Water Footprint of a Super-intensive Olive Grove Under Mediterranean Climate using Ground-based Evapotranspiration Measurements and Remote Sensing

A. M. Nogueira[1*], T. A. Paço[1], J. C. Silvestre[2], L. F. Gonzalez[3], F. L. Santos[4], L. S. Pereira[1]

INTRODUCTION

The water footprint (WF) of a crop, which is the volume of water that is necessary to produce it, relates crop water requirements and yield and 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. The representativeness of super-intensive olive groves has increased in Portugal in the last years, mostly in the Southern region of the country. 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 changing climate conditions. An approach to do this might be the use of the crop WF, which has the utility of being comparable among different cultural systems.

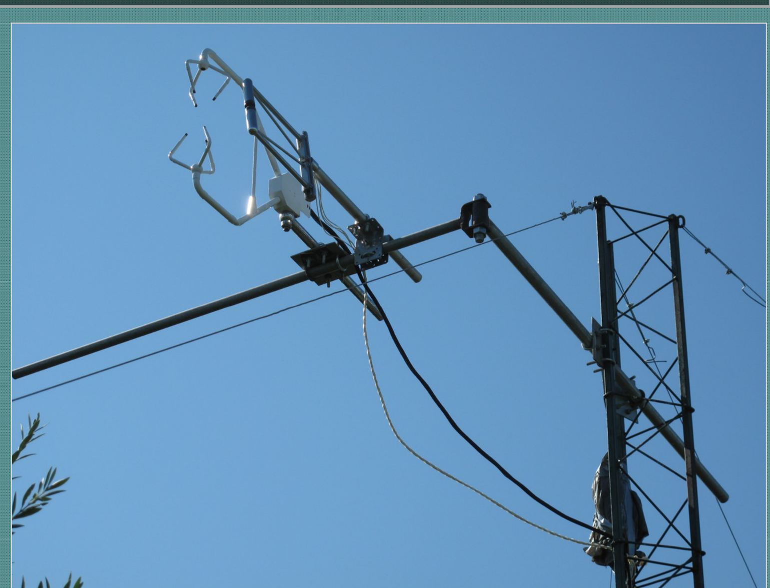
Determining blue and green water footprints is generally achieved using estimates of evapotranspiration (ET) obtained with a crop coefficient approach and of a water use ratio (Hoekstra et al., 2011; Mekonnen and Hoekstra, 2011). However, when ET measurements are available, accuracy of WF estimates might be improved. The potential of using remote sensing techniques for the assessment of WF of crops has been discussed in recent literature (Romaguera et al., 2010). It can provide estimates of actual evapotranspiration, precipitation, surface runoff and irrigation requirements when associated with modelling. The work presented was 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.

The present study shows preliminary data concerning the determination of NDVI from Landsat 5 TM images and comparison with ground data, in a super-intensive olive grove in southern Portugal (cv. Arbequina, drip irrigated, 1975 trees ha^{-1}), during 2011. In this study, we compare the WF estimates using *in situ* ET measurements and remote sensing.

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. Alentejo's climate is Mediterranean with an average annual rainfall between 600 and 800 mm and an average annual temperature between 16 and 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). The olive grove was almost daily evening irrigated during spring and summer with a drip system (emitters with 0.75 m spacing). The wetted area was around 23% of total area and the fraction of 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.



Ground measurements

Plant transpiration was assessed using sap flow measurements by the Granier method (Granier, 1985), between DOY (day of year) 134 and 353/2011. A set of 6 sensors was distributed by seriated trees, according to trunk diameter class frequency, established in a larger sample of the plot. Thirty-minute data were stored in a datalogger (Model CR1000, Campbell Scientific, Inc., Logan, UT, USA). Natural gradients were corrected using data from non-heated sensors during short periods. Evapotranspiration (ET) was measured by the eddy covariance (EC) micrometeorological technique using a three-dimensional sonic anemometer and a krypton hygrometer (Models CSAT3 and KH20, Campbell Scientific, Inc., Logan, UT, USA) connected to a datalogger (Model CR1000, Campbell Scientific, Inc., Logan, UT, USA), from the end of July until the end of August. The sensors were placed on a metallic tower at a measurement height of 4.8 m. 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 a short period, from end of July till the end of August (13 days), while the sap flow measurements were performed from May to December, hence allowing the extension of the data series; for other periods estimates based on the crop coefficient approach (Allen et al., 1998) were used. $T = 0.95\ e^{0.81SF}$ ($R^2 = 0.68$)

