Soil water reserve estimation and vegetation relationships in a Mediterranean sub-humid forested catchment

J. Martínez-Fernández and V. Hernández-Santana

ABSTRACT

A simple water balance model was used to calculate soil water reserve in a Mediterranean forested catchment. The relationship between soil water reserve and leaf water potential and stem water content was analysed. The usefulness of these variables as plant water status indicators was tested. The analyses were developed with a seven-year-long database (2001–2007) in the case of soil water content and with a four-year long one (2004–2007) for the tree variables. The soil water reserve showed similar types of behaviour for every year, with minimum values at the end of summer (75.2 mm in September 2003) and maxima in winter (204.7 mm in January 2001). The balance model built with precipitation, runoff and ET_o simulated the soil moisture content well ($r^2 = 0.85$, $p < 0.001$). Seasonal variations in the tree variables followed a typical trend, maximum values (-0.18 MPa in June 2007 and $0.654\ cm^3\ cm^{-3}$ in May 2004, respectively) being observed at the end of spring, and minimums due to summer drought (-1.5 MPa and $0.520\ cm^3\ cm^{-3}$ in August 2005). The relationship was stronger between soil water reserve and stem water content ($r^2 = 0.85$) than with leaf water potential ($r^2 = 0.67$), suggesting stem water content is a more sensitive indicator of water limitation.

Key words | leaf water potential, Mediterranean conditions, soil moisture content, soil water reserve, stem water content

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INTRODUCTION

The severe conditions that the Mediterranean climate imposes on biological systems (drought and rainfall variability) are expected to increase in the future due to global climate change (Schröter *et al.* 2005). These water-limiting conditions frequently generate long-term water stress to the plants which spatially determine species distribution in the Mediterranean region (Joffre *et al.* 2001). The response to this long-term water stress mainly depends on the relationship between the soil and plants, and is less well known than the reaction of plants to daily changes in water status (Kirkham 2005). A few techniques have been used to study the plant water stress, ranging from measurements of stomatal conductance to determinations of leaf water potential; the assessment of whole-plant transpiration, and stem water monitoring.

Soil moisture is also important to determine plant water stress and it is also a key state variable for understanding a large number of hydrological processes involved in a broad variety of natural processes (geomorphological, climatic, ecological) that act at different spatio-temporal scales (Entin *et al.* 2000). The installation and maintenance of permanent equipment for soil moisture measurements is essential as a support for methodologies based on modelling. However, the measurement of soil moisture requires sophisticated techniques, is time consuming, expensive and demands considerable human resources, regardless of the spatial scale used for the work. Alternatives to manage field measurements include estimations by remote sensing and estimations based on more or less complex models (Albertson & Kiely 2001; Qiu *et al.* 2003). Accordingly, the

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estimation of soil moisture by indirect approaches is an interesting alternative where in situ measurements are difficult or even impossible.

In the present work we used a simple water balance model to calculate the soil water reserve during the forest growing season. From this, the soil moisture content was derived from the soil water reserve. A four-year database was employed to calibrate an equation that was used to estimate the soil moisture content down to a depth one metre and to verify the usefulness of the method. The soil water reserve and plant water status were analysed using the leaf water potential and stem water content as plant water stress indicators. The objectives of this work were: (1) to test the feasibility of a simple water balance model to calculate the soil water reserve and estimate the soil moisture content; and (2) to analyse the relationship between the soil water reserve and the leaf water potential and stem water content and their usefulness as plant water status indicators.

STUDY SITE AND METHODOLOGY

Study site and experimental layout

The research was conducted at a small long-term experimental forested catchment (62 ha) located in the southwest part of the Duero basin (Spain). The Rinconada experimental catchment is located 70 km south of the city of Salamanca, in the western sector of the *Sistema Central* range (Spain). Altitude ranges between 1,140 and 1,450 m.a.s.l., and the terrain has an SW–NE orientation. The catchment rests on a varied geological substrate with a predominance of impermeable rocks (sandstone, shale and quartzite). A limited sector features limestones and below this there is a small aquifer. The soils are mainly Leptosols, Cambisols and Regosols. Their texture is on average silt–loam. The organic matter content is high (around 10%) between 0–15 cm depth, but always is less than 1% below 25 cm depth. The soils are deeper than 1 m, both at the valley bottom and on the hillsides. The climate is sub-humid Mediterranean, with a mean temperature of 10 °C (climate data from 1951 to 2006, measured at a nearby long-term weather station at 998 m.a.s.l.). Mean annual rainfall ranges around 1,000 mm, most of the precipitation being concentrated in the cold part of the year and the dry period coinciding with the warmer season and the growing period of the trees (Martínez-Fernández *et al.* 2004). Mean annual potential evapotranspiration (ET_o) is about 850 mm. Almost 70% of the basin is occupied by a dense *melojo* oak (*Quercus pyrenaica* Willd.) forest. Currently, the forest is fairly homogeneous, with a high tree density (2,300 tree ha^{-1}; mean basal diameter, 14.5 cm; diameter at breast height (DBH), 10.4 cm).

