SAP FLOW AND CANOPY CONDUCTANCE OF RAINFED CITRUS ORCHARD UNDER SUB-HUMID TROPICAL CONDITIONS

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ABSTRACT

Temperature difference method was used to measure sap flow in a seven-year-old citrus orchard during the transition (dry–wet and wet–dry) and peak rainfall periods. Canopy conductance (g_c) of the orange was estimated by inverting the Penman-Monteith model. Transpiration rates were well-correlated with climatic conditions during the three observation periods. On bright days, sap velocity was higher during the peak rainfall period (August September) compared to the dry-wet (April) and wet-dry (November) transition periods. However, significant negative correlations obtained between sap flow and wind direction for sweet orange and lemon during the wet-dry period suggests an advection of moisture from nearby water bodies leading to slight decrease in transpiration when such occurred. Average daily water use of lemon was about 17% higher than sweet orange. The ratio of canopy transpiration (E_c) to potential evaporation (E_p) varied from 43% – 65% and daily g_c ranged from 2.2 ± 0.4 mm s^{-1} to 4.4 ± 1.2 mm s^{-1} during the measurement periods. For higher values of vapor pressure deficit (VPD >1 kPa), sap flow showed a plateau response indicating stomata closure. Under this contrasting evaporative demand (1 kPa to 3 kPa), citrus trees were able to regulate their canopy conductance from 7 mm s^{-1} to 2 mm s^{-1} to maintain a near constant transpiration during the daytime. The good agreement between sap flow based transpiration and climatic variable could be exploited to parameterize a simple mechanistic model to predict citrus water use under rainfed conditions of the study.

KEYWORDS: Sweet orange, lemon sap flow, canopy conductance, monsoon clouds

List of Symbols and Abbreviations

Symbol	Meaning [unit]
ΔT	temperature difference [°C]
ΔT_{max}	ΔT when sap flow is zero [°C]
DOY	Day of year [-]
E_c	canopy transpiration [mm h^{-1}]
E_p	potential evaporation [mm day^{-1}]
g_a	aerodynamic conductance [m s^{-1}]
g_c	canopy conductance [m s^{-1}]
LM	Lemon [-]
LV	Late Valencia [-]
M_D	Mean difference [cm h^{-1}]
r	correlation coefficients [-]
R_H	relative humidity [%]
RV	Red Valencia [-]
SD	standard deviation [-]
S_R	solar radiation [w m^{-2}]
T_a	air temperature [°C]
V	sap flow velocity [cm s^{-1} , cm day^{-1}]
VPD	vapor pressure deficit [kPa]
W_D	wind direction [°]
W_S	wind speed [m s^{-1}]

1. INTRODUCTION

Citrus is one of the most important tropical/subtropical economic horticultural crops of the world (Vu and Yelenosky, 1986). World production has increased rapidly in recent times (FAO, 2004). Citrus is widely cultivated in the Mediterranean (Rana et al., 2005) while its production in the United States, surpasses the combined production of other fruit crops, including apples and peaches (Vu and Yelenosky, 1986). Similarly, citrus production in West Africa has increased by a factor greater than 3 since 1961, while cultivated area stands at 850,000 ha in 2004 (FAO, 2004).

Water requirements and use by citrus have been evaluated using methods such as soil water balance, porometer, sap flow sensors, eddy covariance and estimates based on smoothed climatic data (Van Bavel et al., 1967; Habermann et al., 2003; Yang et al., 2003; Ortuno et al., 2004; Rana et al., 2005). Furthermore, most of the studies on canopy processes have been at leaf scale such as assessing the temperature or vapor pressure deficit (VPD) effects on leaf photosynthesis, leaf transpiration and leaf conductance (Moreshet and Green, 1984; Vu and Yelenosky, 1986; Habermann et al., 2003; Ortuno et al., 2004). Changes in the atmospheric vapor pressure affect the functioning of guard cells, ultimately affecting the stomatal conductance (Zeiger, 1998). A screenhouse measurement has demonstrated that the leaf stomata conductance of sweet orange decreased significantly when exposed to drier air (Habermann et al., 2003), while Ortuno et al. (2004) reported a linear increase in sap flow with increasing vapor pressure deficit below 1.75 kPa in potted lemon trees. Confirmation or otherwise of these results under rainfed, field and tropical environmental conditions typical to West Africa is necessary for the development and management of citrus industry in these regions, where cash-strained economic reality of an average farmer makes investment in irrigation of orchards unaffordable.

