brazil, the Northeast region accounts for about 61.8% of the national production, and the state of Bahia, the largest national producer, produced 718,726 ton of fruits in 2013, which made this state responsible for 74.48% of the northeastern production, followed by Espírito Santo (404,720 ton), Minas Gerais (126,849 ton), and Ceará (118,372 ton) (IBGE, 2015).

The shortage and irregularities of rainfall limit the agricultural production in the Northeast, especially in the semi-arid region; therefore, the use of irrigation is considered indispensable for the maintenance of crops (Coelho et al., 2013); although, increasing irrigation efficiency is still required so as to increase the water-use efficiency (Santos et al., 2013; Santos & Martinez, 2013).

Because papaya is an ongoing fast-growing plant, with flowering, growth and ripening of the fruits occurring simultaneously, it requires constant and adequate water and nutrients supply throughout its cycle (Oliveira & Caldas 2004). As this plant is susceptible to water deficit, the irrigation is performed even in regions where the rainfall goes over 1.200 mm per year, which helps the plant to either maintain or increase its yield (Coelho Filho & Coelho, 2007).

Irrigation enables the plant to maintain the continuous flow of water and nutrients from the soil to the leaves, favoring its physiological processes which results in stronger plants that bear high-quality fruits (Coelho et al., 2000). Water deficit may damage the papaya plant over its cycle, mainly at its vegetative stage, between the 7th and the 11th week after planting, which retards its development. The stress during the flowering stage might lead to the blooming of sterile flowers followed by their fall, which results in reduced yield (Coelho et al., 1999); although, the excess of water around the roots can reduce aeration and affect the uptake of nutrients, leading to a rise in incidence of pests and leaching of nutrients (Marin et al., 1995).

The stem diameter and leaf area are aspects of growth of papaya that are the most affected by the levels of water in the soil, especially under semi-arid conditions. Plant height is the growth feature that is less affected by the amount of water in the soil. In 'Tabuleiro Costeiros', which is a coastal region of Bahia, Brazil, the papaya plant remained growing taller up to 884 days after planting, with a decrease in the average growth rate at 431 days after transplanting(Coelho et al., 2003).

The quality of the papaya fruits can be analyzed through several characteristics, such as physical: weight, length, diameter, shape, color, and texture; and chemical characteristics: total soluble solids (TSS), pH, titratable acidity, and others (Fagundes & Yamanishi, 2001). These features may be affected by several factors as soil and weather conditions, cultivar, time and site of harvest, crop practices, irrigation, and fruit handling before and after harvesting.

Among the main producer hubs in the semi-arid of Bahia, the irrigated district of Ceraíma, Guanambi, has been facing frequent shortage of water; thus, it is necessary to optimize the water use without decreasing the yield and the quality of agricultural goods, especially fruits as they are consumed mostly fresh.

There is a lack of information regarding the vegetative growth and yield of irrigated papaya plants under semi-arid conditions. Therefore, the objective of this study was to evaluate the growth, commercial production, and water-use efficiency of 'Hawaii Gold' papaya subjected to different irrigation depths, under the climate condition of Guanambi, Bahia.

Material and Methods

Experimental area

The study was conducted in an experimental area at the Federal Institute of Science, Education, and Technology Baiano (IF Baiano *Campus* Guanambi), located at the irrigated perimeter of Ceraíma, municipality of Guanambi, southwestern Bahia, Brazil. The geographical coordinates are 14º13'30''S, 42º46'53''W, 535 m of altitude, and the average annual rainfall and temperature are 680 mm and 25.6 ºC, respectively. The soil texture and macronutrients and micronutrients contents in the soil where the crop was planted are shown in the Table 1 and Table 2.

Table 1. Soil texture at depths of 0.0 – 0.20 and 0.20 – 0.40 m at the experimental area.

