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CROP PRODUCTION

Sustained deficit irrigation on yield and fruit water quality of dwarf green coconut

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ABSTRACT: *This study evaluated the effects of sustained deficit irrigation (SDI) on fruit yield and fruit water quality of dwarf green coconut trees. The experiment was carried out in a commercial orchard located in Camocim, Ceará, Brazil. Four years old coconut trees were irrigated during 29 months, using micro-sprinklers, at irrigation depths equivalent to 55%, 77%, 100% and 131% of crop evapotranspiration (ETc). Green coconut fruits were harvested six months after flower aperture and evaluated for number of fruits per plant, volume of coconut water per fruit and total soluble solids of the coconut water. SDI reduced coconut fruit yield, fruit water volume and coconut water yield. Conversely, SDI increased total soluble solids of the coconut water and irrigation water productivity in terms of fruits and coconut water. Deficit irrigation showed no economic advantage over full irrigation due to the small reduction in irrigation costs compared to the substantial reduction in gross revenue.*
Key words: *Cocos nucifera L, irrigation scheduling, coconut water.*

Efeito da irrigação com déficit hídrico sustentado sobre a produtividade e qualidade da água dos frutos do coqueiro anão verde

RESUMO: *Este estudo teve como objetivo avaliar os efeitos da irrigação com déficit sustentado (SDI) sobre a produção e a qualidade da água de frutos do coqueiro Anão Verde. O experimento foi realizado em um pomar comercial localizado em Camocim, Ceará, Brasil. Plantas com quatro anos de idade foram irrigadas por microaspersão, durante 29 meses, com lâminas de irrigação equivalentes a 55%, 77%, 100% e 131% da evapotranspiração da cultura (ETc). Os frutos foram colhidos seis meses após a abertura das flores e avaliados quanto ao número de frutos por planta, volume de água de coco por fruto e sólidos solúveis totais da água de coco. A SDI reduziu a produtividade de frutos, o volume de água do fruto e a produção de água de coco por planta. Por outro lado, a SDI aumentou os sólidos solúveis totais da água de coco e a produtividade da água de irrigação em termos de frutas e água de coco. A SDI não apresentou vantagem econômica sobre a irrigação plena devido à pequena redução nos custos de irrigação em comparação à redução substancial da receita bruta.*
Palavras-chave: *Cocos nucifera L, manejo da irrigação, água de coco.*

INTRODUCTION

Coconut (*Cocos nucifera* L.) is one of the main crops in the Northeast Region of Brazil, where it is grown on 179 thousand hectares, yielding approximately 1,155 million fruits in 2017. Crop yield increased 115% in the last 25 years mainly due to the establishment of new coconut orchards of the dwarf green variety, with intensive use of inputs, including irrigation, aiming to produce green fruits for the growing coconut water agroindustry (BRAINER, 2018).

The coconut palm is considered a plant with high water consumption, since, after the production phase begins, the plant produces flowers and fruits continuously, which is the phenological phase with the highest water demand and highest sensitivity to the effects of soil water deficit (CARR, 2011).

In recent years, the Brazilian Northeast region has experienced a significant reduction in water availability for irrigation as a result of several years of drought in a row. That trend is corroborated by climate change predictions, whose scenarios point to increases in temperature and crop evapotranspiration and reduced rainfall in the region (GONDIM et al., 2011).

When water supplies are limiting, the farmer's goal should be to maximize net income per unit water used rather than per land unit. For this, techniques to increase water use efficiency should be

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adopted, such as the use of more efficient irrigation methods and optimization of irrigation scheduling. To cope with scarce water supplies, deficit irrigation, defined as the application of water below full crop-water requirements, is an important tool to achieve the goal of reducing irrigation water use (FERERES & SORIANO, 2007).

Regulated deficit irrigation (RDI), where irrigation is reduced or limited during a given crop stage, have been successful used for many fruit and nut tree species such as almond, pistachio, citrus, apple, apricot, wine grapes and olive, improving irrigation water use efficiency (FERERES & SORIANO, 2007; CHAI et al., 2016). However, those crops have phenological phases where water consumption is low or the plant is less sensitive to water deficit, when relatively severe water deficits may be imposed.

