Sap flow scaling and crop coefficient of dry-farmed olive orchards converted to irrigation

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Abstract

Tree water uptake is often estimated based in a crop coefficient k_c, a ratio of the tree water uptake and a reference evapotranspiration, *ET0*. The concept behind estimating tree crop coefficient implies that data should be representative of the population of trees analyzed. Ideally it would require the monitoring of a large number of trees in each treatment population. This paper reports on a scaling method to establish stand-level transpiration estimates and crop coefficients from individual sampled tree sap flow measurements. The scaling technique was implemented for individual tree sap flow measurements on the following irrigation treatments: A, fully-irrigated; B, irrigated to provide for approximately 60% of crop evapotranspiration; C, irrigated to provide for 100% of crop evapotranspiration during three critical phase periods: before-flowering, at beginning of pit-hardening and before crop-harvesting, and dry-farming treatment D. Results show that stand transpiration *T* depart from individual tree transpiration values. They consequently were used to establish crop, k_c and water stress, k_s coefficients to account for the cluster's characteristics and degree of tree's water uptake. Using the individual tree transpiration rates would be less appropriate.

INTRODUCTION

Crop coefficient methods are based on an engineering approach that is widely recognized in irrigation agriculture. The core of these methods is the determination of a crop transpiration coefficient, *ks* which represents the evapotranspiration of a given crop, *T* as a proportion of the evapotranspiration, *ET0* of an ideal (reference) crop grown under no limitation of water and nutrients (Allen et al. 1998). *ET0* is derived from meteorological data providing a generally accepted measure of the local atmospheric water demand. The crop coefficient, once established for an ideal water supply and validated for local conditions, can provide for an easy method to determine tree irrigation needs. The objective of this work was to use individual tree sap flow measurements to derive stand transpiration by a scaling up technique, and estimate crop and water stress coefficients to support the irrigation management of olive trees of cv. Cordovil grown in Southern Portugal.

MATERIALS AND METHODS

An 80-plus year old dry-farmed olive orchard planted on a 12 x 12 m spacing layout was used in the experiment. Sap flow rates and transpiration of a representative tree in each irrigation treatment was obtained from implanted heat pulse probes at three different positions around the trunk and by using the compensation heat pulse technique (CHP) described in Green & Clothier (1988) and Green et al. (2003). *ET0* estimates for the site where derived from the recommended by FAO Penman-Monteith combination equation (Allen et al. 1998).

Sap flow scaling and orchard transpiration

Stand transpiration *T* for each irrigation treatment was calculated based on individual tree sap flow, total sapwood area, *SWA* and total canopy area of the treatment cluster of trees. The total canopy area of the cluster of trees in each treatment was estimated from average values taken from a sample of eleven randomly chosen trees multiplied by their total number. The sap flow rates were recalculated to determine the sap flow rate of the tree cluster for each treatment. For the purpose of scaling, the sapwood section of the trunk quantified as an area, i.e. sapwood area, *SWA* was obtained in each individual tree by considering the average sapwood depth as the section visually identified with a light colouration from a set of three core samples extracted with a 150mm *Suunto* increment core borer. The total sapwood area of all trees in the stand was determined considering a set of nine randomly chosen trees of different trunk diameters where a linear relationship was observed between trunk diameter and the sapwood area, thus a linear equation was established defining total sapwood area, *SWA* in m^2 as a function of the trunk diameter, t_{di} in m

$$SWA = 0.1702\, t_{di} - 0.0076 \qquad (1)$$

Each sampled tree equipped with sap flow probes had its sapwood radial profile equipped with three probes with four thermocouple sensors each placed at 5, 12, 21 and 35 mm depth. Considering the average of the three probes in each tree, the total sap flow *Js* is computed as

$$Js = V_1\, SWA_1 + V_2\, SWA_2 + V_3\, SWA_3 + V_4\, SWA_4 \qquad (2)$$

where *Js* is the total sap flow rate in m^3/h; V_n is the average corrected sap flow velocity at thermocouple sensor *n* in m/h; SWA_n is the sapwood area corresponding to the thermocouple sensor *n* in m^2 and *n* is the number subscripts at the four thermocouple sensor positions. The total sap flow rate of the stand Js_{stand} in m^3/h in each treatment is now divided by the total sapwood area of the measured tree (*SWA)* and multiplied by the total sapwood area of the tree stand, SWA_{stand}