In the spring of 2000, a network of 18 soil moisture-measuring stations was installed at this site (Martínez-Fernández & Ceballos 2005). Each station comprises a soil profile equipped with five two-wire TDR probes installed horizontally at depths of 5, 15 25, 50 and 100 cm. The measuring network (Figure 1) comprises three transects with six stations each, arranged perpendicularly to the valley of the catchment. The criterion used for the distribution of the stations was strictly topographic. Thus, on each slope there is at least one station on each section: watershed, middle slope and footslope. The soil moisture content was measured fortnightly and the TDR instrument used was a Tektronix 1502C (Tektronix, Beaverton, OR). The soil water content (SWC) dataset comprised seven years of measurements. Three highly contrasted years (2005–2007) in terms of the amount of rain fallen were used as a calibration period. The other four years (2001–2004) were used as a verification period. Since the work aimed to analyse soil water dynamics and its relation to vegetation ecophysiology (water potential and content), only the data of the growing season of each year were used (June–September).

An automatic weather station (Campbell Scientific, Logan, UK) was installed at the experimental catchment. Relative humidity and temperature (HMP35C probe), rainfall (ARG 100 rainfall tipping bucket), solar radiation (SP-Lite Silicon pyranometer) and wind speed (RM Young 05103 anemometer) were recorded every 10 s and averaged or totalled every 10 min in a CR1000 datalogger.

Runoff was monitored at the bottom of the catchment using an H-flume gauge equipped with a continuous Thalimedes (OTT Messtechnik, Kempten, Germany) water-level recorder. The water level was recorded every 10 min.

Four plots with four representative trees each ($n = 12$) distributed along the catchment (Figure 1) were chosen to

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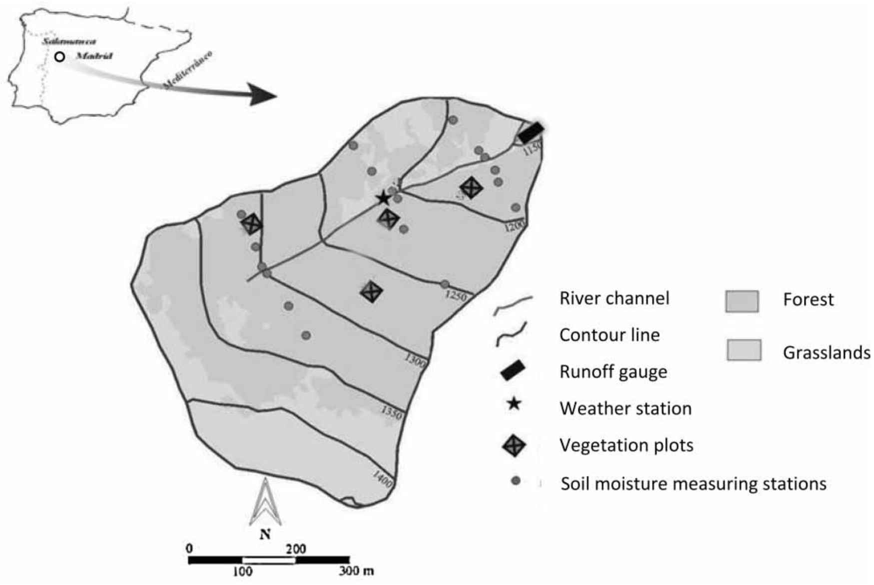

Figure 1 | Location of the experimental watershed and the equipment used in the study.

monitor the stem water content (θ_{St}) every two weeks from June to September (2004–2007). Two TDR probes were inserted radially into the tree stems at 20 and 120 cm trunk height, and θ_{St} was measured with the same equipment as SWC and according to the methodology described in Hernández-Santana & Martínez-Fernández (2008).

Every 2–3 weeks during the growing season (2004–2007), 16 shoot tips with leaves from several *melojo* oak trees were sampled at a height of about 5 m. These trees were located at the four representative plots where θ_{St} was measured. Their water potential ($\psi_{l,p}$) was measured with a pressure chamber (SKYE SKPM 1400, Skye Instruments Ltd, Powys, UK) (Scholander *et al.* 1965). On each sampling date, two leafy shoots from eight trees ($n = 16$) were measured at predawn (just before sunrise).

Each plot was representative of the different forest stages. The maturity and size of the trees were different, although the differences were not very large (Table 1). The density and the leaf area index (LAI) were also different.

Table 1 | Rainfall and runoff at the Rinconada experimental catchment during the period studied (2001–2007)

Experimental plot	Tree (ha^{-1})	LAI (2005/2006)	Mean DBH (cm)	Mean height (m)	Altitude (m)/ orientation
1	1,975	3.40/1.68	11.7	7.4	1,310/100°E
2	1,050	1.65/0.94	13.7	10.77	1,286/15°NNE
3	1,950	4.16/2.73	12.6	9.46	1,244/0°N
4	4,275	3.38/1.38	8.1	6.21	1,216/14°NNE

Methodology

The water balance at catchment scale was calculated using the water balance (input–output) approach (Likens *et al.* 1977), used successfully by Bellot & Ortiz de Urbina (2008) under Mediterranean conditions at a small catchment in Spain:

$$P = R + ET_a + \Delta \mathrm{SWR} \tag{1}$$

where P is precipitation, R is runoff, ET_a represents actual evapotranspiration and soil water reserve (SWR) represents the soil water reserve (i.e. stored water), all of them in mm. This equation assumes that the underlying bedrock is impermeable (i.e. there is no loss of water to deep percolation). Most of the rocks at the Rinconada experimental catchment are impermeable, but limestones are present in a limited sector of the catchment; only the plot located at the highest altitude and the two stations closest to it (Figure 1). Nevertheless, we consider that this premise is acceptable because the water balance model was used to estimate the SWR during the growing season. At the study