Conversely, for plants that remain in the same phenological phase (flowering and fruit development) throughout the year like coconut, it would be more appropriate to use the concept of sustainable deficit irrigation (SDI), where irrigation depths below the maximum crop evapotranspiration are applied. However, the effects of deficit irrigation on green coconut fruit yield and fruit water quality have not been properly evaluated yet. The present study evaluated the effects of sustained deficit irrigation (SDI) on fruit yield and fruit water quality of dwarf green coconut trees.

MATERIALS AND METHODS

The experiment was carried out from August 2016 to December 2018 in a commercial orchard planted with coconut (*Cocos nucifera* L.) variety dwarf green, located in Camocim, Ceará, Brazil (2º 59 'S, 41º 01' W, altitude 22 m). The place presents a tropical climate, with daily minimum temperatures ranging from 17 ºC to 24 ºC and maximum temperatures ranging from 26 ºC to 38 ºC. The average rainfall is 1,091 mm year^{-1} and the rainy season typically lasts from January to May.

The orchard was planted in February 2013, in a 10 m × 10 m triangular spacing (115 plants ha^{-1}) and had a total area of 127 ha. The soil was a Quartzarenic Neosol and its physical and hydraulic properties are presented in table 1. The plants were organically managed and were fertilized every six months, with 15 kg tree^{-1} of organic compost with the following chemical composition: N - 11.1 g kg^{-1}; P – 8.8 g kg^{-1}; K - 3.5 g kg^{-1}; Ca – 10.6 g kg^{-1}; Mg – 4.3 g kg^{-1}; S – 4.0 g kg^{-1}; B – 10.2 mg kg^{-1}; Cu – 38.6 mg kg^{-1}; Mn – 30.5 mg kg^{-1}; Fe – 80.1 mg kg^{-1}; Zn – 90.1 mg kg^{-1}; C organic – 170.5 g kg^{-1}.

Coconut palms were irrigated with one pressure compensating micro-sprinkler per plant, each delivering 70 l h^{-1}, with a wetting diameter of 4.5 m, positioned 0.7 m from the tree trunk. Irrigation water was pumped from a well and presented low salinity, with an EC of 0.6 dS m^{-1}at 25 ºC.

Irrigation scheduling was based on estimated crop evapotranspiration (ETc = ET_0 x Kc x Kr). Reference evapotranspiration (ET_0) was calculated according to the FAO-Penman-Monteith method (ALLEN et al., 1998), using weather data obtained from a meteorological station located close to the orchard. The crop coefficient (Kc) for adult dwarf green coconut plants was considered 1.0, according to MIRANDA et al. (2007). The coefficient Kr was calculated according to KELLER & BLIESNER (1990). Average crop ground cover was 44%, giving a Kr of 0.66 ($Kr = \sqrt{44} \times 0.1$). Irrigation was applied daily (at night), starting whenever no rainfall event ≥ 10 mm occurred in the last 7 days and stopping when a rainfall event ≥ 10 mm happened, following the farmer's practice.

The treatments were applied from October 2016 to December 2018 as follows: two levels of deficit irrigation (50% and 75% of ETc), a control treatment (100% of ETc) and one level above the control treatment (125% of ETc), assigned as T1, T2, T3 and T4, respectively. Irrigation depths were adjusted weekly according to the estimated average ETc.

Table 1 - Physical properties of the soil (bulk density, ρ_a; residual soil water content, θ_r; saturation soil water content, θ_s; and parameters of the water retention curve according to the van Genuchten model (α, *m* and *n*).

Soil layer	-----------------Soil physical properties----------------				------------------------Van Genuchten parameters----------------------				
(m)	ρ_a (kg dm^{-3})	Sand (%)	Silt (%)	Clay (%)	θ_r (m^3 m^{-3})	θ_s (m^3 m^{-3})	α (m^{-1})	*m*	*n*
0-0.3	1.590	86.2	7.7	6.1	0.066	0.376	0.131	0.754	4.060
0.3-0.6	1.596	84.5	8.5	7.0	0.062	0.363	0.139	0.730	3.709

The volumes of water applied to each treatment were measured at two points of the irrigation system. The first measurement was made automatically by a flow meter (Arad Ltd., MS-1½”), connected to the irrigation controller, which measured water volumes delivered to all plants of each treatment. The second measurement was done using flow meters (FAE Alfa MNF ¾”) installed in one lateral of each treatment, whose readings were taken daily.