Sap flow method offers a low cost technology for monitoring whole-tree transpiration that may be combined with meteorological data for continuous and systematic analysis of the bulk stomata behavior in response to transient environmental conditions (Lu et al., 2003; Oguntunde and van de Geisen, 2005). Therefore, this study was undertaken to understand patterns of citrus water use and canopy conductance at critical periods (transition and peak rainfall periods) under changing atmospheric conditions and rainfed situation using sap flow data. The objectives were to: (1) use sap flow technique to measure rates of transpiration in citrus trees at various critical periods in the growing season; (2) determine whether species or varieties significantly affects citrus water use; and (3) characterize the effects of diurnal and day-to-day variations in atmospheric conditions on the temporal pattern of transpiration.

2. MATERIALS AND METHODS

The study was conducted in the forest transition zone of Ghana near Ejura town (latitude 07° 20′ N, longitude 01° 16′ W, 210 m above sea level) in a 2.83 ha, seven-year-old, citrus orchard. The orchard consists of sweet orange (*Citrus sinensis* L; ca 90% Late Valencia and 6% Red Valencia) and Lemon (*Citrus limon* L; ca 4%). Tree density was 278 trees ha^{-1} with mean tree height of 4.60 ± 0.70 m in 15 trees. Leaf area index was measured as 4.64 ± 0.95 m^2 m^{-2} using a canopy analysis system (*LAI*-2000, LiCor, Lincoln, NE). The climate is tropical monsoon characterized with distinct wet (April to October) and dry (November to March) seasons. Total rainfall in 2002 was about 1400 mm but a 20 years (1973 - 1992) average was 1264 mm. The soil texture within the orchard was generally sandy clay loam.

Sap flow in tree trunk was estimated continuously by the method described by Granier (1985, 1987). Each system consists of a pair of 2 mm (diameter) stainless steel needles installed into the tree stem about 10 cm apart in a vertical line (Plate 1). A constant power source was applied to a resistor in the upper (heated) needle. A copper-constantan thermocouple measures the temperature difference between the heated upper needle and unheated lower reference needle. The flow of sap cools the heated needle. Sap velocity was computed with the empirical relationship validated for many species (Granier, 1987; Lu and Chacko, 1998; Braun and Schmid, 1999) as:

$$V = 0.0119\left(\frac{\Delta T_{max} - \Delta T}{\Delta T}\right)^{1.231} \quad (1)$$

where V is average sap flow velocity along the length of the probe (cm s^{-1}), ΔT is the temperature difference observed between the heated and reference needles, and ΔT_{max} is the value of ΔT when sap flow is zero (generally taken as the peak nighttime value of ΔT). Canopy transpiration (E_c, mm h^{-1}) was estimated from averaged sap flow of the gauged trees divided by ground area occupied (Oguntunde et al., 2004).

