

# Water Use by the Olive Tree

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**SUMMARY.** This is a review of water use by the olive tree, in which the most-relevant knowledge from the literature is combined with key results from experiments just finished or currently in progress. We describe the plant characteristics and mechanisms conferring drought tolerance on the olive tree. The root system functionality, hydraulic characteristics of the conductive system, leaf water relations, and transpiration behavior are considered. We explain the most-advanced techniques for optimizing irrigation, based on a more accurate calculation of the crop water needs. The crop responses to deficit irrigation strategies and to the use of wastewater for irrigation are also included. [Article copies available for a fee from The Haworth Document Delivery Service: 1-800-342-9678. E-mail address: [getinfo@haworthpressinc.com](mailto:getinfo@haworthpressinc.com) <Website: <http://www.haworthpressinc.com>>]

**KEYWORDS.** Olive, irrigation, evapotranspiration, drought, roots, sap flow, hydraulic characteristics, leaf water relations, orchard management

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### **WHY THE OLIVE TREE?**

There is an increasing interest in the olive tree and its products in many areas of the world. The reasons for this popularity of the species are not only agronomic, and therefore economic, but also related to the environment and human health. The tolerance of the tree to drought, and its capacity to grow in shallow, poor quality soils, make the species among the most interesting for cultivation in arid and semiarid areas. This agronomic interest of the olive is enhanced by the fact that, despite its tough character, the tree shows a remarkable response to any improvement in the cropping conditions. Reduced water supplies by irrigation, for instance, produce substantial increases in yield. This, together with its salt-tolerant character, makes the olive one of the very few profitable crops in many of the extensive areas of the world with high salinity levels and scarce water for irrigation. Environmentally speaking, the olive is one of the most rewarding cultivated species. It is enough to see the potential conditions for erosion and desertification in many areas where the tree is cultivated, to realize that it plays a mayor role both in minimizing soil losses with its roots and in reducing the air dryness with its transpiration. Other aspects we cannot forget are the crucial contribution of the olive tree to the typical landscape in many areas of Mediterranean climate, and the deep influences of this crop on the culture and tradition of the people living in those latitudes. Finally, but of utmost importance in the recent and growing popularity of the olive as a fruit tree, is the increasing demand of its products, both the oil and the fruits. This favorable market trend is partly due to rigorous dietetic studies proving the advantages of the regular consumption of olive oil for human health.

In contrary to the norm for scientific papers, we have just made a stack of statements about the nature of the olive tree and its importance as a crop without referring to the published work. This is not fair to the reader, since any rational and productive use of the plant must be based on the rigorous application of existing knowledge. We will refer to specific published works in the following sections, mentioning here only the most comprehensive works. Thus, books such as those by Loussert and Brousse (1978), Ferguson, Sibbett and Martin (1994), COI (1996), Guerrero (1997), and Barranco, Fernández-Escobar and Rallo (1998) provide the reader with information on a variety of aspects of the olive, as a plant and as a crop. Excellent reviews about more concrete aspects are those by Lavee (1985, 1986) on flowering, Bongi and Palliotti (1994) on the response to the environment, Xiloyannis et al. (1996) on drought tolerance, and Gucci and Tattini (1997) on salinity tolerance.

Water management in the orchard is one of the issues where farmers, agronomists, and environmentalists demand more information. This is not surprising, taking into account the need for water saving in the areas where

the olive is usually grown, as well as the significant improvement in crop performance when the trees are irrigated. Echoing this interest, the objectives of this work were (a) to describe the characteristics and mechanisms of the cultivated olive tree regulating the water use by the plant, and (b) to analyze the most widely used and advanced irrigation techniques designed for optimizing irrigation practice.

Many of the aspects considered here are illustrated with data obtained from the different research projects we and other members of our Group have carried out from the early 70s at the experimental farm *La Hampa*, of the *Instituto de Recursos Naturales y Agrobiología*, Seville, southwest Spain. The farm is located in the heart of *El Aljarafe* county, considered the most representative area in the world for the cultivation of 'Manzanilla de Sevilla', a cultivar considered by many as the best for table consumption, and which we will refer to here as 'Manzanilla'. Three experimental 'Manzanilla' olive orchards were planted in *La Hampa* in 1968, with the trees at  $5 \times 5 \text{ m}^2$ ,  $5 \times 7 \text{ m}^2$ , and  $7 \times 7 \text{ m}^2$  apart. The farm is at  $37^\circ 17' \text{ N}$ ,  $6^\circ 3' \text{ W}$ , and 30 m above sea level. The climate is typically Mediterranean: a wet, mild season from October to March, with an average rainfall of 500 mm (period 1971-1995), and the rest of the year being dry and hot. More details on the orchard characteristics are given in Moreno, Vachaud and Martín-Aranda (1983), Moreno et al. (1988) and Fernández et al. (1991).

### THE SPECIES AND ITS HABITAT

The olive tree, *Olea europaea* L., is a subtropical evergreen plant of great longevity, probably the most cold-hardy of the subtropical fruit trees (Denney and McEachern, 1985). It is a sclerophyllous and glycophytic species, being more salt- and drought-tolerant than other temperate fruit trees. Some authors include the olive within the category of desert shrubs (Schwabe and Lionakis, 1996). The olive tree is the only species with edible fruits in the family Oleaceae. Although there are different systems for the botanical classification of the species, it is generally accepted that the commercial cultivars are included in the subspecies *sativa* and the wild types belong to the subspecies *sylvestris* (Lavee, 1985, 1996). There is evidence of olive cultivation at around 4800 BC in Cyprus (Loukas and Krimbas, 1983). The origin of the species is not clear, though it seems to be somewhere in the eastern part of the Mediterranean basin or in Asia Minor. It appears that olive plants were sent from Spain and Italy to Central America, South Africa and Australia (Yáñez and Lachica, 1971; Denney and McEachern, 1985).

Although growth is possible in other latitudes, the area for olive cultivation is between  $45^\circ$ - $30^\circ$  north and south latitude, or lower if the altitude is higher (Hartmann, 1953; Yáñez and Lachica, 1971). The olive can be com-

mercially grown in a wide variety of soils, even in shallow and low-quality soils. Only very compact, poorly drained soils are a limiting factor for the crop, due to the sensitivity of the plant to hypoxia (Martín-Aranda, Arrúe and Muriel, 1975; Denney and McEachern, 1985). Optimum values of pH are between 7 and 8, though the olive can grow in soils with pH from 5.5 to 8.5 (Denney and McEachern, 1985). The plant does not respond to photoperiod (Hackett and Hartmann, 1964). There are abundant references in the literature, however, to the importance of temperature for growth and production. For some cultivars, cold requirements in winter may be more than 1000 h of a temperature below 7°C (Hartmann, 1953). Denney and McEachern (1985) referred to several published papers mentioning that the olive sets flower buds in the late winter, approximately eight to ten weeks before full bloom, in response to the progress of winter temperatures. They also mentioned the work of Badr and Hartmann (1971), who showed that exposure of trees to a constant temperature of 12.5°C resulted in significant production of flowers. This temperature, called the "compensation point," is believed to be cold enough to effect vernalization but also warm enough to allow for necessary concomitant cell division. Bongi and Palliotti (1984) reported that the species requires at least 10 weeks below 12.2 to 13.3°C for full expression of flowering, this being best induced when temperature fluctuates between 2 and 15°C for 70-80 days. Sensitivity to temperature is cultivar-dependent (Bongi et al., 1987). The effect of extreme temperatures must also be taken into account. The plant may suffer severe damage with minimum temperatures below -12°C, or at higher minimum temperature if exposure is longer. High temperatures before and during bloom may reduce fruit productivity substantially (Hartmann and Opitz, 1980).

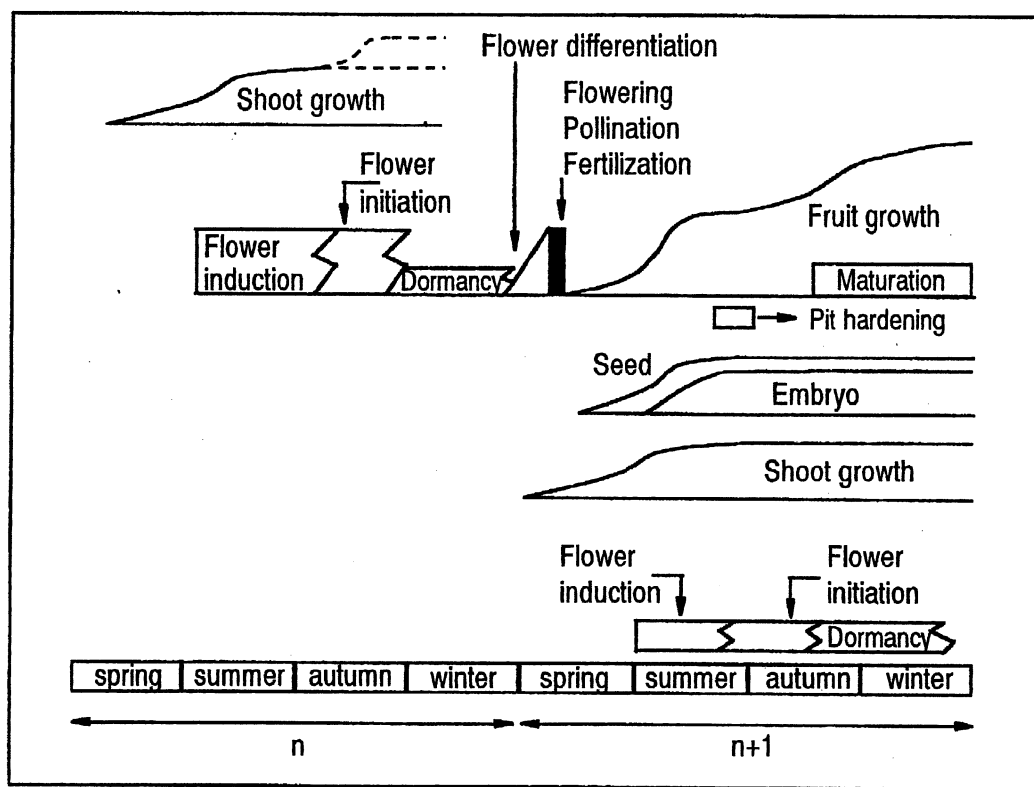
### ***THE BIENNIAL CYCLE OF GROWTH AND PRODUCTION***

The different growth stages of the olive tree must be taken into account for a correct water management in the orchard, especially when deficit irrigation strategies are used. The most complete diagram we have found for the biennial cycle of the olive tree is that of Rallo (1995, 1998), shown in Figure 1.

For the conditions of *La Hampa*, shoot growth takes place from February to August, as in most areas of the Mediterranean basin. Growth late in autumn has been reported in some cases (Abdel-Rahman and Sharkawi, 1974). Cima-to, Cantini and Sani (1990) found that shoot elongation was correlated with the average monthly temperature. Leaves became fully expanded in about three to four weeks, depending on environmental conditions. The olive tree is day-neutral, temperature being the driving factor for flowering and fruiting (Denney and McEachern, 1983). Flowering takes place on 1-year-old wood. High yields are produced in the "on" years, followed by "off" years with



FIGURE 1. Biennial cycle of the olive tree (adapted from Rallo, 1998).



yields being rarely commercial. Alternate bearing in the olive is governed by both endogenous and external factors. We will describe management practices for reducing alternate bearing. The induction of flower buds takes place in summer, around the time of endocarp sclerification (Fernández-Escobar et al., 1992). The number of flowers able to set fruit and to remain until harvest is much smaller in the “off” than in the “on” years. The olive flowers are hermaphroditic and grouped in dichotomous panicles with up to about 40 flowers, but generally set only one fruit per inflorescence. A good crop can be obtained with 1% only of the original flowers setting and fruit remaining until harvest (Griggs et al., 1975). Cross-pollination may increase yield, since most olive cultivars are partially incompatible (Lavee 1986; Fernández-Escobar and Gómez-Valledor, 1985). Flower and fruit abscission takes place in the five to six weeks following full bloom, and is responsible for the small percentage of fruit retained to maturity (Rallo and Fernández-Escobar, 1985). The peak of fruit abscission in ‘Manzanilla’ has been reported to be when the fruits are 3-4 mm in diameter (Troncoso, Prieto and Liñán, 1978). The final number of developing fruits is reached about six to seven weeks after full bloom.

Climatic conditions are critical for fruit set. Hard rain, dry winds, and high temperatures during flowering may affect fruit setting markedly. Lack of light also reduces fruit set, as do thinning practices required to obtain a

marketable size in table cultivars (Suárez, Fernández-Escobar and Rallo, 1984). The olive fruit is a drupe with the seed enclosed in a hard endocarp forming the pit or stone, which solidifies after four to six weeks after fruit set and hardens gradually until about three months after fruit set. The mesocarp continues to grow throughout the whole season. Fruit growth follows a double sigmoid curve, as in most drupè fruits. The seed reaches maturity just before the fruit changes color, in the stage called green maturation. Fruit growth stops when the fruit begins to change color. After the green maturation stage, there is a decrease in chlorophyll content and an increase in anthocyanin accumulation, responsible for the black color of the fruits. In "on" years, when flowering and fruit set are abundant, ripening is delayed, mean fruit size reduced, and oil accumulation slow. Fruit size, oil accumulation, and ripening are highly dependent on the relative load per tree (Lavee, 1986). Sánchez-Raya (1988) and Lavee and Wodner (1991) gave curves for fruit growth and oil accumulation for different cultivars, showing the marked influence of environmental conditions. Fruit yield can be up to 22,000 kg ha<sup>-1</sup> or more. Fruit weight varies between less than 1 g and more than 12 g, depending on the cultivar. The percent of oil content is also a function of the cultivar, varying from about 12 to 28%.

## ***TOLERANCE TO DROUGHT***

### ***The Root System***

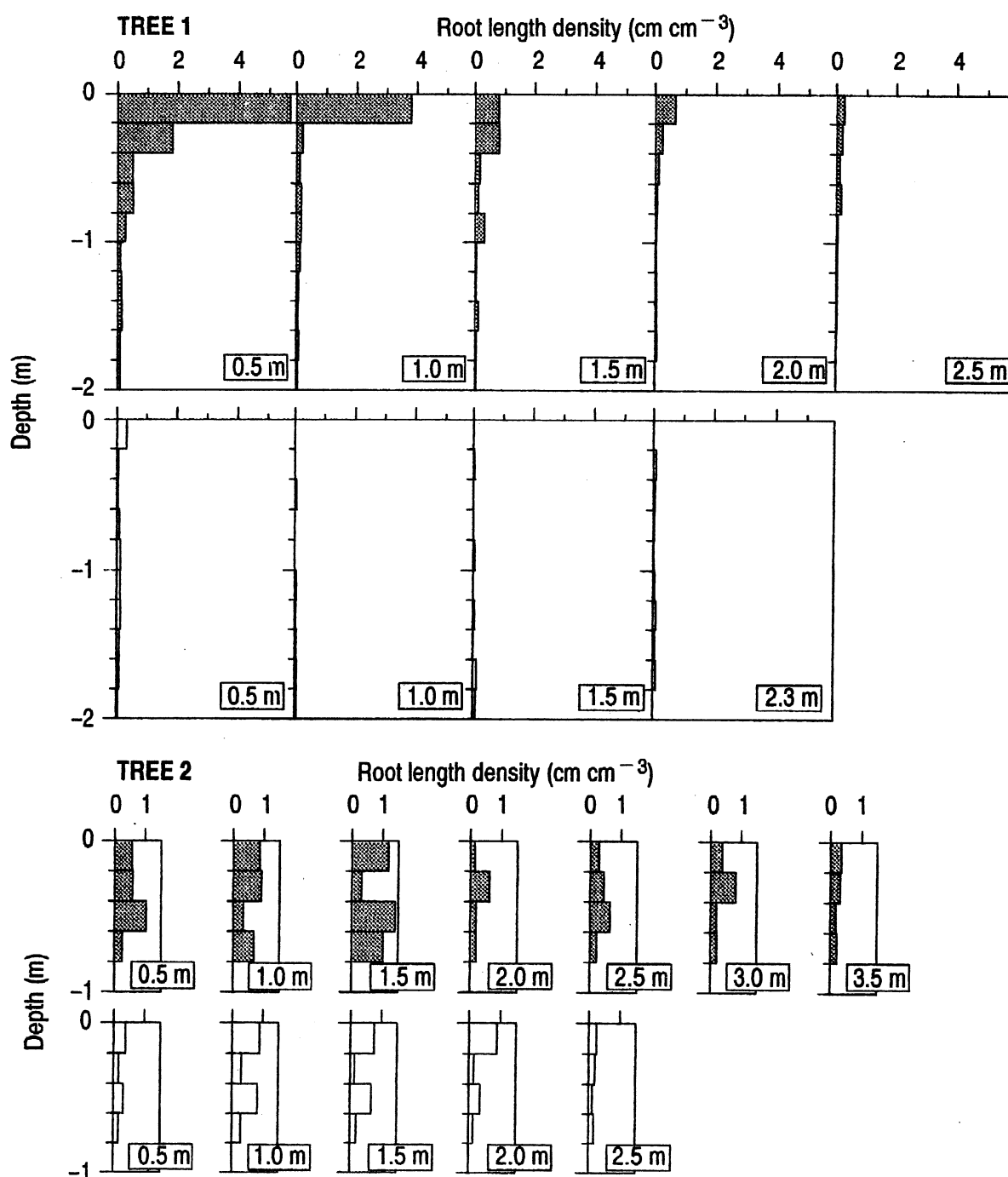
The root system of the olive tree seems to be designed for absorbing the water of the light and intermittent rainfall usual in its habitat, rather than for taking up water from deep layers. Most of the main roots seem to grow more or less parallel to the soil surface, without a dominant tap root. Olive roots are rather sensitive to hypoxia, and poorly drained soils are inadvisable for the crop. A high portion of the root length is of small diameter, which favors the absorption capacity. Absorption by olive roots is also enhanced by high potential gradients between roots and soil caused by osmotic adjustment. The highest root density is found close to the trunk, although the volume explored by the roots can easily extend beyond the canopy projection. Apart from genetic disposition, the distribution of the roots can be markedly influenced by the soil conditions, by neighboring trees, and by the irrigation practice. Olive roots are able to react quickly after a long period of drought, absorbing water immediately that is finally available in the soil. Root growth dynamics are also markedly affected by water in the soil. Irrigation makes roots grow during the dry season, preventing root shrinking and increasing the period of activity of each root. There is evidence from anatomical studies suggesting

that the conductive capacity of olive roots is not reduced by drought, which is another feature of the high adaptability of the species to water stress. All those aspects are described with detail in the following sections. A detailed description of the mentioned variables and techniques can be found in Böhm (1979) and in Smit et al. (1999).