$$Js_{stand} = (Js / SWA)\, SWA_{stand} \qquad (3)$$

To obtain the transpiration *T* in L/h of the hypothetical tree representing the average of the cluster in each treatment, the total sap flow of the stand Js_{stand} in m^3/h is multiplied by 1000 to convert it to L/h, then divided by the canopy area A_{cm} in m^2 of the tree where sap flow was measured and multiplied by the average canopy area of the trees in the cluster A_{cc} in m^2

$$T = (1000\ Js_{stand})(A_{cs}/A_{cm}) \quad (4)$$

The daily transpiration *T* in L/day was then determined by integrating in time the 30 minute-interval measurements provided by the sap flow probes, consisting in a total of 24 measurements per day. Only day light data was used in the calculations, to be sure that radiation was not a limiting factor.

$$T = \sum_{n=1}^{47} \left(0.5 \left(\frac{T_n + T_{n+1}}{2} \right) \right) \quad (5)$$

The daily transpiration *T* in L/day was converted to ground-area based transpiration *T* in mm/day dividing T by the total canopy area of the olive tree population A_{ct} in m^2

$$T \text{ (mm/day)} = T \text{ (L/day)} / A_{ct} \quad (6)$$

Crop and water stress coefficient

Reference evapotranspiration, *ET0* is strictly a measure of the capacity of the atmosphere to influence water loss from an ideally vegetated surface that is subject to no resource limitations (Allen et al., 1998). The goal of establishing *ET0* is to have a reference value of evapotranspiration for a given location against which the evapotranspiration of any crop can be related. *ET0* is related to the evapotranspiration of a crop as follows:

$$kc = ET_c / ET0 \quad (7)$$

where *kc* is crop transpiration coefficient, ET_c is crop evapotranspiration, and *ET0* is reference evapotranspiration. Both *ET0* and ET_c are obtained under optimum conditions. Therefore, k_c parameters are dictated by how different a crop responds to the weather in relation to the reference crop. When k_c for a given crop is known, it is used together with *ET0* to calculate the irrigation requirements or evapotranspiration (ET_c) of the crop. Due to negligible soil evaporation in the drip irrigated treatments, crop coefficient k_c is defined in this work as:

$$k_c = T/ET0 \quad (8)$$

Under the deficit irrigation water treatments, adjustments for low soil water available involved the determination of k_s, a water stress coefficient that was used to modify k_c and to calculate and adjust *T* for water stress condition (Allen et al, 1998) as

$$T = k_c\, k_s\, ET0 \quad (9)$$

The value of k_s ranges between zero and one. When there is adequate soil water available, no stress is imposed in plants and k_s equal 1. Stand-level transpiration estimates from scaling sampled individual trees was used to calculate *T* values for each treatment, A, B, C and dry-farming.

RESULTS AND DISCUSSION

Stand transpiration rates were higher for treatment B and distinct from treatment A that received approximately 40% more water throughout the growing season. A marked decline in sap flow values for treatment C was observed during the peak of summer drought following the irrigation events in July (Table 1). Table 2 gives account on the accumulative stand transpiration values for each treatment, with a total of 704 mm for treatment A, 745 mm for treatment B, 638 mm for treatment C and 404 mm for treatment D. Individual tree transpiration reported in Table 1 were 657 mm for treatment A, 599 mm for treatment B, 726 mm for treatment C and 373 mm for treatment D.

Table 3 shows the average *T/ET0* throughout the irrigation season calculated for each treatment A, B, C and dry-farming, to account for each stand characteristics and water applied. Larger *T/ET0* values occur in March and April when the moisture stored in the soil from winter rains and first irrigation events (Fig 1. and Table 1) is still high. As drought from summer months occurs, olive trees slow down their physiological mechanisms to conserve water and reduce their *T/ET0* ratio, regardless of water applied. Because of their secular adaptation to water limitations, olive trees typically display high resistance to transpiration. Accordingly, despite the large amount of water applied to treatment A, *T/ET0* ratio declined regardless throughout summer, to values as low as 0.6. Also treatment B that received the amount of water necessary to compensate for transpiration showed a similar decline in *T/ET0* values during the same months, but with slightly higher values than treatment A.