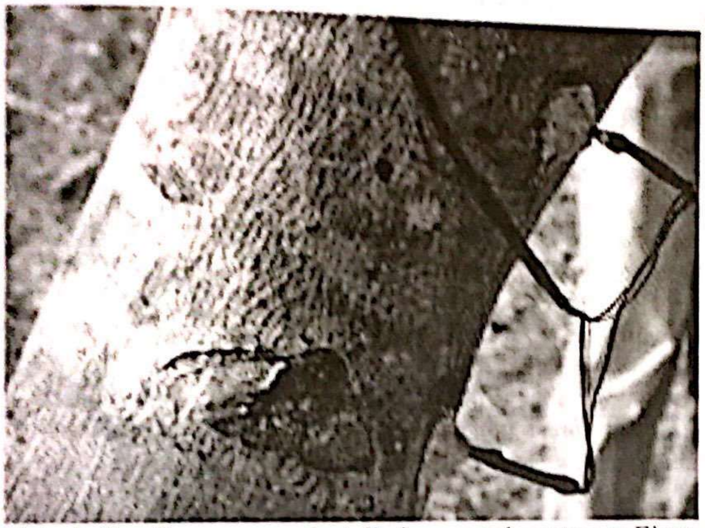

Plate 1. Sap flow sensors installed on a cashew tree at Ejura, Ghana

Half-hourly sap flow measurements were made for 12 days in April (transition from dry to wet: hereafter referred to as Period I), for 32 days in August/September (peak wet: hereafter referred to as Period II), and for 8 days in November (transition from wet to dry: hereafter referred to as Period III). During these periods, a total of six trees were gauged using the most abundant variety (Late Valencia). Additional three trees one for each different variety (Lemon, Red Valencia and Late Valentcia) were gauged for six days in November to study possible difference in their water use.

Meteorological variables were measured about 200 m away from the experimental plot (50 x 50 m^2) located at the center of the orchard. Incoming solar radiation, air temperature, wind speed and direction, relative humidity and rainfall, were sampled at 10 s and recorded as 10 min averages with an automatic weather station.

3. RESULTS AND DISCUSSION

3.1 Climatic Conditions and Citrus Sap Flow

Summary of atmospheric conditions at the study site during the 2002 measurement periods I - III are shown in Table 1. Generally, the conditions were characterized by high humidity and low wind speeds. Dew usually occurred during the early morning hours and citrus leaves often remained wet until 0830 local time. Solar radiation and air temperature were higher during the transition periods (I and III) than the peak rainfall period (II). Period II was characterized with frequent overcast due to monsoon clouds typical of the wet season of West Africa (Jegede, 1997; Oguntunde and van de Geisen, 2005). However, few bright days chosen and compared for the three periods showed similar diurnal and daily climatic values.

Table 1. Mean half-hourly weather variables for the three observation periods (coefficient of variation for daily averages in parenthesis).

Period#	Air temperature (°C)	Relative humidity (%)	Wind speed (m s^{-1})	Solar radiation (W m^{-2})	Rainfall amount (mm)
I (12 days)	27.4 (4.8)	74.3 (6.8)	1.6 (17.3)	228.2 (10.1)	61.3
II (32 days)	24.3 (3.2)	84.5 (2.9)	1.3 (12.2)	169.9 (18.6)	168.5
III (8 days)	25.9 (1.1)	78.9 (2.9)	1.0 (13.0)	235.3 (6.8)	0.0

#Period I: April 03 to 14; Period II: August 15 to September 16; and Period III: November 07 to 14.

For the three observation periods, statistics of sap velocity (V) and canopy transpiration are summarized in Table 2. Mean sap velocity increased gradually from 96 cm day^{-1} (period I) to 104 cm day^{-1} (period III) in the growing season. Similar trend was noted for estimated average transpiration. However, higher variably was recorded during period II as indicated by the standard deviation (SD) values. The ratio of transpiration to Penman evaporation estimates (E_c/E_p) was 43.4%, 65.0% and 45.6% for periods I-III, respectively. The highest ratio for period II was due to relative lowest value of E_p during this period rather than absolute value of E_c, which is actually lower compared to period III (Table 2). A similar pattern, 25%, 49% and 39% for periods I-III, was derived from the result of van Bavel et al. (1967) in an orange orchard at Arizona. Obviously, actual and potential evaporation would be expected to be very close during period II because it is the period of highest surface wetness and humidity. These lower than expected transpiration fractions may be explained in part by (1) frequent canopy wetting from rain, fog, and dew most especially during period II; and (2) the open canopy (30% cover) structure of the orchard, allowing significant understory transpiration. Similar to this result, Giambelluca et al. (2003) observed small transpiration ratio in a small tropical forest parch and attributed this observation to relative significant role of canopy interception and soil evaporation among other factors.

