Knowledge of sap flow variability in tree trunks is important for up-scaling transpiration from the measuring point to the whole-tree and stand levels. Natural variability in sap flow, both radial and circumferential, was studied in the trunks and branches of mature olive trees (*Olea europea* L., cv Coratina) by the heat field deformation method using multi-point sensors. Sapwood depth ranged from 22 to 55 mm with greater variability in trunks than in branches. Two asymmetric types of sap flow radial patterns were observed: Type 1, rising to a maximum near the mid-point of the sapwood; and Type 2, falling continuously from a maximum just below cambium to zero at the inner boundary of the sapwood. The Type 1 pattern was recorded more often in branches and smaller trees. Both types of sap flow radial patterns were observed in trunks of the sample trees. Sap flow radial patterns were rather stable during the day, but varied with soil water changes. A decrease in sap flow in the outermost xylem was related to water depletion in the topsoil. We hypothesized that the variations in sap flow radial pattern in a tree trunk reflects a vertical distribution of water uptake that varies with water availability in different soil layers.

**Keywords:** automatic irrigation control, heat field deformation method, multi-point sensors, Quercus suber, sap flow radial pattern, vertical profile of root absorption, water stress indicator.

**Introduction**

Sap flow techniques can be applied to trees of any age or size but circumferential or radial heterogeneity in sapwood conductivity may result in high variability with probe location sap flow estimates based on single-point measurements. For example, Nadezhdina et al. (2002) reported errors resulting from the assumption of uniform flow at all sapwood depths of from 90 to 300%, depending on species. Ford et al. (2004) found that a single-point measurement resulted in discrepancies in the estimation of daily water use by *Pinus* species of up to 154% relative to estimates obtained by multi-point measurements. Delzon et al. (2004) showed that neglecting the radial variation in sap flow could lead to an overestimation of daily transpiration of up to 47% in 91-year-old maritime pine stands.


In the present study, we investigated radial variability in sap flow in the trunk and branches of mature olive trees (*Olea europea* L., cv Coratina), and examined how the sap flow radial pattern changed during the day with changing soil water content (SWC). We postulated that variation in sap flow radial pattern in response to changes in environmental conditions provides an index of water stress with possible application in the regulation of tree irrigation.

**Material and methods**

**Experimental sites**

The experiments were performed in an olive orchard (*Olea europea* L., cv Coratina) located near Andria, southern Italy (41°12’ N, 16°10’ E, 175 m a.s.l.). Mean annual rainfall is 530 mm, distributed from September to April. Yearly means of minimum and maximum temperatures are 11 and 21 °C, respectively. The loam topsoil is up to 0.5 m deep. Plants (~100 years old) were trained according to the vase system with two main branches at about 0.8–1 m above ground. The orchard was drip-irrigated until two months before the study began. Main meteorological variables (global radiation, air temperature and humidity) were measured 1 m above the canopy. Soil water content was measured once or twice daily by time-domain reflectometry probes at a depth of 15 cm at eight positions in the orchard.
Sap flow measurements

Sap flow was measured by the heat field deformation method (HFD) (Nadezhdina et al. 1998, Nadezhdina and Čermák 2000, Čermák et al. 2004, Nadezhdina et al. 2006a). Deformation of the heat field around a linear heater in a certain (i) tangential section of the stem was taken as a measure of sap flow and calculated as sap flow density, \( q_i \) (g cm\(^{-2}\) h\(^{-1}\)):

\[
q_i = 3600DL_{sw}^{-1}(K_i + (dT_{sym,i} - dT_{as,i}))dT_{as,i}^{-1}Z_{tg}^{-1}
\]  

(1)

where \( dT_{sym,i} \) and \( dT_{as,i} \) are temperature differences (K), recorded by symmetrical and asymmetrical thermocouples, respectively, in the measured i tangential section of a stem, perpendicular to xylem radius (Figure 1); \( Z_{as} \) is the axial distance (cm) between upper end of the symmetrical thermocouple and the heater (\( Z_{as} \) is equal to half of \( Z_{sym} \)); \( Z_{tg} \) is the tangential distance (cm) between the upper end of the asymmetrical thermocouple and the heater; \( K_i = (dT_{sym,i} - dT_{as,i})/L_{sw} \) is the value between both measured temperature gradients (K) in a certain tangential section of a trunk under conditions of zero-flow; \( L_{sw} \) is sapwood depth (cm); and \( D \) is thermal diffusivity of fresh wood (cm\(^2\) s\(^{-1}\)). A nominal value for \( D \) was assumed equal to 2.25 \( \times \) 10\(^{-3} \) cm\(^2\) s\(^{-1}\).