The statistical design was a randomized complete block, with five replicates per treatment. Each experimental unit had 16 plants (four rows with four trees) and perimeter trees were used as guard, leaving four sampling trees in the center of each plot.

Soil water tension was measured daily (between 4:00 PM and 5:00 PM), from March 2017 to December 2018, using tensiometers and a digital tensimeter (Digital PRO Plus, Blumat GmbH & Co.). The tensiometers were installed at 1.0 m from the coconut tree trunks and 0.8 m from the micro-sprinklers, at depths of 0.2 m and 0.6 m, as recommended by MIRANDA et al. (2004). Three tensiometer sets were used for each treatment, each one installed in a different block.

Green coconut fruits were harvested from January 2017 to December 2018, every 21 days (17 harvests per year) and evaluated for number of fruits per plant, volume of coconut water per fruit and total soluble solids of the coconut water. Four plants at the center of each plot were evaluated. After counting the fruits of each bunch harvested, one fruit per plant was chosen at random to measure the volume of water per fruit, using a one-liter beaker with a milliliter rating, and total soluble solids of the coconut water, measured with a digital refractometer (PAL-1, Atago Brasil Ltda). Yield of coconut water per tree was estimated by multiplying the number of fruits per plant by the respective volume of water per fruit in each harvest. The fruits were harvested between six and seven months after flower aperture, when they present the best physical attributes for coconut water processing in the Brazilian Northeast region, according to MACIEL et al. (2009).

Irrigation water productivity (IWP_f) was calculated by dividing fruit yield (fruit $plant^{-1}$ $year^{-1}$) of each treatment by the respective volume of irrigation water applied (m^3 $plant^{-1}$ $year^{-1}$). The irrigation water productivity in terms of coconut water (IWP_{cw}) was calculated dividing coconut water yield (L $plant^{-1}$ $year^{-1}$) of each treatment by the respective irrigation volume (m^3 $plant^{-1}$ $year^{-1}$).

The data were analyzed using analysis of variance procedure and the regression analysis was performed when significant differences among treatments were reported. The software SAS (SAS Institute, 1994) was used for the statistical analysis. Irrigation costs and gross revenue of each treatment were compared to those reported for the same farm by MIRANDA et al. (2019).

To assess the economic viability of the irrigation treatments, annual irrigation costs (irrigation system depreciation + energy costs) and revenues from the sale of coconut water to the industry were estimated for each treatment. The calculations considered an average price of coconut water of 0.29 U\$ L^{-1}, the cost of electricity of 0.05 U\$ kWh^{-1}, an irrigation system acquisition cost of 1,140 U\$ ha^{-1} and an irrigation system lifetime of 10 years. These costs and revenues were compared with those obtained in the same farm, with the irrigation scheduling based on daily applications of fixed irrigation depths along the dry season, as reported by MIRANDA et al. (2019).

RESULTS AND DISCUSSION

Monthly values of rainfall and estimated ET_0 at the experiment site are shown in figure 1A. The rainfall seasons in 2017 and 2018 lasted from January to May. Daily ET_0 values during the dry season (July to December) ranged from 3.5 to 5.0 mm d^{-1}, with the highest ET_0 values occurring from August to November. Actual irrigation depths measured by the flow meters (Figure 1B) corresponded to 56, 77, 100 and 131% of the ETc, for treatments T1, T2, T3 and T4, respectively. Such differences between the irrigation depths planned and those effectively applied to the plots were less than 7% and were probably due to variations in hydraulic pressure among the irrigation sectors and eventual power failures throughout the irrigation season. Daily irrigation volumes applied in each treatment ranged from 82-142 L $plant^{-1}$ day^{-1} for T1, 119-200 L $plant^{-1}$ day^{-1} for T2, 144-259 L $plant^{-1}$ day^{-1} for T3, and 172-332 L $plant^{-1}$ day^{-1} for T4.