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site, the *melojo* oak starts to form leaves in the middle of May and the leaves are shed at the beginning of October. In a previous work it was demonstrated that under these environmental conditions no soil water recharge occurs between May and October, since it was not observed any soil moisture increase at the deepest measurements after rainfall events (Hernández-Santana *et al.* 2008a). It is also assumed in the present work that in the long-term SWR remains relatively constant ($\Delta\mathrm{SWR} = 0$) and ET_a equals $P - R$ (Likens *et al.* 1977). For any other period, the stored soil water changes, and ΔSWR represents the changes in this variable (Bellot & Ortiz de Urbina 2008). Accordingly, ΔSWR was calculated based on the water balance approach:

$$\Delta\mathrm{SWR} = P - R - ET_\mathrm{a}. \tag{2}$$

To calculate the potential maximum daily output from the soil, we used the daily potential evapotranspiration (ET_o), besides the daily measured runoff at the Rinconada experimental catchment. Daily potential evapotranspiration was calculated using the Penman-Monteith method (Allen *et al.* 1998). Once this value had been obtained, it could be compared with the total amount of water input through precipitation, giving SWR variation for a defined period. A similar water balance scheme was used by Vincke & Thiry (2008) to obtain SWR, although those authors included drainage as another output.

The calculated theoretical SWR can be positive or negative, and it indicates a soil water excess or shortage respectively. It is used in this paper as a proxy for the mean SWC and reflects the extent of water stress for vegetation in the catchment during the selected period (Bellot & Ortiz de Urbina 2008). A period of n days before each selected day was used to calculate SWR, because it depends on the previous P, R and ET_o. Thus, SWR represents the potential soil water availability (mm) accumulated n days before. We computed SWR over three years (2005–2007) using periods of 30, 60, and 90 days before. The best relationship between SWR and SWC ($r^2 = 0.85$) was found for 90 days (0.42 and 0.75 for 30 and 60 days, respectively). These results are in agreement with those found by Bellot & Ortiz de Urbina (2008). Thus, the daily SWR pattern was calculated as the difference between the accumulated input (P) and the maximum potential output ($ET_\mathrm{o} + R$) along the previous 90 days.

Statistical analyses

ANOVA and linear and non-linear regression analyses were carried out with SPSS 15.0 (SPSS Inc., Chicago, IL) software. The Nash–Sutcliffe (Nash & Sutcliffe 1970) test was used to assess the goodness of the estimation method. The coefficient (N) of this test can range from $-\infty$ to 1: a value of 1 corresponds to a perfect match between the estimated and measured data, while a value of 0 indicates that the estimations are as accurate as the mean of the measured data. In contrast, a value of less than 0 occurs when the measured mean is a better predictor than the estimator.

RESULTS

Water balance and soil water reserve

During the study period (2001–2007), rainfall ranged between 552.6 mm (2007) and 1291.2 mm (2002). Both values are close to the maximum and the minimum of the long-term rainfall series in the area. Thus, the rainfall in the most humid year was more than twice the rainfall in the driest year (Table 2). Runoff differences were even higher, and maximum annual runoff was more than five times the minimum (Table 2). These data reveal the typical strong hydrological variability of Mediterranean environments. This variability is characteristic not only of semiarid (Piñol *et al.* 1991) but also of humid Mediterranean areas. The runoff coefficient at the Rinconada experimental

Table 2 | Characteristics of the experimental plots studied

Year	Rainfall (mm)	Runoff (mm)	Runoff coefficient (%)
2001	976.6	236.8	24.2
2002	1,291.2	113.2	8.8
2003	1,215.6	279.1	23.0
2004	656.6	124.5	19.0
2005	659.4	53.5	8.1
2006	1,203.8	92.3	7.7
2007	552.6	73.4	13.3

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catchment varied from 24.2 to 7.7%. The runoff coefficient showed similar variability but was lower than those reported for other forested basins under Mediterranean sub-humid conditions (Piñol *et al.* 1995).

The SWC was averaged in a space basis and exhibited a very strong seasonal cycle (Figure 2), ranging from 75.6 mm (September 2003) to 240.7 mm (January 2001). In all the years, the SWC showed a similar behaviour. After the winter–spring maximum, the SWC decreased rapidly from May–June coinciding with the beginning of the *melojo* oak growing cycle. The minimum was reached in August–September, at the end of the dry period. During these two months, the soil water deficit was maximum and the soil reached the wilting point, which lasted for 2–3 months in each year (Hernández-Santana *et al.* 2008b).

The SWR obtained on applying the water balance model for the reference period of 90 days was compared with the SWC values measured from April 1, 2005 until October 31, 2007 (Figure 3). The model simulates the evolution of soil water throughout the period reasonably well, except for the moments of water excess. The difference between the calculated SWR value and that of SWC that occurs in winter months may be related to the existence of a volume of water that is lost through drainage into the small aquifer mentioned previously. During the rest of the time, when soil water recharge was incomplete (after a rainfall event no soil moisture increase was detected at the deepest measurements), the evolution of SWR and SWC was very similar. During the dry period, the parallelism was fairly strong, due to the absence of soil water recharge in that period (increases in soil moisture only in the first centimetres). As the specific aim of this work was to estimate SWR during the growing season of the *melojo* forest, coincident with the dry period, a comparison between the SWR and SWC values during the growing seasons (May–October) of the 2005–2007 period was performed. The three years were fairly well contrasted in terms of the amount of rainfall, including very humid and very dry conditions. A regression analysis was made with the data for these three growing seasons in order to obtain a simple regression model to estimate the SWC from the SWR. As can be seen in Figure 4, the relationship between both variables was very close. An exponential model was fitted, obtaining a high coefficient of determination ($r^2 = 0.85$, $p < 0.001$).

