Combining soil water balance models and water stress indicators for irrigation scheduling
Case study in Portuguese conditions and its context

After a presentation of the irrigation context in Portugal, the authors of this paper review the robustness of two modelling approaches and their combination to better programme irrigation campaigns at plot scale. Two application cases are presented and discussed: one on a horticultural crop with shallow roots (Capsicum annuum L. 'Pompeo F1') and the other on a woody crop with deep roots (Olea europea 'Arbequina').

Irrigation in Portugal

Context

Although there are significant climatic dissimilarities throughout mainland Portugal, irrigation is always needed to ensure competitive yields in most crops. Figure ❶a depicts extreme situations of average rainfall and reference evapotranspiration (Viana do Castelo, in a northwest costal area and Beja, in an interior south-eastern area). In both cases there is a distinct water deficit situation in late spring and summer, but it is much deeper in the case of Beja.

Along with climatic variation, topographic differences between north and south are obvious (Figure ❶b). Tagus River, running (angle of ≈ 45° with North) from the eastern Spanish border towards the western cost, divides the country in two large regions. North of Tagus River, land is hilly, slopes are steep and soils are shallow, with the obvious exceptions of large river valleys. South of Tagus River, topography is rolling and soil depth tends to be greater.

Paradoxically, population density is greater in the northern region (except in mountain areas) and historically it has always been so. The reason lies upon the smaller and shorter water deficit in the NW, which allows better crop yields. Social and economic asymmetries between north and south deepen further the differences among them: small holder's agriculture prevails in the northern region, as well as family farming. Such strong differences have great consequences on the irrigation subsector, dissuading an analysis of the entire country as a whole. Whenever possible, the adopted analysis' unit will be the so-called Agrarian Region, the former seven-region administrative division applying for agriculture (which has recently been substituted by the NUT II five-region division: North, Center, Lisbon and Tagus valley, Alentejo and Algarve):

- Entre-Douro-e-Minho (northwest);
- Trás-os-Montes (northeast);
- Beira Litoral (coastal center);
- Beira Interior (inland center);
- Ribatejo e Oeste (coastal area near Lisbon and Tagus valley);
- Alentejo; and
- Algarve (extreme south).

Irrigable surface in Portugal has always been less than 25% of Utilized Agricultural Land, and it is now close to 15% (Table ❶). Both Irrigable and Irrigated Surfaces have experienced a noticeable decrease over the past decades.

❶ **Mainland Portugal (left) annual rainfall (less than 600 mm and more than 3,300 mm, with July reference evapotranspiration at Viana do Castelo and Beja, 30th years average) and (right) hypsometric map (up to 2,000 m).**
Source: https://snirh.apambiente.pt/

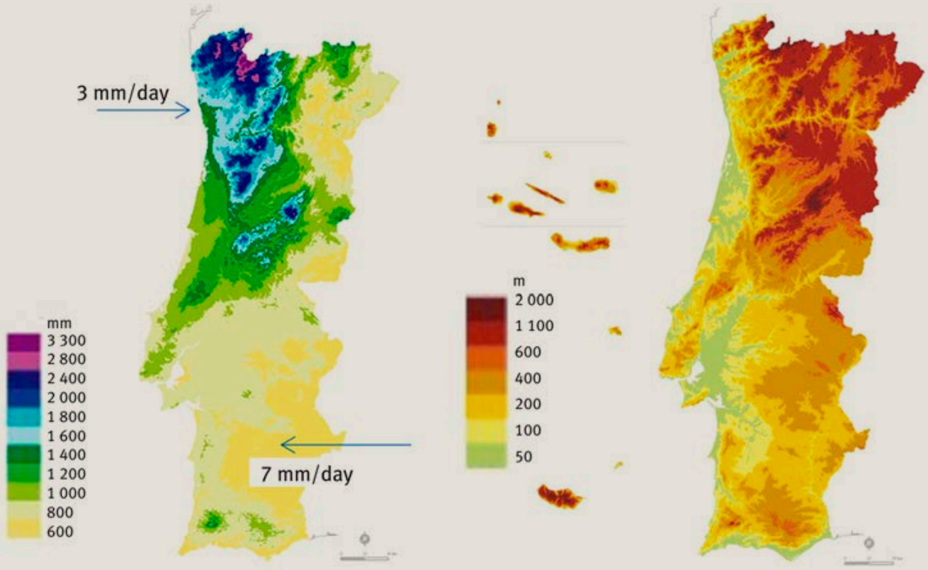


Table ❷ also shows that the option for pressurized irrigation systems is strongly dependent on crop type: 91% of permanent crops (orchards, olive-trees and vineyards) are irrigated by drip-irrigation systems. On the other hand, two thirds of grazing area is irrigated by gravity systems.