Applying an irrigation depth equivalent to 131% of ETc (T4) caused the soil moisture to remain higher than the field capacity (soil water tension < 10 kPa) throughout the dry season, at depths of 0.2 m and 0.6 m, indicating excess irrigation (Figure 2). Conversely, soil water tension (SWT) at 0.2 m depth reached slightly more negative values for T2 during the dry season, and even more negative values for T1. In treatments T1 and T2 the SWT at the depth of 0.6 m reached values more negative than 25 kPa throughout the irrigation season, indicating that the irrigation depths applied to those treatments were not

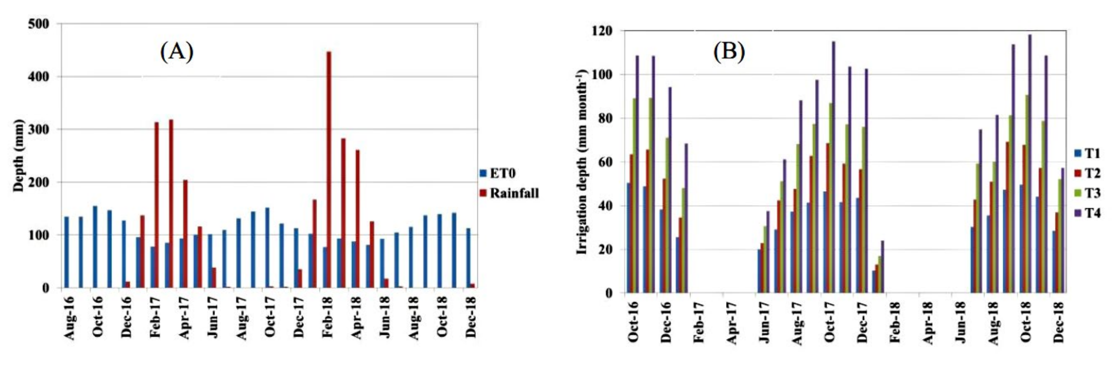

Figure 1 - Monthly values of rainfall and estimated Penman-Monteith reference evapotranspiration (ET_0) at the experimental site (A) and irrigation depths applied in each treatment (B).

enough to wet the effective root depth of the coconut trees, leading to soil water deficit.

For treatment T3, the soil moisture at 0.6 m depth was above field capacity (SWT < 10 kPa) from September to November in both years, indicating that the application of 100% ETc in this period was excessive. That indicates that the Kc value of 1.0 may be high for the Green Dwarf coconut tree during the months of maximum evapotranspirative demand in that region.

In fact, some studies have indicated that on hot and dry days, the coconut tree tends to close stomata and reduce transpiration as a result of increased vapor pressure deficit (VPD), even when the soil water content is at field capacity (CARR, 2011). Progressive stomatal closure and reduced stomatal conductance have been reported by KASTURI BAI et al. (1988) for a hybrid coconut trees (Dwarf × Tall), when the VPD exceeded 2.4 kPa. In the present study that condition occurred at the experiment site almost every day, between 10:00 AM and 2:00 PM, from mid-August to November, which may explain the decrease in the Kc below 1.0 in those months.

Although, adult coconut plants stay in the same development stage (flowering and fruit development) along the whole year, some studies have shown that its Kc during a warm and dry season may be lower than it is on the humid season. ROUPSARD et al. (2006) reported Kc values of 0.79 and 0.59 in the cool and warm seasons, respectively,

