Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Scientific Paper
Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v43n3e20220189/2023

WATER DEMAND AND WATER USE EFFICIENCY IN ‘PALMER’ MANGO CULTIVATION IN THE LOW-MIDDLE SÃO FRANCISCO VALLEY

Francisco B. da Silva Junior[1*], Marcelo J. da Silva[2],
Herica F. de S. Carvalho[3], Cloves Vilas Boas dos Santos[3], Thieres G. F. da Silva[4],
Luciana S. B. de Souza[4], Mario de M. Vilas Boas R. Leitão[1], Magna S. B. de Moura[1, 5]

[1*] Corresponding author. Mestre em Engenharia Agrícola, Universidade Federal do Vale do São Francisco/Juazeiro - BA, Brasil.
E-mail: franciscobento787@gmail.com | ORCID ID: https://orcid.org/0000-0002-8856-8543

KEYWORDS

Mangifera indica L., irrigation, evapotranspiration.

ABSTRACT

The study aimed to determine the evapotranspiration (ETc) of the mango cv. ‘Palmer’ over two productive cycles, analyzing water-use efficiency (WUE) and crop water productivity (CWP) to propose average crop coefficient (Kc) values for improving irrigation management under cultivation conditions in the Low-Middle São Francisco Valley. The study was conducted from July 2019 to May 2021 in a commercial ‘Palmer’ mango orchard in Petrolina, State of Pernambuco, Brazil. Micrometeorological data was collected throughout the experimental period. The crop evapotranspiration (ETc) was determined using Bowen ratio energy balance (BREB), and then the Kc, WUE, and CWP were determined. The highest ETc values occurred during the floral induction phase (5.14 ± 0.85 mm day^{-1}), with a Kc of 0.85; however, the lowest values were observed during the fruit maturation phase (3.60 ± 0.73 mm day^{-1}), with a Kc of 0.91. Average water consumption per cycle was 1445 mm, with a daily average of 4.39 mm day^{-1}. WUE and CWP were 16.9 and 24.5 kg ha^{-1} mm^{-1}, respectively. Average Kc values of 0.81, 0.76, 0.85, 0.90, 0.95, and 0.91 are recommended for the vegetative growth, rest period and shoot maturation, floral induction, flowering, fruit development, and fruit maturation phases, respectively.

INTRODUCTION

Mango (*Mangifera indica* L.) is among the main fruits produced (around 1.5 million tons in 2020) and exported (over 243,000 tons and revenue of nearly US$ 247 million) by Brazil (IBGE, 2020). About 90% of the exported volume comes from the Northeastern Semi-Arid Region, especially the São Francisco River Valley, particularly the Low-Middle region where the fruit farming hubs of Petrolina, State of Pernambuco, and Juazeiro, State of Bahia, are located. This area covers about 30,000 hectares cultivated with mango, accounting for approximately 40% of the national production (Lima et al., 2018; IBGE, 2020).

Annual rainfall in the Low-Middle of the São Francisco Valley is below 500 mm year^{-1}, which is associated with a negative water balance for most of the year, making irrigation essential for mango cultivation (Wei et al., 2017; Medeiros et al., 2018). With the current high and increasing demand for water in agriculture, often applied inefficiently, determining water demand parameters, such as crop evapotranspiration (ETc), is essential to improve irrigation management, aiming for more precise and efficient water use, while maintaining high yields and ensuring sustainable development under conditions of low water availability (Alves et al., 2018; Simões et al., 2021).

---

[1] Departamento de Engenharia Agrícola, Universidade Federal do Vale do São Francisco/Juazeiro - BA, Brasil.
[2] Universidade Federal Rural de Pernambuco/Recife - PE, Brasil.
[3] Universidade Federal de Pernambuco/Recife - PE, Brasil.
[4] Unidade Acadêmica de Serra Talhada, Universidade Federal Rural de Pernambuco/Serra Talhada - PE, Brasil.
[5] Departamento de Agrometeorologia, Empresa Brasileira de Pesquisa Agropecuária, EMBRAPA Semiárido/Petrolina - PE, Brasil.

Area Editor: Fernando França da Cunha
Received in: 10-19-2022
Accepted in: 7-30-2023

Water consumption of mango trees in the Low-Middle region has been studied by several authors (Lopes et al., 2001; Azevedo et al., 2003; Teixeira et al., 2008; Silva, 2019). In these studies, micrometeorological methods were especially applied, focusing on the Bowen Ratio method. Mainly the Tommy Atkins and Kent varieties were studied, which showed an average crop evapotranspiration ranging between 2.3 and 5.9 mm day^{-1}, with the most intense consumption during the fruiting phase, for which the highest crop coefficient (Kc) values, close to 1.0, were obtained (Lopes et al., 2001; Azevedo et al., 2003; Teixeira et al., 2008; Silva et al., 2015; Silva, 2019). However, some aspects remain unclear in these studies, such as potential effects of morphophysiological differences between cultivars and detailed variations throughout a complete cultivation cycle, as most studies focus on post-flowering phases, neglecting the vegetative phase, which spans a significant period of the productive cycle.

In this context, considering the commercial importance of mango varieties like ‘Tommy Atkins’, ‘Kent’, and ‘Palmer’, it is crucial to explore research more extensively to determine water use by these varieties, especially for the ‘Palmer’, which lacks dedicated studies even though being one of the predominant planted variety in the Low-Middle of the São Francisco Valley (Lima et al., 2018).

Therefore, detailing the water consumption and the water use throughout the entire phenological cycle of the ‘Palmer’ mango grown in the Low-Middle of the São Francisco Valley can provide new reference parameters to improve irrigation management of the crop in the region. Hence, the objective of this study was to determine the evapotranspiration of the mango cv. ‘Palmer’ over two productive cycles, analyzing water use efficiency and crop water productivity to propose average crop coefficient values aiming to improve irrigation management under the cultivation conditions of the Low-Middle of the São Francisco Valley.

MATERIAL AND METHODS

Description of the area and experimental period

The study was conducted in a commercial orchard at Andorinhas Farm (9°27’24” S; 40°36’86” W at an altitude of 380 m above mean sea level), located in the municipality of Petrolina, Pernambuco State (Figure 1a), in the Low-Middle São Francisco River Valley, a semi-arid region in Northeast Brazil. The climate is classified as *Bswh’*, according to the Köppen’s classification, with a rainy season concentrated between January and April (Álvares et al., 2013). Climatic normals for the site are shown in Figures 1b and 1c.

