

Estimation of transpiration in oil palm (*Elaeis guineensis* Jacq.) with the heat ratio method

Estimación de la transpiración en palma de aceite (*Elaeis guineensis* Jacq.) por el método del radio de calor

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ABSTRACT

Sap flow sensors were installed on the leaf petioles of 5-year-old oil palms (*Elaeis guineensis* Jacq.) to measure the xylem water flow for 12 days based on the heat ratio method (HRM). It was found that young leaves have higher sap flow rates, reaching values of over $250 \text{ cm}^3 \text{ h}^{-1}$, and that sap flow fluctuations are directly related to weather conditions, particularly the vapor pressure deficit (VPD) component. It was observed that the sap flow rates remained constant and very close to $0 \text{ cm}^3 \text{ h}^{-1}$ between 18:00 and 6:00 h and that the upward and downward movement of sap was faster during the day, with peak levels between 9:00 and 16:00 h. Under the evaluation conditions, the oil palm crop transpiration was estimated to be 1.15 mm $\text{H}_2\text{O}/\text{ha-day}$. The HRM is a highly repeatable method and an useful tool to quantify the total oil palm transpiration. It could potentially be applied to irrigation.

Key words: transpiration, sap flow, vapor pressure deficit.

RESUMEN

En palma de aceite (*Elaeis guineensis* Jacq.) de 5 años de edad se colocaron en la base peciolar de las hojas sensores de flujo de savia, basados en el método del radio de calor (HRM), para cuantificar durante 12 días el movimiento de agua xilemática en la palma. Se encontró que las hojas jóvenes tienen un mayor flujo de savia con valores superiores a los $250 \text{ cm}^3 \text{ h}^{-1}$, se determinó que las fluctuaciones del flujo de savia están directamente relacionadas con las condiciones climáticas siendo el déficit de presión de vapor (VPD) el componente de mejor explicación para dicha variación. Se observó que el flujo de savia es constante y muy cercano a $0 \text{ cm}^3 \text{ h}^{-1}$ desde las 18:00 horas hasta las 6:00 horas, y en el día su ascenso y descenso son rápidos y mantiene sus valores máximos entre las 9:00 y 16:00 h. Se estimó que bajo las condiciones de la evaluación el cultivo de palma de aceite presentó una transpiración de 1,15 mm $\text{H}_2\text{O}/\text{ha-día}$. El HRM resultó un método con alta repetibilidad entre las palmas siendo una buena herramienta para cuantificar la transpiración total de la palma de aceite y podría ser utilizada potencialmente para la aplicación de riego.

Palabras clave: transpiración, flujo de savia, déficit de presión de vapor.

Introduction

Oil palm cultivation in Colombia has grown significantly in recent years (Fedepalma, 2014), with a planted area of 450 thousand hectares distributed in different regions of the country. Oil palm requires large amounts of water for good production (Corley and Tinker, 2003; Paramanathan, 2003; Carr, 2011) assuming an average water requirement of 6 mm per day. However, the measurements used to determine the overall transpiration rate of oil palm have been based on allometric parameters (Kallarackal *et al.*, 2004; Legros *et al.*, 2009) or on gas exchange measurements (Suresh *et al.*, 2010; Rivera *et al.*, 2012; Suresh *et al.*, 2012). All of these studies have allowed us to partly understand

the water demand of oil palms under different controlled conditions; however, the water requirements of oil palm in the field are not well known. Therefore, it is necessary to take direct measurements to determine water use under field conditions over time.

Different measurement methods have been used to quantify the transpiration of plants, including the estimation of water use based on water balance and measurements of precipitation, drainage and changes in the water reserve available to plants (Ruiz-Peñalver *et al.*, 2014), along with the lysimeter method, which, for perennials, requires a large infrastructure, such as that used in the study conducted on date palm (Tripler *et al.*, 2012). However, even though

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this method has been improved, the size of the plant is still a major limitation. For smaller species, inexpensive lysimeters can be used, as reported by Ruiz-Peñalver *et al.* (2014). Another method used is the Granier method (Granier, 1987) and its modifications (Burgess *et al.*, 2001), a technique that measures sap flow rates and the volumetric flow of water in xylem tissue with a short heat pulse as an indicator. This is performed by measuring the ratio of the amount of heat transported to two symmetrically arranged temperature sensors to calculate the quantity and direction of the water flow (Smith and Allen, 1996; Bleby *et al.*, 2004). Research with sap flow meters has been corroborated by other techniques, such as the lysimeter and water balance, with a high correlation between the different techniques. These results show the usefulness of this technique (Trcala and Čermák, 2012; Langensiepen *et al.*, 2014).