Depth (m)	Sand (%)	Silt (%)	Clay (%)	Texture class
0.00 – 0.20	61	20	18	Medium
0.20 – 0.40	57	19	24	Medium

Table 2. Macronutrients and micronutrients contents in the soil at depths of 0.0 – 0.20 e 0.20 – 0.40 m

Depth (m)	P[3]	K[3]	Na[3]	Ca[4]	Mg[4]	B[6]	Cu[3]	Fe[3]	Mn[3]	Zn[3]	S[7]
	------------	------------	------------	------------	------------	mg dm^{-3}	------------	------------	------------	------------	------------
0.00 – 0.20	191	162	0.4	4.3	2.6	1	3.7	11	97	34	191
0.20 – 0.40	128	147	0.4	3.4	1.9	1	1.8	12	60	14	128
	pH[1]	MO[2]	Al[4]	H+Al[5]	SB	t	T	V	m	Prem[8]	EC
		dag kg^{-1}	cmolc dm^{-3}		------------	------------	%	------------	------------	mg L^{-1}	dS m^{-1}
0.00 – 0.20	7.5	1.8	0	0.9	8	8	9	89	0	39.6	0.7
0.20 – 0.40	7.5	0,8	0	1	6	6	7	85	0	38.7	0.5

EC electrical conductivity; Prem = Remaining phosphorus

Conduction of the experiment

The 'Hawaii Gold' papaya seedlings were grown in polyethylene bags under greenhouse conditions. The bags measured 15 cm x 25 cm x 0.006 cm in which a mixture of soil and manure in a 2:1 ratio and 200 g of single superphosphate were added. The bulk densities of the soil and manure were 1000 e 600 kg m^3, respectively. Two seeds per bag were sown, and after 15 days from the emergence, the weaker plant was removed, leaving one plant per recipient.

The tillage consisted of one plowing and one harrowing. The planting holes with 0.50 m of diameter and 0.50 m of depth were dug eight days before the transplanting of the seedlings, using a twist drill coupled to a tractor. In every hole, fertilizer was applied in accordance with the soil test and fertilizer recommendation for the crop (7 kg of manure, 300g of single superphosphate, and 50 g of micronutrients in form of FTE-BR12, containing boron, copper, iron, manganese, molybdenum, and zinc).

The study tested the effects of using different irrigation depths on 'Hawaii Gold' papaya crop, from 50 days after transplanting to the end of the assessment, totaling 395 days. After 60 days from the transplanting, the plants bloomed, and some of them were removed from the area, sparing the most vigorous plants, preferably, the hermaphroditic ones. A spacing of 1.5 m between plants within the row and 2 m between rows of plants was used. Drip irrigation was used with two pressure compensating emitters per plant, whose flow rate was 14.8 l h^{-1} at a pressure ranging from 150 to 200 kPa.

The experimental design was randomized blocks with five irrigation depths and four replicates. The irrigation depths were: T1 – 55%; T2 – 70%; T3 – 85%; T4 – 100%; and T5 – 115% of ETc. Each experimental unit consisted of 20 plants with six measurement plants located in the middle of the block. The treatments were applied between the 50^{th} day and the 395^{th} day after the transplanting of the seedlings. The variables plant height, stem diameter, crown diameter, and number of leaves followed a 4 x 5 factorial design, four periods of measurement and five irrigation depths.

In the seventh month after transplanting, leaf analysis was conducted to monitor the nutritional status of the plant. Based on this analysis, macronutrients and micronutrients contents were determined in the leaf and petiole (Table 3).

Table 3. Macronutrients and micronutrients contents in the leaves and petioles of papaya plants

Identification		N[1]	P[2]	K[2]	S[2]	Ca[2]	Mg[2]	B[3]	Cu[2]	Fe[2]	Mn[2]	Zn[2]	Na[2]
		------------	------------	------------	dag kg^{-1}	------------	------------	------------	------------	mg kg^{-1}	------------	------------	------------
Leaf	T01	4.73	0.55	2.65	0.61	2.92	1.61	59.06	6.95	203.66	46.01	29.10	345.99
	T02	4.67	0.57	3.20	0.62	2.70	1.53	52.89	7.22	248.12	50.85	33.25	495.60
	T03	4.50	0.57	3.16	0.63	2.79	1.28	50.68	6.55	219.44	46.01	27.71	514.30
	T04	4.73	0.47	3.06	0.58	2.33	0.93	47.42	6.42	172.11	43.59	27.71	720.02
	T05	5.08	0.49	2.88	0.61	2.47	0.90	50.42	6.42	202.23	48.43	27.71	663.92
Petiole	T01	1.34	0.17	2.55	0.19	1.76	0.40	20.63	1.34	20.08	14.53	4.11	3450.51
	T02	1.23	0.19	3.11	0.30	2.00	0.48	16.57	2.54	30.12	21.79	5.54	5694.74
	T03	1.23	0.21	3.11	0.22	1.77	0.44	16.84	1.34	20.08	16.95	4.16	5694.74
	T04	1.05	0.17	3.39	0.30	1.67	0.46	16.92	1.74	10.04	15.74	5.54	5507.72
	T05	1.17	0.20	2.83	0.28	1.83	0.40	17.72	1.60	14.34	16.95	4.16	7471.43

1-Sulfuric digestion – Kjeldahl method; 2-Nitric-perchloric digestion; 3-digestion by drying dag/kg = (%); mg/kg = (ppm).