It is worth mentioning that the weight of gravity systems as opposed to pressurized systems shows a close relation to small holder's irrigation (Table ❸). Where this is dominant – northern agricultural regions (Entre-Douro-e-Minho and Trás-os-Montes) and Costal Center (Beira Litoral) – gravity systems still dominate, whereas in the southern regions sprinkler and drip irrigation strongly prevail. Cost and availability of water seems to play a role too, which explains that Algarve region, where irrigation relies on groundwater extracted from deep wells, shows the higher pressurized versus gravity ratio, although most area belongs to small-sized farms.

In Portugal, there are 32 major collective irrigation schemes, most of them relying on large storage dams. These schemes were built by public investment and give an important contribution to combat depopulation and foster development. With recent construction of Alqueva irrigation project (120,000 ha), public irrigation schemes had a sharp growth. Yet, most irrigable land still belong to private schemes, either individual, or traditional (Table ❹).

Irrigated crops are much diversified (Table ❺), with a split dominance of corn (17.5%) forage (18.9%) and olive grove (14.2%). Grazing (11.1%) and orchards (8.3%) also play an important role.

❶ **Irrigable Land (Equipped) and Irrigated Land.**

Land use / Agricultural Region	Used Agricultural Land	Irrigable Land (equipped)		Irrigated Land	
	(ha)	(ha)	(%)	(ha)	(%)
Entre Douro e Minho	211,154	94,829	45%	81,858	39%
Trás-os-Montes	432,873	46,666	11%	38,852	9%
Beira Litoral	125,436	61,116	49%	51,314	41%
Beira Interior	337,031	49,580	15%	35,649	11%
Ribatejo e Oeste	391,006	112,539	29%	101,208	26%
Alentejo	1,956,508	155,123	8%	138,231	7%
Algarve	88,297	16,274	18%	16,170	18%
Mainland Portugal	3,542,305	536,127	15%	464,283	13%

❷ **Irrigated land by major crop group and irrigation system.**

Irrigation system / Major crop group	Gravity		Sprinkler and Drip		Total
	ha	%	ha	%	ha
Permanent Crops	12,245	9	123,254	91	135,499
Temporary Crops	99,993	36	177,131	64	277,124
Grazing	34,443	66	17,561	34	52,004
Total	146,681	32	317,946	68	464,627

❸ Irrigated land by agricultural region and irrigation system.

Agricultural Region / Irrigation system	Gravity		Sprinkler and Drip		Total
	ha	%	ha	%	ha
Entre Douro e Minho	46,809	57	35,268	43	82,077
Trás-os-Montes	27,942	70	11,930	30	39,872
Beira Litoral	25,454	50	25,908	50	51,362
Beira Interior	11,084	31	24,575	69	35,659
Ribatejo e Oeste	19,120	19	82,120	81	101,240
Alentejo	14,653	11	12,695	89	138,248
Algarve	1,618	10	14,552	90	16,170
Mainland Portugal	146,680	32	317,948	68	464,628

❹ Irrigated land by private versus collective schemes.

Water Users Associations & Public Irrigation Companies		Private Schemes		Total
ha	%	ha	%	ha
135,300	25	400,827	75	536,127

❺ Irrigated crop distribution.

Crop Type	Area (ha)	%
Wheat	5,770	1.2%
Corn	81,190	17.5%
Rice (Paddy)	29,250	6.3%
Forage	87,807	18.9%
Grazing	51,661	11.1%
Potato	11,834	2.5%
Sunflower	4,093	0.9%
Tomato for Industry	17,943	3.9%
Other extensive vegetables	10,025	2.2%
Vegetables (intensive)	14,654	3.2%
Citrus	15,048	3.2%
Other Fresh Fruits	25,683	5.1%
Olive Tree	65,887	14.2%
Vineyard	25,181	5.4%
Other Crops	20,706	4.5%
Total	**464,731**	**100,0%**

❻ Irrigated indicators by agricultural region.