The aim of most of the studies that used the heat pulse method was to determine the water balance and flow of assimilates, such as the study by Haijun *et al.* (2015) under mesh-house conditions, in which the total transpiration of banana plants was determined. Based on information provided by the device, they were able to determine the water demand of the plants and, therefore, the optimum irrigation schedule to prevent water stress. The same has been done with cacao (López-López *et al.* 2013) and eucalyptus (Bleby *et al.*, 2012); various studies were able to determine and quantify the sap flow rate with a high degree of accuracy using the heat pulse method.

The aim of this study was to measure the total transpiration of a commercial oil palm plantation under field conditions. We examined climate variables in order to understand which of them play significant roles in transpiration fluctuations. Furthermore, we studied the influences of leaf age on whole plant transpiration. The results have a potential to be used as a decision making tool in water management and supply under a precision agriculture scheme.

Materials and methods

Location of the study area

This study was conducted in the Palmar de la Vizcaína Experiment Field Station, Santander, Colombia (6°58' N; 73°42' W), at an altitude of 140 m, with 75% relative humidity and 32°C of average daily temperature. Five years-old oil palms (*Elaeis guineensis*) arranged in a 9 m wide triangle were selected for evaluation in a 10-ha lot planted in 2011.

During the months of the study, the average rainfall was 280 mm.

Sap flow measurement

The heat ratio method (Bleby *et al.*, 2012; Hölttä *et al.*, 2015) was used to measure the sap flow with SFM1 sensors from ICT International (Australia). These sensors consisted of three needles. One of the needles generates a heat pulse, and the other two are each fitted with two thermocouples (Fig. 1). Three sensors were installed in each palm, in leaves 9, 17 and 25, just before the rudimentary leaflets. The information was recorded every 10 min. throughout the day for cycles of 12 d, which is the time that it takes for the leaf to change positions in the phyllotaxy of the palm. The heat pulse used was 35 J, a value found in previous settings (data not shown). Additionally, tissue samples were collected from the petiole base to determine the leaf tissue thermal diffusivity constant by measuring the wet weight, dry weight and volume of fresh tissue. The heat ratio method (HRM) measures the ratio of the increase in temperature, following the release of a pulse of heat, at points equidistant downstream and upstream from a line heater. Heat pulse velocity is calculated as:

$$V_h = \frac{k}{x} \ln(v_1/v_2)3600 \quad (1)$$

Where k is thermal diffusivity of green (fresh) wood, x is distance (cm) between the heater and either temperature probe, and v_1 and v_2 are increases in temperature (from initial temperatures) at equidistant points downstream and upstream, respectively, x cm from the heater. The probe positions relative to the heater used with the HRM are -0.5 and 0.5 cm, hence $x = 0.5$ cm.

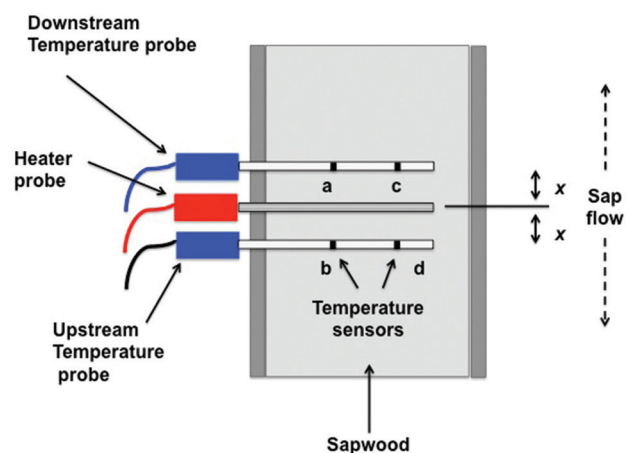


FIGURE 1. Diagram of the heat ratio method used in the sap flow meters. Modified from the Heat Ratio Method (HRM) Installation & Operation Manual, ICT International Pty Ltd., Australia.

