Revista Ambiente & Água
ISSN: 1980-993X
Instituto de Pesquisas Ambientais em Bacias Hidrográficas

Cotrim, Carlos Elizio; Santos, Marcelo Rocha dos; Filho, Maurício Antônio Coelho; Coelho, Eugênio Ferreira; Silva, João Abel da
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Revista Ambiente & Água, vol. 14, no. 3, 2019
Instituto de Pesquisas Ambientais em Bacias Hidrográficas

DOI: 10.4136/ambi-agua.2316

Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

Sap flow in 'Tommy Atkins' mango trees under regulated deficit irrigation

ARTICLES doi:10.4136/ambi-agua.2316

Received: 17 Aug. 2018; Accepted: 06 Feb. 2019

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ABSTRACT

Knowledge of transpiration is of fundamental importance for improving irrigation management. This study measured sap flow of the 'Tommy Atkins' mango tree using Granier's thermal dissipation probe method under regulated deficit irrigation. The work was conducted in a 10-year-old 'Tommy Atkins' mango orchard, irrigated by micro sprinkler, located in the Irrigated Perimeter of Ceraíma, in Guanambi, Bahia, Brazil. Sap flow measurements were carried out on three consecutive days in plants under regulated deficit irrigation, with reductions of 30 and 60% of crop evapotranspiration in three phases of fruit development; beginning of flowering to early fruit growth (Phase I), fruit expansion (Phase II) and physiological maturation of fruits (Phase III). Regulated deficit irrigation led to reduced sap flow in 'Tommy Atkins' mango tree.

Keywords: irrigation management, Granier, transpiration, water use efficiency.

Fluxo de seiva em mangueiras 'Tommy Atkins' sob irrigação com déficit controlado

RESUMO

O conhecimento da transpiração é de fundamental importância para aprimoramento do manejo da irrigação. Objetivou-se com o presente trabalho determinar o fluxo de seiva da mangueira 'Tommy Atkins' utilizando o método da sonda de dissipação térmica de *Granier*, sob irrigação com déficit controlado. O trabalho foi desenvolvido em um pomar de mangueira 'Tommy Atkins' com 10 anos de idade, irrigado por microaspersão, localizada no Perímetro Irrigado de Ceraíma, no município de Guanambi, Bahia. A determinação do fluxo de seiva foi realizada em três dias consecutivos em plantas sob irrigação com déficit controlado, com redução de 30 e 60% da evapotranspiração da cultura em três fases de desenvolvimento do fruto, início da floração ao pegamento dos frutos (Fase I), fase de expansão do fruto (Fase II) e fase de maturação fisiológica do fruto (Fase III). Verificou-se que o déficit hídrico controlado causa redução no fluxo de seiva em mangueiras 'Tommy Atkins'.

Palavras-chave: eficiência de uso da água, Granier, manejo da irrigação, transpiração.

1. INTRODUCTION

The search for increasing yield and quality of fruits implies knowledge of parameters related to irrigation water management. Scarcity and irregularity of rainfall in the Northeast of Brazil indicate irrigation need over the whole year to guarantee production. Consoli *et al.* (2017) mention that climate change will impact water resources within a medium to long-term period. Water-use efficiency is therefore essential in irrigated agriculture due to less water requirement from water resources.

The increase in water-use efficiency might be attained by using high-efficient irrigation systems, such as trickle irrigation combined with the use of water-deficit irrigation strategies. Among these strategies, regulated deficit irrigation (RDI) and partial root-zone drying (PRD) stand out (Santos *et al.,* 2017; Cotrim *et al.,* 2017; Santos *et al.,* 2016a; Lima *et al.,* 2015; Santos *et al.,* 2015; Sampaio *et al.,* 2014).