Experimental design

Thirteen mature olive trees were studied (Table 1). Eight multi-point HFD sensors were used for short-term (from several hours to 3 days) measurements of sap flow radial pattern in 12 olive trees from July 23 to August 2, 2002. Each tree trunk was measured from opposite sides (with the exception of Tree 12). Main branches were measured from one to three cardinal directions in four of the sampled trees. All measurements on a particular tree were conducted simultaneously. Ten additional multi-point sensors provided continuous measurements in the trunk (three sensors) and seven large branches of Tree 7 (Table 1). Needles of the multi-point sensor contained six differential thermocouples, 6 or 10 mm apart.

Data were recorded every minute and stored as 10-min means with data loggers (DL2e, Delta-T Ltd., Cambridge, U.K.; and MIDI-12, EMS, Brno, Czech Republic). Periodically, the insertion depth of the multipoint sensors was changed to allow characterization of the sap flow radial pattern at up to 18 measuring points.

Scaling errors attributable to assumption of constancy sap flow radial pattern

Two simplified contrasting radial patterns of sap flow were considered: Type 1 = rising from about half maximum rate at the outer edge of the xylem to a maximum at mid-sapwood depth and then falling to zero at the inner edge of the sapwood; and Type 2 = falling continuously from a maximum rate just beneath the cambium to zero at the inner edge of the sapwood (Figure 2A). Sapwood depth was assumed equal to 40 mm for both patterns. The Type 1 sap flow radial pattern was assumed when integrating sap flow from single-point measurements. For simplicity, it was assumed that maximum sap flow density for the Type 1 radial profile occurred in the middle of the sapwood and that sap flow density just below the cambium was equal to 50% of its maximum. The error (%) arising from such a calculation, assuming that the actual radial sap flow pattern conforms to Type 2, and not Type 1, was calculated for different single-point sensor positions along the xylem radius as:

\[
\text{Systemic error} = 100 \left( \frac{\text{Flow( Type 1)} - \text{Flow( Type 2)}}{\text{Flow( Type 2)}} \right) \text{Flow( Type 1)}^{-1}
\]

(2)

where Flow( Type 1) and Flow( Type 2) are flow integrated from single-point measurements according to the Type 1 or Type 2 radial flow pattern.
Table 1. Biometrical data of the sample trees and positioning of the multi-point HFD sensors in trunks and branches of olive trees. Abbreviation: RP = radial profile.

<table>
<thead>
<tr>
<th>Tree no.</th>
<th>Sensor positioning (azimuth) on the trunk or branches¹</th>
<th>Sensor type²</th>
<th>Xylem radius (mm)</th>
<th>Depth of the first measuring point below cambium (mm)</th>
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<tr>
<td>1</td>
<td>SW; NW; E</td>
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<td>78</td>
<td>3; 3</td>
</tr>
</tbody>
</table>

¹ Sensor positioning in the trunk includes only an azimuthal sensor orientation. The label Br is added for branches. For big branches, measured from two sides, an azimuthal orientation of the branch is followed by an azimuthal sensor positioning. Measured branches of all trees (except Tree 7) were first order. Measured branches of Tree 7 were second or higher order and sensors were placed at different heights: labels of higher and lower are added to the branch orientation according to sensor position. Sensors were installed on the upper western branch of Tree 7 at two heights (sensor Br_W_higher2 was situated 30 cm higher than sensor Br_W_higher1).

² Numbers indicate distance (mm) between thermocouples along the needle followed by a number indicative of the number of measuring points.

Figure 2. Hypothetical sap flow radial patterns in olive tree stems with position of the single-point sensor at (A) 5, (B) 10 and (C) 15 mm below the cambium, where @ is the position of the sensor, and (D) possible systematic errors of sap flow integration from single-point measurements associated with ignoring natural variability in radial shapes. The Type 1 pattern was taken to be the most typical, but the occurrence of the Type 2 pattern led to substantial errors if scaling-up of sap flow was based on the assumption that the radial pattern of sap flow is always Type 1. Arrows in (A) and numbers (mm) in (D) indicate possible positions of single point sensor below the cambium.
Results and discussion

Meteorological conditions during the experiment

It rained on July 25 and 27 (15 mm of precipitation). On days before these rain events, referred to as the dry period, SWC in the surface soil layers (0–15 cm) was low (~10% vol). Afterward, referred to as the wet period, SWC increased 2-fold.