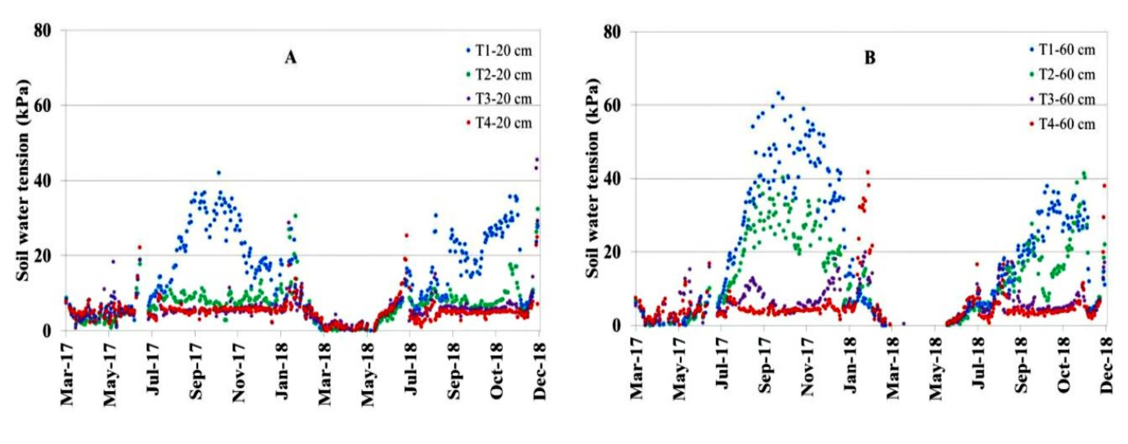

Figure 2 - Soil water tension (kPa) at depths of 0.2 m (A) and 0.6 m (B).

for hybrid coconut plants (Red Dwarf × Vanuatu Tall) in Vanuatu.

Average irrigation volumes applied per plant per year in treatments T1, T2, T3 and T4 were 23.0, 31.8, 41.5 and 54.4 m^3 $plant^{-1}$, respectively. Fruit yield increased as the irrigation volume per plant increased, following a second degree regression model ($P < 0.01$) (Figure 3A). Annual fruit yields ranged from 109 fruits $plant^{-1}$ when irrigation replenished 56% of ETc, to 145 fruits $plant^{-1}$ when the irrigation depth corresponded to 131% of ETc. That maximum yield was smaller than the average yield reported by MIRANDA et al. (2007) for a fertigated dwarf green coconut orchard in the same region (216 fruits $plant^{-1}$ $year^{-1}$). However, it should be considered that the plants of the present study were organically managed and the amount of organic compost applied was probably not enough to allow higher fruit yields.

The volume of coconut water per fruit (V_{wf}) increased significantly ($P < 0.01$), following a quadratic model, as the irrigation depths increased (Figure 3B), from about 496 mL $fruit^{-1}$ to 562 mL $fruit^{-1}$, when irrigation depths increased from 56% to 131% of ETc. Deficit irrigation treatments reduced the V_{wf} by 11% and 8% when the plants were irrigated with 55% and 77% of ETc, respectively, compared to the 100% ETc irrigation level. However, increasing the irrigation depth from 100% to 131% of ETc increased V_{wf} by only 0.5%.

The yield of coconut water (Y_{cw}) was significantly affected by the irrigation treatments ($P < 0.01$), decreasing 28% and 15% and when irrigation depths of 56% and 77% of ETc were applied, respectively, compared to the 100% ETc treatment (Figure 3C). However, increasing the irrigation depth from 100% to 131% of the ETc resulted in an increase of only 8% in Y_{cw}.

In a study carried out at the coastal region of Sergipe, Brazil, in which fixed irrigation volumes (50, 100 or 150 L $plant^{-1}$ d^{-1}) were applied to six-year-old dwarf green coconut palms, AZEVEDO et al. (2006) concluded that increasing irrigation water volumes from 50 to 100 L $plant^{-1}$ d^{-1} resulted in an increase of 12% in fruit yield. When the irrigation