Table 2. Summary of sap velocity (V) and crown transpiration (E_c) estimates during the observation periods in the growing season of 2002.

Observation period	Sap velocity (cm day^{-1}) Maximum	Minimum	Mean ± SD	Transpiration (mm day^{-1}) Maximum	Minimum	Mean ± SD	#E_c/E_p ratio (%)
I	111.31	72.67	96.78 ± 11.21	1.79	1.17	1.56 ± 0.18	43.4
II	158.40	58.68	98.14 ± 21.19	2.55	0.95	1.58 ± 0.34	64.7
III	112.53	92.91	104.60 ± 6.39	1.81	1.50	1.69 ± 0.10	45.7
I to III	158.40	58.68	98.70 ± 17.94	2.55	0.95	1.59 ± 0.29	55.3

#E_c/E_p in the last column is the ratio of crown transpiration (sap flow) to Penman evaporation estimates.

To remove the potential cloudiness and leaf wetness effects on sap flow, five clear days were selected from each of the periods and statistically compared using ANOVA and Bonferroni mean separation test. The same method was used to access the possible differences in water use of Lemon, Red Valencia and Late Valencia measured for six days in November 2002 (Figure 1). The results showed a slight higher (P = 0.043) sap flow density in period II than I, while Lemon transpires significantly higher (P = 0.001) than Late Valencia (Table 3). On the average, lemon transpires about 17% higher than sweet oranges. The observations agreed with previous studies, for example, higher stomata resistance in Valencia than lemon was reported (van Bavel et al., 1967); water use for lemon was about 20% higher than oranges (Wright, 2000); while Giambelluca et al. (2003) reported higher transpiration of many species during wet period compared to dry-wet transition period.

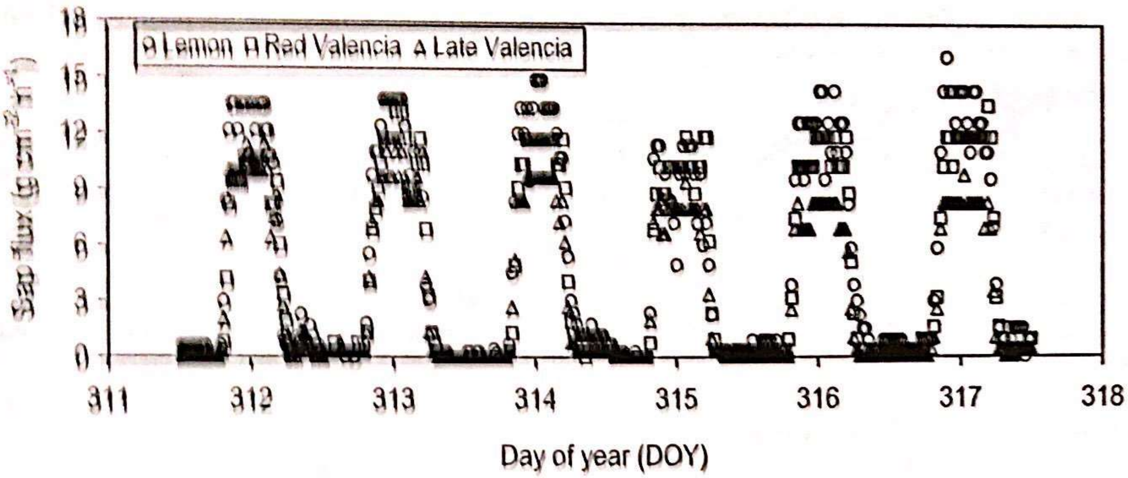

Figure 1. Diurnal pattern of sap flux for Lemon, Red Valencia and Late Valencia for six days in November 2002.

Table 3. Mean difference (M_D) comparison for half-hourly sap velocity values for five bright days each for observation periods I-III and six days of variety effect on water use.