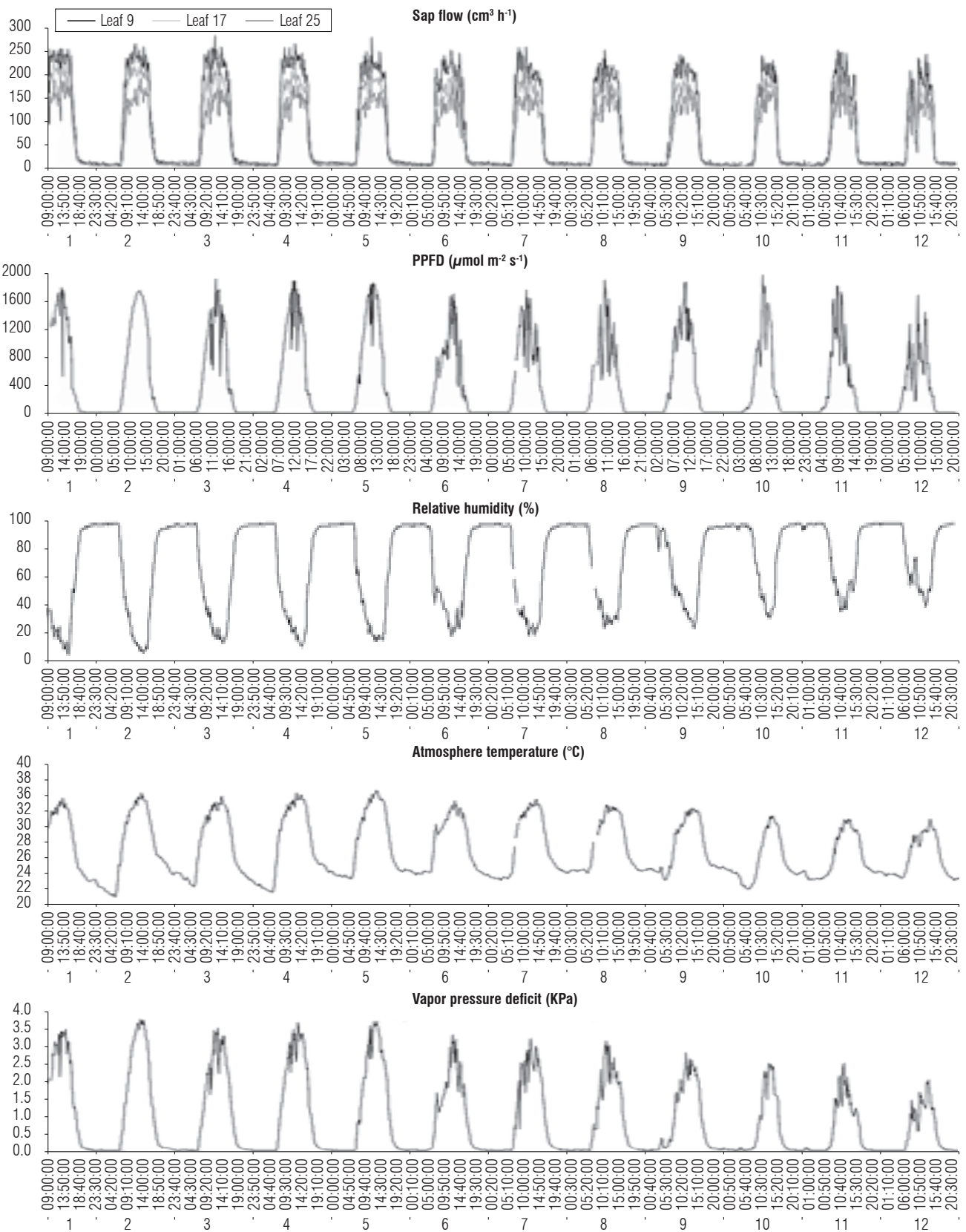


FIGURE 2. Daily sap flow rate in 3 leaves of oil palm during a 12-day sampling period by the heat ratio method ($n=4$). PPFD, photosynthetic photon flux density; RH, relative humidity; AT, ambient temperature; VPD, vapor pressure deficit. Environmental variables throughout the sampling period.

Climate data

Air temperature, relative humidity, photosynthetically active radiation, soil moisture, soil temperature, rainfall and net radiation data were recorded with a Biomet weather station (Sutron Corp - Sterling, VA) anchored to the Eddy Covariance system installed in the study area. The VPD was calculated using software free to Autogrow (<http://www.autogrow.com>) with temperature data, relative humidity and radiation.