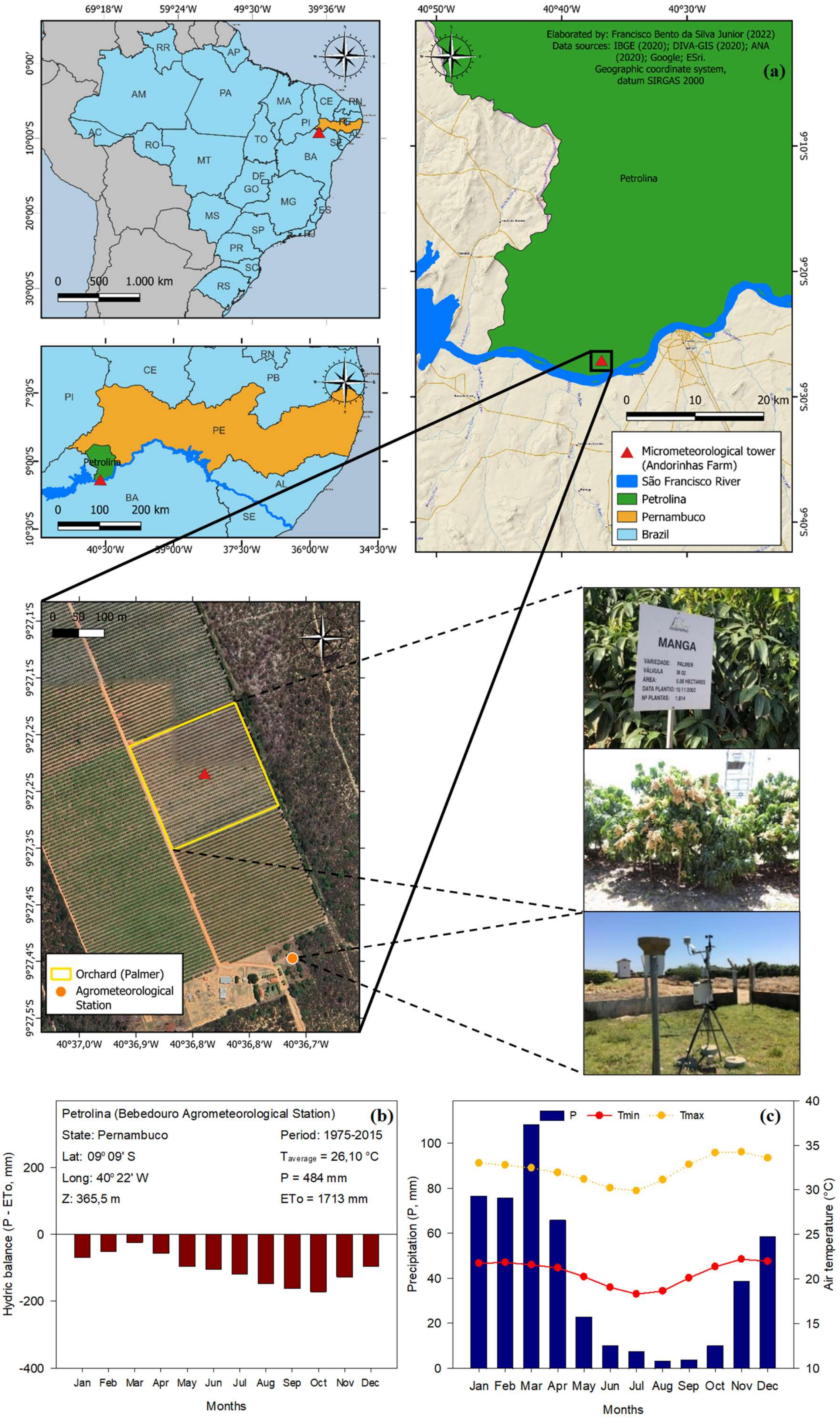

FIGURE 1. Location and climatological conditions of the ‘Palmer’ mango orchard in Petrolina, State of Pernambuco, Brazil.

The experimental area of the orchard covers 5.08 ha, cultivated with 'Palmer' mangoe, grafted onto cv. 'Espada', planted in November 2002, oriented East-West, spaced at 4 m x 7 m (357 plants ha^{-1}). The soil at the studied area is of the Quartzipsamment type (Mouco, 2008), at least 2 m deep, sandy textured, and well-drained. In soil management, with the orchard well established, soil coverage was accomplished through the deposition of vegetative residues from pruning, which were shredded and kept in the planting line. Additionally, each cycle had 30 liters of goat manure added per plant. These practices are crucial for improving soil water retention and availability under such texture conditions.

A micro-sprinkler irrigation system was employed, with field tests showing a flow rate of 21 L h^{-1} (input pressure of 4.5 kgf cm^{-2} and output of 3.9 kgf cm^{-2}), achieving a water application efficiency of 85%. The crop was irrigated daily, split into two sessions, one in the morning (around 09h00) and other at dawn (around 01h00). Adjustments were made based on farm water needs and the crop's phenological stages. Non-irrigation only occurred when rainfall exceeded 5 mm per day or due to irrigation system issues. The total water applied in the mango system is shown in Figure 2d.

The first evaluation cycle (cycle I) started on 03/07/2019; no production pruning occurred in this cycle as the farm adjusted its phytotechnical management to establish a new harvest season. The beginning of the cycle was marked by cleaning pruning after the previous harvest, where only the remains of inflorescence structures, fruiting, and some branches were removed; the end of this productive cycle was on 29/06/2020, with the harvest. This was followed by a resting period and the start of the second cycle (cycle II) happened with production pruning on 14/07/2020, ending with the harvest on 04/05/2021. The phenological stages are highlighted in Table 1, with their respective durations.

TABLE 1. Duration of the phenological stages of the 'Palmer' mango variety grown in the Low-Middle São Francisco River Valley.

Phenological stages	Cycle I	No. of Days	Cycle I	No. of Days
Vegetative growth	03 July 2019 to 28 August 2019	57	14 July 2020 to 12 September 2020	61
Vegetative rest and branch maturation	29 August 2019 to 15 November 2019	79	13 September 2020 to 01 December 2020	80
Floral induction	16 November 2019 to 25 December 2019	40	02-12 December 2020	11
Flowering	26 December 2019 to 12 January 2020	18	13- 27 December 2020	15
Fruit development	13 January 2020 to 01 May 2020	110	28 December 2020 to 31 March 2021	94
Fruit maturation	02 May 2020 to 29 June 2020	59	01 April 2021 to 04 May 2021	34
Total		**363**		**295**

Fertilization was performed at the beginning of each cycle, applying nitrogen (30 kg), phosphorus (20 kg), and potassium (30%). Nutritional needs were determined by farm technicians based on soil analyses (Supplementary Material). At 100 days, counted from the beginning of the cycle, potassium, sulfur, boron, and zinc were applied weekly for about 40 days. At 140 days, dormancy was broken using calcium and potassium-based products. After full flowering, potassium and nitrogen were applied, repeating potassium application 20 days before harvest. After two leaf flushes, Paclobutrazol (PBZ) was applied to the soil as growth regulator at dosages of 35.0 ml $plant^{-1}$ and 4.0 L ha^{-1}.