Agricultural Region / Indicators	Avarage Irrigated Land	Unit Consumption
	(ha/farm)	(m^3/ha)
Entre Douro e Minho	1,9	6,662
Trás-os-Montes	1,8	6,331
Beira Litoral	1,4	8,253
Beira Interior	2,3	7,929
Lisboa e vale do Tejo	7,3	7,787
Alentejo	18,5	6,937
Algarve	2,6	9,973
Mainland Portugal	**3,2**	**7,349**

In order to complete this overview through Portuguese irrigation subsector, Table ❻ shows some relevant indicators and their regional differences.

As already mentioned, Portuguese agriculture is characterised by small-sized farms (72.3% of holdings are less than 5 hectares). Irrigated land sizes are slightly smaller, around 2 hectares per farm, with the exceptions of Tejo valley and Alentejo.

Concerning irrigation requirements, one can see that, in general terms, unit crop consumption reduces southwards, because rainfall follows the same pattern and average temperatures progress in the opposite way, both pulling upwards irrigation requirements, in the southern regions. Exception of Alentejo can be easily explained by the extent of olive trees and vineyards, two crops with low to very low irrigation requirements.

Irrigation scheduling

In this context, water management at the plot scale includes taking important decisions on two aspects usually considered as components of irrigation scheduling strategies (when and how much water to apply), either in conditions of water comfort or moderate water stress.

Comfort means keeping plants at its higher evapotranspiration rate for the meteorological conditions and physical crop conditions (crop evapotranspiration rate, *ETc*, i.e., without water stress), condition often associated with maximum yields. Moderate water stress supposes a reduction in *ETc* via the so called deficit irrigation strategies. Not analysed here are the aspects on how to apply water (irrigation techniques, irrigation application rates, and so forth).

It became common, in the literature, to consider as alternatives two ways of achieving a good management concerning how much water and when, which will be named as A and B:

A. Water balance approach, applied at large, as follows: in the water balance equation, actual evapotranspiration (*ETa*) enters (input data) estimated by simple models, the other relevant terms of the water balance are measured (e.g. precipitation, *P*) or estimated, so they are also inputs for the model. This allows the user to get the changes in the water stored in the soil volume (control volume), as output and, from a known starting point, to obtain the soil water status at a selected time [Equation ❶]. The interpretation of this output in relation to a decision on the irrigation depth to apply (sometimes called irrigation amount) is based on its position regarding the total available water in the soil (*TAW*) and the strategy to follow. For instance, the user can estimate the irrigation requirements (irrigation depth) as equal to the soil water deficit, if deciding to bring the soil to field capacity condition (FC) or to apply less water, leaving the soil in some predefined condition below FC.

B. Water stress indicators approach (in situ automated or non-automated measurements), which works only with those indicators adequate to quantify short term stress, normally used for irrigation scheduling. These can be (to refer the most tested): soil water content, soil water potential, leaf water potential at predawn, stem water potential soon after solar noon, several stem diameter derived variables, relative transpiration (≈ *Ks*, e.g. with sap flow techniques), leaf temperature (e.g. by detection of TIR radiation emitted, by remote or proximal sensing).

If these two approaches are used separately, it needs to be emphasised that the **water balance (A)** approach to get the soil water status informs directly on the two aspects: how much to irrigate (irrigation depths, i.e., water to be applied, in mm, associated with the irrigation water requirements in general) and when to irrigate, being *TAW* estimation based on the following parameters of the system soil water content at field capacity (FC) and at permanent wilting point (PWP) expressed as volumetric fraction (respectively, θ_{FC} and θ_{PWP}, m^3 of water/m^3 of soil), and the allowable depletion fraction, *p* (see Equation ❻, applied in the context of an example for a shallow rooted plant). Usually, by lack of specific studies, *p* is taken from FAO tables (Allen et al., 1998) and adjusted for ETc rates, inspired in the earlier and enlightening work of Denmead and Shaw (1962).

Conversely, the **water stress indicators (B)** inform when to irrigate, if thresholds are known, and possibly also how much to irrigate but, in this case, only based on trial and error. Therefore, this approach is not usable for planning.

None of these possibilities (A or B) is fully satisfactory by itself. The list of uncertainties in the first approach is large and the limitations have been thoroughly discussed (e.g. Ferreira, 2017). The awareness of such limitations, mainly with non-herbaceous and under deficit irrigation, has given way to the popularity of the second approach, which is far from being complete concerning aims and results.