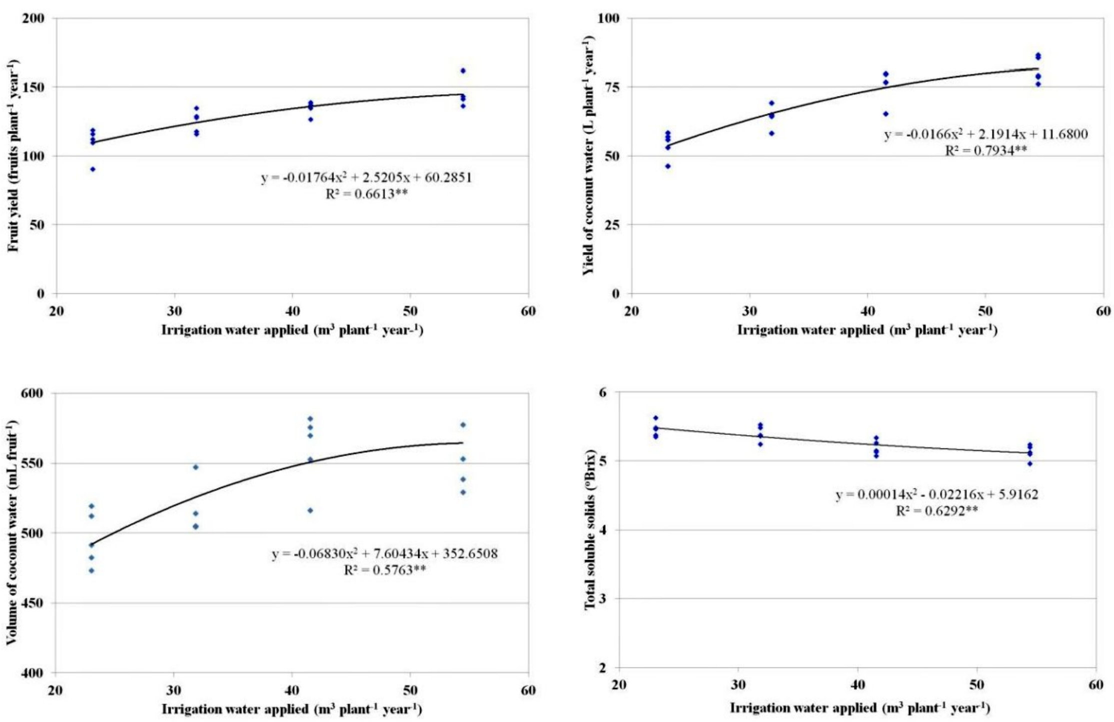

Figure 3 - Fruit yield (fruits $plant^{-1}$ $year^{-1}$), yield of green coconut water (L $plant^{-1}year^{-1}$), volume of water per fruit (mL $fruit^{-1}$) and total soluble solids of green coconut water (°Brix) as a function of irrigation water applied (m^{-3} $plant^{-1}$ $year^{-1}$). (average of years 2017 and 2018). **The model is statistically significant at the significance level of 0.01.

volumes increased from 100 to 150 L plant^{-1} d^{-1} the fruit yield increased only 3.2%. Fruit yields obtained with those irrigation volumes were lower than those of the present study, ranging from 82 to 96 fruits plant^{-1} year^{-1}.

Although, the water consumption of the dwarf coconut tree in the Northeast region of Brazil usually varies from 100 to 240 L plant^{-1} day^{-1}, depending on climatic conditions, there are reports of coconut producers using daily irrigation volumes of up to 350 L plant^{-1} day^{-1} (CARR, 2011; MIRANDA et al., 2007). In a previous study carried out at the same farm of the present study, MIRANDA et al. (2019) reported average yields of 139 fruits plant^{-1} year^{-1} and 64 L of coconut water plant^{-1} year^{-1} with the irrigation scheduling adopted by the farmer, applying fixed water depths of 220 L plant^{-1} d^{-1}along the year. That yield of coconut water is similar to the one obtained with the application of 77% ETc in the present study. However, the volume of water applied by the grower (52.0 m^3 plant^{-1} year^{-1}) was 63% higher than that applied in the 77% ETc treatment (31.8 m^3 plant^{-1} year^{-1}). Thus, the farmer could save 39% of its current irrigation water use, and still obtain the same yield of coconut water, by just scheduling irrigation according to ETc variation along the year.

The total soluble solids (TSS) of the coconut water decreased as irrigation depths increased (Figure 3D). However, the minimum value of TSS of 5.12, obtained with treatment T4, was still above the minimum TSS required by the coconut water industry (TSS $\geq$ 5.0). This showed that deficit irrigation can be used to control coconut water TSS along with other factors such as fruit age at harvest, fertilization, genotype, etc.