Soil water conditions change when using water-deficit strategies; consequently, water conditions of plants, gas exchanges, and leaf temperature are also altered. These variables influence growth, developing, and yielding (Santos and Martinez, 2013). There is some research in the literature on the use of water-deficit strategies in mango trees grown in semi-arid regions of Brazil and how it relates to gas exchanges (Santos *et al.,* 2016b; 2016c; Santos and Martinez, 2013), to root distribution (Santos *et al.,* 2014a), to water uptake (Santos and Martinez, 2013), to flower induction (Faria *et al.,* 2016a), and to leaf nutrient content (Faria *et al.,* 2016b). Nonetheless, information regarding sap flow as an alternative to determine water demand of mangoes under deficit irrigation is lacking.

Among the methodologies used for measuring transpiration of trees, those based on the input of heat to plant stems (Heat Stem Balance Method, Thermal Dissipation Method, and the Heat-Pulse Method) have enabled advances in water relations and are tools for measuring transpiration (Boehringer *et al.,* 2013; Pinto Jr. *et al.,* 2013; Marin *et al.,* 2008; Coelho Filho *et al.,* 2005). These sap flow techniques are non-destructive (Hernandez-Santana *et al.,* 2016), are easy to install, and can simultaneously monitor several plants.

This study measured sap flow as an alternative to determine water demand of 'Tommy Atkins' mango trees under regulated deficit irrigation by using Granier's thermal dissipation probe method.

2. MATERIAL AND METHODS

The experiment was carried out in a 10-year-old 'Tommy Atkins' mango orchard, with trees spaced 8 x 8 meters apart, located at the Irrigated Perimeter of Ceraíma, in the municipality of Guanambi, Bahia state, Brazil (14º17'27'' S and 42º46'53'' W), from June to December 2007. The climate of the region is semi-arid, with altitude of 525 m, average annual rainfall of 680 mm, and average annual temperature of 26ºC. Main climate parameters were measured during the period of experiment from a weather station 500 m away from the experimental area (Table 1).

The soil of the experimental area is a sandy loam-textured Eutrophic Fulvic Neosol with high activity clay. At the depths of 0.00 to 0.20 and 0.20 to 0.40 m, the soil exhibited the following characteristics: density of 1,610 and 1,560 kg m^{-3}; particle density of 2,740 and 2,810 kg m^{-3}; sand, 0.507 and 0.485 kg kg^{-1}; silt, 0.296 and 0.300 kg kg^{-1}; clay, 0.197 and 0.215 kg kg^{-1}, respectively.

Table 1. Monthly precipitation values (P), mean air temperature (T), relative humidity (RH), reference evapotranspiration (ET_o), solar irradiance (SI) and wind speed (WS) for district of Ceraíma – Guanambi, in the year 2007.

Variables	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P (mm)	0.00	0.00	0.00	0.00	0.00	170.00	129.10
T (°C)	22.70	24.60	24.80	27.30	28.10	25.30	24.60
RH (%)	70.80	69.60	68.10	61.80	61.10	67.80	69.60
ET_o (mm day^{-1})	5.04	4.95	6.02	6.38	7.04	5.59	4.97
SI (h day^{-1})	8.68	8.64	9.39	9.17	8.05	6.45	6.53
WS (m s^{-1})	0.42	3.91	3.88	4.20	4.66	3.09	2.35

Tommy Atkins trees were watered to different irrigation depths (Table 2) from which regulated water deficits at two different percentages of crop evapotranspiration (ETc) were applied during three fruit-developing phases: fruit setting (Phase I), fruit growth (Phase II), and fruit ripening or physiological maturation (Phase III). Each treatment consisted of a single mango tree.

Table 2. Treatments: irrigation water depths applied at three fruit developing phases.