Instead of being seen as "alternatives", a combination of these two approaches is a relatively common solution, currently used – in a more or less empirical way – by services providing assistance to farms regarding irrigation scheduling. These two outputs (A and B) can be used for control and adjustments, or to get new information. An example of experimental use and results of this combination in a very simple case-study with a low crop (shallow rooted) is briefly described (not requiring *ETa* measurements). Furthermore, in experiments performed in an irrigated olive orchard where *ETa* (and thus *Kc*) was measured (deep rooted plants, published results), it was possible to go further and consequently an experimentally obtained stress coefficient function could be compared with modelled values.

Shallow rooted plants

The experiment took place in a drip irrigated industrial pepper field (Capsicum annuum L. 'Pompeo F1') located in a private property (38º 57´07" N, 7º48´41", 226 m) near Sousel (Portalegre), temperate climate of mediterranean type (Csa), sandy loam soil. Drippers were 20 cm apart, with nominal flow 0.75 L h^{-1}. Plants were transplanted to the field on 4th May 2018. Four sub-plots were established, two with simple line (T1 and T3), and two with double line with plastic in between (T2 and T4), two aimed to be under no stress (T1 and T2) and two under stress (T3 and T4), so that a stress function was used, and to ensure different values of single side leaf area per unit of ground area (*LAI*). The irrigation flow was permanently recorded in each sub-plot.

Regarding the water balance application, the following nomenclature will be used (details below):

- water stored in the soil root zone, for day i: WS_i (mm),
- daily change in water storage: $\Delta WS = WS_{i+1} - WS_i$ (mm),
- volumetric fraction or soil water content: θ (m^3/m^3),
- volumetric soil water content directly measured: θ_{meas} (m^3/m^3),
- volumetric soil water content modelled: θ_{mod} (m^3/m^3).

Both approaches (A and B) above described were used:

A. *ETa* modelling provided inputs to the water balance equation, in order to get the change in soil water in root volume ($\Delta WS = WS_{i+1} - WS_i$ = output, see Equation ❶) (in here, total water stored in mm, from where soil water depletion and also volumetric fraction or soil water content were obtained, Equation ❷).

B. The water stress indicator for plant/crop or soil water status used was the volumetric fraction measured directly using the classical gravimetic method (details in Carrilho, 2019).

The inputs in the water balance equation used at daily time scale [Equation ❶] are the water stored in the soil correspondent to the root zone, for day i (WS_i, mm), the precipitation (*P*, mm/day) and the irrigation depth (*I*, mm/day), both measured, the estimated *ETa* (mm/day) and, when applicable, the estimated drainage (*D*, mm/day) beyond the control volume (root zone). The output aimed is the water stored in the root zone for the next day (WS_{i+1}) and so forth:

$$WS_{i+1} = WS_i + P_i + I_i - D_i - ETa_i \quad [❶]$$

In order to get the starting point for WS_i, the volumetric fraction or soil water content (θ, m^3/m^3) was directly measured at day i =1($\theta_{meas,i}$) being:

$$WS_i = z_{av,i} \times \theta_{meas,i} \quad [❷]$$

where $z_{av,i}$ is the average depth of root zone for day i, defined as the total volume occupied by roots per unit of total soil area.

The volumetric soil water content for the next day ($\theta_{mod,i+1}$) was approximately obtained from WS_{i+1} (equation ❶) as:

$$\theta_{mod,i+1} = WS_{i+1} / z_{av,i+1} \quad [❸]$$

Comparing the estimated values with the ones measured ($\theta_{meas,i+1}$), the critical parameters of *ETa* estimation can be adjusted so that the best fit for these two series (modelled and measured) is met. The critical parameters considered in this simple approach were obtained as described in next paragraphs.

Variables and parameters required to estimate *ETa*. Equation ❹ was used to estimate *ETa*:

$$ETa = ETo \times Kc \times Ks \quad [❹]$$

where reference evapotranspiration (*ETo*, mm/day) was obtained from the Penman-Monteith equation restricted to the conditions of the reference crop (variables coming from a nearby standard meteorological station and grass parameters as suggested by Allen et al., 1998), *Kc* was considered in its simple version (not dual), in a first round from current tables also found in same FAO 56 manual and the stress coefficient *Ks*, when below unity (i.e., when *SWD* > *TAW p*), was obtained using a simple model (Allen et al., 1998):

$$Ks = (TAW - SWD) / [TAW \times (1 - p)] \quad [5]$$

where *TAW* is total available water, *SWD* is soil water deficit and *p* was taken as 0.3, the allowable depletion factor defining the readily available water ($RAW = TAW \times p$) for which water consumption is not affected ($Ks = 1$). If *SWD* is below *RAW*, $Ks = 1$.