### *Root Distribution and Activity*

The earliest studies on root distribution showed that the main development of the olive root system occurs in the most superficial soil layers. Abd-El-Rahman, Shalaby and Balegh (1966) measured the root length density ( $L_v$ ,  $\text{cm cm}^{-3}$ ) of soil samples taken around 7-year-old olive trees growing in a desert area in Egypt, with only 150 mm mean annual rainfall. They found maximum  $L_v$  values in the layer of 0.15 to 0.30 m in depth and up to 0.30 m from the trunk. Michelakis and Vougioucalou (1988) used the trench method to study the root distribution of 5-year-old 'Kalamon' trees in Crete, observing the highest number of roots in the upper 0.4 m of soil. Pisanu and Corrias (1971) observed a very shallow root system in the roots of 7-year-old olive trees in Sardinia. Their photographs and drawings of the excavated root system clearly illustrate the horizontal development of the roots, and the fact that the roots of contiguous trees avoid competition by developing outwards from the tree row. Núñez-Aguilar et al. (1980) studied the distribution of the root system of rainfed, 12-year-old 'Manzanilla' olive trees in *La Hampa*, using the trench method and the cylinder method based on sampling by auger. They separated the roots in groups of different diameter, finding that most of the roots were of a diameter smaller than 0.5 mm. They observed the highest  $L_v$  values, of about  $0.7 \text{ cm cm}^{-3}$ , at 0.45 m from the trunk and in the top layers of the soil, though high  $L_v$  values were also found at the depth of 1.4-1.6 m and at 1 m from the trunk. They found high water depletion in soil volumes with high root density—the first attempt we have found in the literature to relate root distribution with root activity. Later, Fernández et al. (1991) carried out in the same orchard, and also in a neighboring orchard, a more detailed study on the distribution and activity of the root system of 20-year-old 'Manzanilla' trees, planted at  $7 \times 7 \text{ m}^2$  and under different water regimes (see legend of Figure 2 for details). As they said, "works dealing only with distribution offer little information on root activity. Activity may be higher in zones of low root density than in zones of high density as a compensation mechanism." They used the cylinder and the trench methods to determine root distribution, and labeling with  $^{32}\text{P}$  to determine root activity. Figure 2 shows some of their results on root distribution. Much higher values of root density were found in tree 1 in the direction of the emitters than in that of the perpendicular from the trunk, where the soil was not affected by irrigation. Some roots were found at 2 m, the maximum sampling depth, though the

FIGURE 2. Root length density ( $L_v$ ) measured in two 20-year-old 'Manzanilla' olive trees at  $7 \times 7 \text{ m}^2$  and irrigated by a single lateral drip line placed on the soil surface in each tree row, with four  $4 \text{ L h}^{-1}$  emitters per tree, 1 m apart in tree 1 and 1.2 m in tree 2. Irrigation doses were calculated with a class A evaporation pan, with a reduction coefficient of 0.4 for tree 1 and of 0.7 for tree 2. Both trees had a single trunk and a canopy of about 4.6 m diameter. Tree 1 was in a sandy loam deep soil, while tree 2 was in a sandy clay loam soil with a hard pan at a depth of about 0.8 m. Root density measurements were taken at different depths and at different distances from the trunk, shown in boxes, following the dripper line (gray bars) and its perpendicular from the trunk (blank bars). Values of  $L_v$  were determined in 0.2 m long soil samples of about 1 L volume, taken by auger at each location (adapted from Fernández et al., 1991).



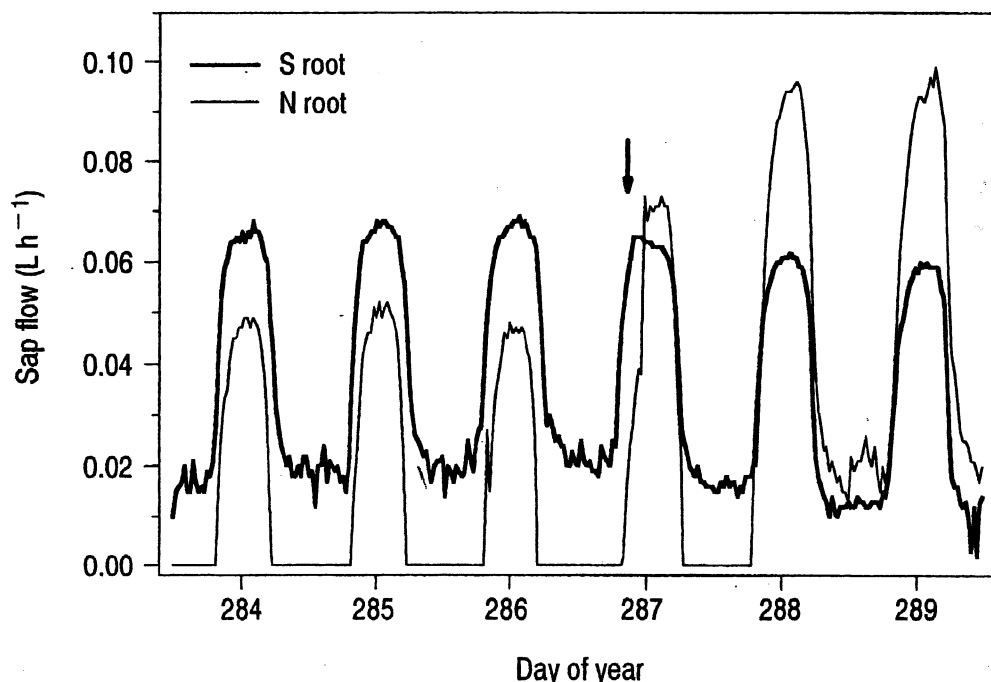
highest root densities were measured in the top layers of soil and close to the trunk. In tree 2, the impedance of the hard calcareous layer at the depth of 0.8 m restricted water and root penetration. This, together with the fact that this tree received larger volumes of water than tree 1, favored the existence of wider bulbs of wetted soil in tree 2 than in tree 1. As a result, the soil in the direction perpendicular to the drip line of tree 2 was affected by irrigation and, consequently, relatively high root densities were found also in that direction (Figure 2). This is a clear example of how water and soil conditions may affect root growth and distribution. Fernández et al. (1991) reported maximum  $L_v$  values similar to those found by Núñez-Aguilar et al. (1980), and their results also agree with the most-abundant roots having a diameter  $< 0.5$  mm. Greater values of  $L_v$  of up to  $1.167 \text{ cm cm}^{-3}$  were observed by Fernández et al. (1987), also in *La Hampa*, at 0.5 m from the trunk and 0.2-0.4 m depth. At other depths, however, root density was generally below  $0.360 \text{ cm cm}^{-3}$ . With the  $^{32}\text{P}$ -labeling technique, Fernández et al. (1987, 1991) found a maximum root activity at 0.5-0.6 m from the trunk and between 0.5 and 1 m depth. They observed that during the dry season root activity was high in the part of the root system well watered by the localized irrigation, and significantly lower in the soil volumes under increasing soil water depletion. Arambarri and Madrid (1974) used the  $^{32}\text{P}$ -labeling technique to study the root activity of rainfed 'Manzanilla' olive trees in *La Hampa*. In the non-irrigated trees, the greatest root activity was found at 0.5 m from the trunk and at 0.6-1 m depth. In an earlier study carried out in Tunisia also with mature rainfed trees, Scharpenseel, Essafi and Bouguerra (1966) recommend applying the fertilizers at 0.5 m depth and at two distances from the trunk, either close to it or at 3-4 m from the trunk, a distance slightly larger than the radius of the canopy.

The most-recent studies on root activity in olive are based on sap velocity measurements in main roots. Moreno et al. (1996) used for the first time in olive the compensation heat-pulse technique, as described by Green and Clothier (1988), to determine the uptake strategy employed by the roots. They worked in *La Hampa*, with 25-year-old 'Manzanilla' trees under different water regimes. Moreno et al. (1996) observed that the non-irrigated tree switched from an extraction by deep roots beyond the dry surface of the soil, to one of near surface following irrigation. Fernández et al. (1996) gave additional data from the same experiment, corroborating the existence of an immediate response in water absorption by the roots of the olive tree after a long period of drought. They monitored the sap velocity profiles at different depths below the cambium of a root belonging to a non-irrigated olive tree, detecting no sap flow in the outer annuli, normally the region of highest flow in irrigated trees. Both Moreno et al. (1996) and Fernández et al. (1996) stated that the outer xylem vessels of the root must have cavitated after being

in dry soil for a long period. Using the same technique for measuring sap flow, we carried out in *La Hampa* further studies on the hydraulic functioning of roots belonging to a semi-irrigated tree, in which water was applied in either the north or the south half of the soil explored by the roots (Fernández et al., 1998a; Díaz-Espejo et al., 1998). We observed an immediate absorption of water by the roots when this was finally available in the soil. In addition, we were able to see how the absorption rate of a root decreased when water was available for other roots growing in different soil areas finally irrigated, as some kind of compensation within the root system (Figure 3). Root absorption at night was also detected in our sap flow measurements, accounting for the recovery of the water stored in the tree when there is no transpiration.

Another feature showing the adaptation of the olive tree to dry areas is that the absorption capacity of its roots seems to be higher than that in other fruit trees. In early studies, Abd-El-Rahman, Shalaby and Balegh (1966) found a high osmotic potential in the sap of 7-year-old olive trees growing in an area of Egypt with only 150 mm per year of average rainfall. They stated that this

FIGURE 3. Sap flows monitored in two main roots—one in the north side (N root, 14.8 mm in radius) and the other in the south side (S root, 15.2 mm in radius)—of a 29-year-old 'Manzanilla' olive tree at *La Hampa*. Sap flows were determined with the compensation heat-pulse technique. A 2.5 m radius pond was built around the tree, divided into two sides, north and south, by a small earthen dyke, in order to semi-irrigate the tree by applying water in one side at a time. The arrow represents an irrigation of 70 mm of water applied to the north side on day of year 287, at 10.25 GMT (adapted from Fernández et al., 1998a).



enables the roots to extract water from the soil at low soil water potentials. Xiloyannis et al. (1996) mentioned that osmotic adjustment in olive roots allowed the plant to maintain turgor and so to prevent or delay the separation of the root from the surrounding soil. In roots of olive plants under high water stress, with predawn leaf water potential of  $-5.2$  MPa, Xiloyannis et al. (1996) measured an osmotic adjustment of  $1.67$  MPa in roots of  $4-5$  mm in diameter,  $1.42$  MPa in roots between  $4$  and  $1$  mm, and  $0.2$  MPa in roots of diameter smaller than  $1$  mm. They mentioned that the olive tree is able to extract water from the soil up to soil water potentials of  $-2.5$  MPa, due to the high potential gradients between leaves, root, and soil created by lowering the water content and water potential of its tissues. Dichio, Nuzzo and Xiloyannis (1997) found in young 'Coratina' olive plants that both the osmotic potential at full turgor and the elastic modulus of tissues increased with water stress, which lead to high water potential gradients between leaf and soil. It seems, therefore, that for the olive tree, the wilting point is reached when the soil is much drier than for other fruit tree species, which are thought to be unable to extract water when the soil water potential is not much lower than  $-1.5$  MPa.

The efficiency of the olive root system is also due to a root/canopy ratio that is usually bigger in non-irrigated trees than in irrigated ones, contributing to the drought tolerance of the species. This has been observed by Nuzzo, Dichio and Xiloyannis (1995), Celano et al. (1997) and Nuzzo et al. (1997), with young 'Coratina' olive trees in southern Italy. In *La Hampa*, Fernández et al. (1991, 1992) observed that the volume of soil explored by the roots of mature 'Manzanilla' olive trees under localized irrigation was smaller than in the case of rainfed trees, in which higher root densities were measured deeper and farther from the trunk. This is a factor to take into account when choosing the irrigation system of the orchard. The fact that trees irrigated by localized irrigation explore a reduced volume of soil may represent a risk for water stress if irrigation is interrupted. The tree may consume the water of the bulbs in very few days, suffering from water stress if the irrigation is not then re-established. This problem is minimized with irrigation systems that wet larger volumes of soil. An incorrect application of water may also affect the activity of olive roots due to their sensitivity to hypoxia. This may not be a problem in soils with hydraulic characteristics favoring drainage, but it should be taken into account if the soil is heavy, with a low hydraulic conductivity. In the rather sandy soils of *La Hampa*, Fernández et al. (1991) did not observe a diminution of root density near the drippers compared with other zones in which aeration conditions were supposed to be more favorable. Michelakis (1986), however, working with drip-irrigated 'Kalamon' olive trees in Crete, reported lower root densities in a small volume of soil under the drippers than in the rest of the wet bulb. He did not give the soil character-

istics. Other aspects to consider when choosing the irrigation system are discussed later.

### *Root Dynamics*

When and where the roots grow is crucial for understanding the functioning of the root system and its relation with the aerial part, and for optimizing irrigation and fertilization. There are, however, very few studies on root dynamics of the olive tree. We have found just the work by Fernández, Moreno and Martín-Aranda (1990) and Fernández et al. (1992) in *La Hampa*, and the work by Celano et al. (1998) in southern Italy. Both of these used mini-rhizotrons made with transparent tubes buried in the soil explored by the roots.

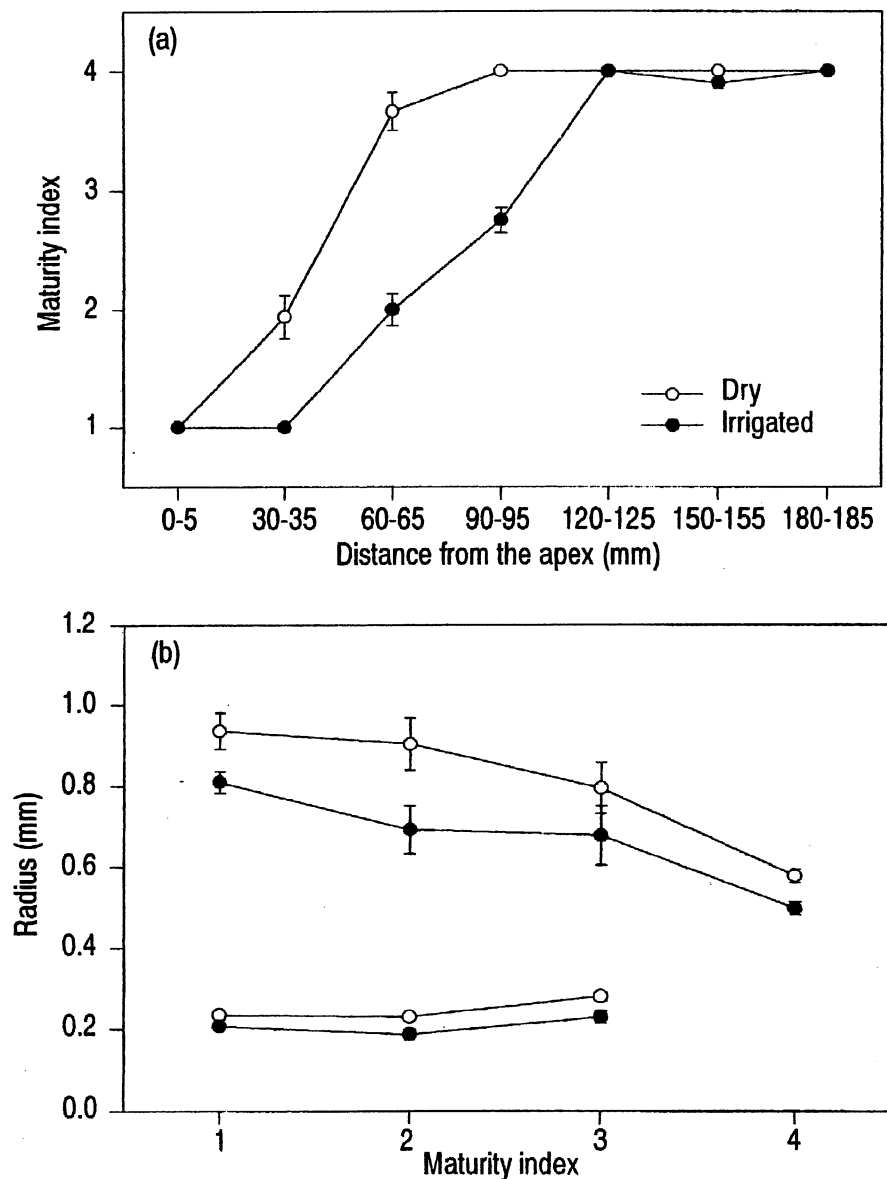
Fernández, Moreno and Martín-Aranda (1990) and Fernández et al. (1992) made their studies of root dynamics in the same orchards where they studied root distribution and activity, to get a comprehensive view of the behavior of the root system of mature olive trees under field conditions and different water regimes. They observed that the period of emergence and growth of new roots was limited to the spring in rainfed trees, while it extended to the whole summer period and autumn in the trees irrigated throughout the dry season. When analyzing the root appearance, they observed that root color changed from the typical pale color of the newly formed roots to a dark brown color in about one month in the case of the rainfed tree, and up to three months in the irrigated trees. Root shrinking was observed in some roots of the rainfed tree when the soil dried out, with partial separation from the surrounding soil. Celano et al. (1998) also observed that root dynamics is very much affected by irrigation. They studied the growth dynamics of the roots together with the growth dynamics of different aerial organs, concluding that the growth pattern is determined by the sink-source competition established between the aerial and subterranean parts throughout the year.