Treatment	Irrigation - % of ETc by phase		
	I	II	III
Rainfed – No irrigation at all phases	0	0	0
Full Irrigation – Irrigation with 100%ETc in all phases	100	100	100
RDI60PI – Irrigation with 60%ETc in phase I and full in phases II and III	60	100	100
RDI60PII – Irrigation with 60%ETc in phase II and full in phases I and III	100	60	100
RDI60PIII – Irrigation with 60%ETc in phase III and full in phases I and II	100	100	60
RDI30PI – Irrigation with 30%ETc in phase I and full in phases II and III	30	100	100
RDI30PII – Irrigation with 30%ETc in phase II and full in phases I and III	100	30	100
RDI30PIII– Irrigation with 30%ETc in phase III and full in phases I and II	100	100	30

Each tree was irrigated daily by a micro-sprinkler with a discharge rate of 56 l h^{-1}. Water depths were corrected to the respective percentage (30, 60, and 100% of ETc) by different valves installed at the beginning of the sub-mainline, so that the irrigation run-time could be regulated. Irrigation depth was determined by reference evapotranspiration, location coefficient (Kl = 0.80) and crop coefficients, as the latter varied from 0.45 to 0.87 from flowering to fruit ripening (Cotrim *et al.*, 2017; Santos *et al.*, 2014b). ET_o was measured by an automatic weather station through the Penman-Monteith method. The total amount of water applied for each treatment is shown in Figure 1.

After the data collection to calculate the sap flow using the Granier method, the leaf area of each branch where probe sensors were installed was estimated using the methodology proposed by Oliveira *et al.* (2005), described later.

The conducting sap flow area of the stem (xylem area) was estimated using its internal diameter (D_{int}), determined by Vellame *et al.* (2012), through the use of the destructive method with application of dyes in several trunks and branches of hose with different external diameters (D_{ext}), according to Equation 1.

$$D_{int} = 0.8746 \times D_{ext} \quad (1)$$

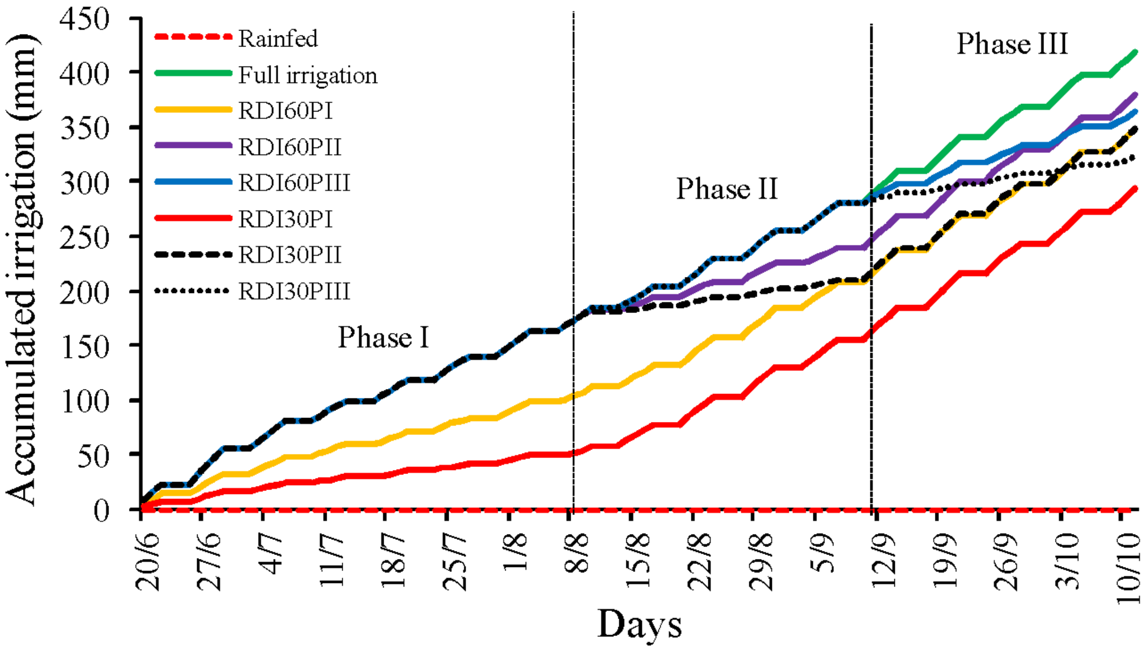

Figure 1. Total amount of water applied to 'Tommy Atkins' mango trees for different irrigation depths during the production cycle of the crop.