TAW was estimated as usually in engineering applications:

$$TAW = (\theta_{FC} - \theta_{WP}) \times z_{av} \quad [6]$$

with the parameters θ_{FC} and θ_{WP} changing as z_{av} increases (roots occupying deeper layers with different properties), being z_{av}, obtained from an adaptation of a sinusoidal function proposed by Borg and Grimes (1986) for root growth, based on a large number of field observations of 48 crop species. These outputs for root depth were compared to local in situ measurements (three per season, Carrilho, 2019) to adjust z_{av}, estimation. *SWD* was generally estimated as:

$$SWD = (\theta_{FC} - \theta_{mod}) \times z_{av} \quad [7]$$

The soil parameters θ_{FC} and θ_{WP} were the result of multiplying the corresponding mass fractions by the soil bulk density (D_a), all measured in situ, in four layers (0 down to 50 cm) with four repetitions.

As for the second approach (B), θ_{meas} samples were taken in the same four soil layers, three positions per plot (drippers line, 20 cm and 40 cm from it), four plots (48 measurements per day). Soil water status was also followed by an external entity using capacitive probes; questionable results not shown.

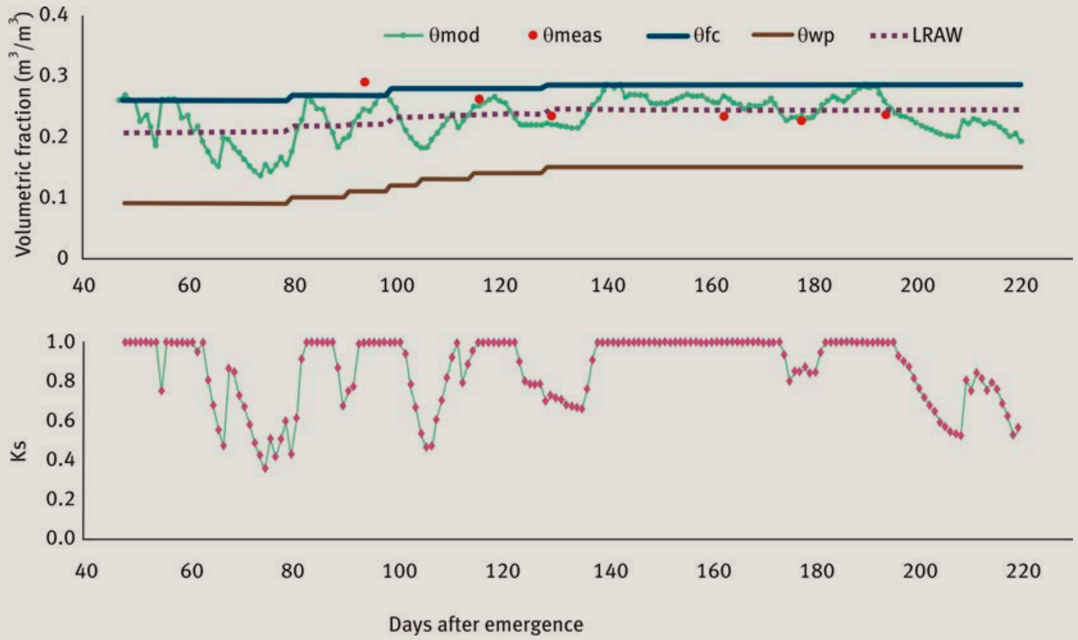
The strategy is: by reducing the uncertainty as much as possible in θ_{FC}, θ_{WP}, z_{av} and by assuming *p* values obtained as described above, *Kc* (for each phenological phase considered) was selected as the unknown, to be obtained experimentally by comparing measured and modelled values of soil water status. Furthermore, in order to inform the interpretation of the *Kc* values obtained this way, the seasonal trend of *LAI* was followed.

The seasonal course of volumetric water content obtained with Equations 1 to 3 was first compared to the values observed in six different dates. The parameters first used (mainly *Kc*) provided bad results (not shown). Consequently, in order to improve adequacy, the *Kc* seasonal line was adjusted for the four treatments individually and the outputs providing better results were analyzed (example in Figure 2a, for treatment T3), with corresponding *Ks* values (figure 2b).

