Transpiration reduction as an answer to water stress: models versus measurements for irrigated olive trees in South Portugal

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Abstract

The so-called stress functions, allowing quantification of transpiration or evapotranspiration reduction, as an answer to water deficit stress (stress coefficient, Ks), are useful tools for irrigation scheduling. It is known that this coefficient depends on several variables and parameters, such as evapotranspiration rate, root patterns/density and soil properties. However, the most common Ks models with practical applicability do not include some of these factors and the experimental work on this matter is not abundant. A well-known model proposed in the FAO 56 manual uses two parameters: the allowable depletion (p) and the total available soil water (TAW) in the root zone, the input variable being the soil water depletion (SWD). We discuss the application of this model in olive trees under specific natural conditions. Two studies were conducted in Alentejo, South Portugal (2011 and 2017), in one intensive and one super intensive drip irrigated olive orchards (*Olea europaea* 'Arbequina'). Transpiration reduction was obtained from sap flow measurements. For both experiments, Ks was related to the estimated SWD. The experimental relationship was compared with modelling outputs. Experimental results show that, in both experiments, the Ks FAO 56 model only fits using parameters such as p= 0.05 and TAW = 350 mm. The suggested p in that manual is 0.7. Furthermore, for such soils, anisotropic canopy and small wetted area (drippers), 350 mm is much more than first approach estimates would suggest. The results can be related with the root system functioning and resilience of olive trees.

Keywords: *Olea europaea*, modelling, Alentejo, roots, irrigation scheduling

INTRODUCTION

The relative reduction of evapotranspiration (ET) or transpiration (Tr), as an answer to imposed water deficit stress, henceforth called water stress, can be expressed by 1-Ks. Ks, the so-called stress coefficient, is applied either to ET or to Tr to estimate actual evapotranspiration (ETa). In the following, we consider Ks' or Ks (Equation 1) as similar for the purpose of simplification. Ks is used when ETa is lower than crop evapotranspiration (ETc), here defined as the maximum ET of a crop (comfort, no stress).

$$ETa = Tr + Es = ETo\,(Kcb \times Ks + Ke) = ETo\,Kc\,Ks' = ETc\,Ks' \qquad [1]$$

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where Ke is the relationship between soil evaporation (Es) and reference evapotranspiration (ETo) and Kcb is the relationship between Tr (no water stress, Ks=1) and ETo.

Assuming Ks function is the relationship between Ks and any water status indicator, for most purposes the input variable quantifies the water status and the output is Ks. In this sense, stress functions are used to estimate Ks, when scheduling deficit irrigation. When using estimated water balance to get soil water status, or when it is directly measured, soil water deficit (SWD) is a convenient input variable.

The parameters of any specified Ks function depend mainly on ET rates, soil root density and distribution (Ferreira-Gama, 1987; Ferreira, 2017). However, experimental studies on such functions are scarce. In general, Ks is estimated with simple models. A well-known model is described in FAO 56 (Allen et al., 1998), according to eq. 2:

$$Ks = (TAW - SWD) / (TAW - p.\ TAW) \quad [2]$$

where the only variable is SWD, estimated from daily ETc, and the parameters are total available water (TAW) and allowable depletion factor (p) = RAW/TAW, being RAW the readily available water (Figure 1).

For engineering applications, the value of p is considered to depend on the crop. This concept has been used at least since the 1950s. In the revised FAO Irrigation and Drainage paper n. 24 (Doorenbos and Pruitt 1977, p. 84 and Table 39, later enlarged in Allen et al., 1998, table 22), it was defined as the fraction of available soil water permitting unrestricted evapotranspiration. The same definition is used here. This concept has suffered from misunderstandings, due to some practical applications in irrigation design where it has been considered as a management parameter.

