# Water Requirements and Footprint of a Super-intensive Olive Grove under Mediterranean Climate

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## Abstract

**The water footprint of a product can be described as the volume of freshwater used to produce it, associated to a geographic and temporal resolution. For crops, the water footprint relates crop water requirements and yield. The components of water footprint, blue, green and grey water footprints, refer to the volumes of respectively, surface and groundwater, rainfall, and water required to assimilate pollution, used to produce the crop yield. The global standard for crop water footprint assessment relies on evapotranspiration models to estimate green and blue water evapotranspiration. This approach has been used in the present study to estimate the water footprint of a very high density drip irrigated olive grove and further compared with data obtained from evapotranspiration measurements or from its components: the eddy covariance method to quantify latent heat flux, a heat dissipation sap flow technique to determine transpiration and microlysimeters to evaluate soil evaporation. The eddy covariance technique was used for short periods in 2011 and 2012, while sap flow measurements were performed continuously, hence allowing the extension of the data series. Measurements of evapotranspiration with the eddy covariance method provided an average close to 3.4 mm d$^{-1}$ (2011) and 2.5 mm d$^{-1}$ (2012). The ratio of evapotranspiration to reference evapotranspiration approached 0.6 and 0.4 for the respective periods. The water footprint of the olive crop under study, calculated with field data, was higher than the water footprint simulated using the global standard assessment and was lower than that reported in literature for olives. Lower values are probably related to differences in cultural practices, e.g., the density of plantation, harvesting techniques and irrigation management. The irrigated high-density olive grove under study had a high yield, which compensates for high water consumption, thus leading to a water footprint lower than the ones of rainfed or less dense groves. Other differences may relate to the procedures used to determine evapotranspiration.**

## INTRODUCTION

The representativeness of super-intensive olive groves has increased in Portugal in the last years, mostly in the Southern region of the country, where it occupies an area over 10000 ha in a total of 160000 ha of olive groves.  In the future, this region is expected to undergo hotter summers, with more intense droughts, as well as less rainy winters and autumns (Santos and Miranda, 2006). This will increase the pressure on water resources management and therefore, given the rising importance of super-intensive groves, it is necessary to evaluate their water consumption patterns and possible future risks associated to climate change. A way to address this problematic is by using the crop water footprint (WF), which is comparable among different cultural systems.

The water footprint of a crop is the volume of water that is necessary to produce it and relates crop water requirements and yield. It was introduced by Hoekstra (2003) and further developed by Hoekstra and Chapagain (2008). The WF concept can be used as an indicator of appropriation of freshwater resources. The components of water footprint, blue, green and grey water footprints, refer to the volumes of respectively, surface and groundwater, rainfall, and water required to assimilate pollution, that are used to produce the crop yield. The concept has been applied to many crops, including olive (e.g., Salmoral et al., 2011) but information on very high density (super-intensive) groves is scarce.

Determining blue and green water footprints is routinely achieved using estimates of evapotranspiration (ET) obtained with a crop coefficient approach and of a water use ratio (Hoekstra et al., 2011; Mekonnen and Hoekstra, 2011). This approach relies on the use of the CROPWAT model from FAO, which in its turn is based on Allen et al. (1998) and Doorenbos et al. (1986), using a single crop coefficient. However, if ET measurements are available or if a model relying on a dual crop coefficient approach is used, accuracy of WF estimates might be improved. Remote sensing techniques for the assessment of WF of crops have also been discussed in recent literature (Romaguera et al., 2010). They can provide estimates of actual ET, precipitation, surface runoff and irrigation requirements when associated with modelling.

The present study compares WF estimates of a super-intensive olive grove in Southern Portugal, obtained by i) CROPWAT model ET estimates (following routine WF determination as in Hoekstra et al. (2011) and Mekonnen and Hoekstra (2011)), ii) *in situ* ET measurements performed with a micrometeorological technique (eddy covariance) combined with sap flow and soil evaporation measurements, iii) remote sensing information (Normalized Difference Vegetation Index, NDVI[1]) and iv) results reported in literature.