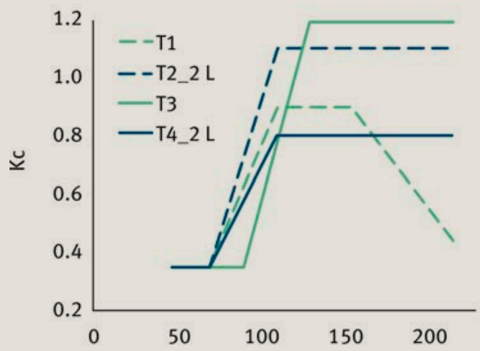
The seasonal trend of *Kc* (Figure 3a) experimentally observed in the four treatments was compared to *LAI* (Figure 3b) showing a relatively good correspondence, mainly for the well irrigated treatments. The main differences in relation to the values presented in Doorenbos and Pruit (1977) and in Allen et al. (1998) – the two FAO manuals 24 and 56 - were the much longer vegetative cycle and the fact that in general *Kc* does not decrease at the end of the observed period (till last commercial harvest).

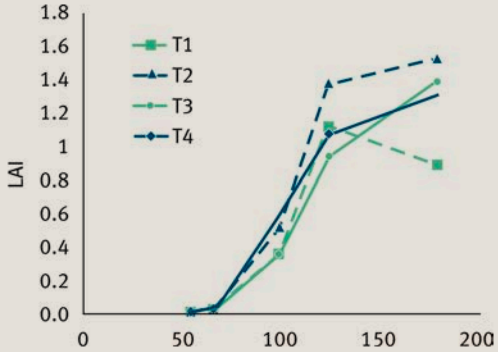
An important methodological conclusion was the possibility, by using this approach, to extract some model parameters even without performing *ETa* measurements. This became possible thanks to the accessible root system, so that soil water status is well represented by the measurements performed which is often not the case in deep rooted plants.

2 Seasonal course of (a, upper) soil water content expressed as volumetric fraction, either measured (θ_{meas}) or modelled (θ_{mod}), in relation to the lines defining the corresponding values at FC, WP and lower edge of RAW, and (b) stress coefficient estimated as in Equation 5.



❸ Seasonal course of (a, left) Kc obtained experimentally in a self-learning process from modelling and soil water content measurements, and corresponding measured LAI (b, right) for four treatments (see text): simple (T1, T3) and double line (T2 and T4), under stress (T3, T4), and without water stress (T1 and T2), for an industrial pepper crop, Portalegre (Portugal). The effect of the short term stress (Figure ❷b) is excluded from these Kc values, which reflect only long term stress impact on leaf development.





Deep rooted plants

As former experimental set-up allowed direct measurements of *Kc*, for the crop under study, the variable selected to be adjusted was *Ks*. Experimental data, for drip irrigated olive orchards (*Olea europea* 'Arbequina'), on *Ks* in relation to several water stress indicators (independent variable), were obtained (*Ks* functions).

The first results are from Ferreira do Alentejo (South Portugal) in an intensive density system (4.75 x 7 m, 20% ground cover), summer 2011. They were reported in Ferreira et al. (2012), Ferreira (2017), Conceição et al. (2017a, b, 2018). Details on materials and methods are described in those publications. In a later experiment (summer 2017) at Serpa, same region, on a super intensive orchard, a new restricted data set not yet fully explored, provided a confirmation of the previous stress function (Lourenço et al., 2020).

In both cases, stress cycles were used in which, for several weeks of summer 2011 and 2017, a sub-plot was kept under stress, while another sub-plot was well irrigated (for reference). The effect on transpiration reduction (sap flow) and several water stress indicators was followed. The focus here concerns the relative reduction on water use (*Ks)* as a short term consequence of water stress.

In the present context, these examples are used to emphasize the need for verification and adjustment of the stress function parameters, *TAW* and *p*, assuming that such form (Equation ❺) describes relatively well the reality observed, which is not always the case (Paço et al., 2012).