Figure 2 describes the environmental conditions observed in the orchard throughout the experimental period.

Micrometeorological monitoring

A seven meter tall micrometeorological tower was installed inside the orchard. It was equipped with sensors to monitor daily micrometeorological variables (Table 2). All sensors were connected to a CR5000 data acquisition system (Campbell Scientific Inc., Logan, Utah, USA), which was programmed to take measurements every 30 seconds and store averages every 10 minutes.

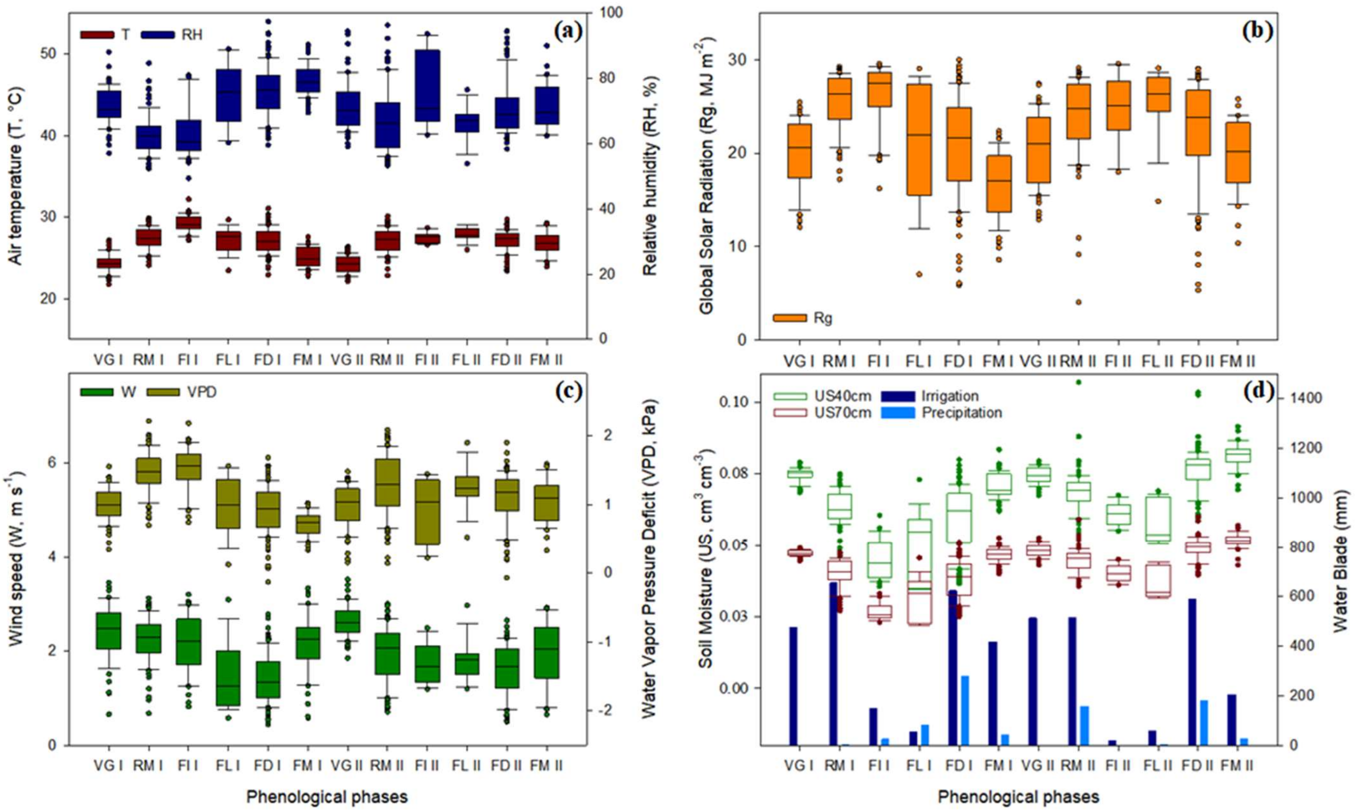

FIGURE 2. Environmental variables observed in the 'Palmer' mango orchard under irrigation throughout the 2019-2020 (cycle I) and 2020-2021 (cycle II) in Petrolina-PE (Brazil), considering the phenological phases: VG - Vegetative growth; RM - Vegetative Rest and Branch Maturation; FI - Floral Induction; FL - Flowering; FD - Fruit Development; and FM - Fruit Maturation.

TABLE 2. Sensors used for micrometeorological monitoring of 'Palmer' mango orchard in Petrolina, state of Pernambuco, Brazil.

Parameter	Instrument	Modelo / Manufacturer / Location	Height (m)
Radiation balance components (Rn)	Net Radiometer	CNR1 Net radiometer, Kipp & Zonen B.V., Delft, Netherlands	7.0
Dry bulb and wet bulb temperature (ts e tu)	Thermocouples	Type T, Copper-Constantan	3.6 e 5.6
Soil heat flux (G)	Heat flux plates	HFT3-REBS, Campbell Scientific, Inc, Logan, Utah, USA	-0.02
Soil moisture (Us)	FDR Sensor	CS615, Campbell Scientific	-0.4 e -0.7
Wind speed (W)	Anemometer	03002 Wind Sentry, R. M. Young Company, Traverse City, Michigan, USA	3.6
Precipitation (P)	Pluviometer	CS700-L Hydrological Services Rain Gage, Liverpool, Australian	8.0

Bowen Ratio Method

Net radiation (Rn) and soil heat flux (G) were measured respectively by the net radiometer and the soil heat flux sensor. The latent heat flux (LE) was estimated using Bowen ratio energy balance (BREB) as already used for mango trees (Silva, 2019; Souza et al., 2018), using the following expression:

$$LE = \frac{Rn - G}{1 + \beta} \tag{1}$$

in which:

Rn - net radiation, W m^{-2};

G - soil heat flux, W m^{-2},

β - Bowen ratio, dimensionless.