## MATERIALS AND METHODS

### The experimental site

This study took place in a commercial olive grove located in Southern Portugal (38◦ 24' N, 7◦ 43' W, 143 m asl), in the region of Alentejo, during 2011 and until July 2012. Alentejo's climate is Mediterranean with an average annual rainfall between 600 and 800 mm and an average annual temperature close to 17 ºC. The production system in the site (property of the enterprise "Olivais do Sul") was based in a "super high density" management technique, recurring to high density tree planting of the cultivar Arbequina (1.35 m × 3.75 m, 1975 trees $ha^{-1}$, mean plant height: 3.7 m (n = 28); mean trunk diameter: 7.17 cm (n = 181), production in 2011: 14 t $ha^{-1}$).The olive grove was almost daily evening irrigated during spring and summer with a drip system (emitters with 0.75 m spacing, 2.3 l $h^{-1}$). The wetted area was around 23% of total area and the fraction of

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[1] The work presented is part of the H2Olive3s project which aims to better understand water dynamics on irrigated olive orchards in the Alentejo region, within a 3 year time scale. The project includes the use of the METRIC model (Allen et al., 2007), on which the Normalized Difference Vegetation Index (NDVI) calculation is part of the process.

ground covered by vegetation was 0.37. The terrain was undulated and the experimental plot was integrated in a total area of approximately 78 ha. Prevailing winds in the plot were from the NW direction.

## Sap flow measurements

Plant transpiration was assessed by sap flow measurements by the *Granier* method (Granier, 1985), between DOY (day of year) 134/2011 and 184/2012. A set of 6 sensors (1 cm heated length, UP GmbH, Germany) was distributed by 6 trees, according to trunk diameter class frequency, established in a larger sample of the plot. Thirty-minute data were stored in dataloggers (Models CR1000 and CR23x, Campbell Scientific, Inc., Logan, UT, USA). Natural temperature gradients in the trunk were corrected using data from a non-heated sensor.

## Soil evaporation measurements

Soil evaporation ($E_s$) was measured with microlysimeters, built from PVC pipes (as in Daamen et al., 1993). A set of six microlysimeters, installed in a reproducible subarea of the plot, was distributed by three influence areas: one between rows and non-irrigated, another in the crop row at a midpoint between emitters, and a third one in the crop row under the emitters. In previous works (e.g., Paço et al., 2006) the outer cylinders of the microlysimeters were left in these fixed positions while the inner cylinders were filled for each measurement day with soil cores extracted from different but homologous positions in the plot. In the present study, given the heavy soil and the difficulty to collect samples, an innovative methodology was followed as an exploratory procedure: both the inner and the outer cylinders were kept always in the same positions, although without irrigation. Soil moisture inside each microlysimeter and in analogous positions in the plot, was measured with a soil moisture sensor (ThetaProbe ML2x). The microlysimeters soil moisture was corrected to match the soil's moisture content in each influence area, though simulating irrigation. Afterwards, the microlysimeters were weighed and put back into place and weighed again subsequently every hour. This exploratory procedure was performed in DOY 263, 293/2011 and 187/2012. $E_s$ estimates were calculated as a fraction of $ET_o$ when the soil surface was wetted only by irrigation and using a dual crop coefficient approach when wetted both by irrigation and rainfall (Allen et al., 1998).

## Evapotranspiration measurements

ET was measured by the eddy covariance (EC) micrometeorological technique using a three-dimensional sonic anemometer and a krypton hygrometer connected to a datalogger (Models CSAT3, KH20 and CR1000, respectively, Campbell Scientific, Inc., Logan, UT, USA). The sensors were placed on a metallic tower at a measurement height of 4.8 m, with a path separation of 0.1 m. The fetch was 470 m, 353 m, 455 m and 504 m for the north, west, south and east directions, respectively (Table 1). Raw data were collected at a 10 Hz frequency and further analyzed with the Software package TK3 (University of Bayreuth, Germany) for correction and calculation of eddy-covariance 30-min data. Data corrections were performed following Foken et al. (2011) and raw data was submitted to a coordinate rotation using the Double Rotation method (Kaimal and Finnigan, 1994), given the non-flat terrain conditions. The spatial representativeness of the measurements was examined through a footprint analysis (Schuepp et al. 1990).

The EC technique was used for short periods (13 days in 2011, during July and August, and 21 in 2012, during June and July), while the sap flow measurements were performed since May 2011 to July 2012, hence allowing the extension of the EC data series by the use of the following relationship (Fig.1): $ET\text{-}E_s = 0.90\ e^{0.86Tsf}$ ($R^2 = 0.69$, Tsf = transpiration obtained from sap flow measurements); estimates based on the crop coefficient approach (Allen et al., 1998) were used for data out of range of the data set used to create this relationship and until the middle of May 2011, when there were no sap flow measurements available.

Data obtained regarding EC, sap flow and $E_s$ are still under analysis and are therefore considered preliminary at this stage. Subsequent data will help improve the mathematical relationships between the three variables and increase the accuracy of ET ground based data.