2.1. Estimation of sap flow density

Thermal dissipation probes (TDP) were installed at branches of similar diameters and located in the mid-section of tree crowns of eight mango trees, one for each treatment.

Probe sensors installed in the branches were completely insulated with neoprene and aluminum foil to prevent external interferences in the natural temperature gradient of the plant's branches. Besides the eight heated sensor probes, three additional unheated probes were installed to measure the ambient temperature of the wood during the experiment, which would be used afterwards as reference probes for correcting the estimated sap flow, following the methodology recommended by Granier (1985).

Probe sensors were made and calibrated in the Irrigation and Fertigation Laboratory of EMBRAPA Cassava and Tropical Fruits (Brazilian Agriculture Research Corporation) (Coelho Filho *et al.*, 2006; Vellame *et al.*, 2012). Each probe consisted of a continuously heated element at constant power of 0.1W per centimeter and an unheated probe (reference probe), which has an internal thermocouple.

2-cm-long probes needed a power of 0.2 W for the heating process. When making each thermal dissipation probe (TDP), we used two veterinary needles with a diameter of 1.6 mm, connected to one another by a thermocouple made of two copper wires (10 cm each) and a constantan wire (18 cm) with a diameter of 0.5 mm.

In the heated probe, a constantan wire of 0.5 mm of diameter and 25 cm long was put through the needle, and then, the wire's tip was wound around the needle. After that, the external part of the needle's tube was coated with resin, with 2 to 3-cm-long tips to be connected to the heating source with adjustable voltage.

2-cm-long probes were inserted into the mango's stem through bores made by a drill, 10 cm apart. The holes were covered by a cylinder made of brass with 3 mm in diameter and 2 cm in length. The empty space between the probes and cylinders was filled with thermal grease to improve the sensibility of the thermal sensors.

Regarding the recording of temperature differences between the two probes (heated and unheated probes) and the solar radiation, a system composed of a data logger (CR10X Campbell SCi) and a multiplexer (AM 416 Relay Multiplexer, CampbellSCi) was used.

To correct the stem’s natural temperature gradient, temperature differences were measured by three unheated probes during the whole data-collecting period to measure sap flow. Natural temperature gradient data of the three unheated sensor probes were compared to natural temperature gradients generated by each one of the 8 probes over the period without heating; as a result, estimation models were created. These can estimate natural temperature gradients of heated probes as a function of natural temperature gradients of unheated probes, for each probe, individually.

Temperature differences of unheated probes were corrected by Equation 2.

$$\Delta T = \Delta T_{mesured} - \Delta TN_{estimated} \quad (2)$$

Where, ΔT is the corrected temperature difference (ºC); $\Delta T_{measured}$ is the temperature difference measured by the non-corrected probe (°C) and $\Delta T_{\text{estimated}}$ is the natural temperature difference estimated by the models (°C).

Flow index (*K*) is the relationship between sap flux density and temperature difference between probes installed in the trunk.*K* is defined using Equation 3, developed by Granier (1985):

$$K = \frac{(\Delta TM - \Delta T)}{\Delta T} = 0.0206 \times Js^{0.8124} \quad (3)$$

Where, ΔTM is the maximum temperature difference obtained by the probe on a given day, °C; ΔT is the current difference temperature, °C; and *Js* is sap flux density, $m^3m^{-2}day^{-1}$;

Sap flow was calculated by using the conducting sapwood area of the xylem, as described by Equation 4:

$$F = 118.99 \times 10^{-6} \times K^{1.231} \times AS \quad (4)$$

Where *F* is sap flow, L day^{-1} and *AS* is the area of the xylem, m^{-2}.