Sap flow radial patterns in trunks and branches of olive trees

An example of short-term sap flow dynamics in the trunk of Tree 8 is shown in Figure 3B where needles of the multi-point sensor were moved twice along the xylem radius. These data were used for reconstruction of the sap flow radial pattern in the tree trunk (Figure 3C). Different sap flow rates corresponded to different periods of the day when the multipoint sensors were moved. Functional depth of sapwood was ~45 mm.

As reported by Fernandez et al. (2001), we found both Type 1 (typical for diffuse-porous and tracheid xylem anatomy trees) and Type 2 (typical for ring-porous trees, especially oaks) sap flow radial patterns in trunks (Figures 4 and 5). Contrary to the results of Fernandez et al. (2001) for an excised olive tree, the shape of the sap flow radial pattern recorded on the same side of the trunk remained rather constant during the daytime (Figure 5). This could be associated with the sparse and well illuminated crowns of the olive trees, as substantial differences in daytime sap flow radial pattern were recorded in trunks of trees with dense crowns (Nadezhdina et al. 2001).

The magnitude of sap flow density in the tree trunk varied over the course of the day as the azimuthal position changed. Sap flow density was similar on the north side of the trunk in the morning and afternoon (Figure 5A), whereas on the south and west sides it was at least twice as high in the afternoon as in the morning (Trees 11 and 12 in Figures 5B and 5C).

The sap flow radial pattern recorded in the branches (Figure 6) was similar to that observed in the trunks: two types of radial patterns were observed. Compared with large branches, heterogeneity of sapwood depth was less in smaller, higher-order branches with diameters up to 176 mm (see Tree 7 in Figures 6 and 7). As reported by Giorio and Giorio (2003) for young trees, the Type 1 sap flow radial pattern dominated in small branches (around 72%) where sapwood depth generally ranged from 30 to 40 mm (in 72% of measured small branches, Figure 7). The maximum sap flow rate in the Type 1 radial profile was most often recorded at 13–22 mm depth, close to the depths observed by Fernandez et al. (2001) and Giorio and Giorio (2003). Sap flow density varied widely probably because of differences in the total area of leaves supported by each branch.

Both types of sap flow radial patterns were about equally frequent in trunks and large branches. Sap flow radial pattern and sapwood depth were highly heterogeneous in trunks and branches with diameters greater than 176 mm (Figure 7). Sapwood depth varied between 22 and 53 mm, but was generally about 45 mm (62% of measured trunks and large branches), close to the published values for olive (Fernandez et al. 2001, Giorio and Giorio 2003). Fernandez and Moreno (1999) reported that the sapwood in the trunk of a 12-year-old ‘Manzanilla’ olive tree stained with safranin was highly heterogeneous: the maximum depth of sapwood varying from 12 to 34 mm, with a mean of 27 mm. These authors reported sapwood depths of 35–49 mm in mature 29-year-old ‘Manzanilla’ olive trees. The same authors observed that sap flow velocity in the trunks of olive trees varied mostly because of the gnarled scars and knots left by pruning in early years.
(Fernandez et al. 1998). Trunks of old olive trees have many inclusions of dead tissue, making it especially difficult to choose an appropriate place for sensor installation.

Scaling errors attributable to assumption of constancy in sap flow radial pattern

Several researchers have compared integration of sap flow taking account of radial variation with sap flow estimated on the assumption that sap flow is homogeneous throughout the sapwood. We made a comparison—based on a simplified situation (Figure 2)—between integration of sap flow associated with the Type 1 and Type 2 radial patterns. The greatest differences in the magnitude of sap flow occurred in the outer 20 mm of trunk or branch xylem, which also had the greatest conductive area. The occurrence of a single-point sensor on a Type 2 radial pattern, instead of on an expected Type 1 radial pattern, led to an underestimation of sap flow density by around 45% for small branches or stems, and an overestimation of sap flow by about 15% for larger branches (Figures 2A and 2D). Systematic errors were less (from –14 to +10%) when the single-point sensor was installed within 5 mm of the cambium (Figures 2B and 2D). However, we found that errors increased when the single-point sensor was installed deeper than 10 mm below the cambium, leading to significant underestimation of total flow. For the case of a single-point sensor installed at a depth of 15 mm below the cambium, the errors ranged from 150 to 95%, being about twice as high for small branches as for large branches and trunks (Figures 2C and 2D).