The macronutrients and micronutrients contents found in the analysis exhibited the nutritional balance in the plants, according to the optimum nutritional requirements determined by Prezotti (1992).

Topdressing was done according to the nutritional demand of the crop and the soil test. As the crop was irrigated, urea and potassium chloride (KCl) rates were split into 12 rates per year; as for the single superphosphate, 6 times a year. The remaining crop practices, such as thinning and phytosanitary treatment, were all carried out following the technical recommendation of papaya management (Sanches & Dantas, 1999). From October 2012 on, a fertigation system was installed, which was used every 15 days, applying 3780 g of urea, 1700 g of potassium nitrate, and 1.0 L of phosphoric acid in total.

During the experiment, some plants of the orchard with the lethal yellowing disease of papaya, caused by the virus Papaya lethal yellowing virus – PLYV, were observed. This disease was controlled by eradicating the symptomatic plants as they appeared to prevent it from spreading in the orchard.

Irrigation management

The irrigation was conducted based on the reference evapotranspiration (ETo) determined on a daily basis by Penman-Monteith, FAO`s standard method (Allen et al., 1998), using data from an automatic weather station installed near the orchard.

The crop coefficient (Kc) used in the calculation of the crop evapotranspiration (ETc) over the period of assessment ranged from 0.4 to 1.2 as recommended by Coelho Filho & Coelho (2007). The water demand was calculated through the Equation 1.

$$ETc = ETo \text{ x } Kc \tag{1}$$

The daily irrigation run time was calculated by using the Equation 2, as in Neves et al. (2013) and Santos et al. (2015).

$$It = \frac{ETc \times Rp \times E_1 \times E_2 \times K_1}{n \times q \times Ae} \tag{2}$$

Where,

It - irrigation run time (h d^{-1}).

Rp - ETc replenishment according to the treatment (decimal).

E_1 - space between plant rows (m).

E_2 - space between plants in the row (m).

K_1 - localization coefficient.

n - number of emitters per plant.

q - drip flow rate (L h^{-1}).

Ae is the application efficiency, which we adopted the value of 0.90.

The monthly values of temperature, relative humidity, average wind speed, reference evapotranspiration (Penman-Monteith), wind gust, and rainfall over the period of evaluation are shown in the Table 4. As can be seen, rain occurred during the study only in November, December, January, and March, which reinforces the necessity of using irrigation and the optimization of the water use since irregularities and poor distribution of the rainfall are always present.

Table 4. Climatic elements gathered from the weather station in the experimental area between the transplanting of the plantlets at the end of the experiment in Ceraima, Guanambi, Bahia, Brazil

Month/Year	Days	Average temperature (ºC)	Relative humidity (%)	Wind speed (m s^{-1})	ETo (mm $month^{-1}$)	Gust (m s^{-1})	Rain (mm)
May/2012	31	25.8	56.7	3.0	158.92	14.2	0.0
Jun./2012	30	25.9	56.5	3.0	153.97	14.0	0.0
Jul./2012	31	24.8	53.5	3.1	173.29	9.7	0.0
Aug./2012	31	23.8	54.5	3.5	177.14	10.9	0.0
Sep./2012	30	26.6	46.5	4.0	221.24	10.7	0,0
Oct./2012	31	27.6	48.0	5.1	240.87	15.7	0.0
Nov./2012	30	25.8	75.2	1.3	108.9	10.5	297.48
Dec./2012	31	28.2	54.8	2.3	217.37	12.4	5.59
Jan./2013	31	27.8	54.1	2.0	171.83	16.7	80.63
Feb./2013	28	28.8	49.1	3.4	201.12	23.1	0.0
Mar./2013	31	29.0	53.2	2.1	186.21	12.9	61.02
Apr./2013	30	27.0	61.8	3.0	163.2	12.9	0.0
May/2013	31	27.0	56.2	2.4	157.41	12.7	0.0
Total/average	396	26.8	55.4	2.9	2331.47	13.6	44.78

During the 12 months of evaluation, November was the only month to exhibit rains that oversupplied the plants with water. When rain occurred, the amount of rainwater was subtracted from the ETc to correct the irrigation depth.