Two power supplies were used based on the total electrical resistance measured at the probes (multimeter) and on the voltage necessary, which was calculated by Equation 5, derived from Ohm’s law.

$$V = \sqrt{P \times R} \quad (5)$$

Where *V* is the voltage of the adjustable power supply, volts; *P* is the power used to heat a 2- cm-long probe, watts; and *R* is the overall resistance of the collection of probes, ohms.

Leaf area of the branches were measured by counting the number of leaves and by estimating the average area per leaf. The latter was determined by measuring the length and width of three hundred leaves collected from approximately 30 randomly-selected plants (33% of the orchard), so that leaves of all sizes were measured. Leaf area was calculated through Equation 6, where 0.60 is a correction factor used for mango (Oliveira *et al.*, 2005).

$$LA = (L \times W \times 0.60) \times TNL \quad (6)$$

Where, *LA* is leaf area, m^2; *L* is the mean length of leaves, m; *W* is the mean width of the leaves, m; and *TNL* is the total number of leaves of the plant or branch.

Diameters of branches and trunks as well as leaf areas of the branch and the whole tree for each treatment are found in Table 3.

Table 3. Diameters of the branch and trunk and leaf area of the branch and the whole 'Tommy Atkins' mango tree where the thermal dissipation sensors probes were installed for each treatment.

Treatment	Diameter (cm)		Leaf area (m^2)	
	Branch	Trunk	Branch	Tree
Rainfed	11.46	83.00	9.33	82.12
Full Irrigation	11.52	85.00	5.34	96.38
RDI60PI	11.33	89.00	8.12	86.73
RDI60PII	11.40	84.00	6.67	92.94
RDI60PIII	11.46	96.00	6.12	74.15
RDI30PI	10.95	84.00	8.23	73.87
RDI30PII	11.52	87.00	6.07	79.66
RDI30PIII	10.38	85.00	8.67	111.62

Besides sap flow per square meter of leaf area, the following data were also analyzed by comparing one to another: sap flow per unit solar radiation (SR), and sap flow per unit reference evapotranspiration (ET_o), calculated by Penman-Monteith, using hourly data from an automatic weather station (Marin *et al.*, 2001).

Due to electrical problems with the sensor probes, sap flow had to be measured on different days during the same phase for some treatments. Therefore, to carry out statistical analysis of data, days on which the weather conditions were similar were selected; however, even under similar radiation conditions, other climate elements interfered with reference evapotranspiration, such as wind speed. Consequently, reference evapotranspiration, solar radiation, sap flow of branches, whole-tree sap flow, branch sap flow/ET_o ratio and branch sap flow/solar radiation ratio were measured on three different days, which were used as replicates. These data were subjected to a normality test, analysis of variance and the means were grouped by the Skott-Knott criteria at a significance level of 5%.

3. RESULTS AND DISCUSSION

Daily means of reference evapotranspiration (ET_o), solar radiation (Sr), sap flow of the branch (SPb), sap flow of the branch/radiation ratio (SPb/Sr), sap flow of the branch/ET_o (SPb/ET_o) and total sap flow of tree, in the fruit development Phases I, II, and III are shown in Table 4. Analysis of variance shows significant effects of treatments on ET_o because some of the data were measured on different days, as previously described. Nonetheless, it was only in Phase II of fruit development that ET_o, measured on days where sap flow measurements were performed at treatments with full irrigation (FI) and RDI at 60% of ETc, formed different groupings by Scott-Knott criteria, even with similar solar radiation. Rainfed plants exhibited the lowest estimated sap flow of the branch, as well as the lowest whole-tree sap flow in all phases (Table 4). This shows how much low soil water availability, due to water deficit, interferes with transpiration. When analyzing Phase I, we verified that sap flow in the branch, SFb/SR ratio, and SFb/ET_o ratio were higher for plants under full irrigation and lower for rainfed plants, which formed a grouping with the treatment RDI at 30% of ETc in phase II (RDI30PII).