Data analysis

The sap flow data were analyzed with SapFlowTool 1.4.1 software from ICT-International / Phyto - IT (Australia). The daily flow and water consumption accumulation over time were calculated to estimate the total transpiration. The data were statistically analyzed with SAS software, the statistical assumptions (homogeneity of variance, normal distribution and randomness) were tested. In order to determine the differences between the palms and leaves, Anova, Duncan's multiple range test, and multiple regressions associated with weather data were performed.

Results

During the sampling days, the soil water potential was constant in a range of -0.1 to -0.2 MPa, and the sap flow showed no significant difference in any of the evaluated palms. However, differences were found between leaf 9 and leaf 25, where leaf 17 had an intermediate value between them. A similar pattern was found in each of the sampled leaves (Fig. 2), where the sap flow rate ranged from 10 to 20 cm³ h⁻¹ overnight - from 18:00 HR to approximately 6:00 HR - increasing 20-fold 2 h after the arrival of the first rays of light (Fig. 2A). The highest flow rates occurred between 9:00 and 16:00 HR (220 cm³ h⁻¹), with fluctuations between 20 and 40 cm³ h⁻¹. At 16:00 HR, the flow rate started to

decrease, reaching the lowest values after 18:00 HR; this cycle repeated every day during the sampling period. Additionally, a reduction in the sap flow was observed after day 7 of the evaluation, associated with a decrease in vapor pressure deficit (VPD).

The volume of water transported through the leaf petiole bases during the sampling period was calculated based on the recorded information (Fig. 3). Leaf 9 transported the largest volume of water (21.65 L), followed by leaf 17 (17.20 L) and leaf 25 (14.6 L) during the 12 d of sampling. This variable showed statistically significant differences over time from day 4. No statistically significant differences were found between palms, which indicated a good repeatability of sampling. Additionally, the volume of water transported increased during the day, as illustrated by valleys related to the lower volume of water transported during the night.

Discussion

The results are similar to those found in pindo palm (Madurapperuma *et al.*, 2009), pine (Chang *et al.*, 2014) and wheat (Langensiepen *et al.*, 2014), among other species. Daily fluctuations are directly associated with soil water conditions and weather variations that influence gas exchange in plants. For example, in jujube (Chen *et al.*, 2014), a reduction in soil water potential and change of meteorological factors caused a direct response in photosynthesis and transpiration rates, which was reflected in reduced sap flow. We found that sap flow rates are closely related to weather variables (Fig. 4), where the vapor pressure deficit (VPD) was the most correlated factor. These results are similar to those reported for oil palm in Indonesia (Niu *et al.*, 2015). A multiple regression was also performed, taking into account the main components (AT, PPFD and VPD) (Fig. 5), in which a high linearity was found. However, it is

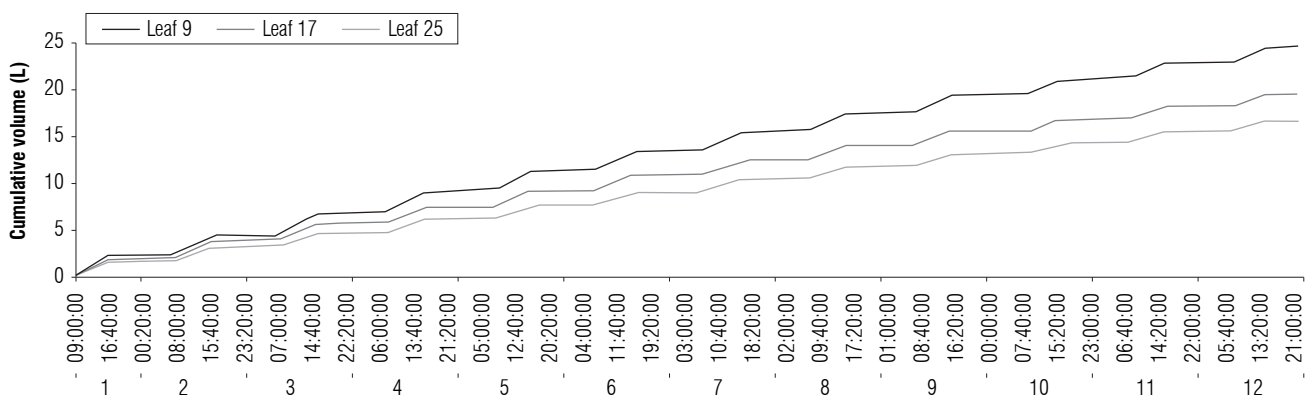


FIGURE 3. Accumulated volume of water transported by 3 leaves of oil palm during a 12-day sampling period by the heat ratio method ($n = 4$).