Table 4 presents the monthly estimates of k_s water stress coefficient for the water deficit treatments C and D, obtained as the ratio of *T/ET0* to corresponding *T/ET0* values of the well-irrigated treatment B. Monthly estimates of k_s water stress coefficient confirm the steadily decline in transpiration rates of treatment C from its June value of 96% of treatment B to 39% by September. Irrigating treatment C helped sustained soil water stress to values close to 77% of treatment B in the month of June and to 52% in August. Nevertheless, trees satisfied most of their atmospheric evaporative demands by extracting water from the larger volume of soil in the 12 x 12 m tree spacing outside of the drip irrigation emitter wet bulb. The dry-farmed treatment that beneficiated from the same amount of rainfall but was not irrigated showed much sharper decline in stress coefficient, with *ks* values of 0.66 in June, 0.44 in August and 0.49 in September.

CONCLUSIONS

Scaled up orchard transpiration based on individual tree transpiration was used to define orchard crop and water stress coefficients. They reflect the structural characteristics of the tree cluster in each treatment and the irrigation regime imposed to treatments. Estimated crop coefficients show that as summer drought occur, olive trees slow down their physiological mechanisms to conserve water and regardless of the water applied they reduce *T/ET0* ratios. During this resting phase applying water in excess of needed to sustain tree transpiration, as for treatment A, is inefficient for vegetative growth and carried losses from soil evaporation. Transpiration rates closely matching crop evapotranspiration obtained from soil water balance estimates (data not reported) recommend taking treatment B derived crop coefficients as more appropriate for scheduling irrigation of cv. Cordovil orchards in Southern Portugal. Applying irrigation to treatment C helped sustain orchard transpiration to 67% of treatment B in July and to 55% until mid August, fact also supported by the monthly estimates of *ks* soil water stress coefficient. Nevertheless, with treatment C irrigation accounting for 11% of the 638 mm total transpiration and the surplus extracted by roots in the large volume of soil in-between tree spacing, using the derived k_c and k_s to schedule irrigation of olive trees seems appropriate only in wet years of well distributed late summer rainfall. In general, and more so in years of no summer and early autumn rains, the irrigation regime of treatment B seems more appropriate for scheduling irrigation of olive trees in Southern Portugal.

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Tables

Table 1. Accumulated values of rainfall, reference evapotranspiration *ET0*, irrigation and transpiration from individual tree sap flow measurements for each treatment, mm.

Start	End	ET0,mm	Rainfall, mm	Irrigation ,mm			Transpiration from sap flow, mm			
				A	B	C	A	B	C	Dry-farming
18-Mar	31-Mar	33.5	44.4	4.7	2.4	3.2	22.7	21.9	34.7	19.0
01-Apr	15-Apr	45.0	19.9	4.7	2.4	3.2	31.9	33.0	49.2	22.6
16-Apr	28-Apr	41.4	9.8	15.8	8.1	0.0	31.3	33.5	46.6	22.8
29-Apr	12-May	58.6	0.0	33.2	16.5	22.6	42.7	39.5	63.5	26.8
13-May	26-May	73.0	0.5	42.7	21.8	6.5	41.5	35.0	63.0	22.8
27-May	09-Jun	79.0	0.0	47.4	24.2	0.0	43.8	39.0	60.5	17.6
10-Jun	24-Jun	79.0	49.2	39.5	20.1	0.0	46.7	43.8	59.5	10.6
25-Jun	06-Jul	69.8	0.0	44.2	22.6	22.6	38.9	37.5	45.5	34.0
07-Jul	19-Jul	82.3	11.5	79.0	40.3	10.8	46.5	47.1	55.7	28.1
20-Jul	03-Aug	97.3	0.0	113.8	58.0	0.0	56.6	55.6	52.2	30.4
04-Aug	17-Aug	84.6	13.1	110.6	56.4	0.0	53.6	52.1	40.7	27.3
18-Aug	09-Sep	124.7	2.3	178.6	91.0	0.0	84.0	88.6	59.0	44.0
10-Sep	25-Sep	61.7	22.2	75.8	38.7	0.0	55.2	72.7	48.3	28.1
26-Sep	20-Oct	72.2	67.5	90.1	45.9	0.0	61.7	N/A	47.1	38.5

Table 2. Stand transpiration *T* estimated, mm from sap flow measurements in individual trees. Results estimate transpiration of hypothetical olive tree for each treatment representative of the average structural characteristics of the cluster.