Period of observation effect					Variety and Species effects				
i	*j*	M_D (*i-j*)	P	*Rk*	*i*	*j*	M_D (*i-j*)	P	*Rk*
I	II	-1.094	0.043	*	LM	RV	0.642	0.352	*NS*
	III	-0.078	1.000	NS		LV	1.519	0.001	*
II	III	1.016	0.069	NS	RV	LV	0.877	0.097	*NS*

*P; significant at 0.05 level, *NS*: not significant, *Rk*: remark, LM: Lemon, RV: Red Valencia and LV: Late Valencia. Mean separation by *Bonferroni* test.

Sap flow was correlated with atmospheric forcing variables for the three periods (Table 4). The results indicate that sap flow is responsive to variations in solar radiation (S_R), air temperature (T_a), relative humidity (R_H), wind speed (W_S), and wind direction (W_D). The transpiration from the three varieties has higher correlation values with R_S, T_a, and R_H than with corresponding W_S and W_D. However, they were all highly corrected at $P<0.001$ levels. Similar highly correlated values were observed for periodic study except for wind direction during period I ($P = 0.021$) and period II ($P = 0.422$). This suggests that W_D does not affect citrus transpiration significantly during period II probably because heterogeneity of surface moisture in the orchard surroundings does not vary much during this very wet period, such that advected air from various directions produced similar effects on transpiration. Negative correlations between W_D and E_c were recorded during the wet-dry transition (period III and variety experiment, Table 4). This may also be interpreted with regards to increasing surroundings moisture heterogeneity during this period such that moist air advected from the brook and swamp, located about 1 km away to the southeastern part of the orchard, influenced transpiration rates at certain times of the day. Although, quantifying the effect of advection on evaporation is not easy as it may occur on different scales and the process is not well understood (Zhang et al., 1999), the inspection of diurnal wind data showed systematic shifts in wind direction mostly between southwesterly and northwesterly, which seems to favor influx of moisture laden air into the orchard during the shifts. Study with eddy correlation over a nearby cashew orchard, during the same wet-dry transition, showed footprint extending beyond 1 km at some time of the day (Oguntunde et al., 2004). To further show that W_D had impact similar to R_H on E_c during period III, relative humidity that obviously has inverse relation with transpiration was correlated to wind direction. Periods I and II had negative and very low correlations (-0.122 and –0.026) while period III had relatively high and significant correlation (0.519) at $p < 0.05$.

Table 4. Correlation of half-hourly sap flux density with meteorological variables for periods I-III and citrus spp. or variety effect experiment.

Meteorological variables	Correlation coefficients (r)					
	I	II	III	Lemon	Red Valencia	Late Valencia
Solar radiation	0.909	0.894	0.914	0.905	0.898	0.913
Air temperature	0.769	0.870	0.919	0.889	0.918	0.904
Relative humidity	-0.779	-0.906	-0.890	-0.861	-0.911	-0.871
Wind speed	0.300	0.618	0.301	0.533	0.478	0.494
Wind direction	0.118[a]	0.034[b]	-0.322	-0.398	-0.363	-0.391

[a]r is significant at 0.05 levels; [b]r is not significant at 0.05 levels; while r is significant at 0.001 levels for all other pairs.

3.2 Regulation of Citrus Transpiration

Canopy transpiration showed maximum daily values ranging from 0.3 to 0.34 mm h^{-1} according to the climatic demand prevailing during the observation periods. Transient responses of E_t to the environmental conditions (VPD and S_R) are shown in Figure 3. Transpiration was highly related to both VPD and S_R with hysteresis loop more pronounced in period I. Over the three periods, the relationship between E_t and VPD showed distinct plateau-type curves indicating stomata closure at high VPD (between 1 kPa and 3 kPa).

Citrus canopy conductance (g_c) was estimated by inverting the Penman-Monteith equation following previous studies (Granier et al. 1996; Lu et al., 2003; Ogunlumde and van de Giesen, 2005). Figure 3 shows the diurnal relationship between g_c and climatic demand (VPD and S_R). During the peak rainfall, period II, mid-morning maximum value reached 10 mm s^{-1} while it was around 7.5 mm s^{-1} during the transition periods. A decrease in g_c was generally observed as VPD increases beyond certain threshold values. The observed pattern have been reported for other species e.g. natural forest (Granier et al. 1996) and grapevines (Lu et al., 2003). It should also be noted that the range of VPD also varied with the observation periods (Figure 3) with dry-wet transition period showing higher humidity deficit.