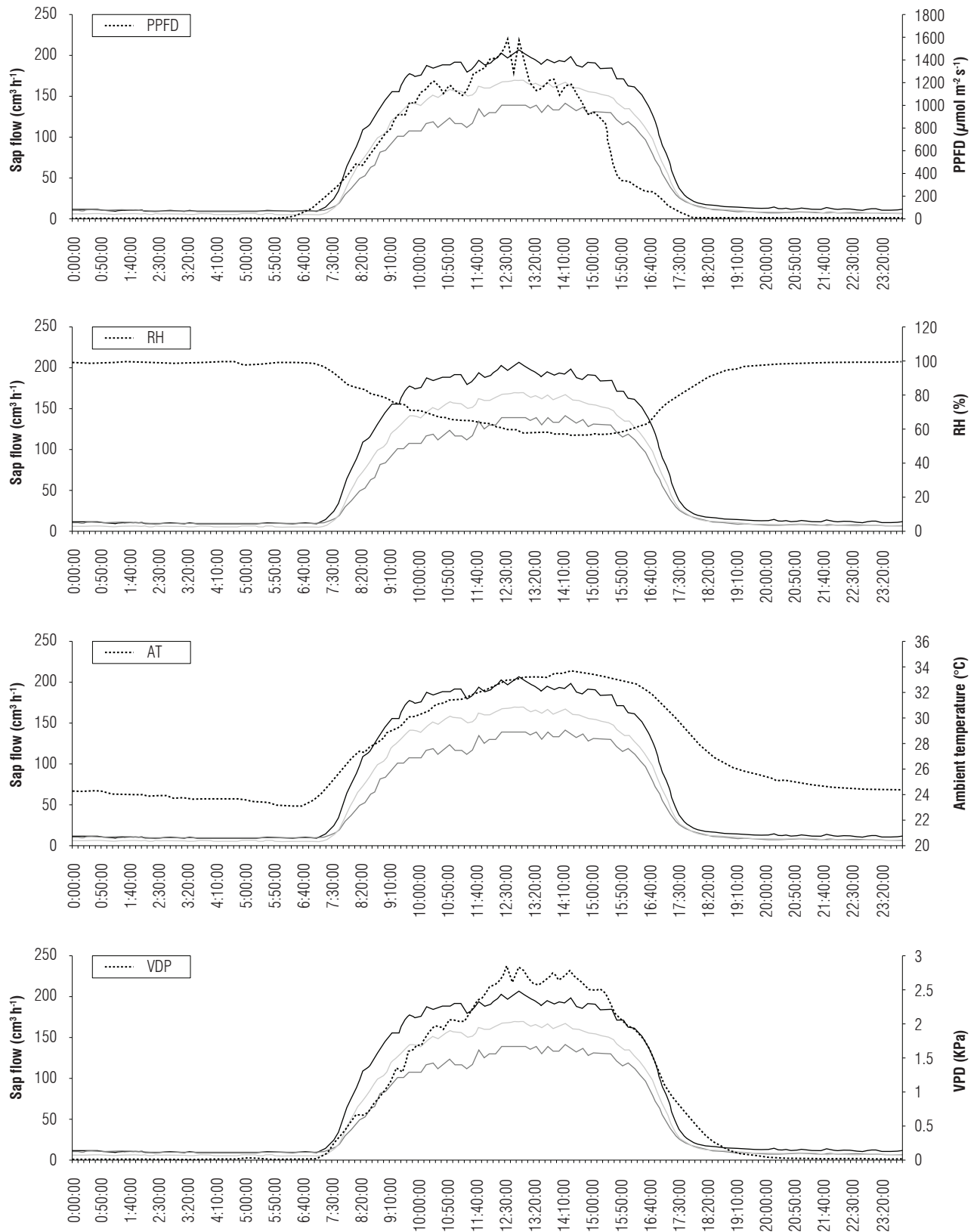


FIGURE 4. Relationship of sap flow rates of 3 leaves of oil palm by the heat ratio method with climate variables. PAR, photosynthetically active radiation; RH, relative humidity; AT, ambient temperature; VPD, vapor pressure deficit ($n = 4$). — Leaf 9, — leaf 17 and — leaf 25.