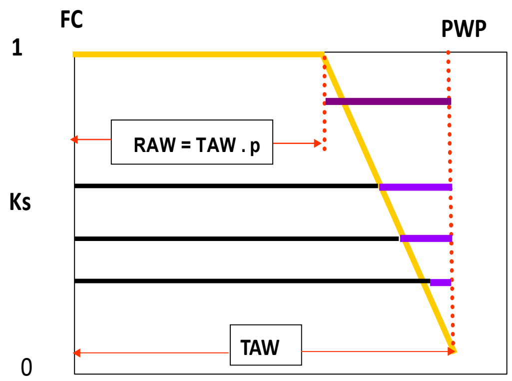

Figure 1. Stress coefficient (Ks) as a function of soil water status between field capacity (FC) and permanent wilting point (PWP) (marked on the right the terms used in eq. 2).

The aim of this study is to compare the experimental results obtained in two irrigated olive orchards and the outputs from the model described above.

MATERIALS AND METHODS

Experimental observations occurred in two olive orchards (*Olea europaea* 'Arbequina'), in South-East Portugal, both about 30 km from Beja. The first in an intensive olive grove and the second in a super intensive olive grove. The climate is temperate with warm and dry summer (Csa, one of the Mediterranean type climates, Köppen-Geiger Classification). The average annual precipitation is 572 mm according to the climatic data provided by the synoptic station at Beja, 30 km distant from the plot, 1971-2000 (IPMA, 2016).

Trees of the first experiment (Figure 2a) located near Ferreira do Alentejo had the following characteristics: 7-years old, drip irrigation, 300 trees/ha, LAI between 1.01 in 2010

(Häusler et al., 2014) and 1.61 in 2012 (Tezza et al., 2019), ground cover ≈ 20%, height between 3.2 and 3.5 m (Conceição et al., 2017).

ET was measured with eddy covariance micrometeorological method and soil evaporation (Es) with a combination of small lysimeters and modelling. Sap flow was obtained by means of the so-called *Granier* technique with slight modifications. Sensors (UP, Ibbenbűren, Germany) and heating system (Mezão, Oeiras, Portugal) were connected to a CR3000 data logger. Transpiration (Tr) was obtained by using the relationship between the difference ET-Es, both terms independently measured as above, and sap flow measured in the main large plot. This step was necessary due to underestimation of sap flow in relation to Tr. This correction provided a long term, reliable data series (Conceição et al., 2017).

The orchard was irrigated (drippers spaced 0.75 m) almost on a daily basis. There were no roots visible in the C2 horizon (1.7 - 2.3 m) and below (Conceição et al., 2017). The total available water (TAW, mm), defined as the water storage in soil between its field capacity (FC) and its permanent wilting point (PWP) both observed in loco, would be 138 mm (for root depth z = 1.2 m), assuming the entire area as uniformly colonized. However, this uniformity in horizontal direction is unlikely in this spatial organization (4.7 m × 7 m) and for trees that are these young. Therefore, this value of 138 mm is the maximum possible TAW assuming such root depth.

The second study was near Serpa, in a super intensive olive orchard (37º56'51''N, 7º31'38''W, 219 m asl, Figure 2b) during summer 2017. The following characteristics apply: 10-years old, drip irrigation, spacing between trees 3.75 m × 1.35 m (about 2000 trees/ha), canopy height and width 2.7 m and 1.5 m, respectively, NDVI = 0.76 (Sentinel 2 imagery, August 2017). Drip irrigation is used with drippers spaced 0.75 m and a flow rate of 2.3 L/h.

Sap flow was measured on 6 trees per plot. The main plot was deficit irrigated following the farmer's current practice while, for two small plots, a stress cycle was managed as described below. Relative Tr was evaluated directly from sap flow rates, simplifying by assuming a nearly linear relationship between ET-Es and sap flow. Due to the nature of the soil, there were no soil water content measurements in this experiment. Soil water depletion was approximated using the cumulated ETa obtained from eq. 1 with parameters derived from Conceição et al. (2017) and unpublished results.

A stress cycle was induced for about six weeks for the first location (Ferreira et al. 2012), and two stress cycles for the second (a first from July 27 to August 14 and a second from September 1 to 21), with one plot well irrigated (comfort) and one plot without any irrigation throughout the cycle.