The values of β were calculated from the equation:

$$\beta = \left(\frac{\Delta + \gamma}{\gamma} \frac{(t_{u1} - t_{u2})}{(t_{s1} - t_{s2})} - 1 \right) \tag{2}$$

in which:

Δ - slope of the saturated vapour pressure curve, kPa $°C^{-1}$;

γ - psychrometric constant, kPa $°C^{-1}$;

t_{u1} e t_{u2} - wet bulb temperatures at two levels (levels 1 and 2) of measurement above the crop canopy, °C, and

t_{s1} e t_{s2} - dry bulb temperature at two levels (levels 1 and 2) of measurement above the crop canopy, °C.

Potential inconsistencies in the BREB method were assessed by examining the errors that resulted in invalid β and LE values, as defined by Perez et al. (1999). This assessment was based on measurements of vapor pressure profiles at various times, the precision of temperature and vapor pressure sensors, and a consistent signal conversion in accordance with the flow-gradient relation. Besides these criteria, values of $\beta < -0.75$ were deemed to cause inconsistencies in determining energy flows (Ortega-Farias et al., 1996).

To fill in invalid values, correlations were proposed using valid LE data obtained by traditional BERB from both cycles and LE data calculated using the modification proposed by Lin et al. (2016) (Equation 3), or with Rn measured at the micrometeorological tower when conditions did not allow using the method of Lin et al. (2016).

$$\beta = 1{,}46\left(\frac{1}{RH}\right)\left(\frac{T}{273}\right)^2 \exp\left[-19{,}83\left(1-\frac{273}{T}\right)\right] \quad (3)$$

in which:

T - absolute temperature, K, and

RH - relative humidity, decimal of %.

Evapotranspiration and Crop Coefficient

Crop evapotranspiration (ETc) was determined for 10-minute intervals, based on consistent LE data, according to Expression 4. These ETc_{10min} values were later integrated into daily average ETc data (mm day^{-1}), considering the period when Rn – G > 0.

$$ETc_{\,10min} = \frac{LE\ t\ f_{time}}{\lambda} \quad (4)$$

in which:

t - time interval for storing the average values of measurements (10 minutes),

f_{time} - time scale adjustment factor (60 seconds); e,
λ - latent heat of vaporization, W m^{-2}.

Daily crop coefficients (Kc) were obtained during the two evaluated productive cycles, according to the following relationship:

$$Kc = \frac{ETc}{ETo} \quad (5)$$

in which:

ETc - crop evapotranspiration, mm day^{-1}, and

ETo - reference evapotranspiration, mm day^{-1}.

Daily ETo was estimated by the Penman-Monteith-FAO 56 method (Allen et al., 1998). To do so, we used data collected at the agrometeorological station located 500 m from the orchard on the study farm.

For results presentation, all daily data were converted to averages per phenological phase of each cycle (Table 1), considering the mango management under irrigated tropical conditions.

Water-Use Efficiency and Crop Water Productivity

Water-use efficiency (WUE, kg ha^{-1} mm^{-1}) was obtained for each production cycle through the expression:

$$WUE = \frac{CP}{I} \quad (6)$$

in which:

CP - crop productivity, kg ha^{-1}, and

I - irrigation, mm.

For productivity determination, all fruits from 10 selected plants were harvested, counted, and weighed. Productivity computation was performed considering the average fruit weight multiplied by the average fruit quantity per plant and the number of plants in one hectare (357 plants ha^{-1}).

Crop water productivity (CWP, kg ha^{-1} mm^{-1}) was determined for each evaluated cycle using the relationship:

$$CWP = \frac{CP}{ETc} \quad (7)$$

in which:

CP - crop productivity, kg ha^{-1}, and

ETc - crop evapotranspiration, mm.

RESULTS AND DISCUSSION

Crop Evapotranspiration

Figure 3 shows the daily variation of crop evapotranspiration (ETc) for the ‘Palmer’ mango orchard across two evaluated productive cycles, along with reference evapotranspiration (ETo). ETc ranged between 0.94 and 7.48 mm day^{-1} and it was lower at the beginning and end of each cycle, which corresponded to the months of May and July. These periods encompass the vegetative growth and fruit maturation phases. On the other hand, ETc was higher during floral induction and flowering phases, which coincided mostly with the last quarter of each year.

ETc is proportional to ETo, which is higher for most of the period, indicating that the crop water demand is below the atmospheric demand. However, in the final phase of cycle I, ETc exceeded ETo on certain days during fruit development. This occurred when ETo dropped because of reduced incoming radiation in the orchard, which continued into the fruit maturation phase. On average, the incoming radiation during this time was 16.8 MJ m^{-2} day^{-1} (Figure 2b). During the same period, soil moisture levels were higher than in other phases (Figure 2d). This increase in soil moisture resulted from an increased rainfall (Figure 2d), allowing ETc to approach ETo values. In contrast, during the same phase in the following cycle, ETo was higher due to increased incoming radiation, while ETc remained like the previous cycle.

After rainfall events, ETc rises and approaches ETo values. The micro-sprinkler irrigation system used allows a wetted area concentrated beneath the canopy (Simões et al., 2018). As a result, on days without rain, values calculated using the Bowen ratio method typically reflect low transpiration and evaporation levels beneath the canopy. In contrast, after rain, the entire surface is moistened, including the inter-row spaces, resulting in increased LE, likely due to increased soil evaporation. As a micrometeorological method, the Bowen ratio energy balance (BREB) accounts for all surface fluxes, including evapotranspiration, without distinguishing between transpiration and evaporation.