The equation was also validated with the rest of the study period not used in the previous phase of calibration. Thus, the equation of the exponential model was used as an estimator of SWC for the growing seasons of the 2001–2004. That period was used to test the applicability of the model to estimate the soil moisture content. The comparison between the measured and estimated SWC values was fairly good. The regression analysis revealed a good fit ($r^2 = 0.85$, $p < 0.001$). In the four growing seasons

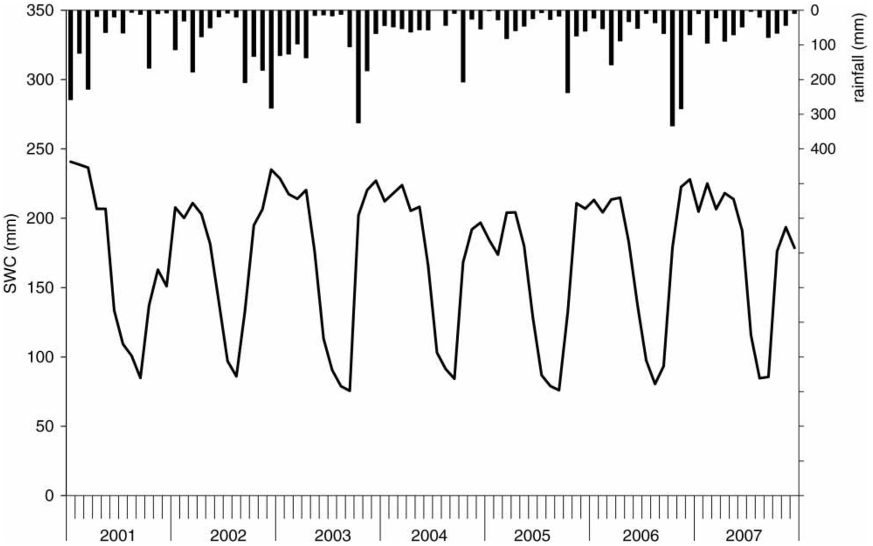

Figure 2 | Average soil moisture content and monthly rainfall from 2001 to 2007 at the Rinconada experimental catchment.

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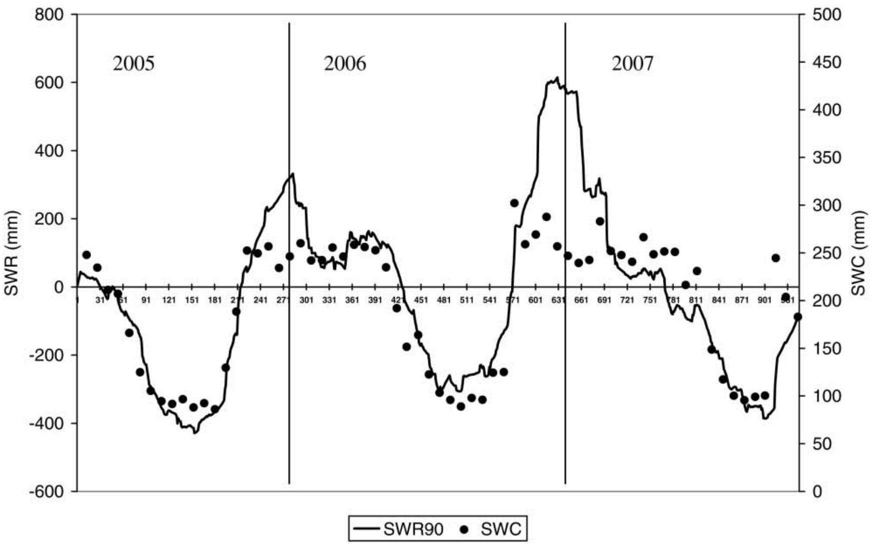

Figure 3 | Soil water reserve (SWR) estimated (line) and soil water content (SWC) measured (dots) from April 1 (DOY 1), 2005 until October 31, 2007.

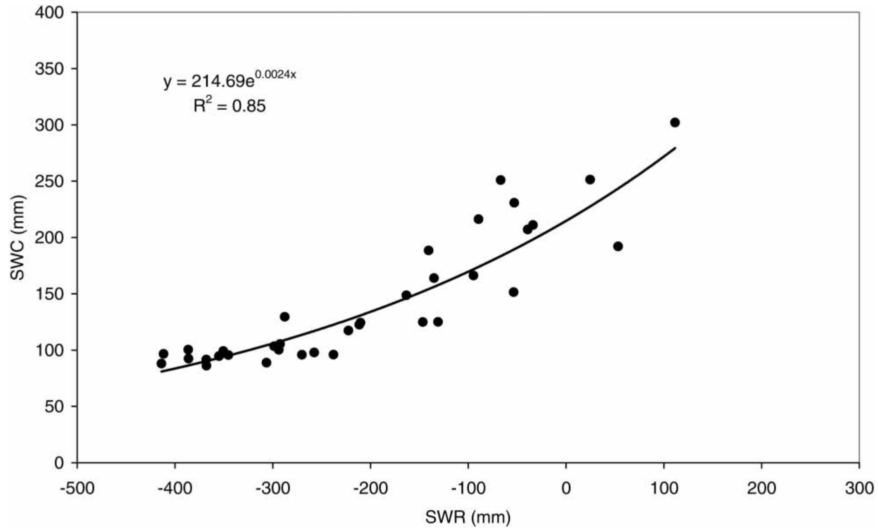

Figure 4 | Regression analysis between soil water reserve (SWR) and soil moisture content (SWC) performed with data for the growing seasons (May–October) of the 2005–2007 period.