### *Root Anatomy*

The only work we have found in olive relating root anatomy with root functioning is that of Fernández et al. (1994). They examined the root development of 2-year-old 'Manzanilla' olive trees grown for four months in 0.8 m<sup>3</sup> containers under wet and dry water regimes. They studied the transition to secondary growth and how the water treatment affected the radius of the root, the central cylinder, and the xylem vessels. Their most relevant results are shown in Figure 4. They found complete transition to secondary growth closer to the apex in the roots grown in dry soil (at about 90 mm) than in the roots grown in watered soil (at about 120 mm). Up to about 50 mm from the



FIGURE 4. Stage of development from primary to secondary growth scored according to a maturity index indicating the degree of vascular cambium development (Figure 4a). Observations were made along roots taken from 2-year-old 'Manzanilla' olive trees grown in  $0.8 \text{ m}^3$  containers with sandy-loam soil and subjected to two water regimens. In the irrigation treatment, the soil was kept about field capacity throughout the four months experimental period. No water was supplied in the dry treatment, with only one irrigation immediately after planting in the containers. Measurements were made in six sequential 5 mm samples taken at 30 mm intervals along the root axis. Each point represents the mean of the six measurements. Vertical bars indicate twice the standard error. Measurements of total root and central cylinder (stele) radius are shown in Figure 4b. The inner wall of the endodermal cells was considered the external limit of the central cylinder. The radial width of each zone was determined by averaging the horizontal and vertical radii. Each point represents the average of eight to 87 measurements for each stage. Vertical bars indicate twice the standard error. The central cylinder was only considered through stage 3 (adapted from Fernández et al., 1994).



root tip, the cortical tissue was wider in the roots grown in dry soil than in watered soil, though the authors warned about the possibility of mechanical stress in the dry soil influencing those results. They did not find significant differences between treatments in the diameter of the metaxylem vessels, which were a mean  $10.21 \pm 0.34 \mu\text{m}$  in roots of the irrigation treatment and  $9.86 \pm 0.35 \mu\text{m}$  in those of the dry treatment. In addition, the radius of the central cylinder was slightly greater in the dry than in the irrigated treatment. They concluded that "although further studies are necessary, certain speculation is possible as to the significance of these features in the adaptability of the olive root system to water stress. The more rapid maturation found closer to the apex in the dry treatment may allow increased water movement through the root system due to the increased water flux associated with secondary vascular development . . . The lack of reduction in metaxylem vessel and central cylinder size under drought suggests that resistance to water flow is not reduced in these tissues."

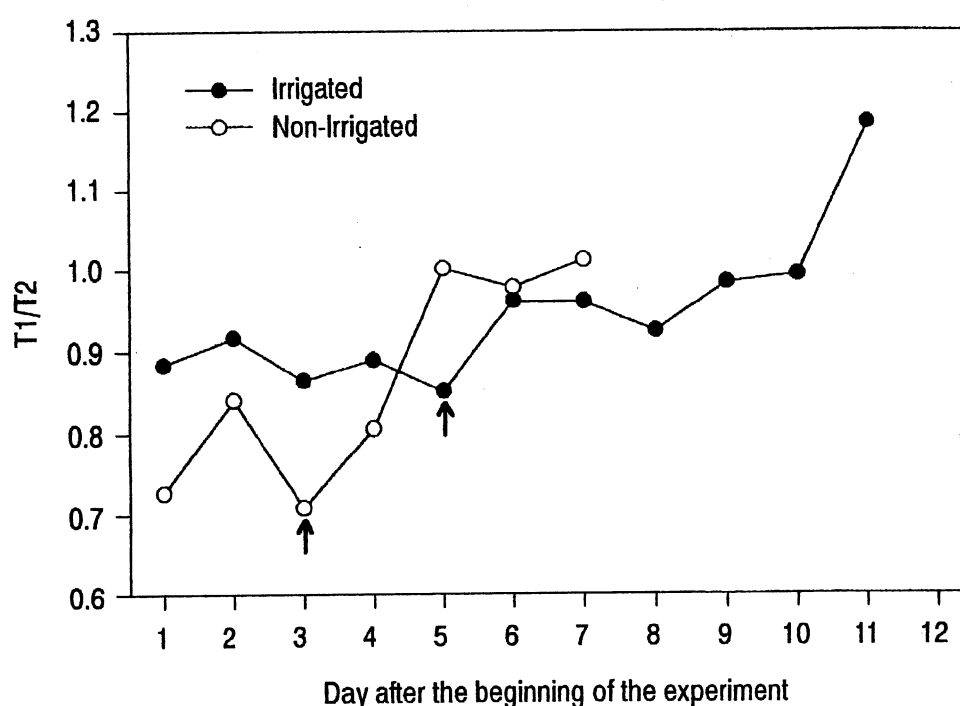
### *Root Signaling*

One of the most interesting mechanisms affecting water consumption has its origin in the root system, though it affects stomata behavior. Evidence has been found in different species, including a fruit tree such as apple (Gowing, Davies and Jones, 1990), suggesting stomatal control by signals coming from the roots. It seems that the roots are able to sense the dryness of the soil and "order" the stomata to close, thereby reducing water losses and preventing excessive water stress. One of the most relevant papers we have found in this line is that by Tardieu and Davies (1993). They suggested an integrated chemical and hydraulic signaling mechanism controlling leaf water relationships. The only reference we have found to a root-to-leaf signaling mechanism in olive is an experiment in pots mentioned by Bonghi and Palliotti (1994). The root system of young 'Frantoio' olive plants was split into two parts, leaving a small portion in drought ( $-1.1 \text{ MPa}$ ) and the rest in optimal water conditions ( $-0.2 \text{ MPa}$ ). They observed stomatal closure in those plants, which appeared to be mediated by a translocated signal coming from the stressed roots. We have recently carried out experiments in *La Hampa* with 30-year-old 'Manzanilla' olive trees, whose results have not yet been published. Figure 5 shows some preliminary results suggesting that the root signaling mechanism is also present in mature trees under field conditions.

### *Hydraulic Characteristics of the Wood*

The olive is a diffuse-porous tree having a dense wood with abundant fibers and little parenchyma. We have measured a mean wood density of

FIGURE 5. Daily evolution of the transpiration ratio calculated by dividing the daily transpiration of an olive tree in which the total volume of soil explored by its roots was wetted by irrigation (T1) by the daily transpiration of a tree in which part of its roots was affected by irrigation and the rest remained in dry soil (T2). The daily transpired amounts were determined from sap flow measurements in the trunk of the trees. Measurements were made in *La Hampa*, with 30-year-old 'Manzanilla' olive trees irrigated throughout the dry season of 1998 (treatment I, open circles), and with trees under dry farming conditions until the beginning of this experiment on August 23 (treatment D, closed circles). Each T1 tree was pond-irrigated, with a pond big enough for wetting the total volume of soil explored by the roots. The T2 trees were irrigated by the a localized irrigation system consisting on a single lateral drip line placed on the soil surface in each tree row, with five  $3 \text{ L h}^{-1}$  emitters per tree 1 m apart. The arrow close to the open circle indicates the day in which irrigation was applied to the trees T1 and T2 of treatment D. The arrow close to the closed circle indicates the day on which the T1 tree of treatment I was irrigated by pond; before that day, the T1 and T2 trees of that treatment were irrigated by the described localized irrigation.



$0.623 \text{ kg L}^{-1}$  in samples taken from the trunk of 'Manzanilla' olive trees. The large amount of fibers, which makes olive wood so hard, accounts for the low vessel lumina of the species in comparison with other diffuse-porous Mediterranean plants. Salleo, Lo Gullo and Oliveri (1985) observed that the vessel lumina, expressed as a percentage of the total xylem cross-sectional area, was about 8% in olive, being 17% in *Vitis vinifera* and *Populus deltoides*. The xylem vessels are thick-walled and generally grouped in radial multiples of two to four vessels, rarely solitary. Growth ring boundaries are

often indistinct. The analysis of the radial sections shows heterogeneous rays, numerous though small intervessel and rayvessel pits, and simple perforation plates (Schweingruber, 1990). In our calibration experiments of the compensation heat-pulse technique for measuring sap flow in olive, from which some preliminary results are given in Fernández et al. (1997), we stained the sapwood of the trunk of a 12-year-old 'Manzanilla' olive tree with safranin. At about 0.74 m above the ground, the average radius below the cambium was 68.2 mm, the area of the sapwood being 112.3 cm<sup>2</sup>, and that of the heartwood 33.9 cm<sup>2</sup>. The maximum depth of the sapwood was highly heterogeneous, varying between about 12 and 34 mm, with an average value of 26.6 mm. Scaramella and Ricci (1988) observed the presence of interxylary phloem in olive, which contributes to the sapwood heterogeneity.

The diameter of the xylem vessels varies depending on the conductive organ. In roots of 2-year-old 'Manzanilla' olive trees, Fernández et al. (1994) measured a mean metaxylem vessel diameter of 10.03 µm. In wood samples taken from the trunk of 29-year-old 'Manzanilla' olive trees, we have found that most of the xylem vessels have a diameter between 33 and 39 µm, with maximum values rarely greater than 50 µm. These values are low in comparison with other diffuse-porous species. The laurel, for instance, has xylem conduits between 50 and 80 µm in diameter (Lo Gullo and Salleo, 1988), and the kiwifruit between 100 and 500 µm (Green and Clothier, 1988). Salleo, Lo Gullo and Oliveri (1985) measured the mean vessel radius in internodes of 1-year-old twigs, finding values of about 11 µm in the proximal internodes, 10 µm in the middle, and 8 µm in the distal internodes. There is little information about the effect of those characteristics on the hydraulic functioning of the conductive tissues of the olive tree. The small diameter of the vessels may account for a low hydraulic conductance, and may also be a protection against cavitation. Tyree and Sperry (1989), however, claimed that the vulnerability to cavitation is determined by the diameter of the intervessel pit membrane pore, rather than by that of the xylem vessel. Measurements of the sap velocity profiles made by Fernández et al. (1996) in roots, and our measurements in the trunk, have shown no flow in the outer annuli of the sapwood of water-stressed 'Manzanilla' olive trees. We believe that this is a consequence of air emboli forming in the xylem vessels of that area.

Thompson et al. (1983) studied the hydraulic architecture of young olive trees. They measured the leaf specific conductivity (LSC, kg s<sup>-1</sup> m<sup>-2</sup> MPa<sup>-1</sup>), which relates the flow rate with the amount of transpiring surface area by the following equation:

$$LSC = \frac{V}{P_x a} = \frac{E}{P_x} \quad (1)$$

where  $V$  is the mass flow rate (kg s<sup>-1</sup>) through a section of stem supplying water to leaves of green surface area  $a$  (m<sup>2</sup>, one side only), and  $P_x$  (MPa

$\text{m}^{-1}$ ) is the pressure gradient over the length of the section. The value of  $V/a$  is the average evaporative flux  $E$  ( $\text{kg s}^{-1} \text{m}^{-2}$ ) for all the leaves fed by the stem segment. Thompson et al. (1983) found for olive larger values of  $E$  ( $2.6 \times 10^{-5} \text{ kg s}^{-1} \text{m}^{-2}$  against  $1.1$  to  $1.6 \times 10^{-5} \text{ kg s}^{-1} \text{m}^{-2}$ ) and smaller values of LSC ( $4 \times 10^{-4} \text{ kg s}^{-1} \text{m}^{-2} \text{MPa}^{-1}$  against  $28$  to  $250 \times 10^{-4} \text{ kg s}^{-1} \text{m}^{-2} \text{MPa}^{-1}$ ) than those reported by Zimmermann (1978) for maple, white birch, and poplar, all of them diffuse-porous trees. Salleo, Lo Gullo and Oliveri (1985) mentioned a number of reasons supporting the utility of the LSC measurements for plant physiologists, despite LSC not allowing for quantitative measurements of the stem hydraulic conductivity. They stated that calculating the hydraulic conductivity of plant stems on the basis of the whole xylem cross-sectional area can cause substantial underestimates of this parameter and that, on the other hand, measurements of the hydraulic conductivity of vessel lumina ignore the permeability to water of fibers and wood parenchyma cells.

Water flow through the soil-plant-atmosphere system is generally assumed to be well described by a model similar to Ohm's law. Larsen, Higgins and Al-Wir (1989) followed this approach to estimate the liquid pathway resistance to water flow ( $R$ ,  $\text{MPa } \mu\text{g}^{-1} \text{cm}^2 \text{s}$ ) in apple, apricot, grape, peach, and olive plants. They calculated the difference between measured values of predawn xylem pressure potential, assumed to be equivalent to the soil water potential, and diurnal xylem pressure potential values measured at the petiole. The value of  $R$  was calculated by dividing that difference by the estimated transpirational flux density. The resulting  $R$  values were 0.511 for apricot, 0.465 for olive, 0.329 for grape, 0.319 for peach, and 0.182 for apple. They stated that the high value of  $R$  in olive, together with stomatal closing, may account for the low transpiration losses per unit leaf area measured in this species. Bongi and Pallioti (1994) mentioned that the large water potential differences between leaves and roots usually found in olive might reflect a strong resistance to water movement. In our field experiments with well-irrigated trees, in which the soil water potential can be assumed to be similar to that of the absorbing roots, we have observed that the drop in water potential from leaves to roots is easily greater than 2 MPa, with a maximum difference of about 4 MPa.

### ***Leaf and Canopy Characteristics***

Olive leaves are well-adapted to avoid excessive water loss under the highly demanding conditions of the areas where the tree usually grows. They show not only several sclerophyllous characteristics, but also active mechanisms controlling water loss. The olive tree can have leaves of up to three years of age. Leaf aging significantly modifies the leaf characteristics and leaf response to the environment, as we will discuss in this and other sections.

In the 'Manzanilla' olive trees of *La Hampa*, we have measured a mean leaf surface of 359 mm<sup>2</sup> one side only, and a mean specific leaf weight (SLW), i.e., the leaf dry weight divided by the leaf surface, of 203 g m<sup>-2</sup> for the current year leaves and 319 g m<sup>-2</sup> for 1-year-old leaves. In samples taken in April, we found that the water content, expressed as percentage of the fresh leaf weight, was 59.9% in the current year leaves and 47.6% in 1-year-old leaves. Details on leaf growth and development are given in a former section.

The high content of cuticular wax (Leon and Bukovac, 1978) prevents water diffusion through the cuticular membrane, transpiration taking place only through the stomata. Another characteristic contributing to reducing water loss under stress is the dense packing of the mesophyll layer in the olive, which produces a low proportion of cell walls exposed to the air (Bongi, Mencuccini and Fontanazza, 1987). The stomata are present only on the abaxial surface. Stomatal density has been reported to range from about 250 mm<sup>-2</sup> to more than 700 mm<sup>-2</sup>, depending on cultivar and nutrient status (Leva, 1977; Bartolini, Roselli and Di Milla, 1979; Bongi, Mencuccini and Fontanazza, 1987). Cultivars resistant to cold have a lower stomatal density than those that are susceptible (Roselli, Benelli and Morelli, 1989). The values of stomatal density found in olive are similar to those of rapidly transpiring plants (Bongi, Mencuccini and Fontanazza, 1987). Stomatal pore widths have been measured by Schwabe and Lionakis (1996) and Vitagliano et al. (1997), among others. The presence of cuticular ledges in the stomata, described by Durán-Grande (1977) and Leon and Bukovac (1978), may make it difficult to measure the stomatal opening. In addition, the olive leaf is subject to patchy stomatal closure over the total leaf surface (Loreto and Sharkey, 1990; Natali, Bignami and Fusari, 1991). Stomatal closure is an active mechanism for preventing excessive water stress under conditions of high atmospheric demand, described with detail in the section *Gas Exchange*. Peltate trichomes of about 130 µm in diameter are present on both faces of the leaf, but their number is about eight times greater on the abaxial than on the adaxial surface. Leon and Bukovac (1978) identified specialized cells at the base of the peltate stalk, reported by Bongi, Mencuccini and Fontanazza (1987) as being effective in limiting water loss. Palliotti, Bongi and Rocchi (1994) observed that the trichomes are a barrier to the diffusion of CO<sub>2</sub> and H<sub>2</sub>O, lowering the boundary layer conductance in the air surrounding the stomata. After removing the trichomes from leaves of 'Manzanilla' olive trees, they found that the total boundary layer resistance was reduced more than 5-fold. Stomatal conductance and leaf transpiration were significantly higher (21.2% and 20.5%, respectively) in trichome-free leaves than in intact leaves. Schwabe and Lionakis (1996), however, questioned the efficiency of the trichomes in reducing water loss, apart from increasing the reflection of radiation. The trichomes have flavonoid constituents that absorb ultravio-

let-B radiation, protecting the leaf against the negative effects of this radiation on growth and development (Karabourniotis, Kyparissis and Manetas, 1993; Grammatikopoulos, Karabourniotis and Kyparissis, 1994).

The optical properties of the olive leaf play an important role in controlling water consumption. Baldy, Lhotel and Hanocq (1985) found that the adaxial surface of the olive leaf absorbs more photosynthetically active radiation (PAR) than the abaxial surface. The abaxial surface reflected 20 to 40% of the PAR. The olive tree is able to reduce the amount of intercepted radiation during drought by increasing leaf rolling and reducing the angle of the leaf with the stem (Schwabe and Lionakis, 1996). The capacity of the olive leaf for leaf rolling, for the upward movement of the leaf, and for the control of stomatal opening—the three main mechanisms influencing water consumption—is lower in the older leaves than in the young ones. In addition, both the reflectance and the transmittance are greater in young than in older olive leaves (Trigui, 1984). Another mechanism that helps the plant to withstand drought is the water intake by the leaves (Spiegel, 1955; Natali, Bignami and Fusari, 1991), though not enough information exists to evaluate the effect of this phenomenon in the reduction of plant water stress.

The tree size and canopy architecture depend very much on pruning practices and plant density. One of the most widely accepted tree shapes for an intensive olive orchard is that of a single trunk with two or three main branches at 0.8-1.5 m from the ground surface, and a round canopy. In any case, pruning practices must favor light interception, since the dry matter production of the olive tree is directly proportional to intercepted PAR. The radiation use efficiency (RUE) is the ratio between accumulated dry matter and intercepted PAR. Mariscal, Orgaz and Villalobos (1998) measured an RUE value of  $1.25 \text{ g (MJ PAR)}^{-1}$  in young 'Picual' olive trees. The RUE seems to be lower in winter and summer than in spring and autumn. The height of the tree must also be controlled by pruning, to minimize harvesting costs, especially in the cultivars for table consumption which are harvested manually. This point will be further discussed in the last section. Villalobos, Orgaz and Mateos (1995) used a plant canopy analyzer and a simulation model to determine leaf area in the olive. They found that the leaf area index (LAI) exceeds 90% of the plant area index (PAI), so the surface area of green leaves alone is more than 90% of the surface corresponding to leaves and stems. We have made rough estimations of LAI in 29-year-old 'Manzanilla' olive trees of *La Hampa*, planted at  $7 \times 5 \text{ m}^2$ , by counting the number of leaves of a fraction of the canopy and extrapolating to the rest. Once the total number of leaves was estimated, we measured the leaf area of a representative sample of leaves with a leaf area meter and calculated the total leaf area of the tree. Results showed that the maximum leaf area of a tree of average size was around  $60 \text{ m}^2$ , measured at the end of the summer after the growing

period, yielding an LAI of 1.71. The usual pruning practices in olive make inadvisable the methods for estimating LAI based on diameter measurements of branches and twigs.