From Figures 2 and 3, it is easy to deduce that citrus transpiration begins in the early morning and reached its peak value between 0830 and 1000 local time in response to incoming solar radiation. Thereafter, light saturation was reached with complete stomata opening at S_R value ca 350 W m^{-2}. Thus, the increase in E_t recorded at higher values of S_R did not result from stomata opening but from an increase in VPD (especially below 1.2 kPa), which increased the driving force for transpiration. Orange was able to maintain a near constant transpiration despite the increasing evaporative demand, by regulating its stomata aperture. Habermann et al. (2003) reported a decrease of more than 50% in leaf conductance of sweet orange when VPD was raised from 1.2 kPa to 2.5 kPa in a controlled environment. Diurnal stomata conductance values reported for 'Valencia' orange in South Africa (Moreshet and Green, 1984) ranged from 0.2 - 16 mm s^{-1}. These are, within the limits of porometer and sap flow measurement errors, comparable to our estimates. The range of daily citrus conductance, directly estimated as well as climatologically obtained values in summer, was 1.0 - 4.0 mm s^{-1} in Arizona (van Bavel et al., 1967). This is in good agreement with the daily values shown in Figure 4.

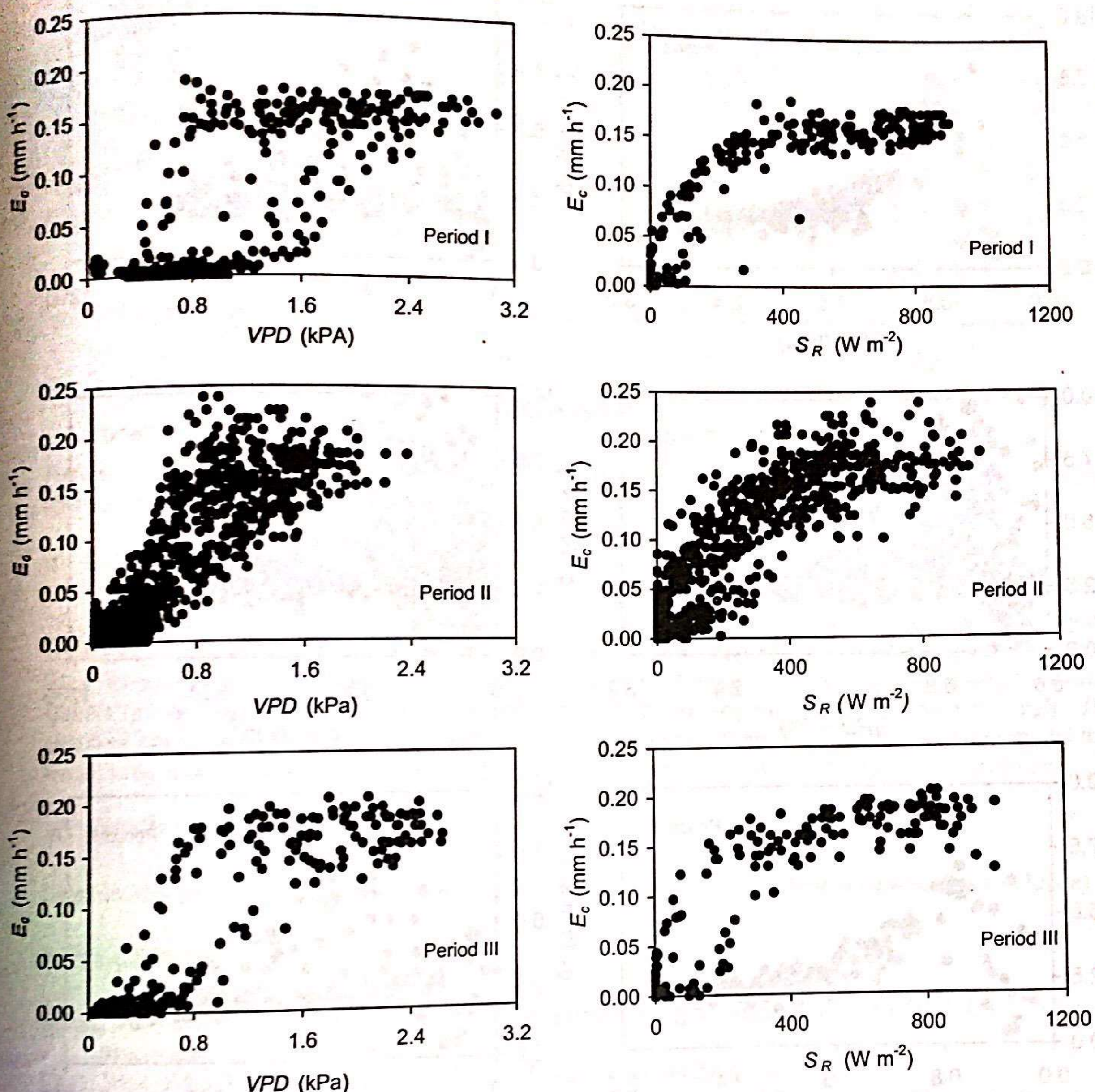

Figure 2. The dependence of canopy transpiration (E_c) on meteorological conditions: solar radiation (S_R) and vapour pressure deficit (*VPD*) during periods I-III, 2002.

