

# Relationships between sap-flow measurements, whole-canopy transpiration and reference evapotranspiration in field-grown papaya (*Carica papaya* L.)

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Received: 3 March 2015 / Accepted: 30 November 2015  
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**Abstract** Whole-canopy gas exchange measurement in papaya can provide a scientific basis to optimize irrigation and fruit yield and quality. The objectives of this study were to: (1) verify the relationship between xylem sap flow measured by the heat coefficient method, and whole canopy transpiration in ‘Gran Golden’ papaya (*Carica papaya* L.), (2) examine the relationship between xylem sap flow determined from calculations based on forcing water flow through a stem section, and whole canopy transpiration, and (3) verify the relationship between transpiration measured in a plant chamber and calculated reference evapotranspiration ( $ET_0$ ). The experiment was conducted in a commercial planting at the Caliman Agrícola SA farm, Sooretama, ES, Brazil in summer and winter. Whole-canopy gas exchange was measured in custom-built, flow-through whole-canopy Mylar® chambers. There was a correlation ( $r^2 = 0.65$ )

between xylem sap flow measured with the heat coefficient (K) method and whole-canopy transpiration rate measured in the chambers. However, sap flow methodology could not convert this correlated response into an accurate estimate of papaya transpiration measured with whole canopy chambers. The sap flow methodologies were linearly correlated with whole canopy transpiration but each would require additional calibration to the crop.  $ET_0$  was correlated with whole canopy transpiration in winter but not in summer likely due to stomatal control of transpiration, as a result of the high leaf temperature and  $ET_0$  in summer. The concept of sap flow to measure transpiration has value in papaya production but supplementary studies will be necessary to improve the accuracy and estimation of the whole-canopy transpiration in the papaya plant.

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**Keywords** Gas exchange · Transpiration · Temperature · Water relations

### Abbreviations

K	Heat coefficient
ET <sub>0</sub>	Reference evapotranspiration
VPD <sub>leaf-air</sub>	Leaf-to-air vapor pressure difference
E	Transpiration
PAR	Photosynthetically active radiation

## 1 Introduction

Papaya is one of the most important fruit crops cultivated in tropical regions (Campostrini et al. 2010). Ripe papaya fruit plant can be consumed fresh and non-ripe fruit is used in salads or can be cooked (Dhekney 2004; Crane 2005). Papaya consumption in developing countries is increasing, partly due to recent findings of the presence of health-beneficial compounds in the fruits which can have great health benefits for the inhabitants of these countries (Evans and Ballen 2012).

In papaya production, water is a resource requiring considerable management because both drought and excess water can reduce productivity (Campostrini et al. 2010; Campostrini and Glenn 2007). The determination of papaya water use is essential for better irrigation and fertigation management. Efficient water and nutrient management reduce water losses through evaporation and drainage, and ensure increased productivity and reduced leaching of harmful chemicals into groundwater.

Drought stress in papaya affects plant growth and sterile flower production (Bernardo et al. 1996) and for that reason irrigation is recommended during dry periods to assure growth and fruit production (Aiyelaadgbe et al. 1986; Malo and Campbell 1986; Srinivas 1996). Soil water availability limits many physiological processes in papaya (Aiyelaadgbe et al. 1986; Marler et al. 1994; Clemente and Marler 1996; Torres Netto 2005; Mahouachi et al. 2007; Campostrini and Glenn 2007; Campostrini et al. 2010; Carr 2014).

On the other hand, papaya is sensitive to low oxygen availability in the soil (hypoxia) which is commonly caused by water logging and excessive irrigation (Ogden et al. 1981; Malo and Campbell 1986), which can cause extensive leaching of nutrients and problems

related to single-leaf gas exchange (Marler et al. 1994; Khondaker and Ozawa 2007). In addition, completely flooded soil can cause death to papaya plants in two days (Wolf and Lynch 1940; Rodríguez et al. 2014) or three to four days (Samson 1980).

Techniques to estimate plant transpiration have been developed to improve irrigation management and elucidate plant water relations. The xylem sap flow rate has been related to transpiration. There are several methods to measure xylem sap flow and with advantages and limitations in terms of ease of use, cost and size of the plant stem on which they can be used (Smith and Allen 1996). Most methods are based on relating temperature to sap movement in the measuring in the stem or trunk. The Granier method (Granier 1985) empirically calibrates probe temperature with trunk water flow. This method has been used to establish the relationship between sap flow and soil gravimetric water measurements, micrometeorological factors and soil water availability during wetting–drying cycles (Lu et al. 2002, 2004). Reis et al. (2006) using technique proposed by Fernández et al. (2001) demonstrated that forcing water through a stem section of papaya at a constant rate was suited to sap flow analysis. The same authors proposed a mathematical model to evaluate the relationship between forced water flow through the trunk and the K coefficient, however, the forced water flow method overestimated xylem sap flow when compared to the Granier method.

Whole-canopy transpiration may represent the most realistic technique to calibrate xylem sap flow using probes because it does not modify the water soil–plant–atmosphere continuum. Contrary to single-leaf gas exchange measurements, whole-canopy measurements can provide information about net carbon assimilation and transpiration by integrating the response of the entire canopy (Poni et al. 1997, 2014; Baker et al. 2014). Measurement of whole-canopy gas exchange facilitates instantaneous estimation of light conversion and water use efficiencies, and provides a tool for quantitative assessment of the impact of soil and air water changes upon biological processes such as gas exchange (Garcia et al. 1990). Smith and Allen (1996) advised that the xylem sap flow technique should be calibrated for each species and xylem sap flow might be directly related to whole-canopy transpiration.