### *Leaf Water Relations*

Leaf measurements of water potential ( $\Psi_l$ , MPa), stomatal conductance to  $\text{H}_2\text{O}$  ( $g$ ,  $\text{mm s}^{-1}$  or  $\text{mmol H}_2\text{O m}^{-2} \text{s}^{-1}$ ), net photosynthesis rate ( $P_N$ ), also called  $\text{CO}_2$  assimilation rate ( $A$ ,  $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ ), and the evaporative flux from the leaves ( $E$ ,  $\text{kg m}^{-2} \text{s}^{-1}$  or  $\text{mmol H}_2\text{O m}^{-2} \text{s}^{-1}$ ) are usually made in studies of plant water relations. Most of the variables can be expressed in different units, to be coherent with those of related variables and with the purpose of the study. Also,  $E_t$  can be used instead of  $E$  when the transpiration of the whole canopy is considered. The value of  $E$  in young plants growing in pots can be monitored by the use of instruments measuring gas exchange between leaf and air, or by weighing, in which case the units are  $\text{kg m}^{-2}$  per unit of time, normally day or hour. In mature plants in the field, the value of  $E$  can be monitored with techniques for determining the sap flow in the trunk or in the main branches, and the units are  $\text{L m}^{-2}$ , also per day or per hour. In trees, the wide range of leaf conditions in the canopy make it difficult to evaluate the meaning of the measurements at leaf level in the water behavior of the tree. Despite this, a good deal of information can be obtained by the measurement of those variables, which, in addition, are relatively easy to make even in fully established orchards with mature trees under field conditions. We are going to summarize here the most-relevant results obtained from the measurement of the variables used when studying leaf water relations in the olive tree. However, it must borne in mind that, as Tardieu and Davies (1993) noted, "Stomatal conductance, leaf and root water potential, water flux, and xylem [ABA] have multiple interrelations which cannot be summarized by a relationship between any of these variables." For those interested in this sort of study, an excellent collection of review articles on ecophysiology was published in 1997 in the *Journal of Experimental Botany* (Environmental Perspectives 1996/7). We analyze in the section *Determining crop evapotranspiration* other techniques designed to study water use at the tree and orchard levels, which avoid the mentioned limitations of the measurements at leaf level.

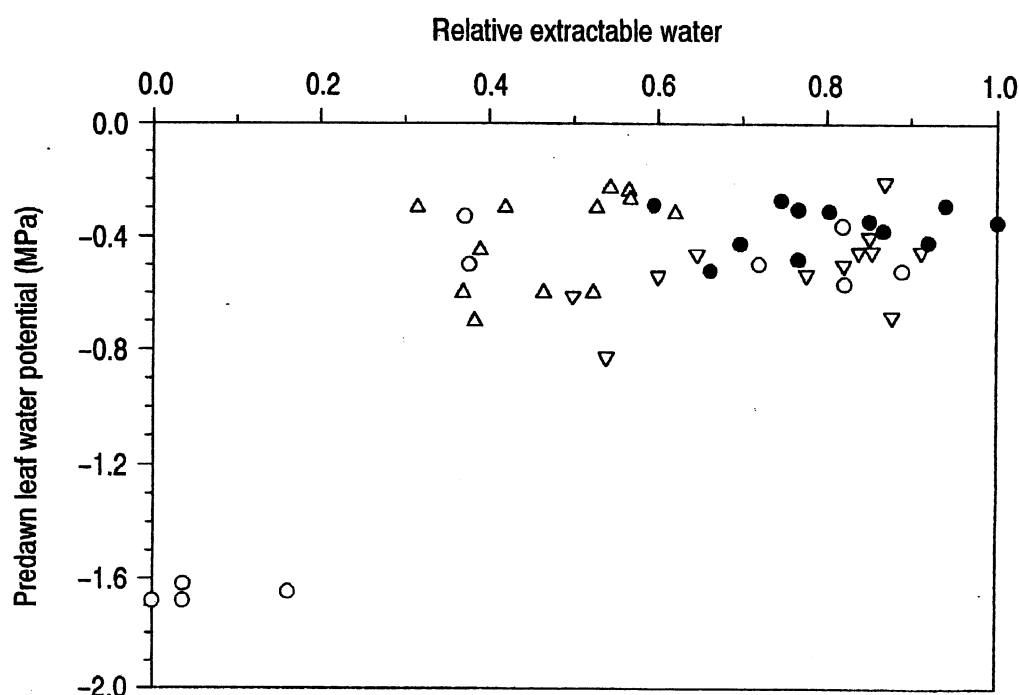
### *Water Status*

Leaf water potential is probably the most widely measured variable for knowing the water status of the plant. Daily and seasonal changes in  $\Psi_l$  measured in different olive cultivars and conditions are shown elsewhere



(Agabbio, Dettori and Azzena, 1983; Xiloyannis et al., 1996; Fernández, Moreno and Martín-Aranda, 1993; Fernández et al., 1997). The predawn leaf water potential ( $\Psi_{pd}$ ) is well-correlated with soil water content (Natali, Xiloyannis and Angelini, 1985). The value of  $\Psi_{pd}$  can be used as an indicator of the degree of water recovery of the tree at night. A value of  $\Psi_{pd}$  below  $-0.5$  MPa is considered to be a threshold for satisfactory recovery (Dettori, 1987). Fernández et al. (1997) plotted the  $\Psi_{pd}$  values measured on mature 'Manzanilla' olive trees under different water treatments against relative extractable water (REW) in the soil (Figure 6). Fernández et al. (1997) found a mean value of  $\Psi_{pd} = -0.46$  MPa for  $REW \geq 0.4$ , and assumed this value of REW to be a threshold for soil water deficit. At midday, the values of  $\Psi_l$  can be quite negative even in well-irrigated trees, if the atmospheric demand is high (Fernández, Moreno and Martín-Aranda, 1993; Moreno et al., 1997). Bongi and Palliotti (1994) mentioned that the large midday  $\Psi_l$  drop in well-irrigated trees might reflect a strong resistance to water movement. They stated that it

FIGURE 6. Relationship between relative extractable water and predawn leaf water potential measured on 26-year-old 'Manzanilla' olive trees at the experimental farm *La Hampa*. Trees were under different water regimes (● weekly pond irrigation to cover the crop water demand; ▽ the same as in ●, but with about 1/3 of the water applied; ○ non-irrigated trees, with rainfall as the only water supply). Data from the experiment by Fernández (1989) carried out in the same orchard (Δ non-irrigated trees) have been used. Each point represents the average of six measurements of predawn leaf water potential per treatment. The mean value of predawn leaf water potential is  $-0.46$  MPa for a relative extractable water  $\geq 0.4$  (adapted from Fernández et al., 1997).



is difficult to establish a critical  $\psi_l$  for growth or physiological processes, and referred to a paper by Rhizopoulos, Meletiou-Christou and Diamantagiotou (1991) in which it is reported that olive leaves can tolerate  $\Psi_l$  values near  $-9$  or  $-10$  MPa without losing rehydration capacity. After reaching a minimum value during the central hours of the day,  $\Psi_l$  became less negative in the afternoon, its value at sunset indicating the degree of recovery from water stress.

The water content at saturation in the olive leaf is lower than in other fruit tree species. Abd-El-Rahman, Shalaby and Balegh (1966) measured  $1.59 \text{ g g}^{-1}$  dry weight in olive,  $5.77 \text{ g g}^{-1}$  in fig, and  $5.85 \text{ g g}^{-1}$  in grape. Fernández et al. (1997) measured in 'Manzanilla'  $1.49 \text{ g g}^{-1}$  in current year leaves and  $0.89 \text{ g g}^{-1}$  in 1-year-old leaves. That means that the olive tissues can reach turgidity with a lower water uptake than other plants, and are able to be at full turgidity after a limited amount of rainfall. Xiloyannis et al. (1996) found a clear linear correlation ( $r^2 = 0.96$ ) between the relative water content (RWC) of olive leaves and their counterpart  $\Psi_{pd}$  values, from 0 to  $-7.0$  MPa. They found that RWC was about 40% when  $\Psi_{pd}$  was as low as  $-7.0$  MPa. Under field conditions, RWC depends not only on the water conditions in the soil and the atmosphere, but also on other factors such as the time of the year and the leaf area per plant (Abdel-Rahman and El-Sharkawi, 1974).

Olive leaves have a high volumetric modulus of elasticity (Bongi and Palliotti, 1994), also called elastic modulus ( $\epsilon$ , MPa). This is a variable inversely proportional to tissue elasticity, representing an applied pressure divided by a fractional change in volume size:

$$\epsilon = \frac{\Delta P}{\Delta V/V} \quad (2)$$

where  $P$  is turgor pressure and  $V$  is cell volume. In the olive,  $\epsilon$  tends to increase with drought. Bongi and Palliotti (1994) observed that at 87.5% of maximal cell volume,  $\epsilon$  was 7 MPa in hazelnut and 22.5 MPa in olive. Loss of turgor of the more rigid cells in olive occurred at 80% of maximal cell volume, while positive turgor was maintained in hazelnut leaves at 66% of maximal volume. Plants with less rigid cells, such as *Agave deserti*, displayed a decrease in  $\epsilon$  and tended to retain higher turgor pressure ( $\Psi_p$ ) under drought conditions (Schulte, 1992). The olive tree does not maintain a low  $\epsilon$  in response to drought, but reduces the osmotic potential ( $\Psi_p$ ). The reduction in  $\Psi_p$  causes the reduction in  $\Psi_l$  responsible for the high capacity of the olive tree for water absorption already mentioned. This reduction in  $\Psi_p$  is responsible for the drop in water potential between the soil and the leaves. Such behavior has been observed by Dichio, Nuzzo and Xiloyannis (1997) in

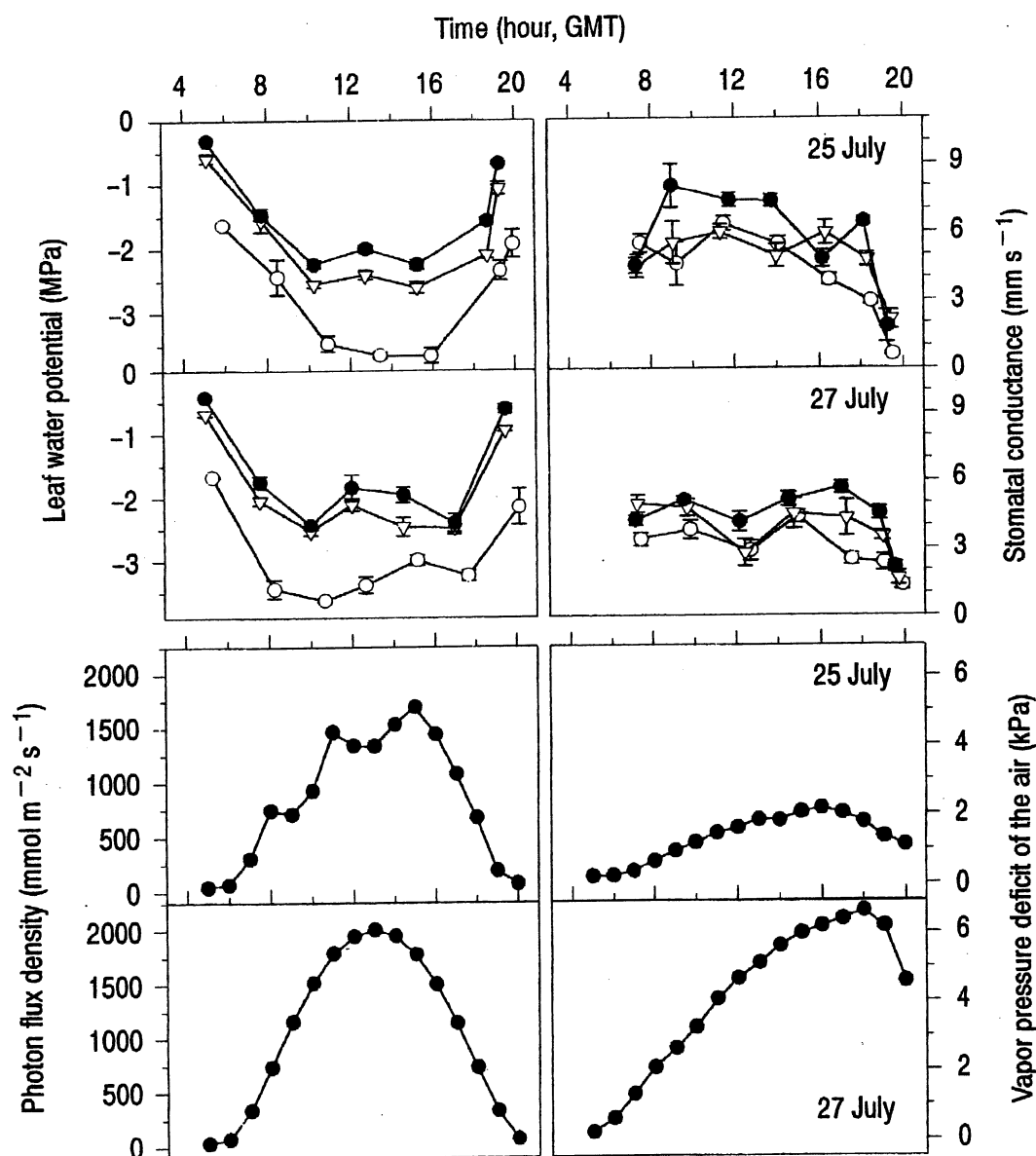
2-year-old 'Coratina' olive trees under different water stress. They reported that the high osmotic adjustment and the rigidity of the cell wall induced high potential gradients between leaves and roots. They calculated the maximum  $\epsilon$  at full turgor in plants at three water stress levels. In the control plants ( $\Psi_{pd} = -0.45$  MPa) and in those of a first level of stress ( $\Psi_{pd} = -1.6$  MPa), the maximum  $\epsilon$  calculated at full turgor was 11.6 MPa. In more-stressed plants ( $\Psi_{pd}$  from  $-3.3$  MPa to  $-5.2$  MPa) the elastic modulus was 18.6 MPa. The  $\Psi_p$  value at saturation was  $-2.06$  MPa in the control plants and  $-2.81$  MPa in the most-stressed plants, indicating a total active osmotic adjustment of 0.75 MPa. At incipient plasmolysis,  $\Psi_p$  varied from  $-3.07$  in controls to  $-3.85$  in the most-stressed plants, with an RWC of 77.8% for the control plants and 74.5% for the more-severely stressed plants. When the olive plants are under stress for a long time, for instance during the long dry season of the Mediterranean areas, maximum  $\epsilon$  can be higher than during the wet season (Dichio, personal communication).

Monthly variations of  $\Psi_p$  in mature olive trees under desert conditions in Egypt were measured by Abd-El-Rahman, Shalaby and Balegh (1966). They found minimum values of about  $-6.8$  MPa in September. They also observed that the values of  $\Psi_p$  in olive were lower than in other xerophytes. They reported mean annual  $\Psi_p$  values of about  $-4.8$  MPa for olive,  $-2.4$  MPa for almond,  $-1.5$  MPa for fig, and  $-1.3$  MPa for grape, among other species. With drought, olive leaves tend to overcome water deficit by solubilizing sugar from the starch reserve, and so  $\Psi_p$  becomes more negative (Tombesi, Proietti and Nottiani, 1986). Starch depletion in conjunction with the rise in soluble carbohydrates and mannitol during the summer has been observed in olive by Drossopoulos and Niavis (1988). Mannitol is a sugar alcohol which in olive represents from 1/2 to 2/3 of the total soluble sugars in leaves and bark (Bongi and Palliotti, 1994). Xiloyannis et al. (1996) also outlined the significant role of the high osmoregulation capacity of the olive tree in its tolerance to drought. They differentiated between the passive osmotic adjustment, due to the loss of water by the tissues, and the active adjustment due to the synthesis of osmolytes.

### Gas Exchange

We have mentioned in previous sections that stomatal closure is a mechanism used by the olive tree for restricting water loss on days of high atmospheric water demand. Figure 7, taken from Fernández et al. (1997), is a good example of this behavior. The figure shows diurnal time courses of  $g$  in olive trees under different conditions of water in the soil, recorded in *La Hampa* on two summer days with different atmospheric water demand. On July 25, a relatively dry, clear-sky day, the stomata opened as soon there was light, and  $g$  increased very quickly during the first hours of the morning. Maximum

FIGURE 7. Diurnal time course of leaf water potential and stomatal conductance measured in 16-year-old 'Manzanilla' olive trees at the experimental farm *La Hampa*. Measurements were made in non-irrigated trees ( $\circ$ ), and in trees with weekly irrigation to cover the crop water demand ( $\bullet$ ) and 1/3 of it ( $\nabla$ ). Each point represents the average of six values per treatment. Vertical bars indicate twice the standard error. Values of photon flux density and vapor pressure deficit of the air recorded on the measurement days are also plotted. The 25th of July was a somewhat fresh and partially cloudy day, whereas the 27th was a clear, hot, very dry day. Relative extractable water in the soil was, for the 25th and the 27th of July, respectively, 0.04 and 0.04 for the non-irrigated trees, 0.65 and 0.61 for the medium watered trees, and 0.87 and 0.77 for the most irrigated trees (adapted from Fernández et al., 1997).



values of  $g$  were recorded early in the morning, before the atmospheric water demand was high enough to cause stomatal closure. For the conditions of *La Hampa*, we have usually measured maximum values of  $g$  before 10.00 GMT, recording values of up to  $12 \text{ mm s}^{-1}$ , though they are rarely over  $10 \text{ mm s}^{-1}$ . The minimum values of  $\Psi_l$  occurred later in the day, usually between 14.00 and 16.00 h GMT. On July 27, the values of  $g$  remained fairly constant throughout most of the day, and they were lower than on the 25th for all treatments, despite low or negligible variations in soil water content for all treatments between the measuring days. This was a consequence of an earlier and more marked stomatal closure on July 27, a day when both radiation and atmospheric demand were greater than on July 25 (Figure 7). The earliest references we have found reporting stomatal control in the olive are those of Migahid and Abd-El-Rahman (1953) and Hammouda (1954), cited by Abd-El-Rahman, Shalaby and Balegh (1966). Apart from the root signaling phenomenon already described, the meteorological driving variables for stomatal opening are light intensity and vapor pressure deficit of the air (Abdel-Rahman and El-Sharkawi, 1974; Fernández et al., 1997). Wind speed seems to have low influence. Upper-bound relationships between  $g$  and  $D_a$  and the photon flux density ( $I_P$ ,  $\mu\text{mol m}^{-2} \text{ s}^{-1}$ ) were obtained by Fernández et al. (1997) for 'Manzanilla' olive trees in *La Hampa*. They found maximum values of  $g$  at relatively low levels of  $I_P$ , from about  $500 \mu\text{mol m}^{-2} \text{ s}^{-1}$ , and a proportional decrease in  $g$  with increasing  $D_a$  for values up to approximately 3.5 kPa. The stomata remained partially opened at higher  $D_a$ . Higher values of  $g$  were observed in the morning, during the opening phase, than in the afternoon for a similar level of  $D_a$  and  $I_P$ . This behavior could be explained by the fact that maximum values of  $I_P$  occur earlier in the day than the maximum values of  $D_a$  (Jarvis, 1976). A similar behavior has been observed in other fruit tree species, such as oak (Hinckley et al., 1975), apple (Jarvis, 1976), and peach (Punthakey, McFarland and Worthington, 1984). The fact that  $D_a$  is the main driving variable for midday stomatal closure seems to be true except for winter time. At that time of the year, soil temperature (Gimenez et al., 1996), or perhaps other factors related to root functioning (Ferreles, Moriana and Ruz, 1998), could cause low  $\Psi_l$  and stomatal closure despite high soil water potential and relatively low atmospheric demand.