**Remote sensing**

Preliminary data concerning the determination of NDVI from Landsat 5 TM images and comparison with ground data is presented. NDVI values were calculated for the following dates of 2011: 01/31, 03/20, 04/05, 05/23, 06/24, 07/26, 08/27, 09/12 and 10/30 using ERDAS IMAGINE software. As reviewed in Café et al. (2008), the dark-object subtraction technique was used for the correction of the images atmospheric scattering. Then the radiometric correction was applied to the images in order to convert digital numbers (DN) [0, 255] in reflectance values [0, 1]. After the NDVI were calculated for the full image area, statistics were generated for an area of interest (*aoi*) inside the study area, this was drawn to be homogeneous, without roads and runoff events. The NDVI values obtained were used to estimate the basal crop coefficient ($K_{cb}$), following the FAO56 dual crop coefficient method (Allen et al., 1998) to calculate the olive orchard ET. The $K_{cb}$-NDVI relation used was described in Simonneaux et al. (2008): $K_{cb}=1.64\times(NDVI–NDVI_{min})$, where $NDVI_{min}$ is the value of a bare soil. Thereafter, a uniformity coefficient was calculated, according to Café et al. (2008), using the following equation: $UC=100\times(1.0–(SD/m)\times(2/\pi)^{0.5})$, where UC is the uniformity coefficient (%), SD is the standard deviation and *m* is the average of the $K_{cb}$ values calculated for the *aoi*.

**Other measurements**

Predawn plant leaf water potential was measured in a few selected days to evaluate plant water status. For this, a *Scholander* type pressure chamber (Scholander, 1965) was used in DOY 216, 244 and 255/2011 (n=12). Data from an automatic weather station placed at an approximate distance of 12 km, in a straight line, to the north northwest direction was used for reference evapotranspiration ($ET_o$) calculations.

## RESULTS AND DISCUSSION

The footprint analysis performed to access the representativeness of the eddy covariance (EC) measurements showed that over 90% of the fluxes sensed come from the intended source area, regarding the four main cardinal points (Fig. 2 and Table 1). Measurements were mainly affected by fluxes coming from an upwind area at a distance of 10.8 m from the tower (maximum of the one-dimensional footprint function, which provides the relative contribution to the vertical flux - $(1/Q_o)\ dQ/dx$ - for a given height $z$, being $Q_o$ the latent heat flux density measured at point $x = (0, z)$). Figure 3 presents data concerning ET obtained directly by the EC technique. ET was in average 3.4 mm $d^{-1}$ (± 0.49, n=13) in 2011 and 2.5 mm $d^{-1}$(± 0.41, n=21) in 2012, for the periods considered. The ratio of ET to $ET_o$ (which represents the product of a crop coefficient ($K_c$) and a stress coefficient ($K_s$)) approached 0.6 and 0.4, respectively in the first and the second year. Accordingly, predawn leaf water potential measurements (2011, data not shown) indicated that plants were under a moderate water stress.

The NDVI values of the experimental field remained stable along the year comparing with the surrounding areas. The $K_{cb}$ values were calculated for the 9 dates of the satellite images chosen and are comparatively higher than the reported in literature (Allen et al, 1998). The UC of the calculated $K_{cb}$ ranged from a maximum value of 90.4 % for 2011/01/31 and a minimum of 87.5 % for 2011/09/12, representing the homogeneity of crop development along the year for the selected area of interest. ET obtained from remote sensing information was overestimated during the dry season (Fig. 3). Even so, the use of high-resolution satellite images can provide ET estimates of a higher spatial resolution then the ones provided by Meteosat or MODIS products, making remote sensing and Earth observation data useful for WF calculations at a farm scale, if more elaborated techniques (see Allen et al., 2007) are further explored.

The water footprint of the olive crop under study was lower than the water footprint simulations reported in literature (Table 2). A potential reason relates to the density of plantation, yield and irrigation crop management. This irrigated olive grove had a high yield, which compensates for a high water consumption, leading to a water footprint lower than the ones for rainfed or less dense groves. Furthermore, as evapotranspiration measurements were used to calculate water footprint instead of the common procedure (using evapotranspiration estimates), this might have also introduced some differences. Regarding this super-intensive grove, the WF estimate produced with the routine procedure (CROPWAT) was lower than the one obtained from ET measurements (Table 2), showing a possibility to improve WF estimates in further work.

## CONCLUSIONS

For the present study, developed in a super-intensive olive grove, evapotranspiration obtained from micrometeorological measurements, during July and August 2011 and June and July 2012, was in average 3.4 mm $d^{-1}$ and 2.5 mm $d^{-1}$, respectively. These measurements, combined with sap flow and soil evaporation measurements were used to produce field based data and calculate the water footprint for the crop. A very simplified approach can divide WF in two main variables: total annuals of crop evapotranspiration and production. Crop evapotranspiration values were within an average-high range, when compared with references in literature, but production was higher than for less intensive groves in the area. This contributes to explain the comparatively low value of WF found, regarding values available in literature for less intensive and rainfed groves.