Whole-canopy gas exchange measurements in papaya plant has not been reported associating xylem

sap flow with whole-canopy transpiration. Thus, the objectives of the study were to: 1) verify the relationship between xylem sap flow measured by the Granier heat coefficient method, and whole canopy transpiration in 'Gran Golden' papaya (*Carica papaya* L.); 2) examine the relationship between xylem sap flow determined from calculations based on forcing water flow through a stem section, and whole canopy transpiration, and 3) verify the relationship between transpiration measured in a plant chamber and calculated reference evapotranspiration ( $ET_0$ ).

## 2 Materials and methods

### 2.1 Plant material and field conditions

The study was conducted in a commercial planting at the Caliman Agrícola SA farm, located in Sooretama, ES, Brazil (19°11'49"S; 40°05'52"W). The site had a low slope, with a soil classified as Haplic Lixsol (FAO 2014). Ten papaya plants 'Gran Golden' genotype (Solo group), spaced 1.5 m in rows and 3.60 m apart were used for this study. Five plants in summer and five plants in winter were used for measuring the whole-canopy transpiration.

Papaya seedlings were transplanted to the field in February 2006 and July 2006 and the experiment conducted in July (winter) and December (summer). During the measurements, plants were 5 months-old with an average leaf area of  $3.53 \pm 0.28 \text{ m}^2$  ( $n = 5$ ) (July, winter) and  $4 \pm 0.5 \text{ m}^2$  ( $n = 5$ ) (December, summer) each with 5 to 6 small green fruit per plant. Canopy leaf area was determined immediately after the gas exchange measurements using the model proposed by Campostrini and Yamanishi (2001).

The crop was irrigated with a drip fertigation system providing supplemental irrigation of 10 L (winter) and 16 L per plant per day (summer). The monthly fertilizer input was:  $106.67 \text{ kg ha}^{-1} \text{ Ca}(\text{NO}_3)_2$ ;  $21.07 \text{ kg ha}^{-1} \text{ MgSO}_4$ ;  $50.33 \text{ kg ha}^{-1} \text{ KCl}$ ;  $9.67 \text{ kg ha}^{-1} \text{ MAP}$  (monoammonium phosphate, source of  $\text{P}_2\text{O}_5$ ) and  $0.35 \text{ kg ha}^{-1}$  micronutrients. In the study area, the plants had an average fruit yield of  $44.2 \text{ t ha}^{-1}$ .

### 2.2 Environmental variables

A weather station (model 700ET, Spectrum Technologies, Illinois, USA) was installed at the study site.

The variables measured were: temperature, relative humidity (RH), wind speed and direction, solar radiation and rainfall (we did not observe rain during summer and winter). The vapor pressure deficit of the air was calculated according to the equation proposed by Jones (1992).

The meteorological station was installed near the experiment, and the data were used to calculate the reference evapotranspiration ( $ET_0$ ) using the Penman equation parameterized by the United Nations Food and Agriculture Organisation (FAO) (Allen et al. 1998).

### 2.3 Whole-canopy gas exchange measurement

Gas exchange was measured in whole plant canopies on four days in July (winter) and three days in December (summer) 2006 from 8:00 to 17:00 h and 6:00 to 17:00 h to winter and summer, respectively. However, in July (winter) the presence of dew inside the chamber prevented measurement prior to 10:00 h. During winter and summer, whole-canopy gas exchange was measured in five plants using an open system similar to that described by Miller et al. (1996) adapted by Glenn et al. (2003) (Fig. 1). The system consisted of a transparent polyester film Mylar® (Dupont, Wilmington, DE, USA) with 97 % transmittance of PAR into the chamber (Corelli and Magnanini 1993; Lakso et al. 1996) enclosing the entire canopy and attached to a centrifugal blower. Each chamber had a volume of  $3.4 \text{ m}^3$  (diameter 1.9 and height 1.2 m). Air flow rate through each chamber was adjusted, based on canopy leaf area, to obtain  $\text{CO}_2$  differentials within the linearity range of the infrared gas analyzer (IRGA; Model 6200 Licor,



**Fig. 1** Whole-canopy gas exchange system showing the air supply system, location of air-blowers and the Mylar chambers

Lincoln, NE) and, at the same time, to minimize air temperature increase inside the chamber. A small thermal differential of 2 °C was recorded at midday between outlet and inlet dry bulb temperatures.

During the experimental days, flow rates were monitored every hour using a flow meter (model Velocicalc® 8345/8346; TSI Incorporated, MN, USA) that measured the inlet air stream into the chamber. Each blower contained six equally spaced openings and ten measurements of the air speed were made from the top of the blower descending to the bottom of the blower. The average hourly air speed was calculated from the 60 determinations within each blower, multiplied by the cross sectional area (0.0781 m<sup>2</sup>) of the fan to determine the average air flow volume that was injected into the chamber (42.38 m<sup>3</sup> min<sup>-1</sup>) (200 L s<sup>-1</sup> m<sup>-2</sup> leaf area in winter and 176.5 L s<sup>-1</sup> m<sup>-2</sup> leaf area in summer). The average air velocity into the chamber was 0.25 m s<sup>-1</sup>.

At the chamber's inlet and outlet, water vapor pressure was monitored with the IRGA adapted with an open valve using the IRGA's internal pump (External Flow Switch) (LI6200, LiCor, USA). This switch (open valve) can be mounted on the LI-6250, and allows the LI-6200 to be quickly toggled between open and closed modes of operation. During the measurements the open mode was used. Each hour, two measurements were made in each chamber, and each measurement lasted 6 min.

The air flow (F) (L h<sup>-1</sup>) through the chambers was calculated by Eq. 1:

$$F = (V_{AR} \times 60 \times 30.5 \times A_V) / 10^3 \quad (1)$$

where  $A_V$  (cm<sup>2</sup>) is the cross-sectional area of output of air-blower;  $V_{AR}$  (ft min<sup>-1</sup>) is the air velocity.