The gross depth was calculated by dividing the net depth by the application efficiency. The cumulative gross depths were 1132.84; 1442.59; 1811.45; 2131.12; and 2450.79 mm for T1 - 55%; T2 - 70%; T3 - 85%; T4 - 100%; and T5 - 115% of ETc, respectively.

Analyzed variables

To evaluate the yield, harvests were performed from February 2013 to May 2013, four months of harvest in total, with an average interval between harvests of eight days. The fruits were harvested when they reached the maturation stage 1 (maturing fruit, change in color, first yellow signs not covering more than 15% of the peel). After harvesting, the fruits were weighed and distributed to 10 fruit-weight classes: A or 0 (less than or equal to 280g), B or 280 (281 to 310g), C or 310 (311 to 340 g), D or 340 (341 to 380g), E or 380 (381 to 430g), F or 430 (431 to 500g), L or 500 (501 to 570 g), H or 570 (571 to 670g) and I or 670 (671 to 800g).

The influence of irrigation depths on plant growth was studied by analyzing the following variables: plant height, crown diameter, stem diameter, and number of leaves. They were evaluated after sexing all plants. The evaluations were conducted at 150, 180, 240, and 270 days after transplanting (DAT). As a parameter of economic interest, the total yield, fruit-weight distribution, and water-use efficiency were evaluated.

The water-use efficiency (WUE) was calculated by using the Equation 3, considering the yield and gross water applied to the treatments (Santos et al., 2015; Santos et al., 2014; Silva et al., 2009).

$$WUE = \frac{Y}{GID} \tag{3}$$

Where,

WUE - Water-use efficiency, in kg $ha^{-1}mm^{-1}$;

Y - Yield, in kg ha^{-1}; and

GID - Gross irrigation depth during the crop cycle, in mm.

The data of total yield, fruit-weight distribution, and WUE were analyzed using analysis of variance and regression to estimate overall yield and water-use efficiency as a function of irrigation depth. As for the variables plant height, stem diameter, crown diameter, and number of leaves, the experiment was arranged in a split-plot design, with the factor 'irrigation depth' assigned at the plot and 'days after transplanting' assigned at the sub-plot, in order to verify the interaction of irrigation depths and plant age on the growth of the crop. These variables were subjected to the analysis of variance and regression. If an interaction is yielded, its splitting would be done in accordance with its significance; otherwise, the main factor was analyzed in accordance with its significance.

At the fruiting period, the occurrence of carpelloidy and pentandry was observed in the orchard. Considering that the climate under which the plants were is semi-arid with high temperatures and low relative humidity, in combination with the high population density of the crop, it appears that these conditions may have influenced the emergence of fruits with such physiological disorders; however, these fruits were not used in the analyses of yield and water-use efficiency.

Results and Discussion

There was no effect on the interaction between measurement period and irrigation depths for the variables of plant growth; though, the measurement period as well as irrigation depths exhibited independent effects.

Plant height, crown diameter, stem diameter, and number of papaya leaves at different measurement periods are shown in Figure 1 while plant height and stem diameter as a function of the percentage of crop evapotranspiration are in Figure 2. A linear response and plateau model was the one that adjusted to the data. Plant height (Figure 1A) and stem diameter (Figure 1C) increased up to 270 days after transplanting; Crown diameter (Figure 1B) increased, peaking at approximately 230 days after transplanting, and from then on, the diameter reduced. This behavior can be explained by the decrease of the leaf petiole and lamina when the plants reach the end of the cycle. The number of leaves per plant did not change throughout the cycle, which indicates the replacement of older leaves by new leaves as the plants develop.