Soil evaporation (Es) was measured with microlysimeters, built from PVC pipes as described by Daamen et al. (1993), to obtain a locally calibrated soil evaporation model. A set of six microlysimeters, installed in a reproducible subarea of the plot, was distributed by three influence areas within the subarea: one between rows and non-irrigated, another in the crop row at a midpoint between emitters, and a third one also in the crop row directly 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 an innovative methodology was followed as an exploratory procedure: both the inner and the outer cylinders were kept always in the same positions, although kept without irrigation. Soil moisture inside each microlysimeter and in analogous positions in the plot, for each influence areas, 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 and 293. Predawn plant leaf water potential (Ψ_p) was measured in selected days to evaluate plant water status and whether plants were under water stress conditions or not. For this, a *Scholander* type pressure chamber was used to measure Ψ_p in DOY 216, 244 and 255 (n=12).

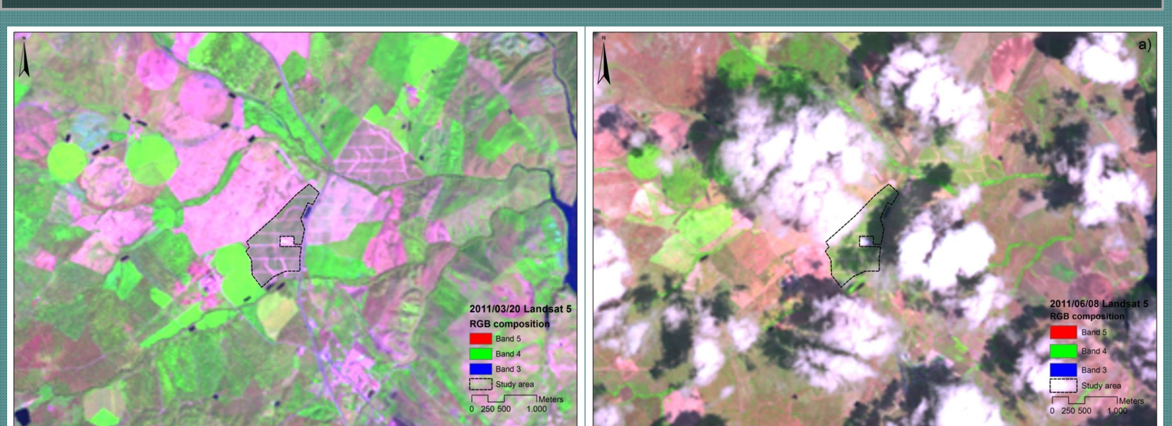


Fig. 1. False color composition used for cloud recognition.

Remote sensing

NDVI values were calculated for the following dates of 2011: 03/20, 05/23, 06/24, 07/27, 08/27 and 10/30. The dates were distributed along the year but with a focus on the summer period; the image of 06/08 (fig. 1) was not possible to use due to cloud cover of the experimental field. The bands 3 and 4 of the Landsat 5 TM images for the mentioned dates were imported and converted in the ERDAS IMAGINE file format and this software was used for pre-processing the images and final calculations.

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, runoff events or ill/not well developed olive trees.

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.