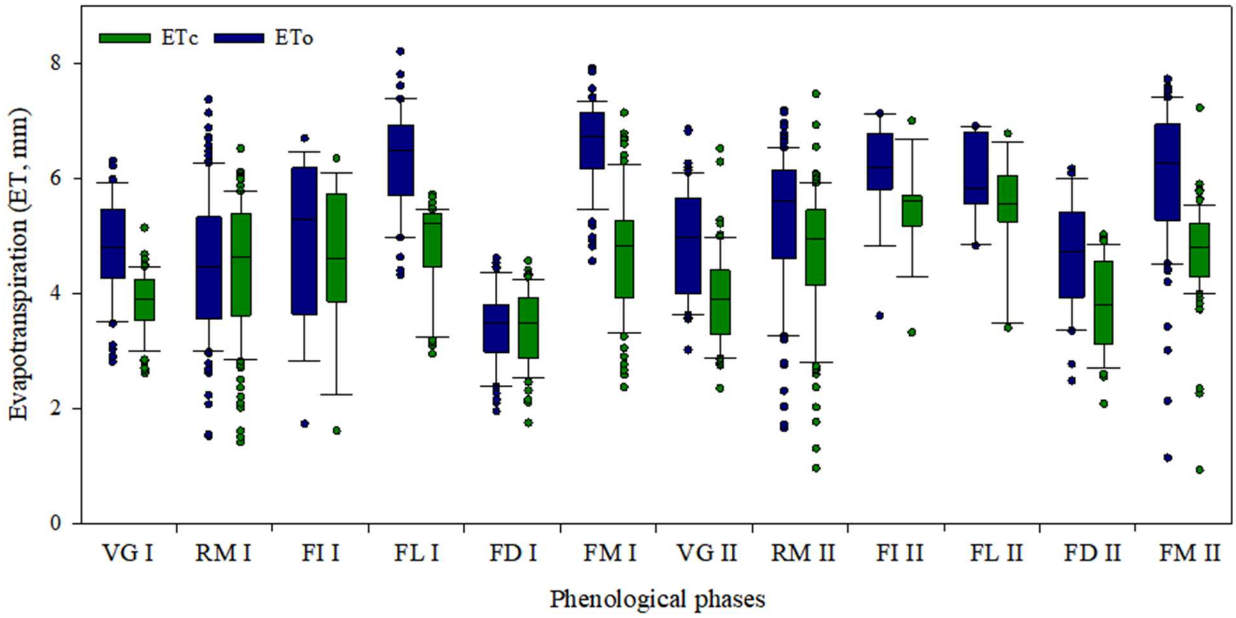

FIGURE 3. Reference evapotranspiration (ETo) and crop evapotranspiration (ETc) of irrigated mango cv. 'Palmer' throughout the 2019-2020 (I) and 2020-2021 (II) productive cycles, in Petrolina municipality, state of Pernambuco, Brazil, considering the phenological phases: VG - Vegetative growth; RM - Vegetative Rest and Branch Maturation; FI - Floral Induction; FL - Flowering; FD - Fruit Development; and FM - Fruit Maturation.

Crop Coefficient

The crop coefficient (Kc) in Figure 4 highlights the impact of crop development on water demand. Average Kc rises from the vegetative growth phase to the vegetative rest and branch maturation phases in both cycles. The Kc varies between the two cycles during vegetative rest and branch maturation to fruit development, with lower values during floral induction and flowering in cycle I than those in cycle II, wherein Kc values remain close to 0.9. Finally, during fruit maturation, there was a decrease in Kc from the previous phase in both cycles.

According to Wei et al. (2017), fruiting requires more water, especially during the first six weeks of fruit formation. During this time, water scarcity can lead to fruit falling off the trees prematurely, as well as a decrease in fruit size and weight in the final phase. On the other hand, adequate water supply ensures optimal physiological processes and productive success.

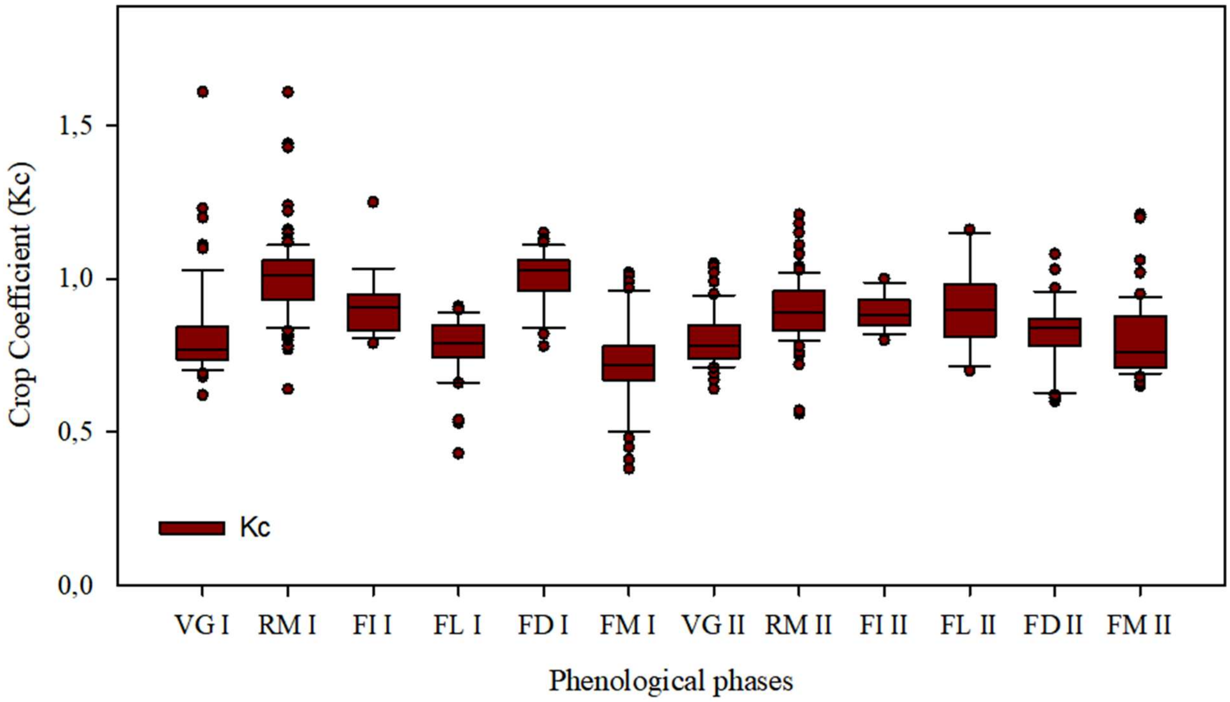

FIGURE 4. Cultivation coefficient (Kc) of mango cv. 'Palmer' irrigated throughout the 2019-2020 (I) and 2020-2021 (II) cycles, in Petrolina municipality, state of Pernambuco, Brazil, considering the phenological phases: VG - Vegetative growth; RM - Vegetative Rest and Branch Maturation; FI - Floral Induction; FL - Flowering; FD - Fruit Development; and FM - Fruit Maturation.

This study presented Kc curve similar to previous studies in the region with other mango varieties. For example, Teixeira et al. (2008) studied the Tommy Atkins cultivar and found Kc values between 0.6 and 1.2 over two production cycles.