Figure 2. Olive orchards of the first experiment (a, left), view from eddy covariance tower in July 2013, at Monte do Pardieiro farm (Ferreira do Alentejo) and of the second experiment ((b, right), sap flow sensors visible, 2017, at Herdade Maria da Guarda (Serpa), Portugal.

RESULTS

The experimental stress function obtained in the first study (Ferreira et al., 2012; Ferreira, 2017) shows a 10%-reduction of transpiration, when SWD or cumulated transpiration since irrigation to FC was 40 mm (Figure 3). Similar results were obtained in the second orchard (not shown). In figure 3, values clearly above the line are linked to cloudy days and cumulated precipitation events of 7.7 mm. Thus, after these events ΣTr would be 7.7 mm above SWD.

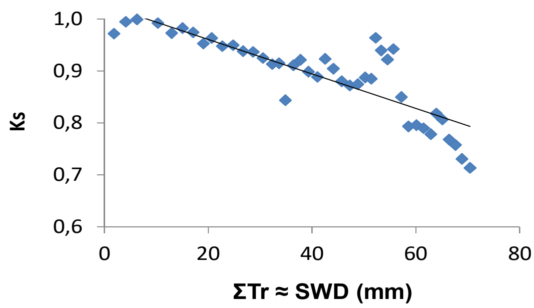

Figure 3. Experimentally obtained stress function, for a stress cycle between Aug. 3 (DOY 215) and Sept. 15 (DOY 258) derived from Ferreira et al. (2012). The line was manually adjusted.

This function provides a reference for comparison with the outputs from simulations from the simple model expressed by equation 2, for different parameters (Figure 4 and 5).

When representing SWD in XX´ axis, each family of lines corresponds to a fixed value of p. As an example, we present outputs for p= 0.8 (Figure 4), a value similar to the 0.7 proposed by Allen et al. (1998) for this crop (without adjustment for ETc).

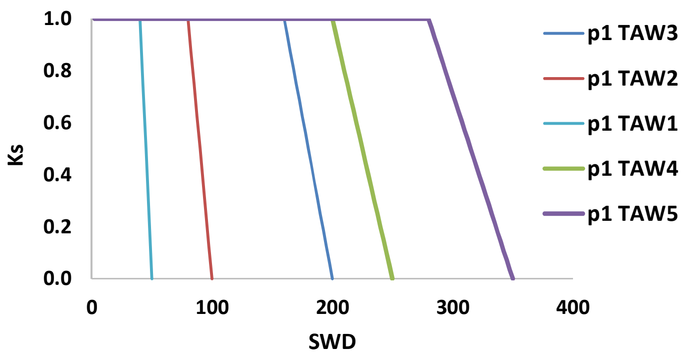

Figure 4. Ks simulation for p1 = 0.8 and TAW1 to TAW5 (respectively 50, 100, 200, 250 and 350 mm).

However, when SWD is expressed as percentage of TAW (XX’ axis), Ks lines appear independent of the value used for TAW (e.g. p1 TAW1 = p1 TAW2, as shown, Figure 5). None of the lines presented in figure 5 closely reflected experimental results except the combination of p5 and TWA5, i.e., p = 0.05 and TAW = 350 mm. Only then, the function obtained by the simple model described above approximates the experimental stress function (Figure 6).

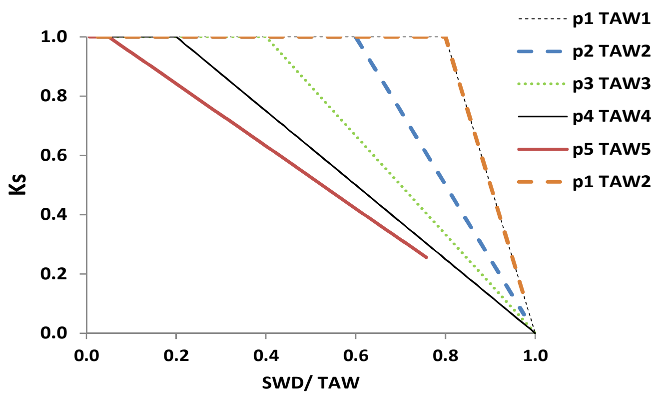

Figure 5. Ks simulation for different depletion factor values (p1 to p5, respectively 0.8; 0.6; 0.4; 0.2; 0.05) and different values of total available water (TAW1 to TAW5, respectively 50, 100, 200, 250, 350 mm) with SWD expressed as a fraction of TAW.