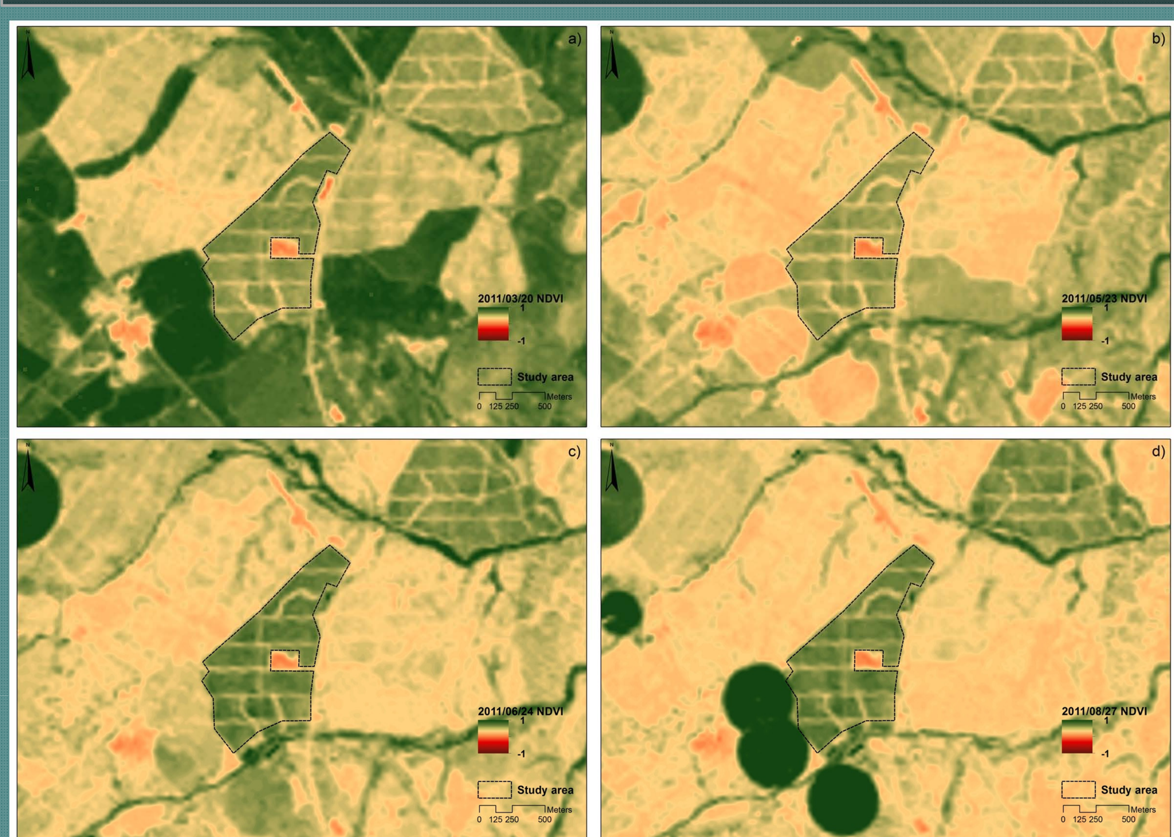


Fig. 2. NDVI images of 4 different dates: a) 2011/03/20, b) 2011/05/23, c) 2011/06/24 and d) 2011/08/27.

RESULTS AND DISCUSSION

Evapotranspiration measured directly with the eddy covariance method was in average close to 3 mm.d^{-1} and the ratio of evapotranspiration to reference evapotranspiration approached 0.6 for the same period. Plants were under a moderate water stress, as confirmed with predawn leaf water potential measurements.

As shown in Fig. 2 the NDVI values of the experimental field remain stable along the year comparing with the surrounding areas. The K_{cb} values (fig. 3) 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, this represents the homogeneity of crop development along the year for the selected area of interest.

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: $ET = K_c \times K_s \times ETo$	1996-2005	Global	3015
Salmoral et al., 2011	Single crop coefficient, CROPWAT: $ET = K_c \times K_s \times ETo$	1997-2008	Spain	1264
Present study	Single crop coefficient, CROPWAT: $ET = K_c \times K_s \times ETo$	2011	Alentejo, Portugal	576
Present study	Field measurements; $ET = T + Es$	2011	Alentejo, Portugal	733
Present study, Remote sensing	Dual crop coefficient: $ET = (K_{cb}+K_e) \times ETo$	2011	Alentejo, Portugal	757

The water footprint of the olive crop under study was lower than the water footprint simulations reported in literature. A possible reason relates to the density of plantation, yield and irrigation crop management. The irrigated olive grove under study had a high yield, which compensates for a high water consumption, leading to a water footprint lower than the ones of 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.