Some authors have found certain correlation between  $\Psi_l$  and  $g$  values (Sorrentino, Giorio and d'Andria, 1998), but at other times, such correlation has not been found (Fernández, Moreno and Martín-Aranda, 1993; Fernández et al., 1997). The influence of environmental factors such as  $D_a$  and  $I_P$  (Jarvis, 1976) and the possibility that the water potential of the stomatal apparatus is different to the bulk leaf water potential (Castel and Fereres,

1982) probably account for the large scatter sometimes found when plotting  $\Psi_l$  against  $g$ .

Maximum  $A$  values are usually measured early in the morning before stomatal closure, the same as for  $g$ . Maximum values of  $A$  of up to  $22 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  have been reported by Angelopoulos, Dichio and Xiloyannis (1996) and Díaz-Espejo et al., (1998). This value is rather low in comparison with that of other fruit trees, though the olive tree is able to maintain relatively high photosynthetic rates over a long period of drought. This low photosynthetic capacity has been related to certain leaf characteristics, such as dense, thick cell walls and the presence of trichomes, as well as the low density of photosynthetic reaction centers (Bongi and Palliotti, 1994). On a typically Mediterranean summer day there is a continuous decrease of  $A$  after the peak value reached in the morning, due to stomatal closure and to other effects caused by water stress. Larcher, Moraes and Bauer (1981) observed in 'Leccino' that  $A$  began to decrease when  $\Psi_l$  fell to  $-1.3 \text{ MPa}$ , and that the photosynthetic capacity was reduced by 50% when  $\Psi_l$  reached  $-2.2 \text{ MPa}$ . With 3-year-old olive plants of the same cultivar, Tombesi, Proietti and Nottiani (1986) reported a reduction of 50% in  $A$  when the available water in the soil was 40% of that at field capacity. If the stomatal closure due to water stress is accompanied by a high light intensity,  $A$  is also reduced by photoinhibition. This phenomenon has been observed in the olive by Bongi and Palliotti (1994) and Angelopoulos, Dichio and Xiloyannis (1996), among others. Basically, it consists of an imbalance in the photosynthetic apparatus caused by a lack of  $\text{CO}_2$  accompanied by high temperature and light fluence. It has been stated that, in moderately stressed plants, the decline of  $A$  after the peak values reached early in the morning is due to the limited  $\text{CO}_2$  supply to the chloroplast caused by stomatal closure. In severely stressed plants, however, the reduction in  $A$  is also due to the inactivation of photosynthetic activity (Angelopoulos, Dichio and Xiloyannis, 1996; Xiloyannis et al., 1996). This may explain why a certain correlation has been found between  $g$  and  $A$  for low or moderately stressed olive plants, but for more-severely stressed plants the two variables are no longer correlated (Natali, Bignami and Fusari, 1991; Angelopoulos, Dichio and Xiloyannis, 1996).

The  $\Psi_l$  threshold for  $A$  seems to be between  $-4.2$  and  $-6.0 \text{ MPa}$ , depending on the stress conditions and plant acclimation (Larcher, Moraes and Bauer 1981; Jorba, Tapia and Sant, 1985; Tombesi, Proietti and Nottiani, 1986). Light saturation for  $A$  occurs from  $1000$ - $1200 \mu\text{mol m}^{-2} \text{ s}^{-1}$  of photosynthetic photon flux density (PPFD) (Baldy, Lhotel and Hanocq, 1985; Natali, Bignami and Fusari, 1991). Fluorescence measurements can be used to evaluate the damage caused by photoinhibition (Bongi, Rocchi and Palliotti, 1994). The same technique was used by Bongi and Lupattelli (1986) to assess the limit of salt tolerance in photosynthesis.

### *Transpiration and Water Use Efficiency*

The olive tree is considered a parsimonious consumer of water. We have already mentioned the marked stomatal control on transpiration, making the maximum stomatal conductance be achieved early in the morning on the days of high atmospheric demand. This does not mean, however, that the maximum transpiration rate is achieved at the same time, as we will see below. Stomatal control, together with the high hydraulic resistance, may be responsible for the transpiration rates in the hottest and driest months of the year being lower than before and after the dry season. This explains why the crop coefficients for the olive tree in the Mediterranean basin are lower in the summer than in spring or autumn. Such behavior was observed in the earliest studies on transpiration. For instance, Abd-El-Rahman, Shalaby and Balegh (1966) cited the works by Evenari and Richter (1937) and Rouschal (1938) in which the limitation of transpiration during the dry summer conditions was outlined. Larsen, Higgins and Al-Wir (1989) compared the transpiration rates of different fruit species. Apple had the highest transpiration rate (100%), followed by peach (57%), grape (39%), apricot (34%), and olive (34%). The water consumption per unit of leaf area of young olive plants in pots has been found to be between  $1 \text{ L m}^{-2} \text{ d}^{-1}$  (Cruz-Conde and Fuentes-Cabanas, 1986) and  $1.7 \text{ L m}^{-2} \text{ d}^{-1}$  (Natali, Bignami and Fusari, 1991). Water consumption was calculated by weighing the pots. Despite differences between the conditions of the pot experiments and those of mature trees in the field, the amounts are not very different from what we have measured in *La Hampa* with 'Manzanilla' olive trees from 25 to 30 years-of-age and with leaf area ranging from about 55 to 60  $\text{m}^2$ . Some of our measurements have already been reported by Moreno et al. (1996). We calculated transpiration from sap flow velocities measured with the compensation heat-pulse technique (see section *Sap flow measurements*) in the trunk of trees under different water regimes. The maximum daily water consumption we found in a well-irrigated tree was  $1.65 \text{ L m}^{-2} \text{ d}^{-1}$ , on a day with maximum values of global solar radiation and air vapor pressure deficit of  $850 \text{ W m}^{-2}$  and 3 kPa, respectively. The highest  $E$  values, however, were rarely higher than  $1.20 \text{ L m}^{-2} \text{ d}^{-1}$  for well-irrigated trees. Maximum sap flow rates were measured in the trunk between 13.00 and 14.00 GMT, despite the porometer measurements' showing that stomatal closure occurred much earlier in the day, at about 10.00 GMT. Even assuming a certain delay between the sap flow in the trunk and water loss by transpiration, it is clear that the maximum transpiration rates occurred later than the maximum stomatal aperture. We have already mentioned that the stomata do not fully close, but remain partially open. Between 13.00 and 14.00 GMT, there was probably the best balance between the degree of stomatal opening and the environmental conditions for enhancing transpiration. The average maximum value of transpiration rate we have

recorded on well-irrigated trees was  $3.05 \times 10^{-5} \text{ L m}^{-2} \text{ s}^{-1}$ . There is no agreement among the different authors reporting on the maximum  $E$  for olive, probably due to the different cultivars and experimental conditions in which the measurements were made. Jorba, Tapia and Sant (1985) worked with 1-year-old 'Arbequina', 'Manzanilla' and 'Sevillana' olive plants in pots. They reported a maximum  $E$  of  $8 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ , without mentioning differences between cultivars. Thompson et al. (1983) reported maximum  $E$  values of about  $2.6 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$  for 4-year-old plants of 'Coratina' and 'Nocellara' grown in pots. It has been reported that the transpiration rate per unit of leaf surface may be lower in irrigated than in non-irrigated olive trees, though the total amount of water lost by transpiration is greater in the irrigated trees due to their larger leaf area (Abdel-Rahman and El-Sharkawi, 1974). Xiloyannis et al. (1996) mentioned that a significant part of the water lost by transpiration comes from the water stored in the tissues of the olive tree during the afternoon and night, which ensures a certain level of leaf functionality in drought conditions. As mentioned before, they observed that olive leaves can lose about 60% of the water stored in their tissues under severe water stress ( $\Psi_l = -7.0 \text{ MPa}$ ). Using the compensation heat-pulse technique in the 'Manzanilla' trees of *La Hampa*, we have been able to record sap flow at night in both the trunk and main roots, accounting for the nocturnal water recovery.

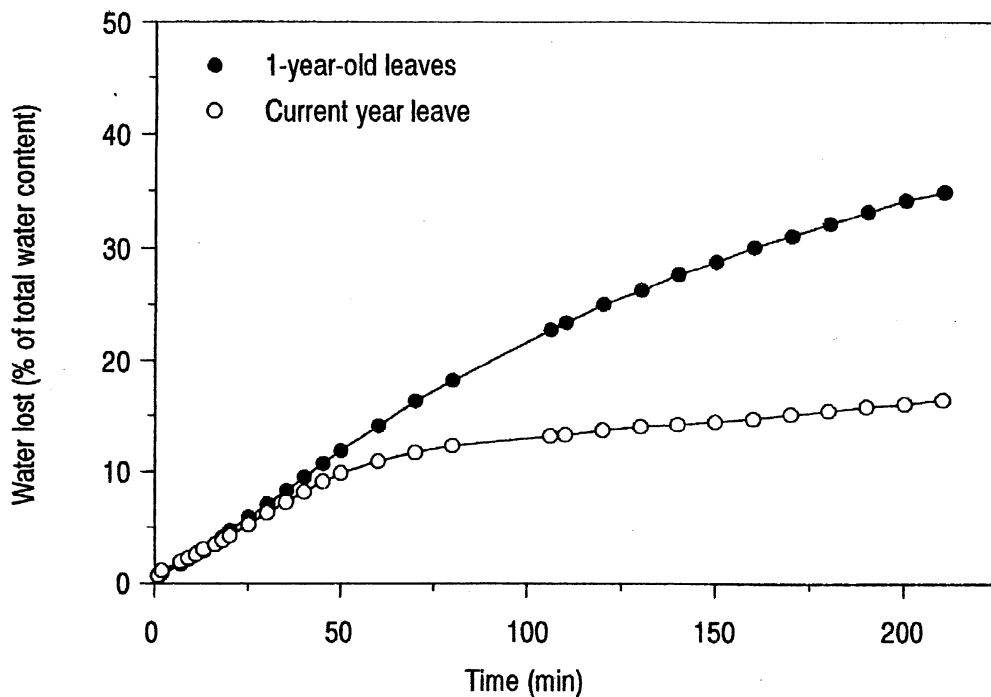
The olive tree uses water more efficiently than other fruit tree species. Bongi and Palliotti (1994) calculated that for the southern Mediterranean area, the number of grams of dry fruit matter per kilogram of water consumed was 3.17 for olive, 2.46 for *Citrus*, and 1.78 for *Prunus*. Xiloyannis et al. (1996) showed the water use efficiency (WUE) values given by different authors for various fruit species. He mentioned WUE values between 5.5 and  $9.6 \text{ g CO}_2 \text{ kg H}_2\text{O}^{-1}$  for olive, between 3.2 and  $4.4 \text{ g CO}_2 \text{ kg H}_2\text{O}^{-1}$  for grape, and between 2.3 and  $3.5 \text{ g CO}_2 \text{ kg H}_2\text{O}^{-1}$  for peach, among other species. Natali, Bignami and Fusari (1991) determined the diurnal time course of WUE for 4-year-old 'Frantoio' olive plants. They found the highest WUE values early in the morning ( $2.28 \text{ g CO}_2 \text{ kg H}_2\text{O}^{-1}$  at 08.30 h), which later decreased ( $1.43 \text{ g CO}_2 \text{ kg H}_2\text{O}^{-1}$  at 18.00 h). They mentioned that the decrease of WUE in the afternoon could be due to photoinhibition and high transpiration rates in the central hours of the day. Bongi and Palliotti (1994) estimated WUE values of 2.16 and  $3.48 \text{ g CO}_2 \text{ kg H}_2\text{O}^{-1}$  for the cultivars 'Ascolana' and 'Moraiolo', respectively.

### *Influence of Leaf Aging*

During aging, there are various changes in the olive leaf affecting water use by the tree. Leaf thickness increases with age, reducing light transmittance and photosynthetic capacity of the leaves in the inner parts of the



FIGURE 8. Water loss of detached, bench-dried 1-year-old leaves and the current season leaves, taken from 27-year-old 'Manzanilla' olive trees irrigated weekly to cover the crop water demand. A group of 10 leaves was weighed in each case. Fresh weight of the 10 old leaves: 2.1706 g; fresh weight of the 10 young leaves: 1.8190 g. Water content of the 10 old leaves: 1.0256 g; water content of the 10 young leaves: 1.0898 g (adapted from Fernández et al., 1997).



canopy (Bongi and Palliotti, 1994). Tissue elasticity is also reduced with leaf aging. Bongi and Palliotti (1994) calculated that in olive leaves at 87.5% of maximal cell volume,  $\epsilon$  was 22.5 MPa in mature leaves and 8.4 MPa in young leaves. The leaf movements and stomatal control already described as mechanisms controlling the water loss in olive are also reduced with leaf aging. Schwabe and Lionakis (1996) observed steeper angles with the stem in very young leaves than in older leaves. Fernández et al. (1997) found that during a water stress period, the stomata remained more open in 1-year-old leaves than in the current year leaves. This loss of stomatal control with aging is illustrated by Figure 8 and by the average values of  $\Psi_l$  ( $-1.11$  MPa in young leaves;  $-1.35$  MPa in old leaves),  $g$  ( $5.2 \text{ mm s}^{-1}$  in young leaves;  $6.3 \text{ mm s}^{-1}$  in old leaves) and  $A$  ( $14.57 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  in young leaves;  $20.66 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  in old leaves) measured by Fernández et al. (1997) in leaves of the current year and in 1-year-old leaves. Bongi, Mencuccini and Fontanazza (1987) also reported variations of  $A$  with leaf aging, with an increase of  $A$  in the first two months, a plateau from month 2 to month 11-13, and a decrease of 50% or more when the leaf is about 2 years old or even older, just before dying.

### *Recovery After Drought*

The  $\Psi_l$  of stressed olive trees recovers quickly after rewatering. It takes longer for the values of  $g$  and  $A$  to recover, the delay being related to the level of water stress previously reached. Natali, Xiloyannis and Angelini (1985) reported the recovery of  $\Psi_l$  the day after irrigating stressed 3-year-old plants of 'Moraiolo', 'Leccino' and 'Plantoio'. Fernández, Moreno and Martín-Aranda (1993) observed that  $\Psi_l$  of water-stressed 20-year-old 'Manzanillo' olive trees recovered significantly just 12 h after rewatering, reaching similar values to those on control plants in just three days. The day before rewatering,  $\Psi_{pd}$  was  $-0.22$  MPa for the control trees and  $-0.51$  MPa for the stressed trees. The minimum values of  $\Psi_l$  reached that day were  $-2.19$  MPa for the control trees and  $-2.83$  MPa for the stressed trees. In later studies with more-severely water-stressed 'Manzanilla' trees ( $\Psi_{pd} = -0.28$  MPa for control trees and  $-1.65$  MPa for stressed trees;  $\Psi_l$  at midday =  $-2.38$  MPa for control trees and  $-3.62$  MPa for stressed trees), Fernández et al. (1997) reported very little difference in  $\Psi_{pd}$  just two days after rewatering, and no difference at all six days after rewatering. From the second day after rewatering, the formerly stressed plants showed greater values of  $\Psi_l$  at midday than the control plants. This phenomenon was also observed by Jorba, Tapia and Sant (1985). They mentioned that this behavior "could be due to the after-effects of stress (Fischer, 1967) perhaps mediated by ABA (Aspinall, 1980) and its control of stomatal conductance and transpiration." A full recovery of  $g$  was also observed in just two days after rewatering. It seems that if the trees reach more-severe levels of stress, the recovery of  $\Psi_l$ ,  $g$  and  $A$  takes longer. Fereres et al. (1996) studied the recovery of 22-year-old 'Picual' after a period of severe water stress in which minimum  $\Psi_l$  values were close to  $-8.0$  MPa. They found that  $\Psi_l$  recovered in about four days, but it took several weeks for  $g$  to recover. The recovery of the photosynthetic capacity was studied by Angelopoulos, Dichio and Xiloyannis (1996) in 2-year-old 'Coratina' olive plants. Their severely water-stressed plants ( $-6.5$  MPa) had not completely recovered five days after rewatering, but the authors observed that the olive has a strong capacity for repairing the inactivation of the primary photochemistry associated with photosystem II (PSII) after long-term photoinhibition and water stress. The authors stated that this is another feature showing the olive tree's tolerance to drought.