Conditions under irrigation deficit in phase I (RDI60PI and RDI30PI) exhibited mean sap flow values of 0.798 and 0.914 L $m^{-2}day^{-1}$, respectively. These values are very close to the overall mean of the treatments that were not subjected to an irrigation deficit during Phase I (0.905 L m^{-2} day^{-1}). Therefore, irrigation deficit did not influence sap flow greatly; however, there was formation of a grouping of different values of sap flow under the rainfed condition as well as under full-irrigation treatment (Table 4). Santos *et al.* (2014b) verified that partial water deficit in the soil as a result of RDI at 50% of ETc did not lead to a significant reduction in transpiration by the ‘Tommy Atkins’ mango in the first evaluation cycle under deficit; nevertheless, in the second cycle, both transpiration and stomatal conductance decreased. The authors reported that the reduction of these two parameters is likely to be related to the time of reading as these reductions only occurred at times of high water demand. In this study, however, sap flow was continuously monitored, which provides a better explanation for the effect of the deficit than non-continuous measurements.

Table 4. Reference evapotranspiration (ET_o), solar radiation (Sr), mean values of sap flow of the branch (SFb), sap flow of the branch/radiation ratio (SFb/Sr), sap flow of the branch/ET_o (SPb/ET_o) and total sap flow of tree (SFt), in fruit development Phases I, II, and III of ‘Tommy Atkins’ mango tree, irrigated by micro-sprinklers.

Phase	Treatment	ET_o	Sr	SFb	Ratio		SFt
		mm day^{-1}	MJm^{-2} day^{-1}	L m^{-2} day^{-1}	SFb/SR	SFb/ET_o	L day^{-1}
I	Rainfed	4.37	20.64	0.620c	0.030c	0.142c	50.93d
	Full Irrigation	4.37	20.64	1.255a	0.059a	0.280a	120.97a
	RDI60PI	4.37	20.64	0.798b	0.038b	0.183b	69.19c
	RDI60PII	4.37	20.64	0.776b	0.037b	0.177b	72.10c
	RDI60PIII	4.37	20.64	0.944b	0.046b	0.216b	70.02c
	RDI30PI	4.37	20.64	0.914b	0.044b	0.209b	67.46c
	RDI30PII	4.37	20.64	0.697c	0.034c	0.159c	55.49d
	RDI30PIII	4.37	20.64	0.852b	0.041c	0.195c	95.10b
II	Rainfed	5.16a	24.03	0.672e	0.028e	0.130d	55.20e
	Full Irrigation	4.59c	22.33	0.956c	0.043b	0.208a	92.14b
	RDI60PI	4.96b	23.20	0.845d	0.036c	0.170b	73.24d
	RDI60PII	5.16a	24.03	0.914c	0.038c	0.177b	84.94c
	RDI60PIII	5.16a	24.03	0.784d	0.033d	0.152c	58.17e
	RDI30PI	5.16a	24.03	1.111a	0.046a	0.215a	82.03c
	RDI30PII	5.16a	24.03	0.647e	0.027e	0.125d	51.53e
	RDI30PIII	5.16a	24.03	1.015b	0.042b	0.197a	113.34a
III	Rainfed	5.09	23.72	0.794c	0.033b	0.156b	65.16c
	Full Irrigation	5.15	23.81	1.117a	0.047a	0.217a	107.66a
	RDI60PI	5.19	24.80	0.899b	0.036b	0.173b	77.93b
	RDI60PII	5.09	23.72	0.844c	0.036b	0.166b	78.48b
	RDI60PIII	5.19	24.80	0.769c	0.031b	0.148b	57.02c
	RDI30PI	5.09	23.72	1.075a	0.045a	0.211a	79.44b
	RDI30PII	5.14	24.32	0.963b	0.040b	0.187b	76.71b
	RDI30PIII	5.09	23.72	0.926b	0.039b	0.182b	103.37a

Moreover, in Phase I, as for the whole-tree sap flow, there was formation of 4 groupings of SFt, following the same logic of sap flow in the branch, expect for the condition RDI30PIII, which exhibited the second highest value of SFt, likely on account of the highest leaf area of the plant (Table 3).