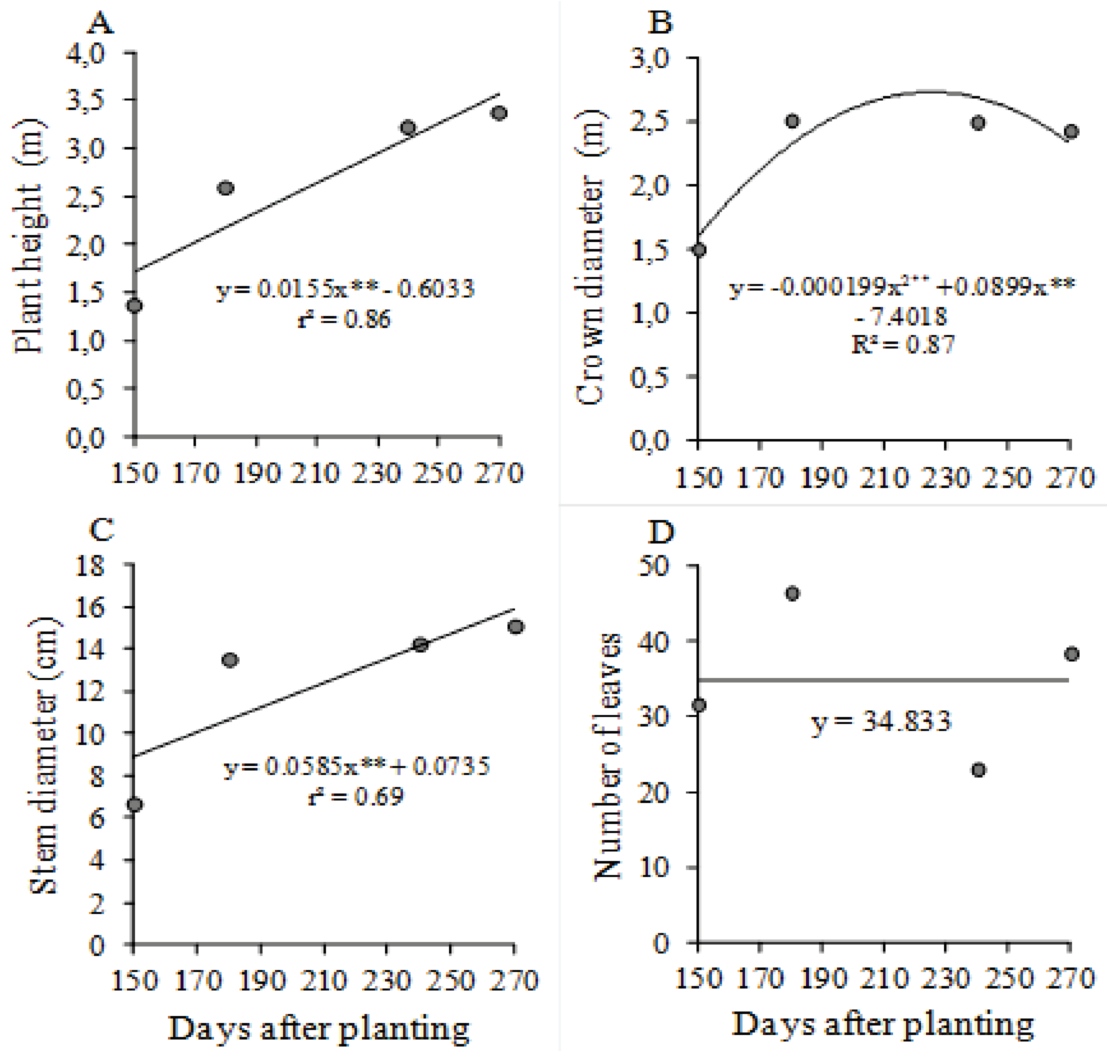

Figure 1. Growth characteristics of 'Hawaii Gold' papaya plants in different periods of measurement. Plant height (A), crown diameter (B), stem diameter (C), and number of leaves (D) *Significant at 0.05 probability level by t-test; **Significant at 0.01 probability level by t-test.

Evaluating the growth of 'Tainung Nº 1' papaya plants, Coelho Filho & Coelho (2007) found no significant differences ($p<0.05$) in stem diameter, plant height, and total leaf area in the first year of papaya cultivation irrigated by different localized irrigation systems and under soil and weather conditions of Recôncavo of Bahia, Brazil, with the average plant height of 2.36 m and average plant stem diameter of 0.11 m at 325 days after transplanting. It can be noted that the variety used herein has further growth than the 'Tainung Nº1' since at 270 days after transplanting, regardless of the irrigation depth, plant height and stem diameter were 3.37 m and 0.15m, respectively.