The irrigation water productivity in terms of fruits (IWP$_f$) increased significantly from 2.7 to 4.7 fruits m^{-3} when the irrigation depths decreased from 131% ETc to 56% ETc (Table 2). The same occurred for irrigation water productivity in terms of coconut water (IWP$_{cw}$), which increased significantly from 1.5 to 2.4 L m^{-3}, when the irrigation depths decreased from 131% ETc to 56% ETc. That is in accordance with CARR (2011), who stated that regulated deficit irrigation may have a role in increasing the water productivity of irrigated coconut palms. According to FERERES & SORIANO (2007), that is also observed for most crops.

The lowest IWP$_f$ obtained in the present study (2.7 fruits m^{-3}) was similar to that reported by MIRANDA et al. (2019) for the same farm, but with the application of a slightly lower irrigation volume (52 m^3 plant^{-1} year^{-1}). However, the average IWP$_{cw}$ of the farm (1.2 L m^{-3}) could be improved by 96%, 68%, 52% and 25%, if irrigation was scheduled to apply 56%, 77%, 100% and 131% of ETc, respectively.

AZEVEDO et al. (2006) reported IWP$_f$ values of 1.95, 1.94 and 1.80 fruits m^{-3}, when fixed irrigation volumes of 50, 100 and 150 L plant^{-1} d^{-1}, were applied to six-year-old dwarf coconut trees, respectively. These values were lower than those obtained in the present study, and unlike it, they found no significant difference between the treatments.

Despite the large variation in irrigation volumes among treatments, the corresponding variation in irrigation costs was small compared to the change in gross revenue (Table 3). Consequently, the best economic return was obtained with the maximum irrigation depth (131% ETc), which represented an income increase of 897.92 U$ ha^{-1}, compared to the farmer´s current irrigation scheduling. Conversely, deficit irrigation would reduce irrigation costs little, but significantly decrease farmer´s incomes. It should be noted that these results were greatly affected by the low price of electricity for irrigation, whose tariff for night

Table 2 - Average values of irrigation volumes applied per plant (I), fruit yield (Y$_f$), coconut water yield (Y$_{cw}$) and irrigation water productivity in terms of fruits (IWP$_f$) and coconut water (IWP$_{cw}$). 2017-2018.

Treatment	I (m^3 plant^{-1} year^{-1})	Y$_f^*$ (fruits plant^{-1} year^{-1})	Y$_{cw}^*$ (L plant^{-1} year^{-1})	IWP$_f^*$ (fruits m^{-3})	IWP$_{cw}^*$ (L m^{-3})
T1	23.0	109.4 c	54.2 c	4.7 a	2.4 a
T2	31.8	124.9 bc	64.3 b	3.9 b	2.0 b
T3	41.5	135.2 ab	75.6 a	3.3 c	1.8 b
T4	54.4	144.9 a	81.4 a	2.7 d	1.5 c

* Means followed by the same letter within a column are not significantly different (P < 0.05) according to Tukey's test.

Table 3 - Annual irrigation cost (I_c), irrigation cost variation compared to the management adopted by the farmer (DI_c), gross revenue from coconut water sales (GR_{cw}), variation in gross revenue compared to that obtained by the farmer (DGR_{cw}) .

Treatment	I_c (U$ ha^{-1})	DI_c (U$ ha^{-1})	GR_{cw} (U$ ha^{-1})	DGR_{cw} (U$ ha^{-1})	Balance (U$ ha^{-1})
T1	636.54	-75.39	2816.82	-509.31	-433.92
T2	659.42	-52.51	3341.72	15.59	68.10
T3	684.65	-27.28	3928.99	602.86	630.14
T4	718.30	+6.37	4230.42	904.29	897.92
Farmer	711.93		3326.13		

irrigation (from 9:30 PM to 6:00 AM) has discounts of 73% over the price practiced during the day.

CONCLUSION

Sustained deficit irrigation reduced dwarf green coconut fruit yield, fruit water volume and, most notably, coconut water yield. Conversely, SDI increased total soluble solids of the coconut water and irrigation water productivity in terms of fruits and coconut water. Deficit irrigation showed no economic advantage over full irrigation due to the small reduction in electricity costs compared to the reduction in gross revenue.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

The authors contributed equally to the manuscript.

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