analysed during the verification period, the coefficient of determination between the measured and estimated values ranged between 0.87 (2004) and 0.96 (2003). As an example, Figure 5 shows the results of the estimation during the 2004 growing season. The relationship between the SWC values measured and estimated during this growing season is very close ($r^2 = 0.87$, $p < 0.001$). The results from the Nash–Sutcliffe efficiency for the verification period (2001–2004) were quite satisfactory, affording a value of $N = 0.76$.

Temporal evolution of predawn leaf water potential and stem water content

Temporal differences in θ_{St} were observed during the four years studied (2004–2007) (Figure 6). In all years, maximum values were reached in May and were associated with new leaf growth (leaf sprouting takes place at the end of May and leaf growth occurs mainly in June) and the absence of a soil moisture deficit. Thereafter, the stem water content gradually decreased along the summer. The minimum

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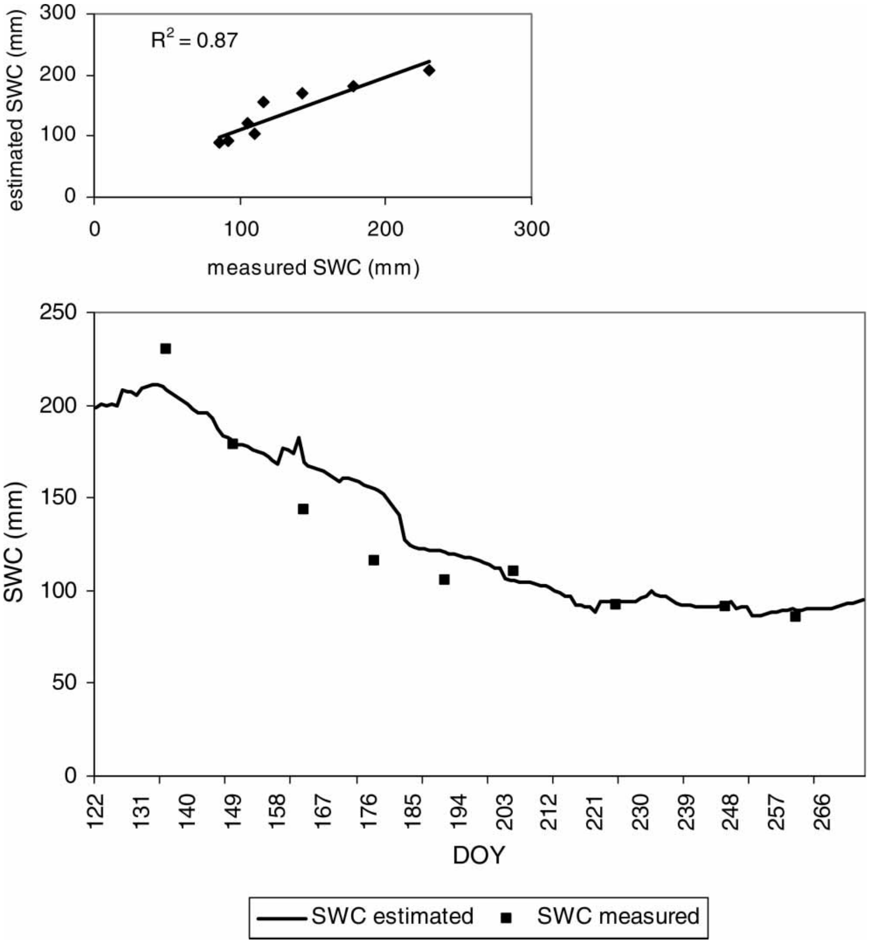

Figure 5 | Comparison between measured and estimated soil water contents during the growing season of 2004.

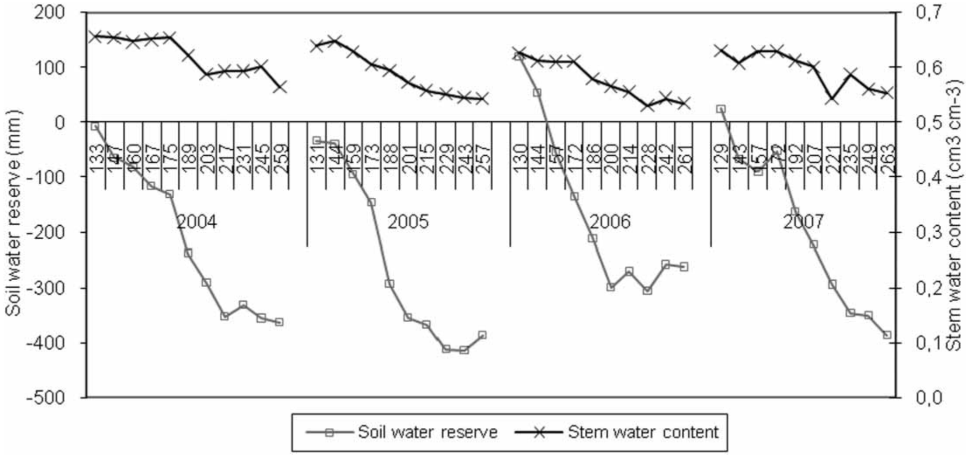

Figure 6 | Evolution over time of the stem water content (black crosses, left axis) and soil water reserve (white squares, right axis).