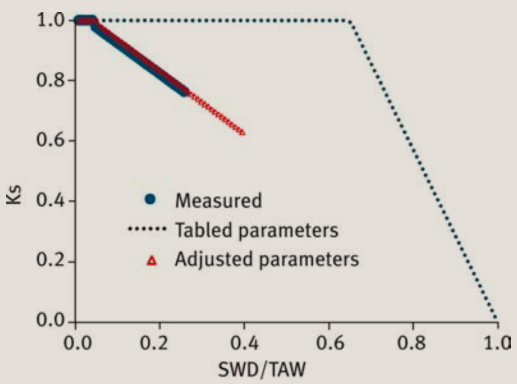
The method of analysis in this short presentation consists in showing the parameters for the conditions under analysis and comparing it with those that would come from recommendations in manuals. Further on, the interpretation is supported by complementary studies on root functioning for the first experiment, and also on other study, by the same team on a nearby rainfed olive traditional stand.

The direct use of the approach described (shallow rooted plants) most likely turns out to be inapplicable in a stand with deep rooted plants. This is because it can be unrealistic to rely on the assumption that the changes in soil water storage measured in accessible layers reflect plants water use. In this case, long term measurements of crop water use were performed using a combination of eddy covariance and soil evaporation measurements (for the reliability) with sap flow techniques (for the long term). The careful application of such techniques in the olive stands here referred is complex but was already described in detail (e.g. Conceição et al., 2017 and Tezza et al., 2019).

During both stress cycles (2011 and 2017), in which a sub-plot was kept under stress, while other was well irrigated, *Ks* was not modelled but experimentally obtained as approximately the relationship between water use in both sub-plots (assuming *Kc* as being the same, for the duration of the stress cycle). The results allow the derivation of one function for transpiration reduction (Ferreira, 2017, 2020) which was confirmed in the simpler and later Serpa experiment (Lourenço et al., 2020).

The parameters in Equation ❺ that precisely fitted the experimental results were $p = 0.04$ and $TAW = 310$ mm (Figure ❹).

❹ Relationship between Ks and SWD expressed as a fraction of TAW. Comparison between measured values and those modelled with tabled parameters (FAO 56 tabled p = 0.65, with adjustment for ETc rates it would be 0.75) and TAW = 138 mm (derived from tabled root depth, z = 1.2 m, for ground cover of 20%, and soil parameters, assuming full colonization in horizontal). Also shown model outputs using the experimentally adjusted parameters: p = 0.04 and TAW = 310 mm.



The difference between the two values for *TAW* (168 mm and 310 mm, Figure ❹), suggests that roots develop much deeper than tables and first observations would suggest. Conversely, the value found for *p* is quite different from the one suggested in tables. This fact was consistent with our observations of moderate stomatal closure at a relatively earlier stage of water stress, in this cultivar, which behave as near-isohydric (Conceição et al., 2017b).

Furthermore, overall results from the three years of flux measurements provided further insights on aspects related with the volume exploited by roots:

1. drip irrigated olive trees, submitted to the farmer practices regarding deficit irrigation, had a total water use during irrigation season higher than the total irrigation volumes measured (Conceição et al., 2017) in spite of being young. The interpretation could be that plants are using significant amount of water stored from winter and early spring in relatively deep layers.
2. soil water status follow-up down to 1.3 m (together with studies on hydraulic redistribution on rainfed stand and also on one irrigated) also suggest an important exploitation of deep soil layers (e.g. Conceição et al., 2018, Ferreira et al., 2018). Besides and more important, in this stand, the water available between the soil surface and 1.3 m was not enough to ensure the fluxes observed (data not published). Consequently, measurements in upper soil layers, most likely only have indicative value (limitations of soil measurements when used alone in deep rooted plants).

Consequently, in this case-study concerning a deep rooted woody crop very resilient and well adapted to severe summer water scarcity, usual modelling approaches for *ETa*, alone and without verification, can severely fail, in case of the generally applied deficit irrigation (evapotranspiration reduced by stress). Conversely, soil measurements alone can also fail for irrigation scheduling purposes. In these situations, predawn leaf water potential proved to be quite useful but unfortunately was not automated (Conceição et al., 2017). A selected stem diameter derived variable required a well irrigated plot for reference, which is not practical (Ferreira et al., 2012).

If modelling *ETa* is crucial, to extract model parameters without *ETa* measurements, as was done in the example with shallow rooted plants , it represents a challenge for deep rooted ones. Eventually a trial and error exercise can provide partial answers, even statistical approaches (e.g. Azevedo, 2019) being possible. ■

Further reading...

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