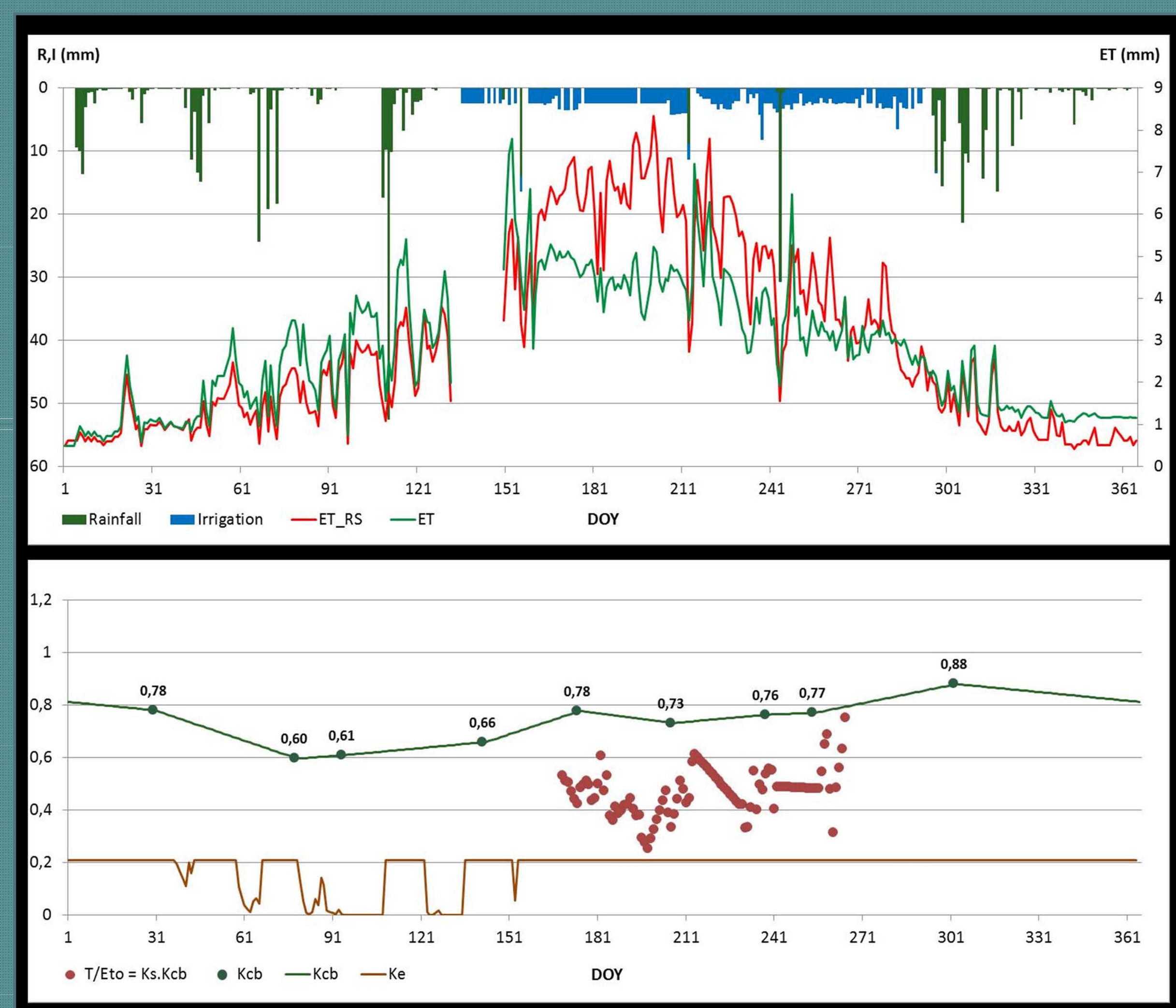


Fig. 3. a) 2011 daily estimates of cultural evapotranspiration estimated from field measurements (ET) and using remote sensing (ET_RS). b) Basal crop coefficients estimated with remote sensing (green line and dots) and obtained from ground measurements (T/ETo), soil evaporation coefficient (K_e).