We have already mentioned that our measurements of sap flow in roots indicated a quick water absorption by roots of olive trees after a long period of drought, when the water was finally available in the soil. This explains the quick recovery of  $\Psi_l$  mentioned above. Despite this quick response, the tree may not fully recover if the water supply after the drought period is scarce. In our experiments (Fernández et al., 1996, and Moreno et al., 1996), we measured sap velocities at different depths below the cambium in main roots of a

25-year-old 'Manzanilla' olive tree in *La Hampa*, which was without any water supply from the end of May until September 12. Results showed that, despite a significant increase in water uptake, the conductance capacity of the roots did not recover after rewatering, since no flow was detected in the outer sapwood annuli, probably because the vessels remained cavitated. Measurements of  $\Psi_l$  and water consumption by the tree also showed a partial recovery, indicating that the irrigation on September 12 was not enough for a full recovery of the tree.

### **IRRIGATING THE ORCHARD**

The olive tree's outstanding adaptation to drought enables it to grow and to produce commercial yields under rainfed conditions in areas where the average rainfall is not much more than 500 mm, and where the dry season can last for five or six months. There are, however, two main reasons for irrigating the olive orchard. On one hand, the plant has a marked response to additional water supplies, even if only small doses of water are applied. On the other hand, in the new intensive orchards, where the maximum crop productivity is pursued, plant densities range from 250 to 400 trees ha<sup>-1</sup> or more, which means a significant increase in leaf surface per unit of soil surface compared with traditional, rainfed orchards. Under those conditions, rainfall is not enough and irrigation becomes a necessity. Water, however, is scarce and sometimes of low quality in the areas where the olive is cultivated. There is, therefore, an increasing interest in new techniques designed for a more accurate estimation of the irrigation doses. Deficit irrigation and irrigation with both saline and wastewater are also major subjects for current research on water management in olive orchards.

#### ***Crop Response to Irrigation***

Most of the critical biological processes for growth and production of the olive tree (Figure 1) occur during the dry season in most areas where the olive is cultivated. Water supplied by irrigation minimizes the negative effects of water stress on crop performance, summarized in Table 1. When water stress is present, shoot growth is reduced, though less than root growth. Here the olive shows one of its mechanisms of adaptation to drought—the root/canopy ratio is usually greater in non-irrigated than in irrigated olive trees (Xiloyannis et al. 1996; Celano et al., 1999). This enhances root water uptake under rainfed conditions. Flowering and fruiting are negatively affected by water stress. Lavee (1985) cited the work by Fahmi (1958) showing that an adequate water supply during differentiation is critical for normal inflorescence

TABLE 1. Effects on the growth and production of the olive tree of water stress in different periods of the annual cycle (adapted from Beede and Goldhamer, 1994, and Fereres, 1995).

| Phenological event                   | Period of the year   | Effect of water stress                                 |
|--------------------------------------|--|--|
| Shoot growth                         | Mainly from late winter to the beginning of summer, and autumn | Reduced shoot growth                                   |
| Flower bud development               | February to April  | Reduced flower formation                               |
| Bloom                                | April to May   | Incomplete flower                                      |
| Fruit set                            | May to June  | Poor fruit set, increased alternate bearing            |
| Fruit growth due to cell division    | June to July   | Reduced fruit size due to the decreased cell division  |
| Fruit growth due to cell enlargement | August to harvest  | Reduced fruit size due to the decreased cell expansion |
| Oil accumulation                     | September to harvest   | Reduced fruit oil content                              |

development. It has been reported that the occurrence of water stress two or three weeks after fruit set, before pit hardening, reduces pit size (Lavee, 1986). When the stress occurred later, the pericarp/pit ratio was smaller in the fruits from stressed trees than in fruits from the non-stressed ones, though this was due in most cases to reduced pericarp weight, pit size not being affected. Appropriate irrigation management prevents significant water stress and causes marked positive effects on the olive performance. Irrigation increases trunk diameter and shoot growth, as well as the number and size of the fruits (Michelakis 1990; d'Andria et al., 1998; Magliulo et al., 1998). Agabbio, Dettori and Azzena (1983) reported that irrigation increased the pulp/stone ratio and reduced the percentage of dry matter in the fruits. Manrique (1996) observed in 'Picual' olive trees that fruit growth did not stop during the dry season in irrigated trees, resulting in a greater oil production in the irrigated trees than in the non-irrigated ones. Lavee et al. (1990) also observed an increase in total fruit and oil production with irrigation, though the relative oil content based on fresh weight was considerably higher in the fruits of non-irrigated trees than in those with irrigation. Irrigation, together with an adequate orchard management, reduces alternate bearing (see last section). The contrary can be obtained if irrigation is applied in a badly managed orchard, since alternate bearing depends on a variety of factors (Poli 1986a, 1986b; Lavee and Wodner, 1991). Pastor, Castro and Vega (1997) reported that

irrigation increases the canopy volume, the number and size of the fruits, and the total oil production. Beltrán, Jiménez and Uceda (1995) and Pastor et al. (1995) reported a decrease with irrigation in the polyphenol content and in the specific absorptions K225, K232, and K270. Patumi et al. (1998) also reported a lower polyphenol content in irrigated trees compared with non-irrigated trees, though this did not affect the organoleptic and storage characteristics of the oil.

### *Determining Crop Evapotranspiration*

The amount of water consumed by the crop is called crop evapotranspiration ( $ET_c$ , mm). Dettori (1987) reported  $ET_c$  values for the olive crop of 620 and 560 mm for areas of 1200 and 1000 mm of annual potential evapotranspiration ( $ET_p$ , mm), respectively. Fereres (1995) and Villalobos et al. (1998) estimated an  $ET_c$  of 700-800 mm for olive orchards in southern Spain, where  $ET_p$  is about 1400 mm. Goldhamer, Dunai and Ferguson (1993, 1994) made an economic analysis of olive crop revenues following use of increasing irrigation doses in a mature 'Manzanilla' olive orchard in California. They found an increasing response in the crop gross revenue with irrigation up to about 950 mm. It can be concluded that the  $ET_c$  value varies for each orchard, depending on environmental conditions, crop characteristics, and orchard management. The optimum value of  $ET_c$  must be known for calculating the irrigation requirements ( $IR$ , mm). These are given by the equation

$$IR = ET_c - P_e \quad (3)$$

where  $P_e$  (mm) is the effective precipitation. This is calculated as a percentage of the total rainfall, normally 70%, though this value can be lower in sloping orchards with restricted infiltration and greater in flat orchards with soils of high infiltration rate. The resulting value of  $IR$  can be increased for inefficiencies of the application system and leaching requirements. In the following sections, different approaches for estimating  $ET_c$  are described.

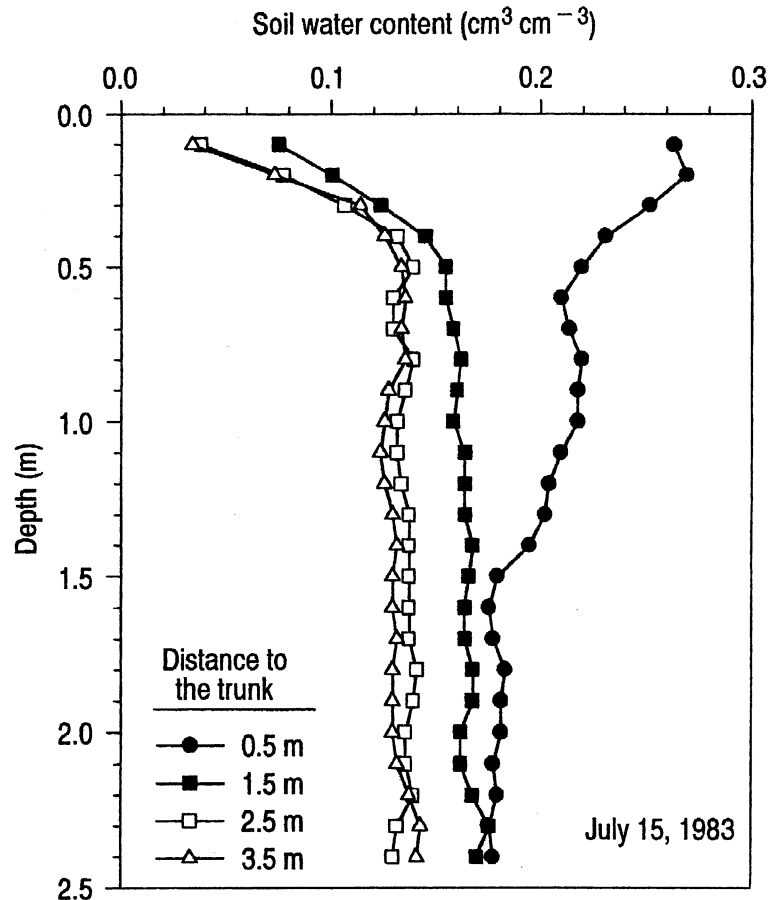
### *The Soil Water Balance Approach*

The value of  $ET_c$  can be derived from the water balance equation applied at orchard level. The method has a low temporal resolution, a few days at best. It is laborious and time consuming, requiring detailed monitoring of the equation components. In addition, the hydraulic properties of the soil profile, such as the hydraulic conductivity-soil water content relationship, must be accurately determined (Moreno, Vachaud and Martín-Aranda, 1983; Moreno et al., 1998; Vanderlinden, Gabriels and Giráldez, 1998). The spatial variabil-

ity of these properties has to be taken into account in order to establish to what degree local measurements can be extrapolated to the plot scale. Temporal variability can also be significant. For given climatic conditions and soil type, tillage methods and irrigation practices are the main factors affecting the soil structure of the top layers, and consequently their hydraulic properties (Messing and Jarvis, 1993; Moreno et al., 1997, 1998). Despite the difficulties, studies of soil hydraulic properties are needed for running models simulating water and solute transport in the soil and water use by the crop. Moreno et al. (1988) evaluated the representativeness of soil water content measurements in an olive orchard. They took into account the spatial variability of soil texture and the space-time series of water content measurements in the soil. Caution is needed, however, when estimating  $ET_c$  from the water balance equation applied to extensive field areas, because of errors due to the mentioned spatial variability of parameters such as soil water storage and hydraulic conductivity. If such variability is high, aerodynamic and empirical approaches, although based mainly on atmospheric observations, are a better choice for estimating  $ET_c$  (Villagra et al., 1995).

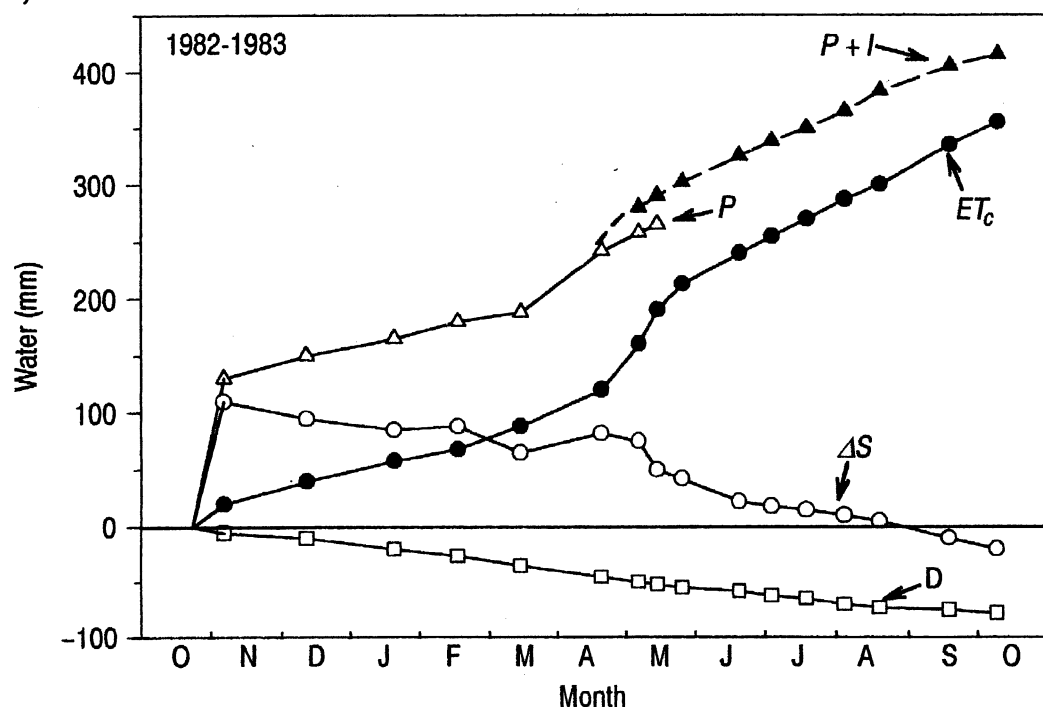
Examples on the use of the water balance approach for determining the amount of water used by mature olive trees under different water regimes can be found in the literature. In most cases, the water balance equation was applied for the whole irrigation period, taking into account just the total amount of water supplied by irrigation and the soil water content at the beginning and end of the experimental period (Michelakis and Vougioucalou, 1988; Goldhamer, Dunai and Ferguson, 1993). In other cases, the changes in water storage within the root zone were frequently monitored as a way of determining the root water extraction patterns (Martín-Aranda et al., 1982). At *La Hampa*, Moreno et al. (1988) estimated  $ET_c$  from the water balance equation applied to an olive orchard of 16-year-old 'Manzanilla' olive trees at a spacing of  $7 \times 7 \text{ m}^2$  and under drip irrigation. The irrigation system consisted of a lateral drip line per row of trees with four  $4 \text{ L h}^{-1}$  drippers per tree. A deficit irrigation was applied, calculated from total weekly evaporation of a class A pan, adjusted by a reduction coefficient of 0.4. With this reduction coefficient, the trees used during the dry season part of the water stored in the soil at the end of the rainy season. On average, the trees depleted 30% of the total available water in the root zone. The estimation of the water balance components was carried out using a model that separated the soil areas affected by irrigation from the non-affected ones. The model included a weighting method for changes of water storage in the mentioned areas. The affected and non-affected areas were established according to differences in the soil water content profiles at different distances from the tree trunk (Figure 9). The same weighting approach was followed for the drainage calculations. Drainage was estimated by calculating the amount of water lost below

FIGURE 9. Water profiles at different distances from the trunk of an olive tree irrigated by a single lateral drip line placed on the soil surface in each tree row, with four  $4 \text{ L h}^{-1}$  drippers per tree, 1 m apart. The ground area wetted by each emitter was a circle of about 0.7 m in diameter, and the maximum width of the wetted bulb was about 1.1 m (adapted from Moreno et al., 1988).



the maximum depth reached by the roots. In the calculations, the hydraulic conductivity-soil water content relationship, the hydraulic gradient, and the changes of water storage in each period between two consecutive measurements were taken into account. Results from the hydrological year 1982-83 are shown in Figure 10. The values of the water balance components in the orchard for six consecutive years, determined by Moreno et al. (1988) and Fernández (1989), are shown in Table 2. The greatest water losses by drainage were recorded in years with high rainfall and low  $ET_p$ . In years with heavy rainfall, greater drainage was recorded during the first part of the irrigation period, due to the high soil hydraulic conductivity below the root zone (Moreno, Vachaud and Martín-Aranda, 1983). Water losses by runoff ( $R$ , mm) were significant only in periods of heavy rainfall. Evaporative demand was low in those periods, allowing  $R$  to be calculated from the water balance equation after assuming  $ET_c = ET_p$ . The values of  $R$  obtained by Moreno et al. (1988) using this indirect approach agreed with previous results

FIGURE 10. Cumulative value of the water balance components during the hydrological year 1982-1983, calculated for an olive orchard with 12-year-old 'Manzanilla' olive trees at  $7 \times 7 \text{ m}^2$  spacing. The trees were irrigated daily during the dry season, from April to September, with a drip-irrigation system. A deficit irrigation approach was followed, designed for the trees to use 30% of the available water in the soil. The unknown component in the equation was  $ET_c$ .  $P$  = precipitation,  $I$  = irrigation;  $\Delta S$  = variation of the water stored in the soil;  $D$  = drainage;  $ET_c$  = crop evapotranspiration (adapted from Moreno et al., 1988).



obtained experimentally by Moreno (1986). The increasing  $ET_c$  throughout the years was due to the increase in tree size. Table 2 also shows the value of the water balance components for the hydrological year 1997-98, in which the orchard was irrigated with enough water to cover the crop demand. This was a year of heavy rainfall (the average calculated for the period 1971-95 in the area is 500 mm), with rains of high intensity in winter, which caused a large runoff.

The total value of  $ET_c$  determined for an olive orchard can be split into its two components, provided soil evaporation ( $E_s$ , mm) or tree transpiration ( $E_t$ , mm) is determined separately. Moreno, Vachaud and Martín-Aranda (1983) estimated  $E_s$  in a drip-irrigated olive orchard at *La Hampa* as a function of the water content of the top soil layers. Recently, Palomo et al. (1998a,b) conducted some experiments in the same orchard to validate the results obtained by Moreno, Vachaud and Martín-Aranda (1983), and obtained an empirical equation for estimating  $E_s$  for the orchard conditions of *La Hampa* (Figure 11).