In Phase II of fruit development, rainfed condition and RDI30PII exhibited the lowest values of SFb, forming the same grouping, which is evidence that in this phase, water deficit at 30% of ETc affects transpiration, similarly to the rainfed condition. In regard to whole-tree sap flow, a behavior akin to that of Phase I was observed, in which the plant under the treatment RDI30PIII exhibited higher SFt.

Sap flow values varied in average from 0.784 to 1.111 L $m^{-2}day^{-1}$ in plants under the following conditions: Full Irrigation, RDI60PI, RDI60PIII, RDI30PI, and RDI30PIII. All of them were not subjected to water deficit during the fruit development Phase II. Their sap-flow values were comparable to those found in Phase I, thus, lower than those found by Oliveira *et al.* (2005), who used the heat balance method, and found values between 0.36 and 3.00 L $m^{-2}day^{-1}$. The analysis done of the sap flow in the branch (SFb), in L $m^{-2}day^{-1}$, was also valid for the values of SFb/SR ratio and SF/ET_o ratio, both of which exhibited similar behavior, even though the results were not obtained during the same period for all treatments.

Sap flow in the branch during the fruit development Phase III is lower under the rainfed condition, forming the same grouping with the condition RDI60PIII whereas the condition RDI30PIII, which also had a water deficit in the same phase, formed another grouping, with a higher sap flow value. As occurred in previous phases, whole-tree sap flow with water deficit at 30% of ETc was similar to the SFt of the treatment under full irrigation, which might be due to the leaf area of the tree.

Daily variations in estimated sap flow, for eight treatments, during Phases I, II, and III of mango fruit development, are depicted in Figure 2. It can be observed that sap flow values estimated by Granier's method follow the values of solar radiation measured over the course of three evaluation days for every treatment. This shows a typical behavior that has been also found in studies conducted by Vellame *et al.* (2012), Rojas (2003), and Paço (2003). Among the treatments Full Irrigation, RDI60PII, RDI60PIII, RDI30PII, and RDI30PIII, which were not subjected to any water deficit during the fruit development Phase I, only the treatment RDI30PII exhibited a value low of estimated sap flow (Table 4).

By looking at the results of sap flow in the three phases (Figures 2A, 2B, and 2C), a discrepancy is verified between profiles that describe the estimated sap flow of mango trees with the global solar radiation. Coelho Filho (2002) mentions that at the early hours of the morning, sap flow occurs due to the transpiration of water stored within plant tissues, and, at the end of the day, when transpiration tends to cease, sap flow continues to occur for the purpose of replenishing the water lost from the tissues during the day.

When analyzing the treatments Full Irrigation, RDI30PI, RDI30PII, RDI60PIII and RDI60PII, which were not under any irrigation deficit condition during Phase III of fruit development (Figure 2C), we could observe many similarities among them. Although, for treatments under water deficit during Phase III of fruit development, the rainfed condition and RDI60PIII exhibited lower estimated sap flow values than those aforementioned values recorded in treatments not subjected to irrigation deficit.

Estimated sap flow values varied from 0.697 and 1.255 L $m^{-2}day^{-1}$ under conditions that were not subjected to water deficit during the three phases of fruit development. These values are within the limits found by Oliveira *et al.* (2005), for four three-year-old mango cultivars (Tommy Atkins, Palmer, Haden, and Van Dyke), in Cruz das Almas, Bahia state, Brazil. This author used the heat balance method, and the sap flow values found varied from 0.36 to 3.00 L m^{-2} leaf day^{-1}.

4. CONCLUSIONS

Granier's thermal dissipation probe allows detecting fluctuations in sap flow by the lower water availability as a result of the application of irrigation deficit.

Regulated irrigation deficit reduces sap flow in 'Tommy Atkins' mango trees.