Table 3 presents the mean of ETc per phenological phase for each cycle, along with ETo and Kc values. ETc increased during Cycle I and Kc decreased in average from vegetative growth (Kc = 0.82) to vegetative rest and branch maturation (Kc = 0.72). This suggests that during this phase, the plants consume less water than atmospheric conditions allow and requires more water during new leaf growth compared to the vegetative rest and branch maturation stages. Higher water consumption during rest and branch maturation, when ETc was 4.69 mm day^{-1}, was conditioned by atmospheric conditions that enhanced ETc, confirmed by higher ETo at this stage. Kc increased in the followed phases when it reaches 1.0 in average during the fruit development and maturation, reflecting as well the crop water needs that approaches the atmospheric demand.

TABLE 3. Crop evapotranspiration (ETc), reference evapotranspiration (ETo), and crop coefficient (Kc) of irrigated mango ‘Palmer’ in Petrolina municipality, state of Pernambuco, Brazil, throughout the 2019-2020 (I) and 2020-2021 (II) productive cycles.

Phenological stages	**Cycle I**			**Cycle II**			**Average**		
	ETc	**ETo**	**Kc**	**ETc**	**ETo**	**Kc**	**ETc**	**ETo**	**Kc**
	mm day^{-1}			**mm day^{-1}**			**mm day^{-1}**		
Vegetative growth	3.85	4.19	0.82	3.92	4.31	0.80	3.89	4.25	0.81
Vegetative rest and branch maturation	4.69	5.93	0.72	4.73	5.43	0.80	4.71	5.68	0.76
Floral induction	4.87	5.79	0.78	5.40	5.36	0.91	5.14	5.58	0.85
Flowering	4.51	4.63	0.91	5.48	5.69	0.89	5.00	5.16	0.90
Fruit development	4.44	4.35	1.00	4.75	4.91	0.90	4.60	4.63	0.95
Fruit maturation	3.41	3.24	1.00	3.79	4.32	0.82	3.60	3.78	0.91
Average	**4.22**	**4.97**	**0.88**	**4.46**	**5.35**	**0.84**	**4.49**	**4.85**	**0.86**

In cycle II, Kc values followed a similar pattern to the previous period, but the value of 0.80 was maintained during vegetative growth and rest, followed by an increase during floral induction, higher than the previous cycle (Kc = 0.91). One reason was that the soil water availability was higher because of the rainfall events, despite the reduced irrigation, being higher in this period than the previous one mainly in the inter row parts of the orchard. Another difference was the decrease in Kc during maturation (Kc = 0.82) compared to the previous cycle, which may be related to changes in crop management, reducing the duration of this phase and distinct environmental conditions like radiation and soil water availability.

Water Use Efficiency and Crop Water Productivity

Figure 5 shows that irrigation applied 2,393.1 mm in cycle I and 1,918.3 mm in cycle II. Accumulated rainfall was 448.5 mm in cycle I and 377.7 mm in cycle II. In both cycles, water inputs were excessive compared to accumulated crop evapotranspiration of 1,554.4 mm in cycle I and 1,439.4 mm in cycle II.

In Cycle I, the total orchard productivity was 27.53 t ha^{-1}, equivalent to 134 fruits per plant. In contrast, Cycle II saw an increase to 42.77 t ha^{-1}, or 218 fruits per plant. The average productivity in the first cycle was close to the regional average for mangoes in the Low-Middle of the São Francisco Valley, which is 28.7 t ha^{-1}, as reported by IBGE (2020); this value was exceeded in the second cycle. This difference emphasizes the impact of varying management practices between cycles. Cycle I started with a cleaning pruning conducted after the previous harvest to align the production cycle with buyer demands, whereas Cycle II involved a production pruning with an already standardized production system. These conditions led to a higher production of inflorescences in cycle II, which may be linked to higher temperatures during floral induction in this cycle (Figure 2a), resulting in more fruits per plant. Additionally, these factors likely contributed to enhanced leaf development, thereby increasing the resources available for photosynthetic processes, biomass accumulation, and fruit production.

Irrigation-based WUE was equivalent to 11.5 kg ha^{-1} mm^{-1} in cycle I and 22.3 kg ha^{-1} mm^{-1} in cycle II. The difference in WUE between cycles is due to the management practices adopted, as the crop has better productivity in cycle II compared to cycle I. Simões et al. (2021) obtained values of 22.7 and 36.6 kg ha^{-1} mm^{-1} for two cycles of mango cv. ‘Kent’ grown in Petrolina-PE, using an irrigation depth of 100% of the recommended ETc. In a study conducted in Spain under a subtropical Mediterranean climate, Zuazo et al. (2019) obtained a WUE of 21.2 kg ha^{-1} mm^{-1} for cv. ‘Tommy Atkins’. Therefore, irrigation can be managed more efficiently by developing strategies to reduce water application under similar conditions to the evaluated orchard, while maintaining or even increasing productivity, as highlighted by Simões et al. (2021). This would reduce costs associated with irrigation and increase WUE (Hahn et al., 2022).