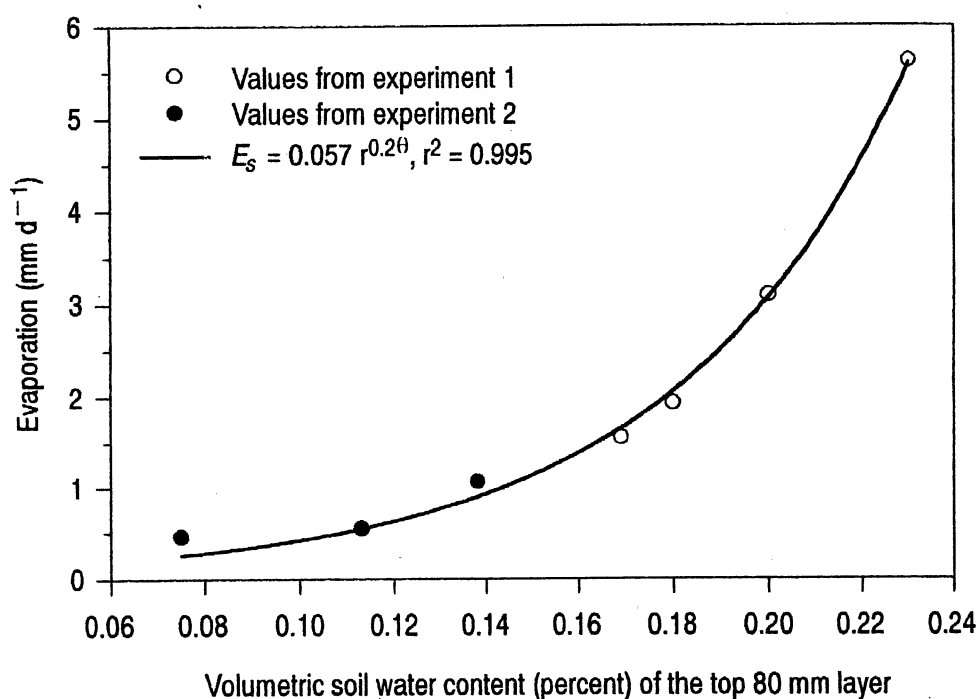
TABLE 2. Annual values of the components of the water balance equation determined in an olive orchard at *La Hampa* when the trees were irrigated (1) for six consecutive years with a deficit irrigation designed to use up to 30% of the available water content in the soil, and (2) for one year in which irrigation was enough to replace the crop water demand. Crop evapotranspiration was the unknown component of the equation.  $P$  = precipitation;  $I$  = irrigation;  $\Delta S$  = difference between the soil water stored in the soil at the beginning and at the end of the experimental period;  $D$  = drainage;  $R$  = water runoff;  $ET_c$  = crop evapotranspiration;  $ET_p$  = potential evapotranspiration calculated by the FAO-Penman equation (adapted from Moreno et al., 1988, Fernández, 1989, and unpublished data).

| Irrigation mode | Hydrological year | $P$<br>(mm) | $I$<br>(mm) | $\Delta S$<br>(mm) | $D$<br>(mm) | $R$<br>(mm) | $ET_c$<br>(mm) | $ET_p$<br>(mm) |
|-----------------|-------------------|-------------|-------------|--------------------|-------------|-------------|----------------|----------------|
| (1)             | 1982-1983         | 258         | 133         | -20                | 73          | 0           | 338            | 1486           |
|                 | 1983-1984         | 542         | 65          | +45                | 157         | 82          | 323            | 1239           |
|                 | 1984-1985         | 584         | 87          | +2                 | 238         | 69          | 362            | 1381           |
|                 | 1985-1986         | 438         | 101         | -37                | 87          | 95          | 394            | 1410           |
|                 | 1986-1987         | 544         | 95          | +35                | 61          | 77          | 466            | 1492           |
|                 | 1987-1988         | 707         | 87          | -34                | 167         | 225         | 436            | 1570           |
| (2)             | 1997-1998         | 717         | 387         | 1                  | 118         | 345         | 640            | 1406           |

### Evaporation Pans

Evaporation pans are cheap and easy to use, and give reasonably good estimates of  $ET_c$  provided siting and management are correct. The most common type is the class A pan of the U.S. Weather Service. The standard installation and management are described in Doorenbos and Pruitt (1977). The evaporation of a reference crop ( $ET_r$ , mm) is obtained by multiplying the pan evaporation ( $E_{pan}$ , mm) by a pan coefficient ( $K_p$ ). The  $ET_r$  is the  $ET_p$  of an identifiable crop, such as alfalfa or grass, covering the whole ground surface and well-supplied with water. The  $ET_c$  for a particular crop can be calculated by multiplying  $ET_r$  by the corresponding crop coefficient  $K_c$ . This is the approach followed by Milella and Dettori (1987) and Dettori (1987) for olive. They determined the crop water requirements in a young orchard of 'Olia manna' olive plants in Sardinia, concluding that the optimum  $K_c$  was 0.5 from May to September, and 0.55 in April and October. They justified the use of greater  $K_c$ , of about 0.6, only in the case of the biggest fruits having a high commercial value. Evaporation pans have been used sometimes in a different way than that described by Doorenbos and Pruitt (1977). Michalakakis, Vouyoukalou and Clapaki (1996), for instance, estimated  $ET_c$  by multi-

FIGURE 11. Relationship between the evaporation from the soil surface of an olive orchard and the volumetric soil water content of the top 80 mm soil layer. The experiments were conducted in an olive orchard at *La Hampa* on typically hot, dry summer days (average  $ET_p = 8 \text{ mm d}^{-1}$ ). The orchard was planted with manure 'Manzanilla' olive trees at  $7 \times 7 \text{ m}^2$ . Data from two experiments were considered. In experiment 1, evaporation from the soil surface was empirically determined with microlysimeters. In experiment 2, data obtained during the hydraulic characterization of the orchard soil by Moreno et al. (1988) were taken into account (adapted from Palomo et al., 1998).



plying  $E_{pan}$  by a coefficient  $K_c$  that they called crop coefficient, which must not be confused with the standard definition of  $K_c$ . They established different irrigation regimes for 12-year-old 'Kalamon' olive trees in Crete by using different irrigation systems and water doses for keeping the soil water potential around the roots in the ranges from  $-0.02$  to  $-0.06 \text{ MPa}$  (treatment  $\psi_{0.2}$ ) and from  $-1.0$  to  $-1.5 \text{ MPa}$  (treatment  $\psi_{15}$ ). They found that  $K_c$  increased from May to September from 0.4 to 0.65 for the  $\psi_{0.2}$  treatment, that it was about 0.3-0.4 for the  $\psi_{15}$  treatment, and that it decreased from 0.2 to 0.05 for the non-irrigated treatment. Another example of a simplified use of the evaporation pan is that of Moreno et al. (1988) and Fernández (1989). They wanted the olive trees at *La Hampa* to use part of the available water in the soil. They calculated the irrigation doses from weekly  $E_{pan}$  measurements adjusted by a reduction coefficient of 0.4 and referred to the projected area of the canopy, which was  $12 \text{ m}^2$ . This way of using the evaporation pan is easier than the standard procedure, and it can be recommended if the applied reduction coefficient has been previously validated as appropriate for the purpose.

It is difficult, however, to extrapolate the same reduction coefficient to orchards with different crop characteristics and environmental conditions. A rough estimate of  $ET_p$  can be obtained by dividing  $E_{pan}$  by 1.24 (Beede and Goldhamer, 1994).

### Combination Methods

When climatic data recorded close to the orchard are available,  $ET_r$  can be calculated by combination methods. These are described elsewhere (Jensen, Burman and Allen, 1990; Burman and Pochop, 1994). They enable accurate estimates of  $ET_r$  provided the combination equation used has previously been validated as appropriate for the area. Any other combination equation can lead to significant errors in the estimation of  $ET_r$ . In *La Hampa*, for instance, we use the FAO-Penman equation, which Mantovani (1994) evaluated as the best for the area. The mean annual  $ET_r$  calculated by this equation for the period 1987-96 was 1499 mm. However, the value of  $ET_r$  calculated by the Kimberly Penman equation for the same period was only 1185 mm (79% of the FAO-Penman  $ET_r$ ). In the case of olive orchards,  $ET_c$  can be calculated by multiplying  $ET_r$  by a crop coefficient  $K_c$  accounting for crop differences between the olive and the reference crop, and by a reduction coefficient  $K_r$  accounting for the percentage of ground surface covered by the crop:

$$ET_c = K_r K_c ET_r. \quad (4)$$

One of the main disadvantages of this approach is that information on  $K_r$  and  $K_c$  is scarce. The value of  $K_r$  for the olive tree is unknown.  $K_r$  values obtained for fruit tree species living in similar conditions to those of the olive tree are used, such as the  $K_r$  values obtained by Fereres et al. (1981) for almond. Monthly values of  $K_c$  have been determined for the conditions of southern Spain (Table 3). Pastor and Orgaz (1994) determined  $K_c$  for the conditions of Córdoba, assuming negligible soil evaporation. Orgaz and Fereres (1997) took evaporation into account, which explains their higher  $K_c$  values. Fernández et al. (1998b) experimented in *La Hampa* with the  $K_c$  values given by Pastor and Orgaz (1994) for the irrigation season, from March to October. They reported that the values must be increased by 0.05 for getting good results. The olive orchard in which Fernández et al. (1998b) validated  $K_c$  was planted with mature trees covering 34% of the ground surface, irrigated daily by a drip line lateral placed on the soil surface in each tree row, with five  $3 \text{ L h}^{-1}$  drippers per tree 1 m apart. Using the increased  $K_c$  values, it was found that the soil matric potential in the wet bulb was greater than  $-0.02 \text{ MPa}$  throughout the irrigation season, and water losses by drainage were 13% of the total amount of water supplied by irrigation. Values of

TABLE 3. Crop coefficients ( $K_c$ ) obtained for olive orchards in south Spain.

| Month     | Pastor and Orgaz (1994) | Orgaz and Fereres (1997) |
|-----------|-------------------------|--------------------------|
| January   | 0.50                    | 0.65                     |
| February  | 0.50                    | 0.65                     |
| March     | 0.65                    | 0.65                     |
| April     | 0.60                    | 0.60                     |
| May       | 0.55                    | 0.55                     |
| June      | 0.50                    | 0.55                     |
| July      | 0.45                    | 0.50                     |
| August    | 0.45                    | 0.50                     |
| September | 0.55                    | 0.55                     |
| October   | 0.60                    | 0.60                     |
| November  | 0.65                    | 0.65                     |
| December  | 0.50                    | 0.65                     |

$K_c$  shown in Table 3, and those reported by Fernández et al. (1998b), are applicable to orchards of the same characteristics and conditions as those for which they have been validated. Apart from the lack of information on  $K_c$  and  $K_r$ , another disadvantage of the method is that no less than a week of weather records is needed for an accurate estimate of  $ET_r$ . Then, irrigation doses for the week are calculated based on the  $ET_r$  of the previous week. This lack of temporal accuracy can lead to either excess or lack of water in the soil, especially if the latter has a low water retention capacity.

This approach is, however, perhaps the most widely used nowadays in the olive orchards where irrigation is controlled. It was the one used by Pastor and Orgaz (1994) in a 'Picual' olive orchard in Córdoba, and by Fernández et al. (1997, 1998b) at *La Hampa*. Table 4 shows the average values of  $IR$  calculated by Fernández et al. (1998b) in *La Hampa* for an olive orchard of 286 mature trees  $\text{ha}^{-1}$ , with a maximum LAI of 1.7 and 34% of ground cover. Following the approach described here, the calculated  $IR$  for satisfying the crop water demand was about  $3,800 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ . Some authors claim that a localized irrigation system must wet a minimum of 25-30% of the corresponding ground surface of each tree. We believe, however, that the volume of soil affected by irrigation is more critical than the wetted ground surface. This is supported by the root signaling phenomena occurring in the olive tree, already described. With the irrigation system of Fernández et al. (1997, 1998b), consisting of five  $3 \text{ L h}^{-1}$  drippers per tree 1 m apart, the average ground surface wetted by the drippers was  $3.9 \text{ m}^2$  per tree, and the volume of wetted soil was 28% of the total soil volume corresponding to each tree.

TABLE 4. Daily potential evapotranspiration ( $ET_p$ ) and effective precipitation ( $P_e$ ) calculated for every week of the irrigation season of an olive orchard at the experimental farm *La Hampa*. Data are the average of a 25-year-data set measured from 1971 to 1995 at the weather station of the farm. Details of the values of the crop coefficient ( $K_c$ ) and the reduction coefficient ( $K_r$ ) are given in the text. These have been used for calculating the crop evapotranspiration ( $ET_c$ ) and the irrigation requirements ( $IR$ ), using Equations 3 and 4 mentioned in the text. Data are from a mature olive orchard with mature trees planted at  $7 \times 5 \text{ m}^2$ , covering 34% of the ground surface, and drip irrigated to satisfy the crop water demand (adapted from Fernández et al. 1998b).

| Month     | Week | $K_r$ | $K_c$ | $ET_p$<br>( $\text{mm d}^{-1}$ ) | $ET_c$<br>( $\text{mm d}^{-1}$ ) | $P_e$<br>( $\text{mm d}^{-1}$ ) | $IR$<br>( $\text{mm d}^{-1}$ ) |
|-----------|------|-------|-------|----------------------------------|----------------------------------|---------------------------------|--------------------------------|
| March     | 1    | 0.70  | 0.70  | 2.5                              | 1.22                             | 0.76                            | 0.46                           |
|           | 2    | "     | "     | 2.9                              | 1.42                             | 1.00                            | 0.42                           |
|           | 3    | "     | "     | 3.2                              | 1.57                             | 0.81                            | 0.76                           |
|           | 4    | "     | "     | 3.7                              | 1.81                             | 0.88                            | 0.93                           |
| April     | 1    | "     | 0.65  | 3.7                              | 1.68                             | 1.02                            | 0.66                           |
|           | 2    | "     | "     | 4.2                              | 1.91                             | 0.77                            | 1.14                           |
|           | 3    | "     | "     | 4.3                              | 1.96                             | 0.79                            | 1.17                           |
|           | 4    | "     | "     | 4.5                              | 2.05                             | 1.20                            | 0.85                           |
| May       | 1    | "     | 0.60  | 5.2                              | 2.18                             | 1.23                            | 0.95                           |
|           | 2    | "     | "     | 5.6                              | 2.35                             | 0.50                            | 1.85                           |
|           | 3    | "     | "     | 5.6                              | 2.35                             | 0.43                            | 1.92                           |
|           | 4    | "     | "     | 5.8                              | 2.44                             | 0.22                            | 2.22                           |
| June      | 1    | "     | 0.55  | 6.1                              | 2.35                             | 0.22                            | 2.13                           |
|           | 2    | "     | "     | 6.2                              | 2.39                             | 0.39                            | 2.00                           |
|           | 3    | "     | "     | 6.4                              | 2.46                             | 0.50                            | 1.96                           |
|           | 4    | "     | "     | 6.5                              | 2.50                             | 0.00                            | 2.50                           |
| July      | 1    | "     | 0.50  | 6.9                              | 2.42                             | 0.00                            | 2.42                           |
|           | 2    | "     | "     | 7.2                              | 2.52                             | 0.00                            | 2.52                           |
|           | 3    | "     | "     | 7.4                              | 2.59                             | 0.00                            | 2.59                           |
|           | 4    | "     | "     | 7.2                              | 2.52                             | 0.00                            | 2.52                           |
| August    | 1    | "     | 0.50  | 7.1                              | 2.49                             | 0.00                            | 2.49                           |
|           | 2    | "     | "     | 6.8                              | 2.38                             | 0.00                            | 2.38                           |
|           | 3    | "     | "     | 6.5                              | 2.27                             | 0.00                            | 2.27                           |
|           | 4    | "     | "     | 6.0                              | 2.10                             | 0.00                            | 2.10                           |
| September | 1    | "     | 0.60  | 5.6                              | 2.35                             | 0.00                            | 2.35                           |
|           | 2    | "     | "     | 5.1                              | 2.14                             | 0.00                            | 2.14                           |
|           | 3    | "     | "     | 4.6                              | 1.93                             | 0.00                            | 1.93                           |
|           | 4    | "     | "     | 4.0                              | 1.68                             | 0.53                            | 1.15                           |
| October   | 1    | "     | 0.65  | 3.6                              | 1.64                             | 0.78                            | 0.86                           |
|           | 2    | "     | "     | 2.7                              | 1.23                             | 1.76                            | —                              |
|           | 3    | "     | "     | 2.5                              | 1.14                             | 1.35                            | —                              |
|           | 4    | "     | "     | 2.2                              | 1.00                             | 0.85                            | —                              |

### *Eddy Covariance*

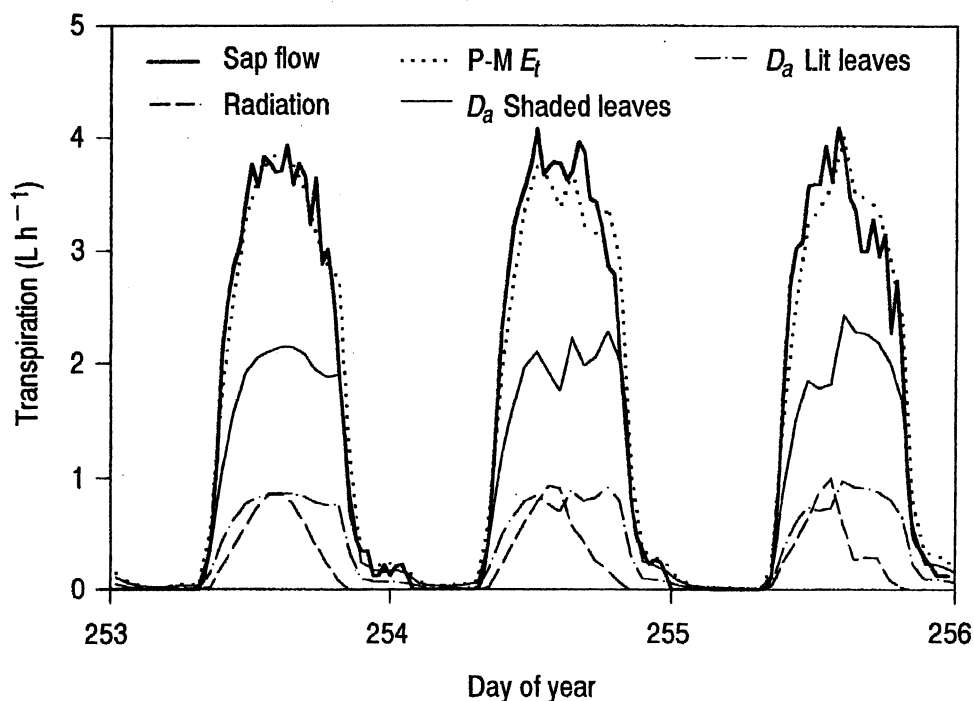
The technique of eddy covariance, also called eddy flux or eddy correlation, was first described by Swinbank (1951), though commercial instrumentation allowing the application of this method for calculating  $ET_c$  is only recently available. The technique is described in detail by Rosenberg, Blad and Verma (1983), among others. The method is based on continuous measurement of wind speed and air vapor pressure by complex instrumentation able to measure those variables in short periods of time. Evapotranspiration is calculated with a high temporal resolution, but the instrumentation is complex and requires well-trained people. In addition, the technique behaves well only in large, flat areas. The only work we know in which this technique has been used to estimate the olive  $ET_c$  is that of Villalobos et al. (1998). They used the technique in an olive orchard of LAI = 1.4 and 40% ground cover, measuring above the trees to estimate  $ET_c$ , and below the trees to estimate  $E_g$ . No details on the performance of the technique were given.