And the air density (D) in g m<sup>-3</sup> was calculated with Eq. 2:

$$D = 101300 / (287.05 \times (T_{ar} + 273.15)) \quad (2)$$

where  $T_{ar}$  is the air temperature (°C).

The whole canopy transpiration rate (E) [g (H<sub>2</sub>O) h<sup>-1</sup>] was calculated by Eq. 3:

$$E = ((D \times (18/29) \times \Delta H_2O) / 1013) \times F \quad (3)$$

where  $\Delta H_2O$  is the water vapor pressure in the air output at the chamber top minus the water vapor pressure at the air inlet.

Total daily transpiration was estimated by integrating the area under the curve of transpiration versus

time using Logger Pro (Vernier Software, Portland, Oregon, USA).

In order to determine if plants within the chamber were subjected to adverse temperatures, the leaf temperature of the upper third of the plant canopy inside and outside the chamber was measured using an infrared thermometer (Infrarot-Thermometer, TFA, Germany). Four plants adjacent to those with whole canopy chambers were measured. The canopy temperature at the top of each plant was measured three times per hour with the thermometer approximately 0.3 m away from the canopy and sampling the circumference of the canopy. The thermometer was maintained at a 90° angle with the leaf blade. We did not find significant differences in leaf temperature for plants outside and inside the chambers.

## 2.4 Sap flow measurements

The sap flow sensors (two pairs per plant) (TDP 30, Dynamax Co., Houston, TX, USA), 2 mm in diameter and 30 mm in length, were inserted radially into the node of the each papaya trunk enclosed in a whole canopy chamber (Reis et al. 2006) at a height of 0.3 m above the soil. The probes were vertically separated by 50 mm. The trunk and probes were covered with foam insulation to minimize trunk temperature variation, and the data were collected every 30 min. Using the temperature difference between sap flow gauges, the heat coefficient (K) was calculated by Eq. 4:

$$K = [(\Delta T_{max} / \Delta T) - 1] \quad (4)$$

where K is the heat coefficient;  $\Delta T_m$  the maximum temperature difference (°C) between sensors in active xylem (night time: 20 h), and  $\Delta T$  is the temperature difference (°C) between sensors in active xylem at a specific time. The xylem active area was calculated using dye in stems of plants with the same age as those in the study (Reis et al. 2006). Zero flow was confirmed at night.

### 2.4.1 Granier model

The Granier system consists of two sensor probes (Lu et al. 2004). Each probe consists of a heating element (which also represents the effective sensing part of the probe, typically 20 mm long), wound around a steel needle containing a T-type thermocouple (copper-constantan), with the thermocouple tip located in the

middle of the heating element. The constantan ends of the two thermocouples are connected to measure the temperature difference between the two probes at the ends of the copper wires. The two probes are typically inserted radially into the stem 100–150 mm apart, in pre-inserted heat-distributing tubes made of aluminium or copper (Lu et al. 2004), previously the tube was first fixed onto the probe (Granier 1985). The downstream (upper) probe is continuously heated at constant power (0.2 W) while the upstream (lower) probe is left unheated to measure the ambient temperature of the wood tissue and acts as a reference probe. Temperature difference between the two probes is influenced by the heat dissipation effect of sap flow in the vicinity of the heated probe. Granier (1985) showed that  $K$  was highly correlated with the sap flux density ( $F_d$ ) (Lu et al. 2004). A series of calibrations of the sap flow probes on several sample stems of three different tree species (*Pseudotsuga menziesii*, *Pinus nigra* and *Quercus pedunculata*) provided an experimental relationship between  $K$  and  $F_d$ , which was independent of the tree species studied. The empiric equation proposed by Granier (1985) for the relationship between  $K$  and  $F_d$  was calculated by Eq. 5:

$$F_d = 118.99 \times 10^{-6} \times K^{1.231} \quad (5)$$

#### 2.4.2 Reis model

Reis et al. (2006) constructed an experimental system that maintained a stable water flux through a papaya stem section with a constant pressure, simulating the xylem sap flow through the stem (forced-flow through a stem section) (Fernández et al. 2001). In this work, Reis et al. (2006) adjusted the water flux by varying the water pressure in the stem section. They developed a mathematical model to fit the relation between  $K$  values and sap flow density, using the exponential model:  $F_d = 0.5511 \times K^{1.9104}$ . The derived laboratory calibration model (Reis et al. 2006) estimated larger  $F_d$  values than predicted by Granier (1985) for equal  $K$  values (Reis et al. 2006).

#### 2.4.3 $ET_0$ methodology

The hourly reference evapotranspiration ( $ET_0$ ) was calculated as described in Allen et al. (1998) and divided by the total leaf area of the plants to estimate the potential transpiration.

## 2.5 Experimental design and statistical analysis

There were five single-tree replications for whole canopy gas exchange measurements in summer and winter. Each day was used as a replicate over time due to the uniformity of environmental conditions (Fig. 2). The treatment means were compared using the Tukey test at 5 % probability level, with SAEG (System Analysis and Statistics Genetic) developed by the Federal University of Viçosa, Brazil.