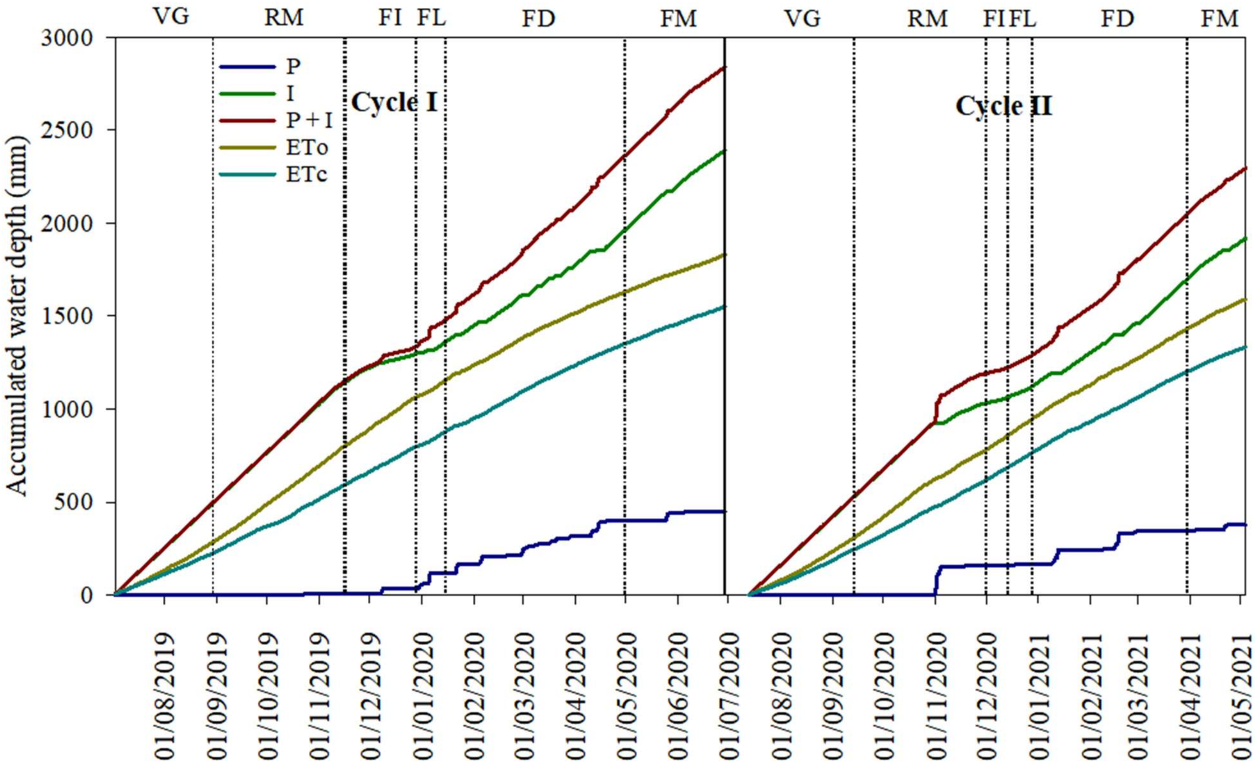

FIGURE 5. Accumulation of precipitation (P), irrigation (I), precipitation + irrigation (P+I), reference evapotranspiration (ETo), and crop evapotranspiration (ETc) water depths in an irrigated ‘Palmer’ mango orchard over the 2019-2020 (I) and 2020-2021 (II) cycles, in Petrolina, state od Pernambuco, Brazil, considering the phenological phases: VG - Vegetative growth; RM - Vegetative Rest and Branch Maturation; FI - Floral Induction; FL - Flowering; FD - Fruit Development; and FM - Fruit Maturation.

CWP was 17.7 kg ha^{-1} mm^{-1} in cycle I and 32.1 kg ha^{-1} mm^{-1} in cycle II. The difference between cycles again arises due to the distinct management practices employed in each cycle. The higher value for cycle II is closer to the value obtained by Teixeira & Bastiaanssen (2009), for the same region, on the cv. ‘Tommy Atkins’, with a CWP of 40.0 kg ha^{-1} mm^{-1}.

CONCLUSIONS

(1) Average water consumption during a complete productive cycle of irrigated ‘Palmer’ mango growing in the Low-Middle São Francisco Valley was 1,445 mm.

(2) The prevailing environmental conditions in each phase influenced crop evapotranspiration (ETc) changes throughout the cycle. The highest ETc occurred during the Floral Induction phase, averaging 5.14 mm day^{-1} (Kc = 0.85) due to a greater soil water availability caused by frequent rainfall events. It was lower during the Fruit Maturation phase, averaging 3.60 mm day^{-1} (Kc = 0.91), when there was less intense incident radiation in the orchard.

(3) Based on the two cycles evaluated, we recommend average crop coefficient (Kc) values of 0.81, 0.76, 0.85, 0.90, 0.95, and 0.91 for the respective phases of vegetative growth, rest and maturation, floral induction, flowering, fruit development, and maturation. These values can be used as a reference for better water application in irrigated ‘Palmer’ mango cultivation under similar conditions in Brazilian semi-arid areas. As recommended by irrigation management, soil, plant, and atmospheric conditions should be monitored on the property for optimal vegetative and productive performance of the plants, and necessary adjustments should be made according to the orchard’s needs.

(4) The water use efficiency of the orchard evaluated was low, as the irrigation applied significantly exceeded the water consumption of plants. Thus, in ‘Palmer’ mango production systems under similar conditions, strategies to reduce water application in irrigation management should be considered.

ACKNOWLEDGEMENTS

The authors express their gratitude to the Federal University of the São Francisco Valley (UNIVASF), especially to the Graduate Program in Agricultural Engineering, and to the Brazilian Agricultural Research Corporation (EMBRAPA) for their collaborative contributions to this research. We also thank Fazenda Andorinhas for their partnership, provision of the study area, and sharing of crop management information. This work was supported by the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES), Funding Code 001.

SUPPLEMENTARY MATERIAL

Chemical properties of soil from the 0-30 cm depth layer, in two periods over two productive cycles of ‘Palmer’ mango orchard, in Petrolina municipality, state of Pernambuco, Brazil.

Soil Chemical Analysis

Locality: Andorinhas farm
Municipality/State: Petrolina/PE
Crop: ‘Palmer’ Mango
Depth: 0 – 30 cm

	M.O.	**pH**	**pH**	**P-rem.**	**P-M-1**	**P-res.**	**S-SO_4^{2-}**
	g kg^{-1}	(H_2O)	(KCl)	mg L^{-1}	---------------- mg dm^{-3} ----------------		
05 December 2019	8.1	**	6.6	**	19.8	5.1	12.5
19 November 2020	7.3	**	5.8	**	44.8	4.8	3.1

	Ca^{2+}	**Mg^{2+}**	**K^+**	**Na^+**	**Al^{3-}**	**H+Al**	**SB**	**T**
	-- $cmol_c$ dm^{-3} --							
05 December 2019	6.15	0.54	0.09	0.04	6.81	0.0	0.34	7.15
19 November 2020	2.40	0.52	0.07	0.20	3.19	0.0	0.31	3.50

	M	**V**	**C.E.**	**Fe^{2+}**	**Mn^{2+}**	**Cu^{2+}**	**Zn^{2+}**	**B**
	------ % ------		dS m^{-1}	------------------------ mg dm^{-3} ------------------------				
05 December 2019	0.0	95.27	0.50	10.8	14.5	1.5	32.4	2.10
19 November 2020	0.0	91.04	0.39	29.2	26.6	2.0	34.0	0.27

	Relationship between bases				**Saturation (%)**			
	Ca/Mg	**Ca/K**	**Mg/K**	**(Ca+Mg)/ K**	**Ca**	**Mg**	**K**	**Na**
05 December 2019	11.4	71.8	6.3	78.1	86.0	7.5	1.2	0.5
19 November 2020	4.6	34.6	7.5	42.0	68.4	14.8	2.0	5.8

M.O.: Soil organic matter (muffle method)
P-rem.: Remaining phosphorus
P-M-1: Phosphorus - mehlich-1 extractor
P-res.: Phosphorous resin method
SB: Sum of exchangeable bases
T: Cation exchange capacity
m: Aluminum saturation index
V: Base saturation index
C.E.: Electrical conductivity in the saturation paste extract

REFERENCES

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration - Guidelines for computing crop water requirements. Rome, FAO (Irrigation and drainage paper 56).