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value was reached at the end of September 2005. Similar trends were observed for the other three years. Once the soil had been rewatered due to rainfall, the stems were partially recharged after the summer. The variation in mean stem water values ranged between 19% for 2005 to 12% for 2007. The years 2004 and 2006 followed an intermediate trend (about 15%). Significant differences ($p < 0.0001$) were found in the decrease in θ_{St} during the summer of all four years. In 2004 and 2007, significant differences were found between June and September; in 2005 one month before, and in 2006 between June and the rest of the months.

Throughout the four consecutive summers, $\Psi_{l,p}$ was relatively high (Figure 7). Although a decrease was observed from spring to the end of summer, these values always remained above -1 MPa, except for some days in August and September. This was especially the case in 2005, when the values of some trees reached absolute minimum values, ranging from about -1.1 to -1.8 MPa. The highest values were recorded at the beginning of June (-0.3 MPa in 2004 and 2006, -0.4 MPa in 2005 and -0.18 in 2007). The lowest mean obtained was -1.5 MPa in 2005, whereas in 2004 and 2006 the lowest mean measurement was about -0.8 MPa, and in 2007 it was -0.65 MPa. The predawn leaf water potential tended to be slightly lower in 2005 than in the other years. The statistical analysis revealed that only in this year were there differences ($p < 0.0001$) in $\Psi_{l,p}$ between June and September.

ANOVA analyses revealed the absence of significant differences of each plot average θ_{St} and $\Psi_{l,p}$ between the four experimental plots. Thus, it seems that differences (tree density, tree size or soil properties) among the plots are not sufficiently pronounced to produce variations.

Tree water status in relation to the soil water reserve

During the study period (2004–2007), the continuous increase in the deficit resulted in lower θ_{St} and $\Psi_{l,p}$ values. These results confirmed that the SWR (i.e. availability or shortage) affected the tree water status, as reflected by θ_{St} and $\Psi_{l,p}$. The regression analyses revealed that the relationship between SWR and $\Psi_{l,p}$ for the data from the four years was lower than for the θ_{St}–SWR relationship, and the type of equation was also different.

The regression analysis of θ_{St} and SWR (Figure 8) was carried out with two years (2004 and 2005) with very different amounts of rainfall and hence different SWR conditions (Table 2). The results pointed to a clear and significant relationship between both variables ($r^2 = 0.85$, $p < 0.0001$). A linear regression equation was fitted to the pooled data ($n = 19$), yielding the expression

$$\theta_{St} = 0.0002 * \mathrm{SWR} + 0.6633 \qquad (3)$$

The appropriateness of this equation was verified with the data for 2006 and 2007 ($n = 16$), which were not used

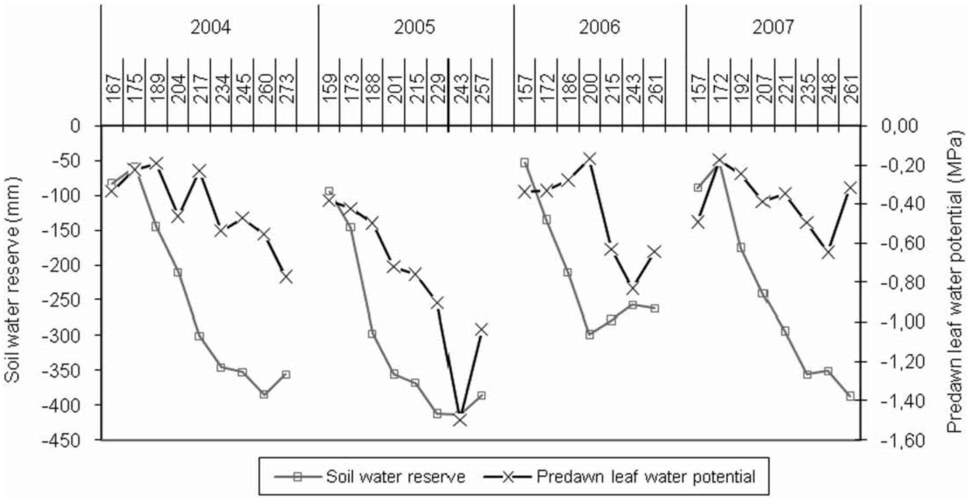

Figure 7 | Temporal variation of the predawn leaf water potential (black crosses, right axis) and soil water reserve (white squares, left axis).