## 3 Results

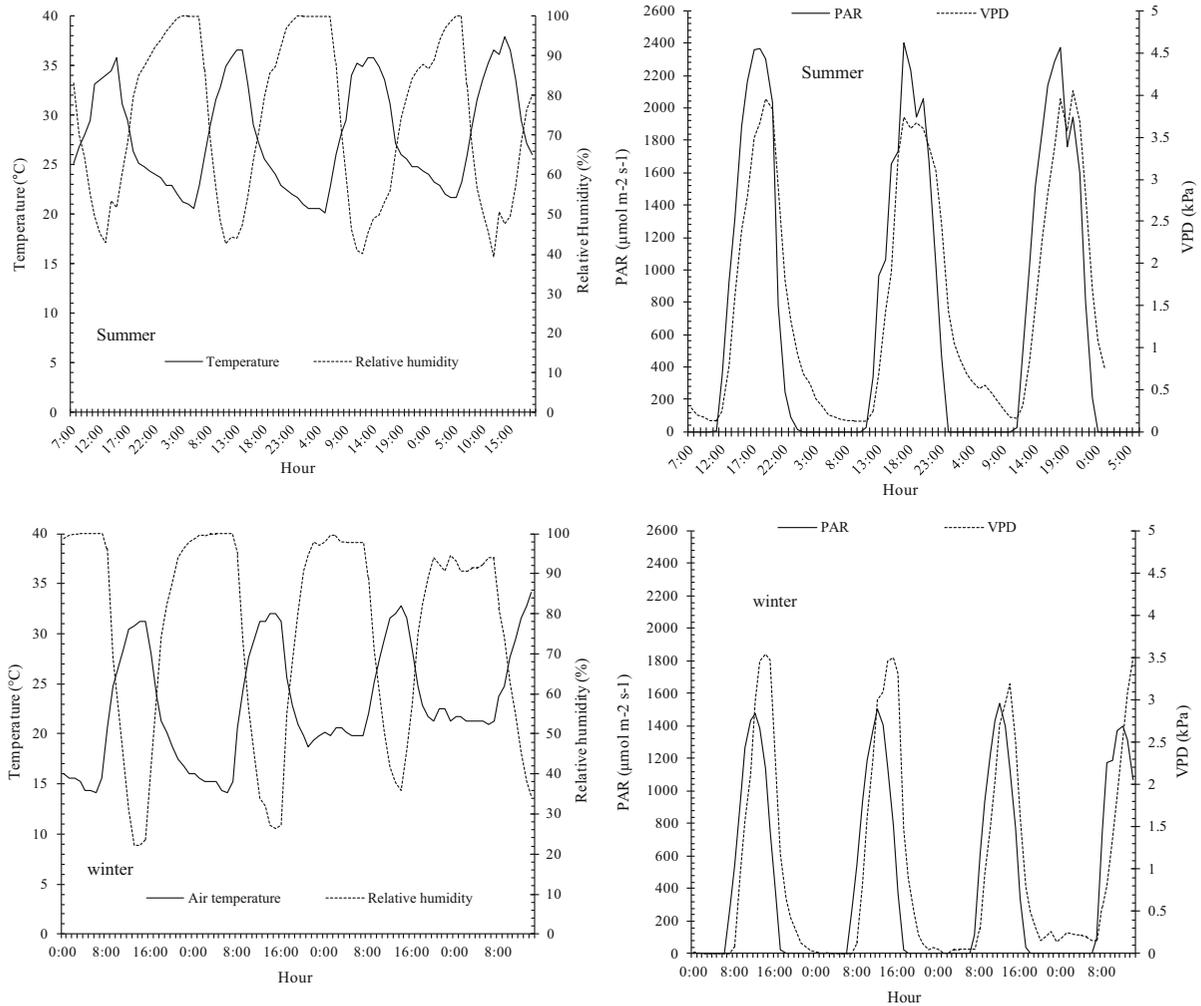
### 3.1 Micrometeorological variables, and leaf temperature

The environmental conditions were consistent during the experiment (Fig. 2). During the four days in winter the minimum relative humidity was 22 % and minimum temperature values was 14 °C. In summer, the minimum RH and temperature were 40 % and 21 °C, respectively. The maximum temperature was 33 °C (winter) and 38 °C (summer). The vapor pressure deficit (VPD) had the maximum value at 2:00–15:00 h (local time) [3.5 (winter) and 4.0 (summer)]. During the four days in winter and three days in summer, the sky was completely clear and the maximum PAR was 1440 and 2440  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , for winter and summer, respectively. Maximum PAR occurred at around 13:00 h. The high summer PAR resulted in higher leaf temperatures with a maximum value of 43.9 at midday, while in winter the maximum value was 37.5, at 14:00 h (Fig. 3).

### 3.2 Whole-canopy gas exchange

Maximum whole-canopy transpiration was 0.46 L  $\text{H}_2\text{O m}^2 \text{h}^{-1}$  (7.04  $\text{mmol H}_2\text{O m}^{-2} \text{s}^{-1}$ ) from 8:00 to 13:00 h in winter (Fig. 4). In winter, data were not collected from 8:00 to 10:00 h due to dew on the mylar chamber. From 1:00 to 17:00 h the whole-canopy transpiration rapidly decreased to zero. The integrated daily measurement of whole-canopy transpiration was 15 L  $\text{H}_2\text{O plant}^{-1} \text{day}^{-1}$  (4.24 L  $\text{m}^{-2} \text{leaf area day}^{-1}$ ) (Fig. 4).

In the summer, there was no dew on the mylar chamber and measurements were made each 1 h starting at 8:00 h and ending 17:00 h. The maximum



**Fig. 2** Environmental conditions during the four days of measurements. We measured temperature, relative humidity, photosynthetically active radiation (PAR) and air vapor pressure deficit (VPD) in the Winter and Summer

whole-canopy transpiration was  $0.36 \text{ L m}^{-2} \text{ h}^{-1}$  ( $5.5 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) from 8:00 to 9:00 h. From 9:00 to 17:00 h the whole-canopy transpiration decreased to zero. The integrated daily measurement of whole-canopy transpiration was  $10 \text{ L H}_2\text{O plant}^{-1} \text{ day}^{-1}$  ( $3.8 \text{ L m}^{-2} \text{ leaf area day}^{-1}$ ) (Fig. 4).