Dynamics of sap flow at different xylem depths during changing environmental conditions

Because of technical difficulties, continuous measurements of sap flow in the trunk and branches throughout the experimental period were made only on Tree 7. The radial profile was Type 2 on the south-east side of the trunk and Type 1 on the north side (Figures 4 and 8). Sap flow at different xylem depths on these sides of the trunk responded differently to rain events followed by a period with high evaporative demand (Figure 8). The outermost xylem (2, 5 and 12 mm below cambium) showed more rapid sap flow after rain (mainly on the north side), whereas sap flow remained unchanged in the inner xylem layers (21–37 mm). Sap flow in the outermost xylem (5 mm) on the north side of the trunk increased after the rain events to values recorded in the deeper xylem (21 mm) with the result that the radial pattern changed from Type 1 to Type 2. In general, the ratio of daily sap flow in the inner xylem to the outer xylem (SFR_inn/out) tended to be higher dur-
ing the dry period (Day 205 in Figures 8D and 8E).

Fernandez et al. (2001), who measured the radial pattern of sap flow in trunks of 29-year-old “Manzanilla” olive trees, also observed that the degree of sap flow radial variability changed following changes in available water and found a sap flow profile weighted toward the outer xylem (Type 2 pattern) in the trunk of irrigated olive trees, whereas water-stressed trees showed a profile of sap flow weighted toward the center of the trunk (Type 1). These authors suggested that the absence of flow in the outer annuli of the sapwood was a result of stomatal control in young leaves and cavitation. Although we agree with this hypothesis, we emphasize that both stomatal control and cavitation are consequences of high driving forces under conditions of limited available soil water.

**Relationship of sap flow radial pattern to water uptake**

The nature of the variable shape of the sap flow radial pattern observed in trunks of olive trees was not identified. It likely reflects heterogeneity of water uptake by roots, which is higher at the tree base and becomes less pronounced with tree height (Čermák and Kučera 1990). Studies on the distribution and activity of the root system of olive trees (Fernandez et al. 1990, 1991, 2001, Moreno et al. 1996, Fernandez and Moreno 1999) show that olive trees have superficial root systems and no dominant tap roots. We hypothesize that olive trees reach deeper (thus wetter) soil horizons through sinkers, as reported for many trees growing in climates with long dry summers (Caldwell and Richards 1989, Burgess et al. 1998). Fernandez et al. (2001) recorded evidence of hydraulic lift by olive roots, although methodological limitations of the compensation heat-pulse velocity (CHPV) technique for low and reverse flows did not allow them to document this event clearly.

Our analysis of radial patterns suggests that different parts of the stem xylem might be connected with roots having access to deep water sources or with superficial laterals. If superficial roots are supplied through sinkers, a decrease in sap flow in the outermost stem xylem during drought should be more substantial as a result of concurrent water sinks (roots, foliage) from the same source of water (Nadezhdina et al. 2004, 2006b). Nadezhdina and Čermák (2003) showed that the radial pattern of sap flow in a tree trunk may reflect the vertical pattern of root activity in the corresponding soil sector. Unfortunately,
we did not study sap flow in roots during this experiment; however, investigations on cork oak (*Quercus suber*) demonstrated synchronous changes in both sap flow radial pattern in a tree trunk and vertical distribution of root absorption activity during the growing season (Figure 9; Nadezhdina et al. 2004). The highest flow in the shallow roots and in the outer stem xylem from both sides of cork oak trunk was recorded when the upper soil layers were wet (spring). In contrast, when the soil was dry (late summer), the flow from these roots dramatically decreased, whereas flow increased both in roots with connections to deep soil zones and in the inner trunk xylem. When sap flow decreased in the shallow roots, negative flow was recorded throughout the night, indicating hydraulic lift from deeper soil layers. The ratio of flow from the inner to the outer stem xylem increased with drought, as observed in our olive trees.

Based on these observations, we hypothesize that the heterogeneity of the radial sap flow profile is higher in olive trees subjected to localized irrigation than in trees growing in rain-fed conditions or with irrigation wetting the soil uniformly. We postulate that sap flow from the side of the tree adjacent to the position of the sprinkler or dripper would probably result in a Type 2 sap flow radial pattern, whereas the sides of the stem associated adjacent to the nonirrigated drier conditions would give rise to a Type 1 sap flow radial pattern.