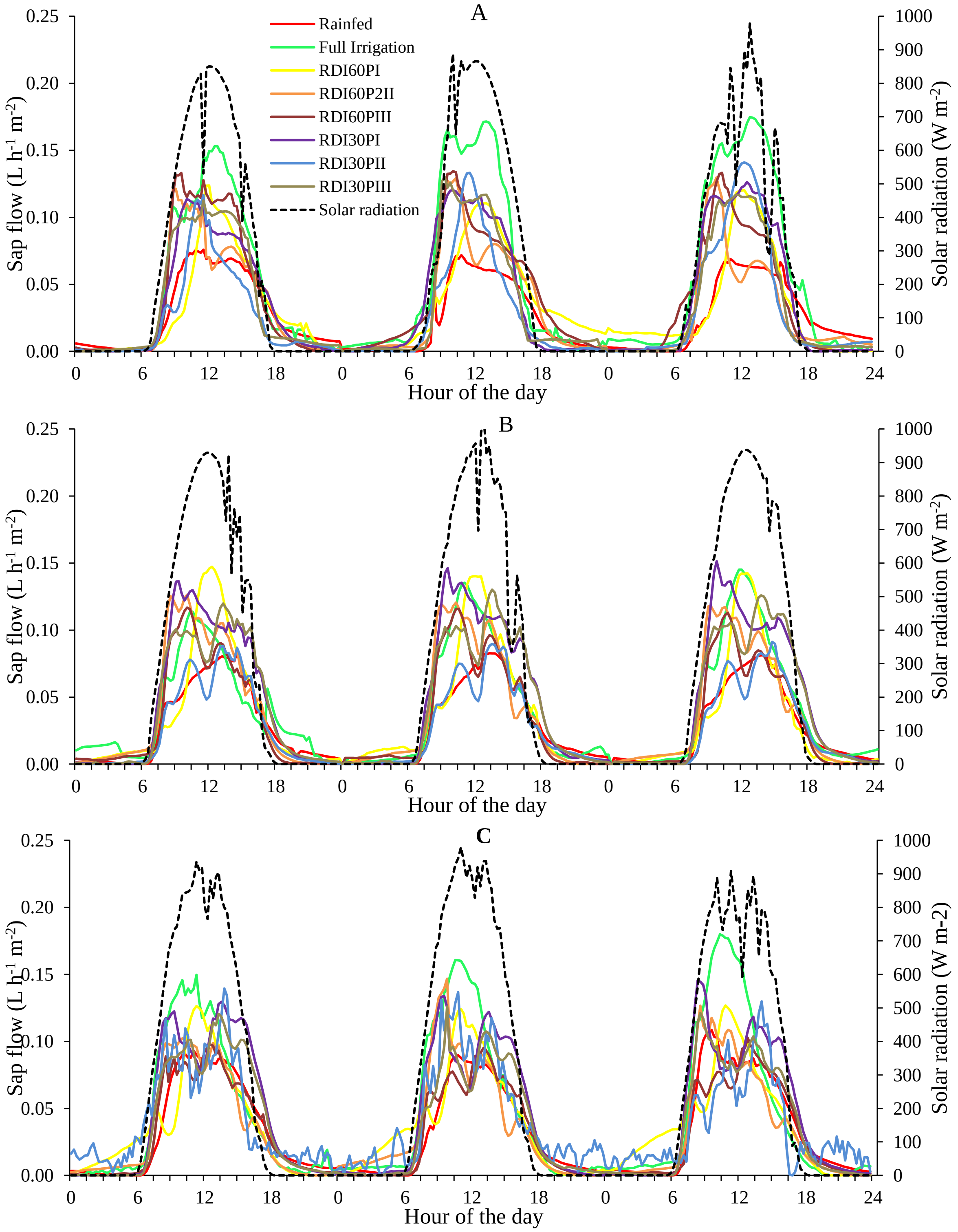

Figure 2. Daily variation in sap flow (SF) of 'Tommy Atkins' mango and solar radiation (SR), for the eight treatments during Phase I (A), Phase II (B), and Phase III (C) of fruit development, irrigated by micro-sprinklers.

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