Regardless of the development stage, plant height and stem diameter increase as the irrigation depth increases up to 74.94% and 77.40% of ETc, respectively (Figure 2), with an average height of 2.68 m and average stem diamater of 0.1248 m. It is infered from this outcome that the increase in irrigation depth greater than 77.40% of ETc has a stronger relationship with the increase in yield than with the plant growth. Lima et al. (2015) observed the effects of deficit irrigation and partial rootzone drying on papaya, and found that 30–50% drying of the rootzone does not significantly alter plant growth in comparison with full irrigation.

According to the analysis of variance, there was no effect of the irrigation depths on yield, nor on the water-use efficiency, with mean values of 23.5 t ha^{-1} and 13.8 kg ha^{-1} mm^{-1}, respectively. These results show that the irrigation of the papaya tree in the semi-arid region can be used with depths lower than the crop evapotranspiration without losses in yield, contributing to the sustainability of water resources. The yield of papaya can attain much higher values than those found in this study; nonetheless, yield estimate at 115% of ETc is 24.23 t ha^{-1} for harvests performed at up to 360 days after

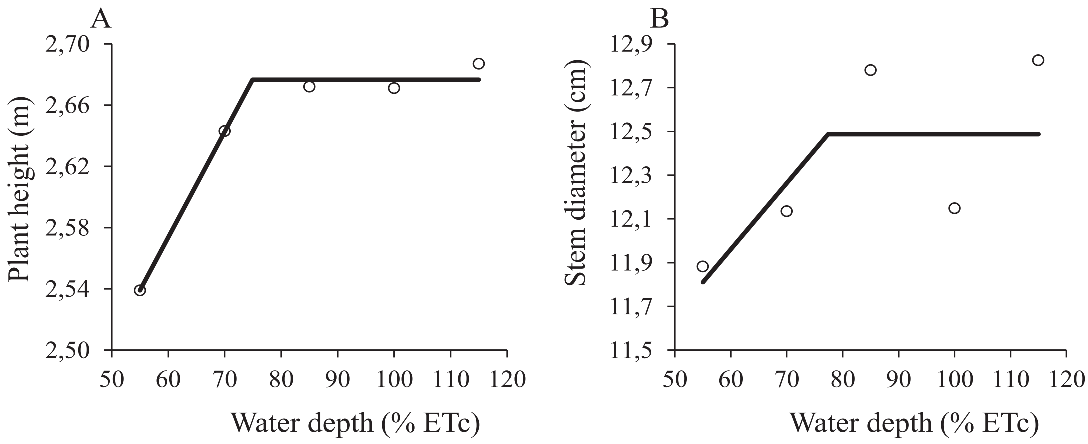

Figura 2. Growth characteristics of 'Hawaii gold' papaya plants under different water depths. Plant height (A) and stem diameter (B).

transplanting. Coelho Filho & Coelho (2007) looked into the effects of different localized irrigation systems on the production of papaya. They found that the average yield up to 361 days after transplanting was 24.98 t ha^{-1}, which is consistent with the results found herein. The results obtained in this study differ from those found by Santos et al. (2008) who assessed the yield of 'Tainung Nº1' papaya in the Jaguaribe-Apodi Irrigation District in the state of Ceará, Brazil. The authors concluded that yield increases with higher irrigation depths. Perhaps, this variety has a lower sensitivity to water deficit. These results also differ from those obtained by Silva et al. (2001) in which 'Sunrise Solo' papaya was the variety of study, and Garcia et al. (2007), who studied the 'Formosa' papaya. These authors evaluated the influence of irrigation depths on papaya yield and concluded that yield linearly increases as the irrigation depths increase.

Fruit-weight distribution for the different treatments is in Figure 3. Based on the analysis of variance, only the fruit-weight class F (431 to 500 g) had a significant effect of irrigation depth on yield. Regardless of treatment, the highest yield was of the fruit-weight class 0-280 g, so all treatments had the majority of fruits placed in the class A. Except for class A, classes D, E, and F exhibited the highest yields, which meet the standards of export markets, considering that each country has a particular market with different requirements regarding the weight and size of fruits. The Portuguese market prefers larger fruits in the range of 449-650 g, the German and French markets have slightly lower demand in weight, ranging between 350-439 g, and the Swiss prefers fruits in the range 290-349 g (Balbino & Costa, 2003).