### 3.3 Xylem sap flow

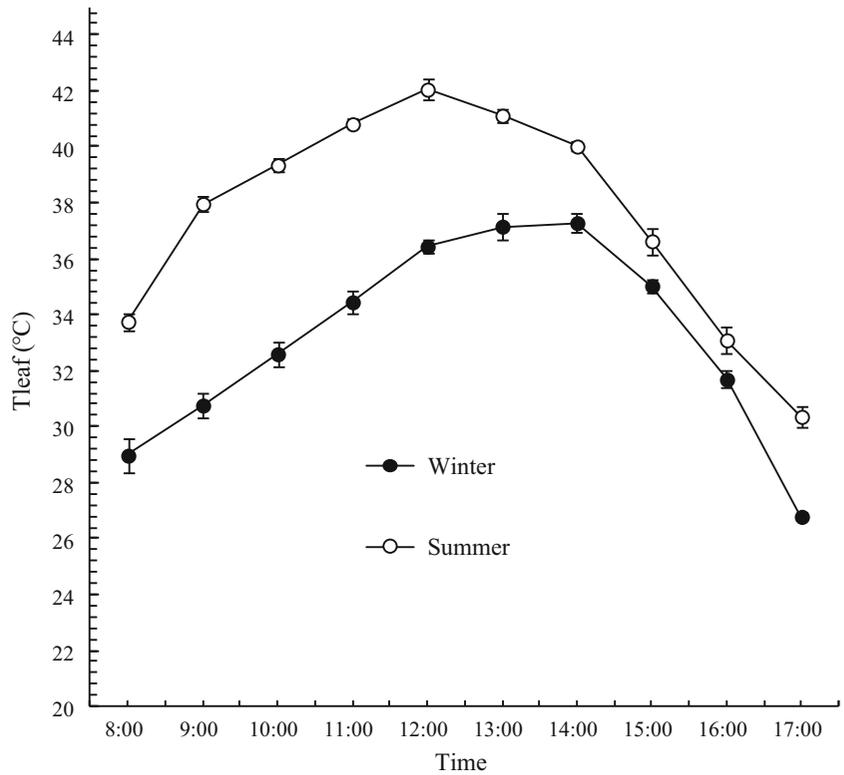
There was a linear relationship between whole-canopy transpiration and probe temperature of the probes (K coefficient) inserted into the trunk (Fig. 5). The K values ranged 0.08 to 0.38 and whole canopy

transpiration varied from 0 to  $0.46 \text{ m}^{-2} \text{ h}^{-1}$  (0 to  $7.04 \text{ mmol m}^{-2} \text{ s}^{-1}$ ). In winter the presence of dew within the chamber prevented measurement prior to 10:00 h (Fig. 5). In summer, the data from 6:00 to 8:00 h deviated from all other data likely due to a lag phase of water uptake and these data were deleted from the calculation of the regression equation.

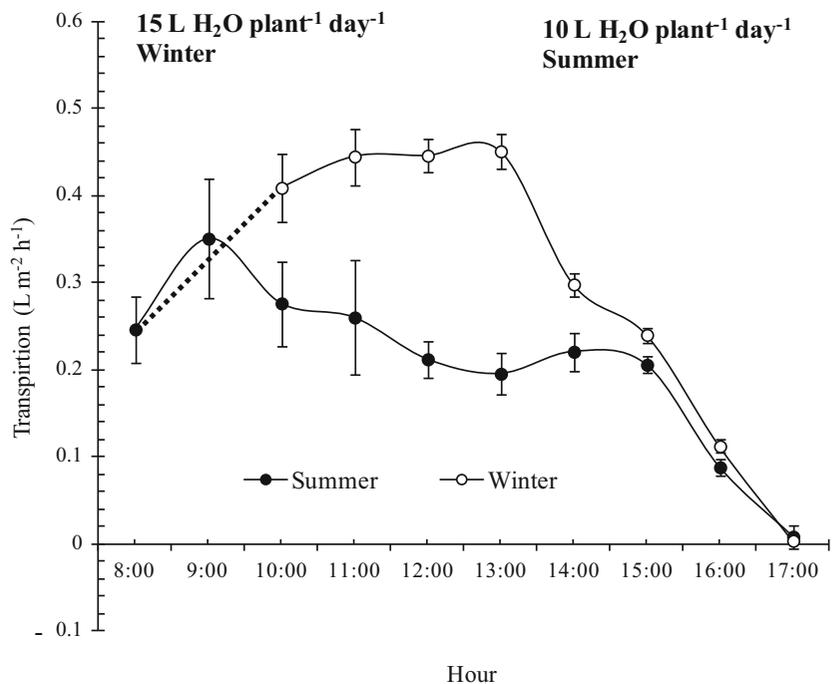
### 3.4 Models compared

The proposed model by Reis et al. (2006) in summer and winter overestimated transpiration between 10:00 and 16:00 h, when compared with the Granier and  $\text{ET}_0$  methods (Fig. 6). In the summer, between 9:00