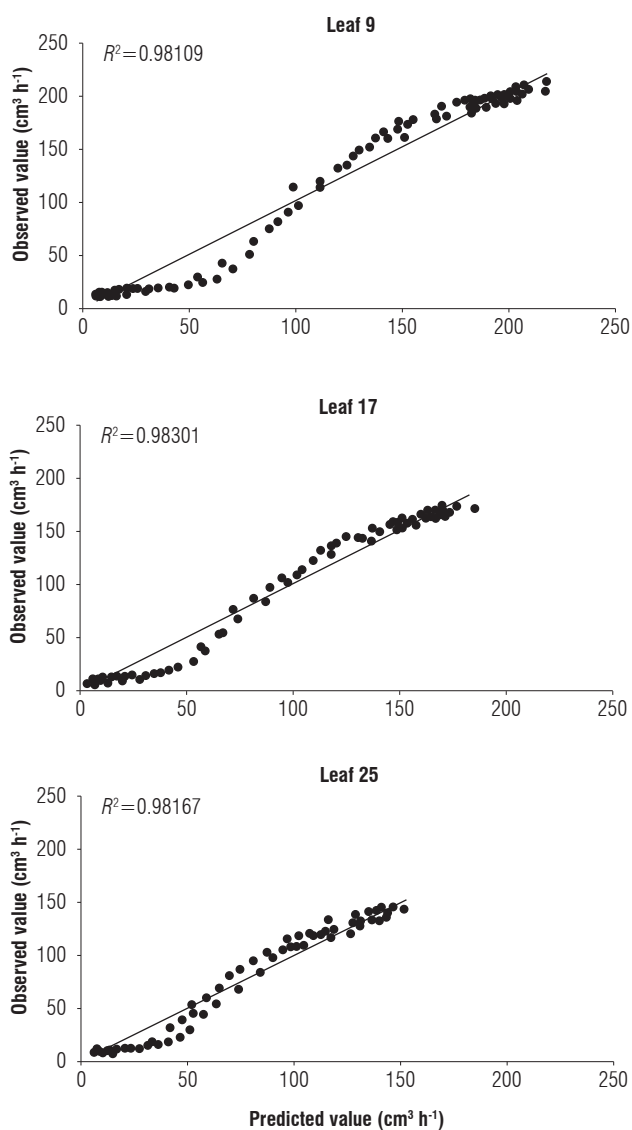


FIGURE 5. Multiple regression for leaves 9, 17 and 25 of oil palm, taking VPD, PPFd and RH into account to develop predictive models ($n=4$).

necessary to include other variables to complete a predictive model for irrigation, as was done for *jujube* and *banana* (Lu *et al.*, 2002; Haijun *et al.*, 2015; Chen *et al.*, 2014).

Based on the water flow data, including 33 leaves, our estimates of whole-plant water use were calculated as the sum of the rates from individual leaves, which is necessary and useful to assess canopy variability. We found that water use per palm was substantially higher in young leaves than in older leaves. The estimated water consumption per palm was 80.5 L d^{-1} , for a transpiration of 1.15 mm d^{-1} , very similar to the value reported by Niu *et al.* (2015). In the literature (Mutert *et al.*, 1999; Corley and Tinker, 2003), the estimated values based on evapotranspiration

and allometric calculations are higher, possibly because those estimations do not directly measure plant water consumption.

Conclusions

The analysis of sap flow measurements showed that each leaf had a different water consumption rate, and young leaves had higher water consumption values. This monitoring allowed us to determine that, for the measurement conditions, the transpiration of one hectare of oil palm was 1.15 mm d^{-1} . The sap flow rates in the oil palm were closely related to weather variations, particularly vapor pressure deficit, VPD, which is the variable that best explains the fluctuations in water movement in oil palm. Additionally, measurements showed high repeatability using the heat ratio method (HRM) of ICT-International (Australia). However, it is necessary to assess the crop in different seasons to determine water requirements during the dry season and to integrate crop transpiration data with the evapotranspiration data of the ecosystem.

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