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## Tables

Table 1. Distance from the measurement point (eddy covariance) to the plot limit; CNF – cumulative normalized flux obtained for the footprint analysis performed.

| Direction | Fetch (m) | CNF |
|---|---|---|
| East | 504 | 0.96 |
| West | 353 | 0.94 |
| North | 470 | 0.95 |
| South | 455 | 0.95 |

Table 2. Comparison of the olive grove water footprint obtained with evapotranspiration (ET) measurements (present study) and estimates (present study and literature); $K_c$ – crop coefficient, $K_{cb}$ – basal crop coefficient, $K_s$ – stress coefficient, $K_e$ – soil evaporation coefficient, T – transpiration, $E_s$ – soil evaporation.

| Olive study | Crop water use calculation | Study period | Spatial resolution | Blue + Green Water footprint ($m^3$/ton) |
|---|---|---|---|---|
| Mekonnen and Hoekstra, 2011 | Single crop coefficient CROPWAT:<br>$ET = K_c \times K_s \times ET_o$ | 1996/2005 | Global | 3015 |
| Salmoral et al., 2011 | Single crop coefficient CROPWAT:<br>$ET = K_c \times K_s \times ET_o$ | 1997/2008 | Spain | 1264 |
| Present study | Single crop coefficient CROPWAT:<br>$ET = K_c \times K_s \times ET_o$ | 2011 | Alentejo, Portugal | 576 |
| Present study | Field measurements<br>$ET = T + E_s$ | 2011 | Alentejo, Portugal | 671 |
| Present study, Remote sensing | Dual crop coefficient<br>$ET = (K_{cb}+K_e) \times ET_o$ | 2011 | Alentejo, Portugal | 757 |

**Figures**

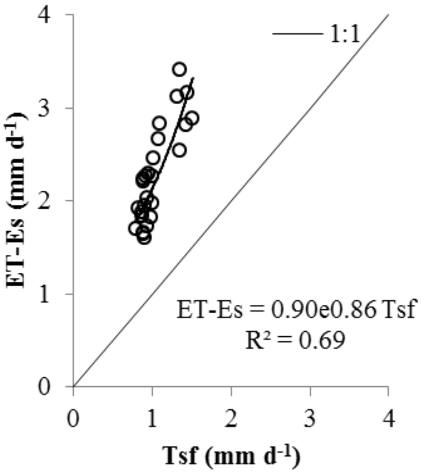

Fig. 1. Relationship between transpiration (ET-$E_s$) obtained eddy covariance ET measurements minus soil evaporation ($E_s$) and transpiration obtained with sap flow measurements (Tsf), 2011 and 2012 data.

Fig. 2. Footprint analysis for the flux measurements performed; ($1/Q_o$) dQ/dx - relative contribution to the vertical flux for a given height *z*, (continuous line) being $Q_o$ the latent heat flux density measured at point x = (0, *z*); CNF–cumulative normalized flux (dashed line), with marked values for the cardinal directions.

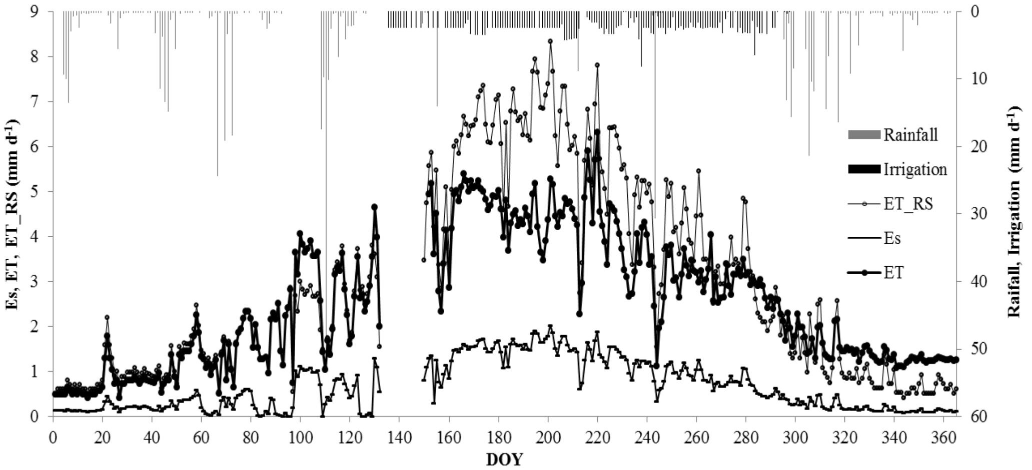

Fig. 3. Olive grove evapotranspiration obtained from field measurements (ET), soil evaporation ($E_s$) and evapotranspiration obtained from remote sensing information (ET_RS), DOY = day of year, 2011.