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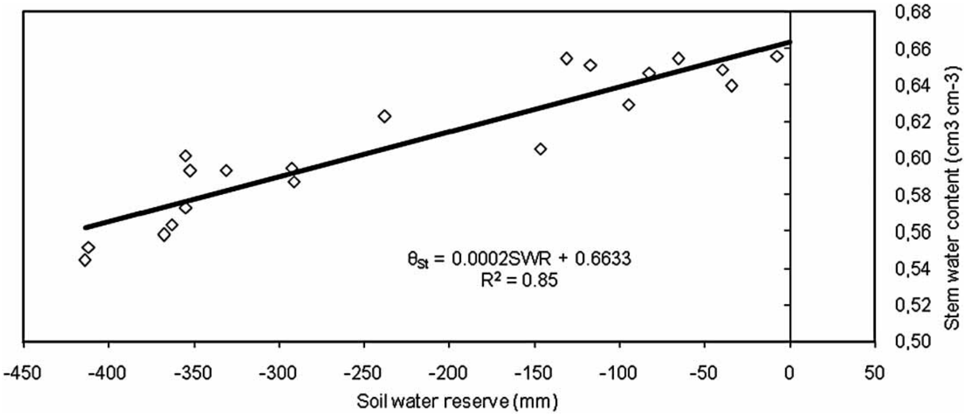

Figure 8 | Relationship between the soil water reserve and the stem water content.

to construct the proposed curve. The relationship between the measured and estimated values was strong and significant ($r^2 = 0.73$, $p < 0.0001$). The mean error (−0.8%) was low and no significant bias was detected. The root mean square error (RMSE) analysis (2.6%) was also satisfactory.

The data used to analyse the SWR–$\Psi_{l,p}$ relationship were those measured in 2004 and 2005. The regression equation fitted to the pooled data ($n = 17$) afforded a negative exponential function (Figure 9):

$$\Psi_{l,p} = -0.15 * e^{-0.0045 * SWR} \tag{4}$$

Although this relationship is strong and significant ($r^2 = 0.67$, $p < 0.0001$), the verification results with the measurements taken in 2006 and 2007 were not as good (mean error 5%, RMSE 15%) as in the case of θ_{St}, as also occurred with the results of the calibration equation. Figure 9 shows two different regions for the evolution of $\Psi_{l,p}$ versus SWR. For SWR values higher than about −300 mm, $\Psi_{l,p}$ remained almost the same. For lower SWR values, $\Psi_{l,p}$ underwent a noteworthy decrease. This means that for a variation of 27% in high SWR, $\Psi_{l,p}$ only varied by 19%. However, for values lower than −300 mm the same difference in SWR (27%) led $\Psi_{l,p}$ to decrease by 68%. This interval, defined by the −300 mm SWR threshold, indicates the most critical period in terms of water stress.

DISCUSSION

In water-limited environments the use of simple models similar to the one used here can offer an alternative to study soil water dynamics. The premise of the absence of deep drainage is acceptable in certain environments owing

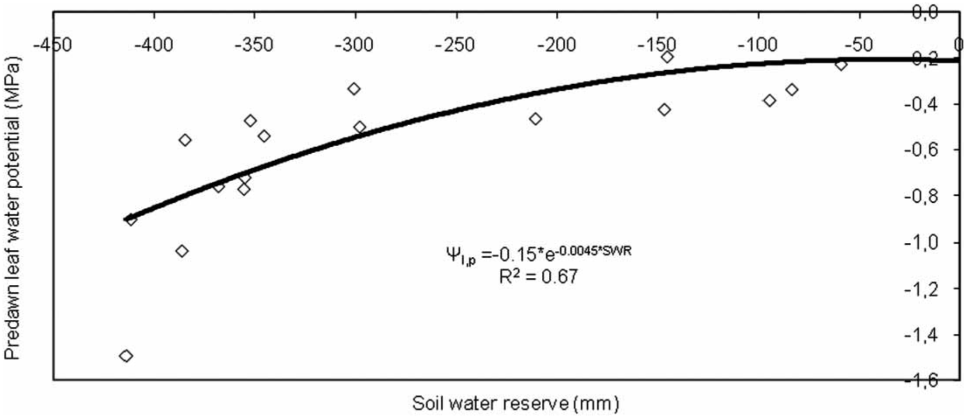

Figure 9 | Relationship between the soil water reserve and the predawn leaf water content.

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to climatic restrictions (Reynolds *et al.* 2000) or geological characteristics. In environments with strong seasonal rainfall differences, such as those found in the Mediterranean area, the proposed methodology is especially useful for the study of soil water dynamics during the most critical periods (i.e. the growing season).

In the present work we demonstrate that a simple water balance model can be used as a good estimator of the SWR and hence of the SWC (i.e. soil water conditions). For basins where only basic equipment (weather and discharge stations) is available, the method used in the present work could be useful for estimating variables such as the SWC, which needs a costly and time-consuming experimental layout. The SWR can be used as a good parameter for the analysis of the plant water status in water-limited environments such as those in the Mediterranean area (Bellot & Ortiz de Urbina 2008).

Although the years used in the present study were highly contrasted in terms of the amount of rainfall (Figure 2), estimation of the SWC was very satisfactory in all cases. This estimation faithfully reproduced the huge decrease occurring in the SWC that regularly takes place each year. The estimated SWC also revealed what had been previously observed experimentally. Thus, each year the soil water becomes completely exhausted in the first metre of soil under the *melojo* oak forest. The combined action of the summer drought and of the transpiration of the trees meant that for one or two months (August–September) there was no water available for the plants in the first metre of soil but the trees had access to deeper water such as the estimated within SWR (Figure 8). The linear relationship between θ_{St} and SWR shows that the whole hydrologically active soil profile during the growing season was used by trees. That relationship demonstrates that trees take water beyond 1 m depth as was investigated in a previous study (Hernández-Santana *et al.* 2008b).