CONCLUSIONS

A very simplified approach can divide WF in two main variables: total annuals of crop evapotranspiration and production. For the present study, developed in a super-intensive olive orchard in 2011, evapotranspiration values fell into an average-high range when compared with references in literature, but production is higher than for less intensive groves in the area. This helps to explain the comparatively low value of WF found.

Data presented here is preliminary and subsequent data will help us improve the mathematical relationships between sap flow, soil evaporation and evapotranspiration and improve ET ground based data.

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 EO data useful for WF calculations at a farm scale.

REFERENCES

Allen RG, Pereira LS, Raes D, Smith M (1998). Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. Rome, Italy.

Allen RG, Tasumi M, Trezza R (2007). Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Model, J. Irrig. And Drain. Engrg. 133:380-394.

Café C, Branco R, Pereira LS, Tavares R (2008). Estima de coeficientes culturais basais usando imagens Landsat. Aplicação ao regadio do Caia.

Daamen CC, Simmonds JS, Wallace JS, Laryea KB, Sivakumar MVK (1993) Use of microlysimeters to measure evaporation from sandy soils. Agric Forest Meteor 65:159-173.

Foken T, Leuning R, Oncley SP,Mauder M, Aubinet M (2011). Corrections and data quality. In: Aubinet M et al. (eds), Eddy covariance: a practical guide to measurement and data analysis. Springer, Berlin, Heidelberg.

Granier A (1985). Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres. Annales des Sciences Forestières 42:193-200.

Hoekstra A Y (Ed) (2003). Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade, Delft, The Netherlands, 12–13 December 2002, Value of Water Research Report Series No. 12, UNESCO-IHE, Delft, The Netherlands.

Hoekstra AY, Chapagain AK (2008). Globalization of water: Sharing the planet's freshwater resources, Blackwell Publishing, Oxford, UK.

Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen, MM (2011). The water footprint assessment manual: Setting the global standard. Earthscan, London, Washington p. 228.

Kaimal JC, Finnigan JJ (1994). Atmospheric boundary layer flows: their structure and measurement. Oxford University Press, New York, NY, 289 pp.

Mekonnen MM, Hoekstra Ay (2011). The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15:1577-1600.

Paço TA, Ferreira MI, Conceição N (2006). Peach orchard evapotranspiration in a sandy soil: comparison between eddy covariance measurements and estimates by the FAO 56 approach. Agric Water Manag 85:305-313.

Romaguera M, Hoekstra AY, Su Z, Krol MS, Salama MS (2010). Potencial of Using Remote Sensing Techniques for Global Assessment of Water Footprint of Crops. Remote Sens. 2010, 2, 1177-1196.

Salmoral G, Aldaya MM, Chico D, garrido A, Llamas MR (2011). The water footprint of olives and olive oil in Spain. Spanish J. of Agric. Res. 9: 1089-1104.

Santos FD, Miranda P (Eds) (2006). Alterações Climáticas em Portugal. Cenários, Impactos e Medidas de Adaptação - Projecto SIAM II. Gradiva, Lisboa.

Simonneaux V, Thomas S, Lepage M, Duchemin B, Kharrou H, Berjami B, Boulet G, Chehbouni G (2008). « SAMIR », A tool for irrigation monitoring using remote sensing for landcover mapping and evapotranspiration estimates.

[1] CEER – Biosystems Engineering/Instituto Superior de Agronomia/Technical University of Lisbon (TULisbon), Lisboa, Portugal
[2] INRB – Instituto Nacional dos Recursos Biológicos, Dois Portos, Portugal
[3] UNESP – Universidade Estadual Paulista, São Paulo, Brasil
[4] University of Évora, Évora, Portugal
[*] corresponding author: anogueira@isa.utl.pt, tel.: +351 213653346, fax: +351 213653287

ACKNOWLEDGEMENTS

This work received support from: 1) Project **H2Olive3S** - *Integration of in situ biophysical information on crop and land surface with remotely sensed observations to model olive water use and irrigation scheduling at local and regional scales* (PTDC/AGR-PRO/111717/2009), 2) Program Ciência 2008, FCT-Portuguese Foundation for Science and Technology. The authors thank the enterprise "Olivais do Sul" (owner of experimental field) and Dr. Matthias Mauder (Karlsrue Inst. Technology, Germany) for support.