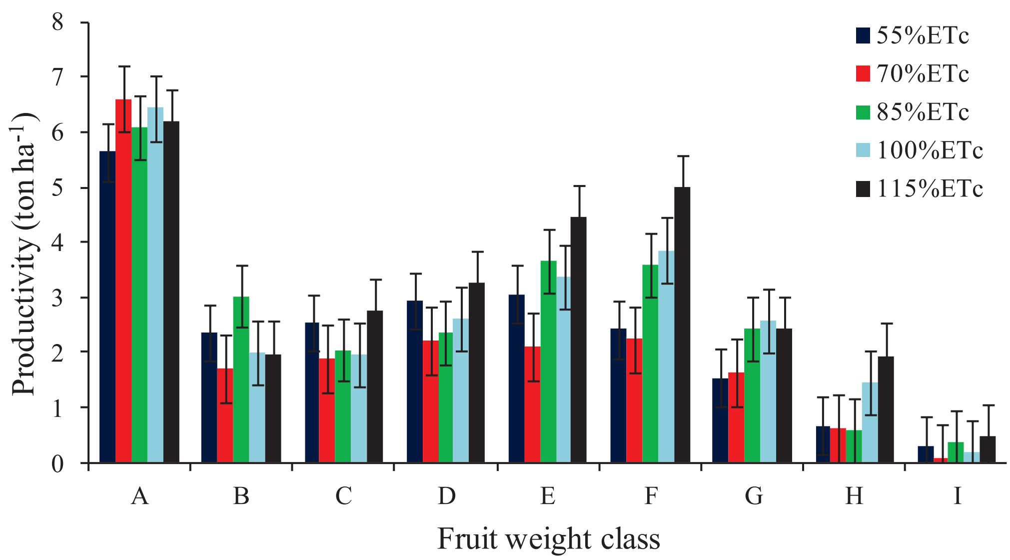

Figure 3. Fruit-weight distribution of papaya plants for different treatments, with standard deviation of the means on the top of the columns: A (less than or equal to 280g), B (281 to 310g), C (311 to 340g), D (341 to 380g), E (381 to 430g), F (431 to 500g), G (501 to 570g), H (571 to 670g) and I (671 to 800g).

The yield for the fruit-weight class F (431 to 500g) responded linearly to the irrigation depth (Figure 4). Yield in this class was estimated to be 2.07 t ha^{-1} irrigated with 55% of ETc to 4.78 t ha^{-1} irrigated with 115% of ETc, which corresponds to an increase of 131% in yield. In absolute values, the yield per fruit-weight class was higher in treatments with higher irrigation depths (T4 and T5). This is a satisfactory result since it meets the fruit-weight standards in overseas market.

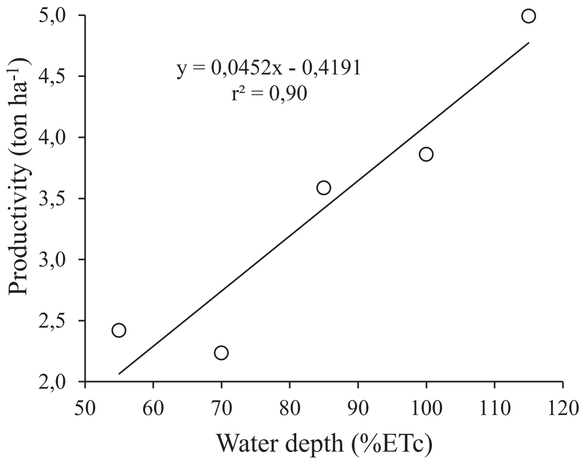

Figure 4. Yield of the fruit-weight class F (431 to 500g) of papaya plants and model for estimating yield as a function of water depth.

Conclusion

The total yield, water-use efficiency, plant height, number of leaves per plant, and crown diameter of 'Havai Gold' papaya do not change as a consequence of irrigation depths; however, yield of the fruit-weight class F linearly rises with irrigation depths. Considering that the water depths above 74.94 and 77.40% of ETc do not increase plant height and stem diameter, respectively, the irrigation management of papaya in the region of study can be scheduled with 75 to 100% of ETc.

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