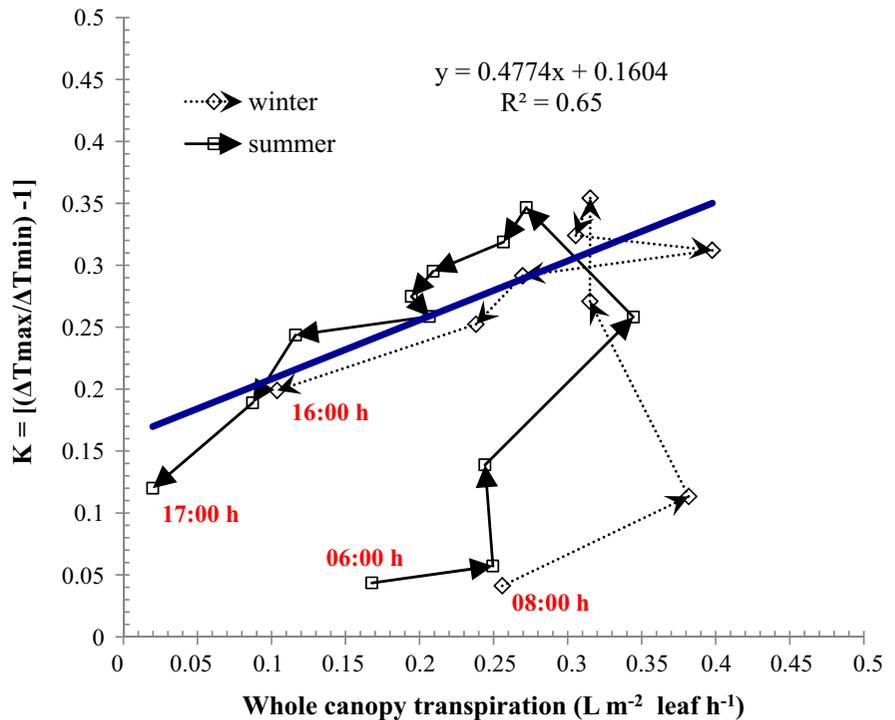
**Fig. 3** Leaf temperature of field-grown ‘Gran Golden’ papaya during four days (Winter and Summer). *Bars* represent standard error (n = 15)



**Fig. 4** Whole-canopy transpiration ( $L\ m^{-2}\ h^{-1}$ ) in ‘Gran Golden’ papaya during four days (Winter and Summer). *Bars* represent standard error (n = 20). Data were not collected from 8:00 to 9:00 h due to dew on the leaf surfaces and mylar leaf chamber. *Dotted lines* represent an extrapolation to sunrise.  $10\ L\ H_2O\ plant^{-1}\ day^{-1}$  (summer) and  $15\ L\ H_2O\ plant^{-1}\ day^{-1}$  (winter) are the area below the curves for whole-canopy transpiration



**Fig. 5** Relationship between mean hourly whole-canopy transpiration and the xylem sap flow heat coefficient (K) in 'Gran Golden' papaya during four days in winter and summer. Arrows indicate the chronological progression during the day. Whole canopy transpiration data excluded from the regression were 8:00 to 9:00 h in winter related to dew on the leaf surfaces and Mylar chamber and lag phase in summer from 6:00 to 8:00 h



and 16:00 h, both the Reis et al. (2006) model and  $ET_0$  overestimated transpiration while Granier underestimated transpiration. All of the models were significantly different from the 1:1 relationship between actual and predicted transpiration rates (Fig. 7).

#### 4 Discussion

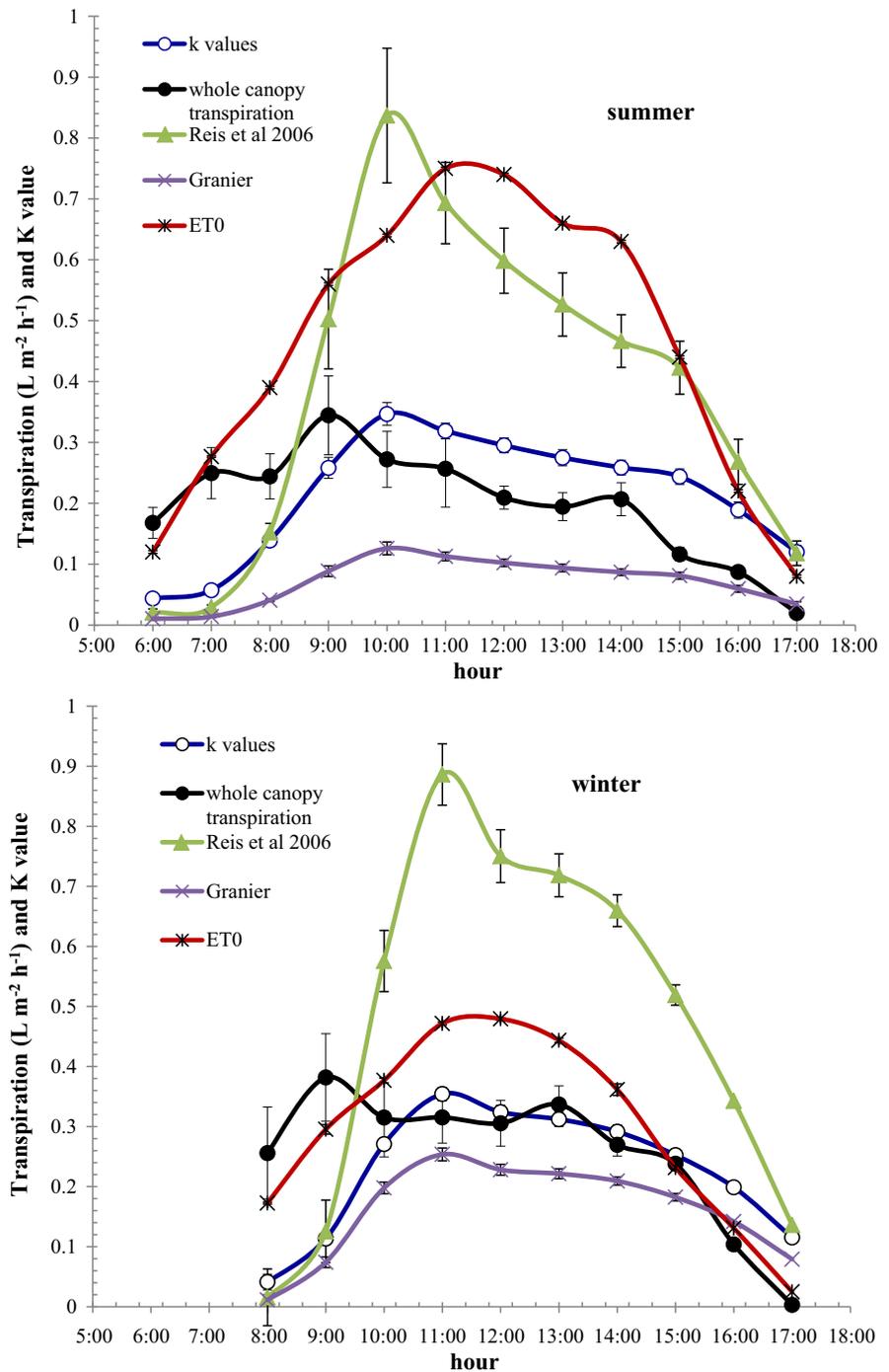
Air temperature influences papaya physiology indirectly via leaf temperature and stomatal behavior by way of  $VPD_{\text{leaf-air}}$  (El-Sharkawy et al. 1985; Marler and Mickelbart 1998; Machado Filho et al. 2006; Reis et al. 2011; Campostri et al. 2010). In the present study, leaf temperature inside the chamber in summer was higher than that during winter (Fig. 3). Thus, reduced whole canopy transpiration of papaya plants grown under field conditions in the summer (Fig. 4) was presumably due to stomatal closure.