Start	End	Treatment			
		A	B	C	Dry-farming
18-Mar	31-Mar	24.0	28.6	31.4	20.6
1-Apr	15-Apr	33.6	43.2	44.6	24.4
16-Apr	28-Apr	32.9	43.8	42.3	24.4
29-Apr	12-May	44.8	51.5	57.7	28.5
13-May	26-May	43.6	45.5	57.3	24.3
27-May	9-Jun	46.0	50.8	55.2	22.1
10-Jun	24-Jun	48.9	57.1	54.3	12.3
25-Jun	6-Jul	40.8	48.8	41.6	40.4
7-Jul	19-Jul	48.7	61.1	50.7	30.1
20-Jul	3-Aug	55.1	67.2	44.9	30.3
4-Aug	17-Aug	56.1	67.7	37.3	29.0
18-Aug	9-Sep	87.9	115.6	54.2	46.8
10-Sep	25-Sep	56.5	64.3	23.2	29.7
26-Sep	20-Oct	84.8	N/A	43.4	40.6

Table 3. Monthly k_c , estimated as *T/ET0*, the ratio between scaled transpiration for each treatment, mm/day and Penman-Monteith *ET0*, mm/day.

	A	B	C	Dry - farming
Mar	0.75	0.92	0.88	0.65
Apr	0.80	1.02	1.03	0.59
May	0.69	0.73	0.88	0.40
Jun	0.61	0.70	0.67	0.46
Jul	0.60	0.74	0.57	0.39
Aug	0.67	0.84	0.44	0.37
Sep	0.91	1.01	0.39	0.49
Oct	N/A	N/A	1.04	0.70

Table 4. Monthly water stress coefficient k_s for treatment C and D obtained as the ratio of their *T/ET0* estimates (table 3) to corresponding *T/ET0* values for the well-watered treatment B.

	C	Dry - farming
Mar	0.96	0.70
Apr	1.00	0.59
May	1.20	0.55
Jun	0.96	0.66
Jul	0.77	0.53
Aug	0.52	0.44
Sep	0.39	0.49
Oct	1.00	0.70

Figures

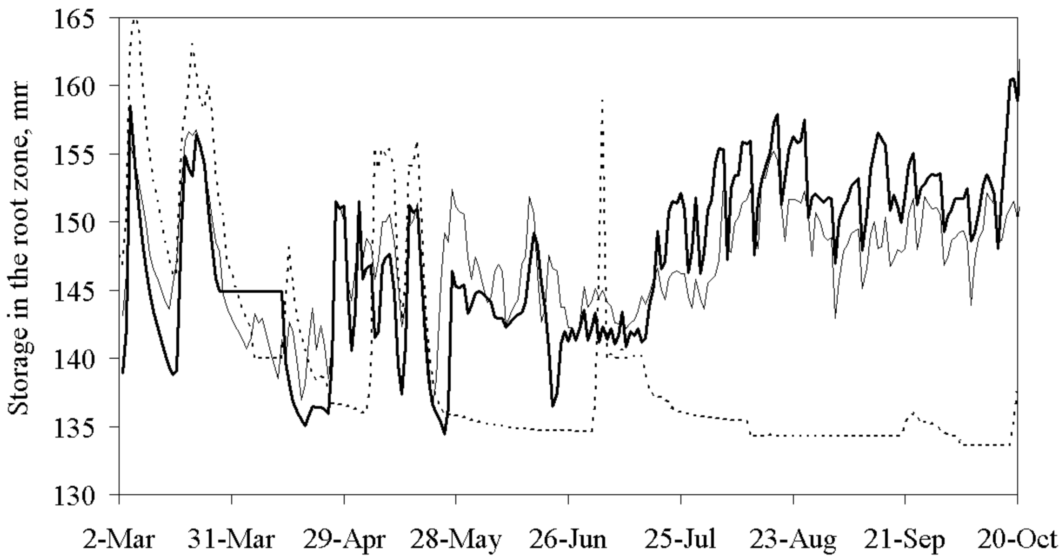

Figure 1. Water storage in the root zone computed with watermark sensors for each treatment: treatment A, ━━; treatment B, ——;treatment C, - - - .