*Sap flow radial pattern as water stress indicator*

An important finding of our study is the possibility of using the ratio of daily values of sap flow densities in the inner to the outer stem xylem (SFR_in/out) as a water stress indicator for automatic irrigation control. Nadezhdina (1999, 2000) demon-

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**Figure 8.** Dynamics of (A) selected meteorological variables and (B and C) sap flow in different xylem depths. Abbreviation: VPD = air vapor pressure deficit. Measurements were made on the (B) south-eastern (SE) and the (C) northern (N) sides of the trunk of Tree 7. Numbers are depths (mm) of measurements below the cambium. Right panels represent the ratio of daily values of sap flow densities in the inner to the outer stem xylem, SFR_in/out, for the (D) SE and (E) N sides of the trunk.

**Figure 9.** Seasonal changes in dynamics of sap flow in the stems and roots of a *Quercus suber* tree. The outer (~5 mm below cambium) and the inner (~25 mm below cambium) xylem were measured from the (A) western and the (B) southern sides of cork oak trunk and (C) in two roots: shallow and deep root, south and west oriented, respectively close to the end of the rainy season (March 13, 2003, left panels) and after 3.5 months without rain (August 14, 2003, right panels), at the Rio Frio experimental site (Palmela, Portugal).
Figure 10. (A) Seasonal dynamics of reference evapotranspiration ($ET_0$, ●), soil water content in the upper soil layer ($SWC_{20}$ cm, □) and the ratio of daily values of sap flow densities in the inner to the outer stem xylem (SFR_in/out, ■) are shown. Sap flow densities were measured on the south side of a Quercus suber tree (Rio Frio site, Palmela, Portugal, 2003). (B) Relationships between variables: SFR_in/out versus $ET_0$ (●) and SFR_in/out versus $SWC_{20}$ cm (□). The data inside the left and right ellipses correspond to wet (March to mid-June) and very dry (August to mid-September) soil, respectively. The data corresponding to moderate SWC are in the area between mid-June and the lower values represent October. (A) Horizontal and (B) vertical dashed lines represent the assumed threshold value occurred under high, moderate and low evaporative demands, respectively, corresponding to decreasing SWC.

Stratified that relative parameters are more effective than absolute values for the automation of irrigation because they allow the influence of drought to be identified earlier, and a certain threshold value, important for constructing and operating the control unit, can be used without measurement of other variables. As an example of the use of SFR_in/out for automation of irrigation, consider Figure 10 showing the seasonal dynamics of this ratio at the southern side of a cork oak together with the dynamics of reference evapotranspiration ($ET_0$) and soil water content in the upper soil layer ($SWC_{20}$ cm). The ratio SFR_in/out increases with increasing drought integrating the influence of both meteorological and edaphic conditions. For the same evaporative demands, values of SFR_in/out can be much higher for dry soil than for wet soil (Figure 10A). On the other hand, the same value of SFR_in/out can correspond to different combinations of $ET_0$ and SWC, including low, high or intermediate (Figure 10B).

Conclusions

(1) Sapwood depth in 62% of the observed trunks and large branches (> 176 mm in diameter) of mature olive trees cv. Coratina was about 45 mm. In small branches, sapwood depth was less heterogeneous varying from 30 to 40 mm in 72% of the observed branches. Independently of tree size, age and sensor location (stem or branch), sapwood depth ranged between 22 and 55 mm with a higher variability in trunks compared with branches, in agreement with the values reported by Giorgio and Giorgio (2003) for young trees and by Fernandez et al. (2001) for mature trees.

(2) Two asymmetric types of radial patterns were observed: Type 1, with maximum flow near the middle of the sapwood, and Type 2, with the highest flow recorded just beneath cambium. In most cases, the sap flow radial pattern was relatively constant during the day but it was highly variable in space. The Type 1 pattern was more common (72%) in the smaller branches and the smaller trunks, whereas in large branches and trunks, both types of sap flow radial patterns occurred with similar frequency.

(3) Even when the scaling-up procedure is based on radial sap flow heterogeneity, systematic errors during flow integration from single-point measurements can arise if applying only one type of profile and one position as reference. This conclusion is supported by (1) the finding that the magnitude of flow changes during the day in a different way depending on azimuthal position, and by (2) the experimental evidence indicating that the radial profile changes with degree of water stress, expressed as SFR_in/out. A single profile cannot be used throughout the season if important changes occur in tree water status.

(4) Sap flow in the outermost xylem of olive trees with a Type 1 radial pattern was substantially increased by rain events, suggesting that sap flow radial pattern can reflect the vertical distribution of water uptake (in response to relative changes in the vertical distribution of soil water availability). This was confirmed by our later observations in an oak stand. The ratio of sap flow in the inner/outer xylem (SFR_in/out) could therefore be explored as a water stress indicator with a potential use in automatic irrigation control.

Acknowledgments

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