The decrease of whole-plant transpiration after 1:00 h in the winter and 9:00 h in the summer (Fig. 4) may be due in part to: 1) soil water uptake lagging behind transpiration demand after 13:00 h (winter) and 9:00 h (summer), creating a temporary water

stress with partial stomatal closure, 2) high and medium VPD [3.5 kPa (winter) and 1.5 kPa (summer)] and 3) the interaction between the factors mentioned in 1) and 2) above and PAR. The reduction in PAR caused rapid stomatal response in tropical regions because the intermittent clouds create large fluctuations in PAR during the day (Clemente and Marler 1996).

Reduced whole-canopy transpiration in papaya in the summer was due to high leaf temperatures and high  $VPD_{\text{air}}$  (4.0 kPa) that caused stomatal closure. In fact, papaya has optimal growth and development at air temperatures between 21 and 33 °C (Knight 1980), or according to Lassoudiere (1968), between 22 and 26 °C. This information emphasizes the role of temperature acting indirectly on transpiration in papaya via increases in  $VPD_{\text{leaf-air}}$ . The  $VPD_{\text{leaf-air}}$  may be a fundamental factor for agricultural zoning of papaya cultivation because it will determine the regions with the greatest productive capacity. Several studies (El-Sharkawy et al. 1985; Marler and Mickelbart 1998; Machado Filho et al. 2006; Reis et al. 2011) have shown that even with high soil water availability, a high  $VPD_{\text{leaf-air}}$  contributes significantly to the reduction of stomatal conductance and,

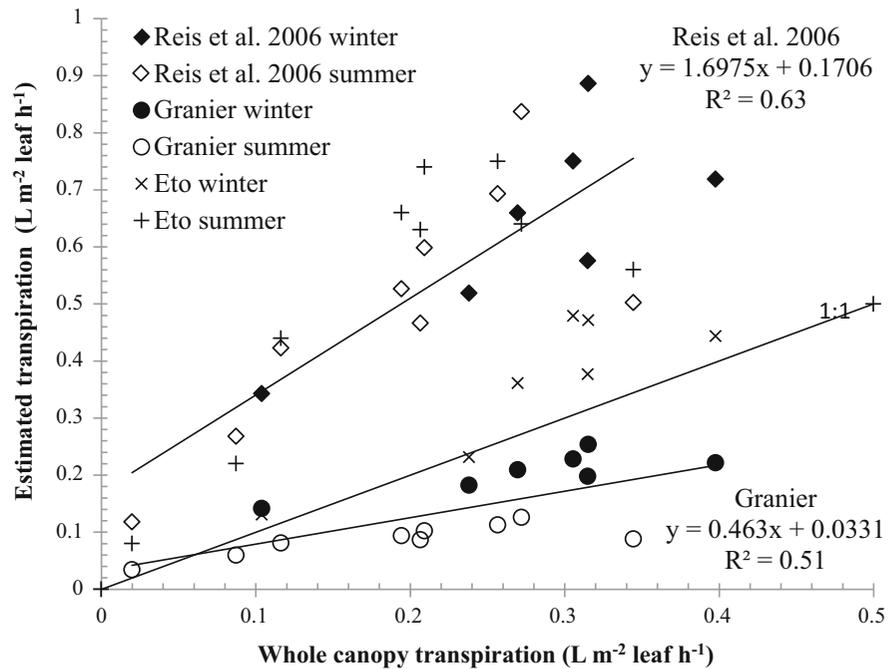
**Fig. 6** Relationship between measured and predicted whole-canopy transpiration determined using the Granier and forced water method of sap flow and reference evapotranspiration ( $ET_0$ ) in 'Golden' papaya in Summer and Winter. Whole canopy transpiration data excluded from the regression were 8:00 to 9:00 h in winter related to dew on the leaf surfaces and Mylar chamber and lag phase in summer from 6:00 to 8:00 h. The vertical bar represents  $\pm$  standard error (SE) of the mean of 15 replicates



consequently, to reduction in transpiration. El-Sharkawy et al. (1985) observed a similar relationship between  $VPD_{\text{leaf-air}}$  and  $g_s$ . They found that papaya was extremely responsive to  $VPD_{\text{leaf-air}}$ ; in

environments with a 3.5 to 4.5 kPa  $VPD_{\text{leaf-air}}$ , net photosynthetic rates (A) were nearly halved as compared with plants grown in environments with  $VPD_{\text{leaf-air}}$  of 1.0 to 1.5 kPa.