Álvares CA, Stape JL, Sentelhas PC, Gonçalves JDM, Sparovek G (2013) Köppen's climate classification map for Brazil. Meteorologische Zeitschrift 22(6): 711-728. http://doi.org/10.1127/0941-2948/2013/0507

Alves ES, Lima DF, Barreto JAS, Santos DP, Santos MAL (2018) Determinação do coeficiente de cultivo para a cultura do rabanete através de lisimetria de drenagem. Irriga 22(1): 194-203. http://doi.org/10.15809/irriga.2017v22n1p194-203

Azevedo PV, Silva BB, Silva VPR (2003) Water requirements of irrigated mango orchards in northeast Brazil. Agricultural water management 58(3): 241-254. DOI: http://doi.org/10.1016/S0378-3774(02)00083-5

Hahn F, Valle S, Navarro-Gómez C (2022) Pruning and water saving management effects on mango high-density and mature orchards. Agronomy 12: 2623. https://doi.org/10.3390/agronomy12112623

IBGE - Instituto Brasileiro de Geografia e Estatística (2020) PAM - Produção agrícola Municipal. Available: https://sidra.ibge.gov.br/pesquisa/pam/tabelas. Accessed Feb 16, 2022.

Lima JRF, Almeida GVB, Pereira A, Araújo Júnior JN (2018) Análise do mercado de manga produzida no Vale do São Francisco: cenário atual e perspectivas para o curto prazo. In: Congresso da Sociedade Brasileira de Economia, Administração e Sociologia Rural do Regional Nordeste. Juazeiro, UNIVASF: SOBER-NE, Anais... Available: http://www.alice.cnptia.embrapa.br/alice/handle/doc/1099656. Accessed Jun 20, 2022.

Lin KM, Juang JY, Shiu YW, Chang LFW (2016) Estimating the bowen ratio for application in air quality models by integrating a simplified analytical expression with measurement data. Journal of Applied Meteorology and Climatology 55(4): 1041-1048. http://doi.org/10.1175/JAMC-D-15-0080.1

Lopes PMO, Silva BB, Azevedo PV, Silva VPR, Teixeira ADC, Soares JM, Espínola Sobrinho J (2001) Balanço de energia num pomar de mangueiras irrigado. Revista Brasileira de Agrometeorologia 9(1): 1-8. Available: http://www.alice.cnptia.embrapa.br/alice/handle/doc/134336. Accessed Aug 08, 2022.

Medeiros RM, Holanda RM, Viana MA, Silva VP (2018) Climate classification in Köppen model for the state of Pernambuco – Brazil. Revista de Geografia (Recife) 35(3): 219-234. Available: https://periodicos.ufpe.br/revistas/revistageografia/article/view/229388. Accessed Aug 02, 2022.

Mouco MAC (2008) Manejo da floração de mangueiras no semi-árido do nordeste brasileiro com inibidores da síntese de giberelinas. Phd Thesis, Universidade Estadual Paulista “Júlio de Mesquita Filho”.

Ortega-Farias SO, Cuenca RH, Ek M (1996) Daytime variation of sensible heat flux estimated by the bulk aerodynamic method over a grass canopy. Agricultural and Forest Meteorology 81(1-2): 131-143. https://doi.org/10.1016/0168-1923(95)02278-3

Perez PJ, Castellvi F, Ibanez M, Rosell JI (1999) Assessment of reliability of Bowen ratio method for partitioning fluxes. Agricultural and Forest Meteorology 97(3): 141-150. https://doi.org/10.1016/S0168-1923(99)00080-5

Silva JS, Campeche LFDSM, Barbosa DF, Lira RM, Barnabé JMC, Souza DHS (2015) Estimation of the mango crop evapotranspiration in the São Francisco Valley. Revista Geama 1(2): 128-140. Available: https://www.journals.ufrpe.br/index.php/geama/article/view/489

Silva MJ (2019) Evapotranspiração e coeficiente da cultura da mangueira ‘Kent’ cultivada no Submédio do Vale do São Francisco. Master Thesis, Universidade Federal do Vale do São Francisco.

Simões WL, Andrade VP, Mouco MA, Silva JS (2021) Produção e qualidade da mangueira ‘Kent’ (Mangifera indica L.) submetida a diferentes lâminas de irrigação no semiárido nordestino. Revista em Agronegócio e Meio Ambiente 14(2): 1-11. http://doi.org/10.17765/2176-9168.2021v14n2e7832

Simões WL, Ferreira PPB, Mouco MAC, Lima MAC, Guimarães MJM, Silva JAB (2018) Produção e respostas fisiológicas da mangueira cv. Keitt sob diferentes sistemas de irrigação no Submédio do São Francisco. Irriga 23(1): 34-43. http://doi.org/10.15809/irriga.2018v23n1p34

Souza PJOP, Rodrigues JC, Sousa AML, Souza EB (2018) Diurnal energy balance in a mango orchard in the northeast of Pará, Brazil. Revista Brasileira de Meteorologia 33(3): 537-546. http://doi.org/10.1590/0102-7786333012

Teixeira AHC, Bastiaanssen WGM (2009) Uso do sensoriamento remoto para a determinação da produtividade de água no Submédio São Francisco. In: Simpósio Brasileiro de Sensoriamento Remoto. Natal, INPE, Anais... Available: http://www.alice.cnptia.embrapa.br/alice/handle/doc/161996. Accessed Jul 29, 2022.

Teixeira AHC, Bastiaanssen WGM, Moura MSB, Soares JM, Ahmad MUD, Bos MG (2008) Energy and water balance measurements for water productivity analysis in irrigated mango trees, Northeast Brazil. Agricultural and Forest Meteorology 148(10): 1524-1537. http://doi.org/10.1016/j.agrformet.2008.05.004

Wei J, Liu G, Liu D, Chen Y (2017) Influence of irrigation during the growth stage on yield and quality in mango (Mangifera indica L). PLoS ONE 12(4): e0174498. https://doi.org/10.1371/journal.pone.0174498

Zuazo VHD, Pleguezuelo CRR, Ruiz BG, Gordillo SG, García-Tejero IF (2019) Water use and fruit yield of mango (Mangifera indica L.) grown in a subtropical Mediterranean climate. International Journal of Fruit Science 19(2): 136-150. https://doi.org/10.1080/15538362.2018.1493960