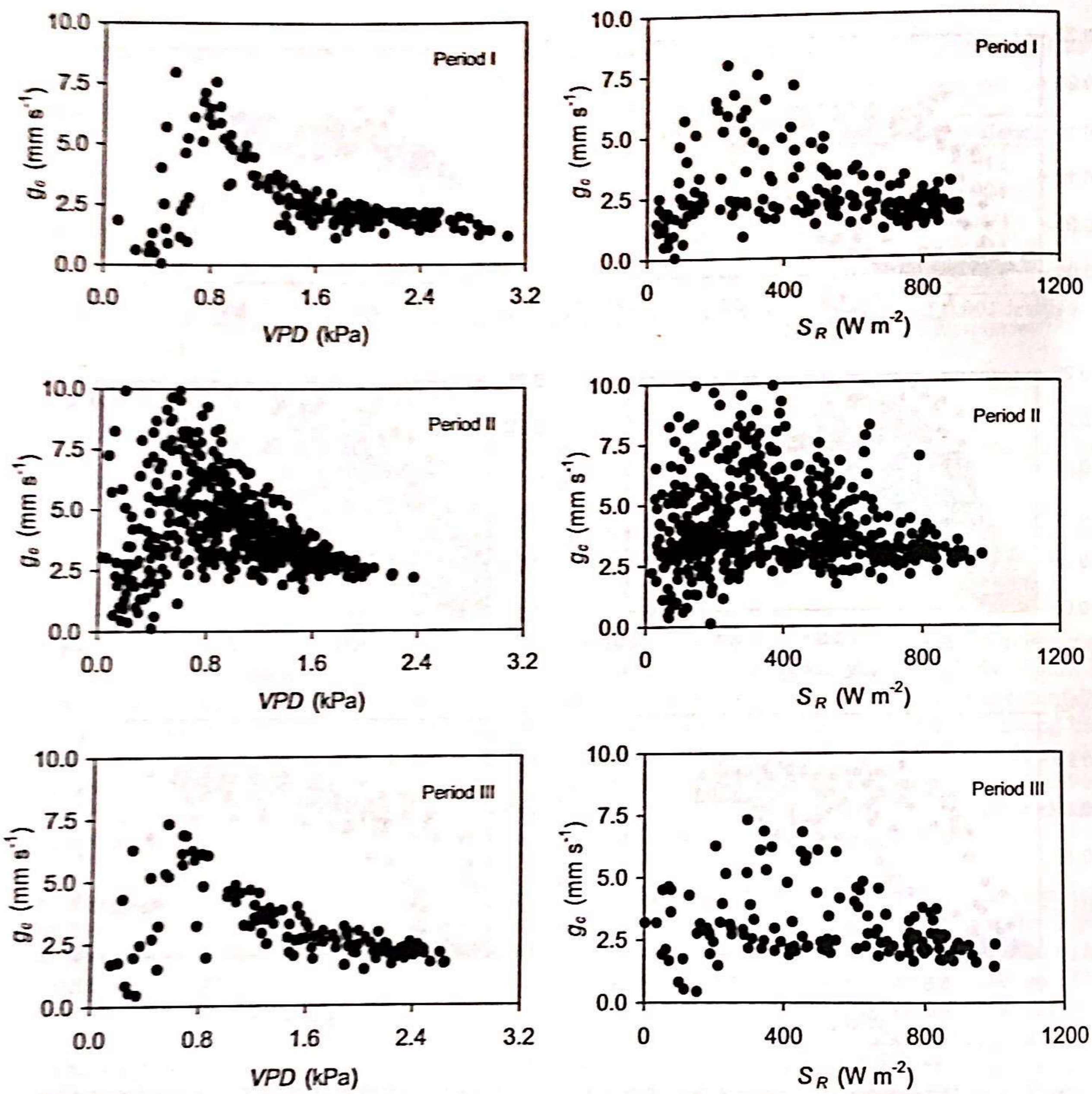

Figure 3. Response of orange canopy conductance (g_c) to solar radiation (S_R) and vapour pressure deficit (*VPD*) during periods I-III, 2002.

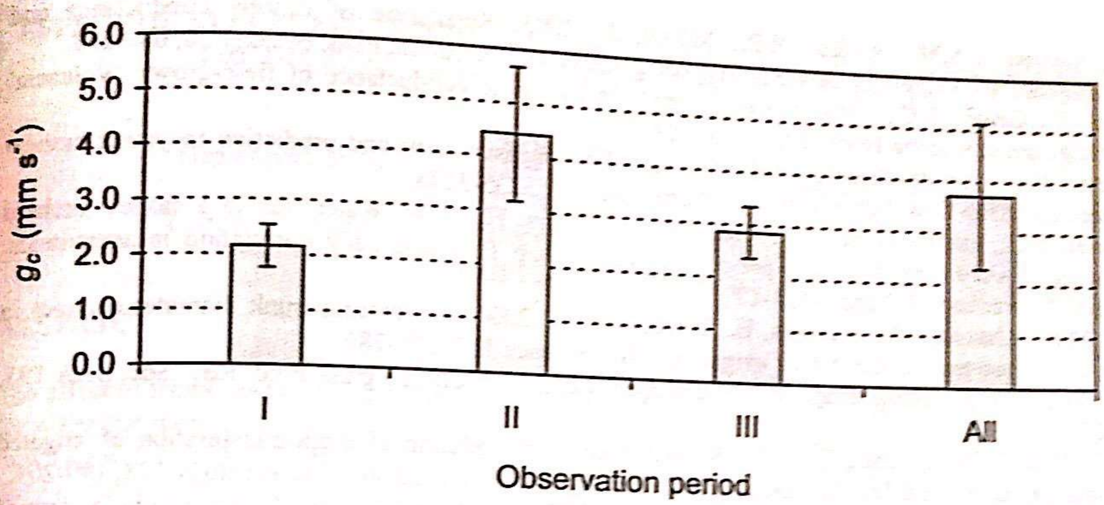

Figure 4. Growing season ranges of canopy conductance (g_c) of the rainfed citrus orchard. The vertical spike is one standard deviation.

4. CONCLUSION

This result demonstrated that sap flow data are useful to investigate physiological and eco-hydrological responses of rainfed citrus orchard during transition and peak rainfall periods of the growing season. Wind direction played a significant role, similar to that of relative humidity, during the wet-dry transition. Generally, the dependence of citrus transpiration on meteorological variables was very high. The observed good relationship should be useful in parameterising a simple Valencia transpiration model that would help in predicting water use of orange in this area. This is the subject of a forthcoming article.

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