**Fig. 7** Relationship between the mean hourly measured and predicted whole-canopy transpiration determined using  $ET_0$ , the Granier and forced water method of sap flow (Reis et al. 2006) in ‘Gran Golden’ papaya in summer and winter. Whole canopy transpiration data excluded from the regression were 8:00 to 9:00 h in winter related to dew on the leaf surfaces and Mylar chamber and lag phase in summer from 6:00 to 8:00 h



#### 4.1 Sap flow and whole-canopy transpiration rate

The heat coefficient (K) was significantly related to the whole-canopy transpiration rate ( $r^2 = 0.65$ ) (Fig. 5). We observed a delay (lag phase) between whole-canopy transpiration and K at 6:00–8:00 h (summer). However, in winter the presence of dew inside the chamber prevented measurement prior to 22:00 h (Fig. 5), and therefore we did not include these data in the regression. A delay has been reported between transpiration as measured by sap flow compared with a model in kiwifruit vines (Edwards and Warnick 1984), but no delay was seen comparing sap flow and whole-canopy gas exchanges in grapevines (Dragoni et al. 2006). In papaya plant, Reis et al. (2006) using the relationship between sap flow and instantaneous transpiration rate with a portable photosynthesis system (LI-6200, Licor, USA) showed that under conditions of high instantaneous transpiration, a non-linear relationship was observed between transpiration and xylem sap flow, and the authors explained that was due to a lag phase in which transpiration increases without the same change in sap flow values. The stored water present in the papaya canopy above the point of insertion of the probes could contribute to whole-canopy transpiration values without xylem water

tension development. Zhang et al. (1997) observed a higher availability of stored water in *Larix* and *Picea*. In Pecan (*Carya illinoensis* ‘Wichita’), the small early morning lag may represent water immediately available in leaves, petioles and small branches (Steinberg et al. 1990). However, a linear relationship has been reported between transpiration measured using a heat-balance probe and a whole-canopy canopy gas exchange chamber (Dragoni et al. 2006). Kempe et al. (2014) reported papaya is a giant herbaceous species and maintaining adequate tissue turgidity and water availability is necessary to maintain the rigidity (turgor pressure between 0.82 and 1.25 MPa) (Kempe et al. 2014) of the stem as well as increase productivity. In addition, Ferraz (2008) reported that papaya plant had 0.10 m<sup>2</sup> leaf area per cm<sup>2</sup> active xylem, and this reduced relationship between leaf area and active xylem area can explain the lag phase. In accordance with these authors, we can report that the existence of a lag phase may occur in papaya.

When the two models [chamber methodology and forced-flow through a stem section (Reis et al. 2006)] were compared, the mathematical model proposed by Reis et al. (2006) overestimated the sap flow in summer and winter (Figs. 6 and 7). This differential response may be due to forced-flow through a stem

section promoting artificial water movement in xylem vessels which may eliminate cavitation bubbles in the xylem that reduce water conduction (Hölttä and Sperry 2014). We conclude that the whole plant chamber methodology provides a more realistic behavior of the water xylem movement through the papaya trunk growth-field than the forced-flow method.

$ET_0$  overestimated whole-canopy transpiration rate in the summer, but showed a good relationship in winter (Figs. 6 and 7). This lack of fit in summer is primarily due to stomatal closure due to water stress restricting the potential transpiration rate despite full irrigation. In contrast, the reasonable fit of  $ET_0$  in winter indicated that the plant was able to meet the  $ET_0$  demand and stomatal closure due to water stress was not apparent (Fig. 7). Due to the stomatal control of transpiration (E) versus  $ET_0$  control of E, irrigation cannot be accurately scheduled using estimates of  $ET_0$  in summer. For this reason, sensors or other technology are needed to accurately estimate actual transpiration.

There was a significant and meaningful relationship between K and whole plant transpiration (Fig. 5) indicating that sap flow measurement was related to transpiration. However, neither the Granier (1985) nor the Reis et al. (2006) methodology could convert this correlated response into an accurate measurement of papaya transpiration measured with whole canopy chambers (Fig. 7). Both sap flow methodologies were linearly correlated with whole canopy transpiration but each would require additional calibration to the crop. Lamentably, the regression relationships for summer and winter are significantly different, precluding the use of  $ET_0$  as a means of calibrating the sap flow sensors during the winter when water stress and stomatal control of E is minimal. The concept of sap flow to measure transpiration is valuable in papaya however, additional studies are necessary to improve a model to accurately and consistently estimate whole-canopy transpiration in papaya plant to schedule irrigation in commercial fields.

**Acknowledgments** We acknowledge the support of Caliman Agrícola S/A, Financiadora de Estudos e Projetos (FINEP, Brazil), Fundação Carlos Chagas de Apoio à Pesquisa no Estado do Rio de Janeiro (FAPERJ, Brazil), National Council for Scientific and Technological Development (CNPq, Brazil) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES, Brazil). We are also thankful to Dynamax (Houston,

Texas, USA) for providing the probes to measure the xylem sap flow. We are also thankful to Dr. Bruce Schaffer, Tropical Research & Education Center (TREC), University of Florida, USA for helpful grammar corrections.

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