In conclusion, there are two important differences between the parameters taken from manuals and those experimentally observed. First, the value of p for olive trees in table 22 (Allen et al., 1998, page 165) is 0.65, while the observed value was 0.05. Second, the value for TAW formerly indicated as an hypothesis for the soil of the experiment (138 mm), similar to the one estimated with z from tables (for GC 40-60%: z =1.2-1.7 m) was considered excessive for the reasons described. However, both still stand far below 350 mm, suggesting z >> 1.2 m.

In other words, the experimental results when stress is imposed showed (1) an extremely low p, suggesting a very early reduction in Tr and (2) an unusual discrete reduction of Tr (very high TAW, 350 mm), as if roots have access to a much larger soil volume than a first observation of the system would suggest.

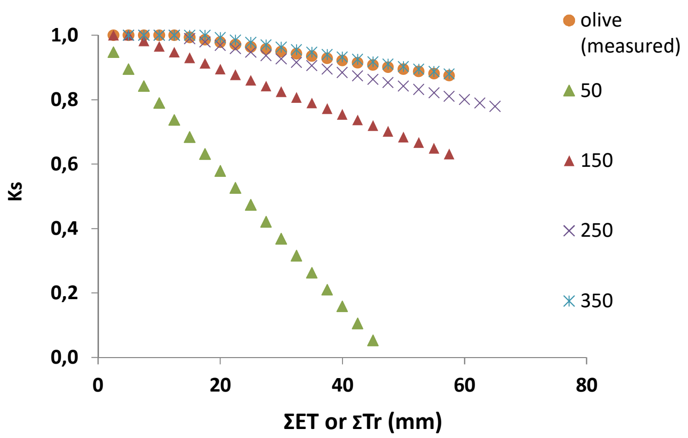

Figure 6. Stress function obtained by FAO model for p5 (p = 0.05) and for different values of TAW (50 to 350 mm) versus experimentally obtained stress function.

DISCUSSION AND CONCLUSION

The adjustment of the outputs for the stress function using the model suggested in Allen et al. (1998) to the experimental observations is possible only by using very disparate parameters from those attributed to the depletion factor (p) in this crop (0.05 versus 0.65). Furthermore, the TAW that enables the model to adhere to the experimental observations (350 mm) supposes a root colonization in the horizontal direction and a root depth largely above those expected considering apparent anisotropy, soil type and irrigation system. However, the discrete horizontal redistribution observed in the first plot (Nadezhdina et al., 2012) and the fact that plants used more water than the total volume of irrigation (unpublished) reinforce these observations giving hints to reconsider the procedure to determine TAW in such cases.

The results are consistent with other indications in the same direction (water balance and hydraulic redistribution, as in Ferreira, 2020). This points out that olive trees initiate a slow and early decline in ET. However, the trees may also explore much deeper soil layers than suggested in the literature, even in the case of young olive groves with localized irrigation. In conclusion:

(1) for irrigation management of olive trees, the FAO model for Ks should be used with special caution when choosing the parameters, mainly p;
(2) the colonization of the soil by the roots is much higher than usually considered in current applications;
(3) the resilience of olive trees to water deficit stress seems partly explained by an increased exploitation of water from larger soil volumes.

ACKNOWLEDGEMENTS

This work was partly supported by the projects WUSSIAAME (PTDC/AACAMB/100635/2008), TELERIEG (SOE1/P2/E082) and WASA (ERANETMED/0006/2014). Fundação para a Ciência e Tecnologia (FCT, Portugal) financed the fellowship SFRH/BD/66967/2009, related with first experiment.

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