Seasonal variations in $\Psi_{l,p}$ and θ_{St} followed a typical trend, maximum values being observed at the end of spring, followed by a progressive decline during the summer drought. The decrease in $\Psi_{l,p}$ in the summer resulted from decreases in the SWR (Figure 7). However, the $\Psi_{l,p}$ values were not very low as compared to other values found for this species (−3.2 MPa, Mediavilla & Escudero 2003), indicating that the trees studied here had access to deeper stored water. More similar values of absolute maximum measurements at predawn have also been reported by Gallego *et al.* (1994) for the same region. The relatively high values and the small variation in $\Psi_{l,p}$ during 2004, 2006 and 2007 are consistent with the access of the roots to deeper stored water. The non-significant variation in $\Psi_{l,p}$ (except for 2005) indicates that no clear water stress situations occurred, which is not concordant with the decreasing rates of SWR estimated to a depth of 100 cm, with especially low values at the end of the growing season. Accordingly, water would have to be pumped from depths greater than 100 cm through capillary action, or be absorbed by a deep tap root. Although a denser root system of the *melojo* oak is found in the first 50 cm (Gómez Manzaneque *et al.* 1998), a deep pivoting system has been shown to be very important for the maintenance of transpiration rates throughout the summer, and a depth of at least 250 cm has been reported for the same study site (Hernández-Santana *et al.* 2008b).

In 2005, the variation in and the low value of $\Psi_{l,p}$ suggested that the trees had undergone more acute water stress (Figure 7). This situation would have been caused by an incomplete recharge of the soil, owing to the very small amount of rainfall that fell along the year, which was reported to be exceptionally dry (in the last 55 years, only four were drier than 2005, Hernández-Santana *et al.* 2008b).

The relationship between the SWR and $\Psi_{l,p}$ shows that $\Psi_{l,p}$ decreased more steeply as the summer drought progressed (Figure 9) as is established in the soil water and potential relationship. The higher values of SWR represent a condition of adequate water availability for this species in the study area. The main effect of the soil water deficit on $\Psi_{l,p}$ appears in the region of the curve where the SWR falls below −300 mm. Beyond this point, $\Psi_{l,p}$ decreases sharply in response to small changes in the SWR. Similar results were found by Bellot & Ortiz de Urbina (2008) for *Quercus ilex*.

The θ_{St} values pointed to differences in the temporal water status along the four years, whereas $\Psi_{l,p}$ did not (except for 2005). This suggests that θ_{St} is a more sensitive indicator of water limitation. When the soil water deficit became more severe (2005), θ_{St} exhibited minimum values and the greatest variation. The regression analysis revealed that θ_{St} was the variable most strongly related to the soil water status. As pointed out by Tyree & Ewers (1991), most of the mass of a tree is contained in the bole, which is in close hydraulic contact with the soil, so the bole will reflect

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changes in soil water potential more closely than $\Psi_{l,p}$. Several authors have suggested that water stored in stems might be used in transpiration to overcome the lack of water during the summer (Waring & Running 1978; Wullschleger *et al.* 1996; Kravka *et al.* 1999). This decrease in water is the result of an incomplete daily recovery of the stem water content during the growing season due to soil water deficit (Hernández-Santana *et al.* 2008a).

The results obtained here support the usefulness of both $\Psi_{l,p}$ and θ_{St} to reflect tree water stress. The analyses carried out suggest that tree water status is closely related to SWR. However, it was also found that θ_{St} was more closely related to SWR. The poorer reflection of the evolution of SWR by $\Psi_{l,p}$ can be explained in terms of the difficulty of an equilibrium between the SWC and the plant water status being reached in some areas with different climatic conditions (Bellot & Ortiz de Urbina 2008). In dry sites, it has been demonstrated that plant water storage is permanently refilled by continuous sap flow overnight and at predawn (Cérmak *et al.* 2007). Therefore, θ_{St} reaches equilibrium with the SWR more easily than $\Psi_{l,p}$. In the present study, stem water content declined linearly and showed a strong hydraulic relationship with SWR (Figure 8), hence closely tracking changes in soil moisture; the lack of equilibrium of $\Psi_{l,p}$, would be better detected with θ_{St}. Only under very low SWR did $\Psi_{l,p}$ change substantially.

CONCLUSIONS

The water balance method used here could be useful for estimating soil moisture contents and has the advantage of being less complicated and less time-consuming than *in situ* measurements. The SWR can be used as a good parameter for plant water analysis at this catchment.

The results obtained support the usefulness of both leaf water potential and stem water content to reflect tree water status; these variables are also closely related to the SWR. It was found that stem water content is more closely related to the SWR, probably because the trunk is in closer hydraulic contact with the soil and it is thus easier for the stem water content to reach equilibrium with the soil water reserve.

Finally, according to current measurements this species seems to be relatively well watered through a deep root, and the trees used water beyond the first metre of soil avoiding clear water stress during most of the period studied. These results showed hence that ET_o was close to and good estimator of ET_a. Nevertheless, in the near future it is highly likely that drier conditions will be more frequent, as predicted by climate changes scenarios and corroborated through long-term rainfall analysis of the study area (Hernández-Santana *et al.* 2008a).

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