### *Sap Flow Measurements*

The short-term water-use dynamics of the olive tree can be evaluated from sap flow measurements in the trunk, branches, or roots. This sort of information is essential for a better control of the high frequency irrigation systems normally used in olive orchards. Detailed descriptions of the existing methods for estimating sap flow and their applicability to different species and purposes were given by Swanson (1994), Smith and Allen (1996) and Braun (1997). All these methods use heat as a tracer for sap movement. They can be grouped into heat-balance and heat-pulse methods. In the heat-balance methods, the conductive organ is heated electrically by an attached gauge, and the mass flow is calculated as a function of the heat taken up by the moving sap stream. In the heat-pulse methods, heater and temperature probes are located in the sapwood of the conductive organ, and the mass flow is calculated from the travelling speed of heat pulses sent every certain time by the heater probe. All methods measure transpiration fluxes in real time, enabling the highest time resolution in the determination of  $E_t$ .

Since 1994, we have been using at *La Hampa* the compensation heat-pulse (CHP) technique described by Green and Clothier (1988). The papers by Moreno et al. (1996) and Fernández et al. (1996) are the first published work we are aware of in which sap flows were measured in olive. They measured sap flow in main branches and roots of 25-year-old 'Manzanilla' olive trees under different water regimes. A good agreement was found between the transpiration determined by the CHP technique and that predicted by the Penman-Monteith equation (Figure 12). Major features of the hydraulic behavior of the olive tree during recovery from water stress were also identified from the sap flow data. For instance, an immediate water uptake by the roots

FIGURE 12. The calculated and predicted transpiration from one of the two main branches of a 25-year-old 'Manzanilla' olive tree in *La Hampa*. Transpiration was calculated from sap flow measurements made by the compensation heat-pulse technique. The Penman-Monteith expression was used for estimating transpiration. The tree was pond-irrigated once a week. The last irrigation before the measurements was on day of the year 252. Shown here are the terms of the Penman-Monteith expression; namely the radiation term, the vapor pressure deficit driven term associated with the lit leaves, and this term for the shaded leaves (adapted from Moreno et al., 1996).



once water was finally available in the soil was observed, though recovery was not completed due to the presence of air emboli in xylem vessels of the sapwood's outer annuli. We have calibrated the CHP technique for olive to obtain accurate estimates of the volume of sap flow from the measured sap velocities. Preliminary results on calibration were published by Fernández et al. (1997), and a more detailed paper is in preparation. Daily values of  $E_t$  for two 28-year-old 'Manzanilla' olive trees, one irrigated and the other without irrigation, were determined in *La Hampa* by Díaz-Espejo et al. (1998). They found clear differences in water consumption between treatments. In addition, they monitored  $\Psi_l$ ,  $g$  and  $A$  in the same trees in which sap flows were measured, to study the relations between those measurements at leaf level and the amount of water consumed by the tree. Fernández et al. (1998b) and Palomo et al. (1998a,b) evaluated the applicability of the CHP technique for estimating  $ET_c$  in an olive orchard. As mentioned before, they obtained an empirical equation for estimating  $E_s$  in the olive orchard of *La Hampa* (Figure 11). Fernández et al. (1998a) reviewed the performance of the CHP

technique, outlining its advantages and limitations. They concluded that the CHP technique is reliable and of low maintenance, suitable for use in commercial olive orchards for long periods of time. It provides information on the dynamics of both water uptake by roots (Figure 3) and tree transpiration (Figure 13), and is useful for determining the effect of meteorological conditions and soil water status on both processes. The capability of the technique for estimating  $E_t$  is limited, however, by the considerable heterogeneity of the conductive area in mature olive trees, which may cause a high variability in the sap flow measurements, depending on probe location. We are currently using the CHP technique in further analysis of the hydraulic behavior of the olive tree to obtain information for the diagnosis of the onset or severity of tree water stress. The main hydraulic features we are using for that purpose are the delay in water uptake by roots observed early in the morning in stressed trees (root S versus root N in Figure 3), and the occurrence of cavitation in the xylem vessels of the sapwood's external annuli (Figure 14). Apart from our work with the CHP technique, the only published work we have found related to the measurement of sap flows in olive is that of Dichio et al. (1998). They used a heat-balance method to determine  $E_t$  in 2-year-old 'Coratina' olive plants grown in containers, and compared the results with the data obtained by weighting. They reported a good agreement between the two ways of estimating  $E_t$ , with maximum differences of  $\pm 8\%$ .

FIGURE 13. Daily transpiration fluxes determined from the sap flow measured with the compensation heat-pulse technique in the trunk of a 29-year-old 'Manzanilla' olive tree at *La Hampa*, and vapor pressure deficit of the air measured on the same days (adapted from Fernández et al. 1998a).

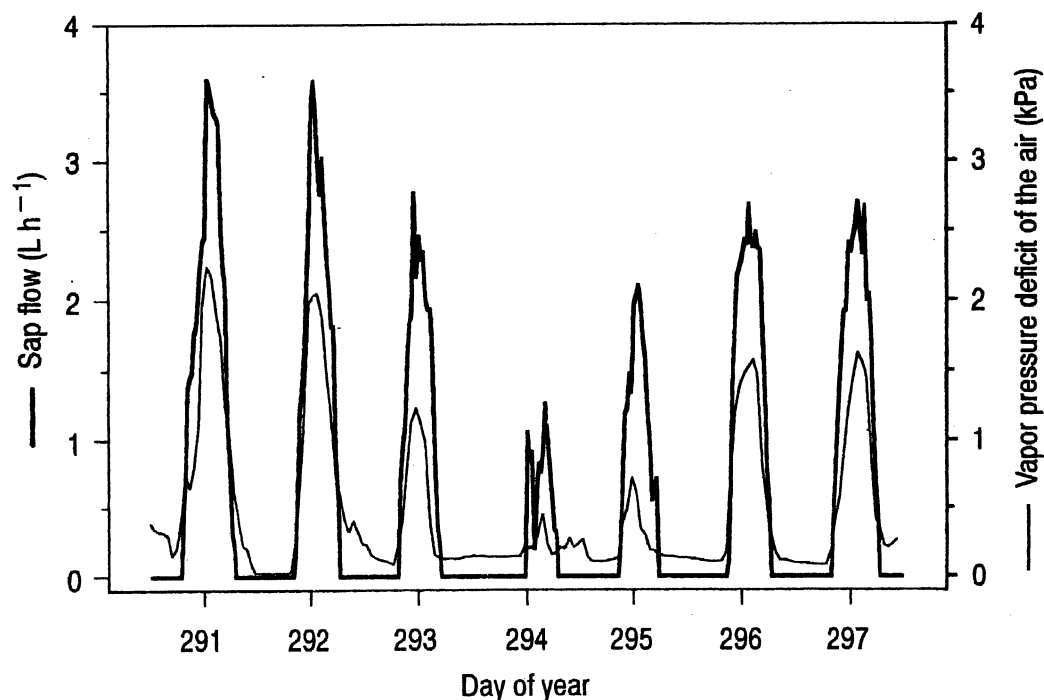
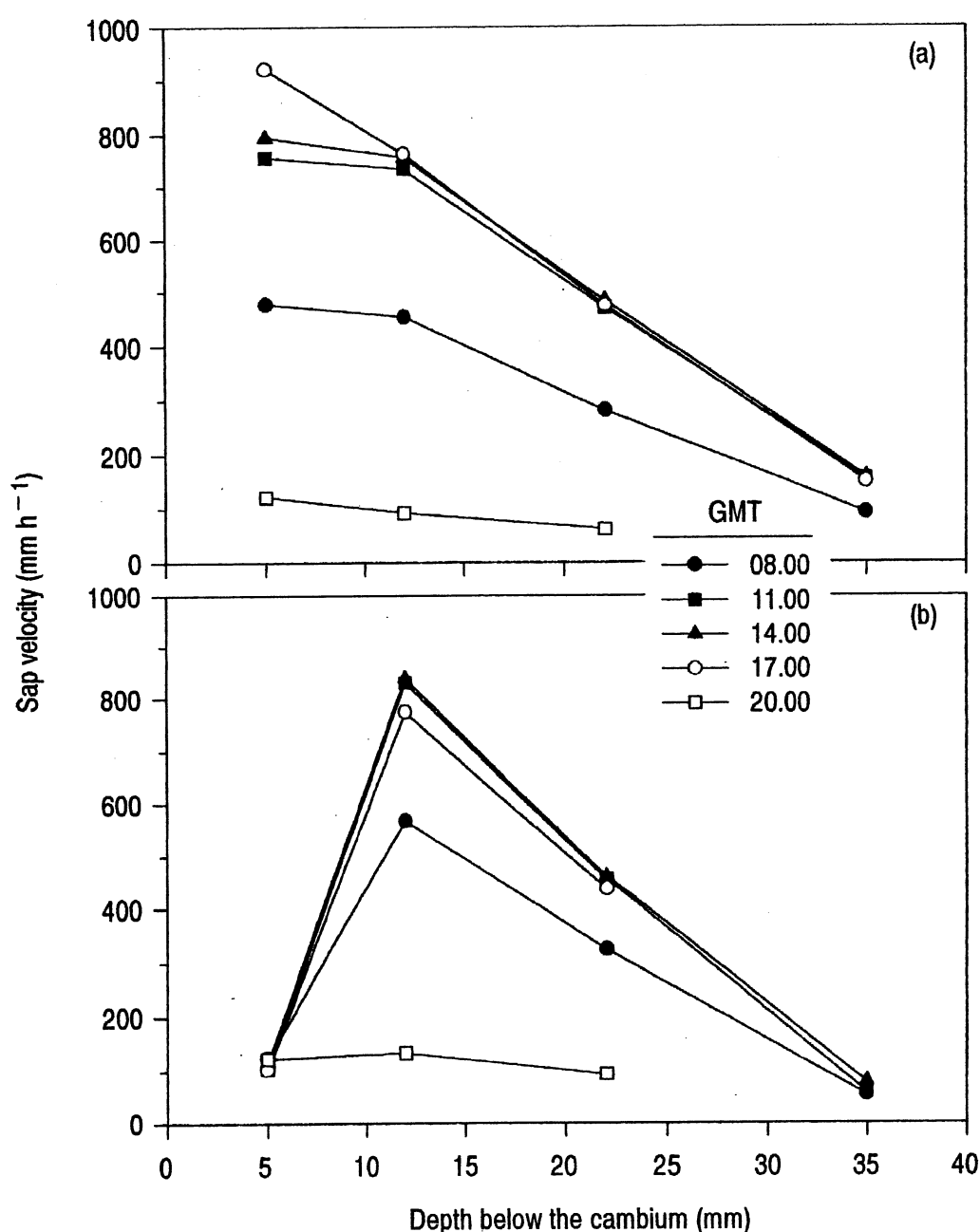




FIGURE 14. The diurnal rise and fall in the radial pattern of sap velocity by the compensation heat-pulse technique in the trunk of (a) a well-watered 29-year-old 'Manzanilla' olive tree at *La Hampa* on 6 August 1997. The FAO-Penman calculation of water use for a well-watered short crop for this day was 6.1 mm. The tree received daily irrigation, and the surface soil water content (0-1 m) around the tree was on average  $0.27 \text{ cm}^3 \text{ cm}^{-3}$ ; and (b) a water-stressed olive tree of the same orchard, on 15 August 1997, in which the FAO-Penman evaporation was 7.7 mm. The surface soil water content (0-1 m) was below  $0.14 \text{ cm}^3 \text{ cm}^{-3}$ . This lower value of water use on a day of higher FAO-Penman evaporation indicates the severity of the water stress.



### Modeling

Very few modeling exercises for assessing water consumption by the olive tree have been published. This may be due to the difficulty in accurately estimating LAI, one of the variables to which the models are more sensitive. Bongi and Palliotti (1994) mentioned the CRIS model for estimating the irrigation requirements of olive orchards. They reported an estimated annual consumption of 603 mm. They outlined the low  $ET_c$  estimated for olive, as compared with that estimated by the model for peach ( $1088 \text{ mm yr}^{-1}$ ) and *Citrus* ( $904 \text{ mm yr}^{-1}$ ). Moreno et al. (1996) calculated, from sap flow measurements, the amount of water transpired by the leaves of one of the two main branches of a 25-year-old 'Manzanilla' olive tree at *La Hampa*, and compared the results with the transpiration estimated by the Penman-Monteith equation. The values of leaf stomatal conductance and leaf-canopy boundary-layer conductance given to the model were determined from measurements in the orchard. The authors found a good agreement between the calculated and the simulated transpiration amounts (Figure 12). They used the model to estimate separately the three terms of the Penman-Monteith expression, namely the radiation term, the vapor pressure deficit driven term associated with the lit leaves, and this term for the shaded leaves. Recently, Villalobos et al. (1998) fitted an empirical model to estimate canopy conductance in two irrigated olive orchards in Córdoba, southern Spain. They were able to estimate  $ET_c$  in the orchards by combining the model with that of Ritchie (1972) for estimating  $E_s$ . They estimated average annual values of  $ET_c$ ,  $E_s$  and  $E_t$  of 812, 291 and 521 mm, respectively, for an intensive orchard with LAI 1.4 and ground cover 40%. For a less intensive orchard with the same LAI and ground cover of 30%, the estimated values were 748 mm for  $ET_c$ , 293 mm for  $E_s$  and 454 mm for  $E_t$ .

### IRRIGATION STRATEGIES WHEN WATER IS SCARCE

The amount of water supplied by deficit irrigation (DI) is lower than the crop requirements for an optimum development. Despite not allowing maximum crop performance to be achieved, deficit-irrigation strategies are interesting for olive, since water is scarce in many areas where the species is cultivated. Of the different DI modalities described in the literature, one of the most widely used is controlled deficit irrigation (CDI), or regulated deficit irrigation (RDI), in which the water supply is reduced or even interrupted except for the stages in which the crop is most sensitive to water stress. There are references in the literature to supplementary (Abdel-Rahman and El-Sharkawi, 1974) and complementary (Lavee et al., 1990) irrigation, in which water is supplied by irrigation a limited number of times throughout the crop

season. An extreme case of this sort of DI is that reported by Pastor and Orgaz (1994) for an orchard with deep soils of high retention capacity, in which water was applied just once in winter, when water for irrigation was available. In a recent paper, Goldhamer (1997) studied the influence of RDI on the performance of mature 'Manzanilla' olive trees. He had a control treatment with 900 mm and three RDI treatments, with reductions of 12.9, 20.8 and 39.5% from the control. Fruit size was smaller in the most-severe RDI treatment than in the control. No significant differences were found in flesh oil content on a fresh or dry weight basis in the fruits harvested in January for oil. The author concludes that RDI saving about 20% (185 mm) of  $ET_c$  may be enough to maintain top yields and quality. Michelakis (1990) and d'Andria et al. (1998) observed no differences in crop production between trees irrigated with enough water for replacing control  $ET_c$  and those with doses 30 to 50% lower. The effect of DI on the leaf water status and gas exchange of mature 'Manzanilla' olive trees was studied in *La Hampa* by Fernández et al. (1997). They had a control treatment with no irrigation and two irrigation treatments, one with weekly irrigation to replace  $ET_c$  for maximum production (I treatment) and the other with 1/3 of this (I/3 treatment). Values of  $\Psi_l$  and  $g$  of the I/3 trees were quite close to those measured in the I trees, the differences with the control trees being much greater. The success of DI in the olive seems to be based, therefore, on the marked crop response to reduced water supplies. A correct DI strategy requires knowing the biological stages in which the olive is most sensitive to water stress. For 'Manzanilla', complementary irrigations must be applied just before flowering, at pit hardening, and a fortnight before harvesting. Alegre and Girona (1997), however, reported that fruits affected by water stress during pit hardening recovered with later water supplies. The recommended DI strategy may be different for table and oil cultivars. Alegre and Girona (1997) cited a paper by Romero et al. (1997) in which it was reported that oil quality was better in 'Arbequina' olive trees irrigated with DI than in those irrigated with enough water to meet the crop water requirements.

As mentioned before, we have used in some olive orchards at *La Hampa* a deficit irrigation designed for the trees to use part of the water stored in the soil at the end of the rainy season (Moreno et al., 1988; Fernández 1989). The use of this approach in an olive orchard has been reported by Pastor and Orgaz (1994), among others. It allows a certain depletion of soil moisture in the root zone, normally established as a percentage of the available water in the soil calculated as the difference between the water in the soil at field capacity and that at wilting point. The value of such percentage can be calculated by balancing the reduction of marketable product with the increased cost of a more generous irrigation. A difficulty in establishing the allowed depletion amount is the determination of what is the soil water

content for wilting point in the olive tree. We have already mentioned that it can be significantly lower than for other fruit trees growing in Mediterranean areas. The available water in the olive orchards of *La Hampa* is about  $3,000 \text{ m}^3 \text{ ha}^{-1}$ . An allowable water depletion of 25%, recommended by Pastor and Orgaz (1994), means  $750 \text{ m}^3 \text{ ha}^{-1}$ . The average  $ET_c$  for maximum crop performance in the area is about  $3,800 \text{ m}^3 \text{ ha}^{-1}$  (Table 4). Therefore, with this DI approach, about 20% of irrigation water can be saved.

### **IRRIGATING WITH LOW QUALITY WATER**

The lack of water in the areas where the olive is grown and the increase in recent years of the area under cultivation enhance the use of low quality waters for irrigating olive orchards. This is favored by the moderate-to-high tolerance of the olive tree to the presence of salts in the soil (Troncoso et al., 1983; Tattini et al., 1995). Even municipal wastewater (Saavedra, Troncoso and Arambarri, 1984) and dilute sea-water (El-Gazzar, El-Azab and Sheata, 1979; Bongi and Loreto, 1989) have been considered for irrigating the olive tree. The effects of salinity on olive performance have been reported by many authors. It is not our aim to detail them here; they have been summarized by Fernández (1997) and Gucci and Tattini (1997). Regarding water for irrigation, reduction in crop performance has been reported when water with electrical conductivity (EC) greater than  $5.5 \text{ dS m}^{-1}$  was used (Freeman, Uriu and Hartmann, 1994). The limit of salt content in irrigation water for the olive tree has been established as  $8 \text{ g L}^{-1}$  of solid residue (Zarrouk and Cherif, 1981). The sodium adsorption ratio (SAR) should not exceed 9 for maximum production (Freeman, Uriu and Hartmann, 1994). Mature olive trees tolerate higher SAR than young trees. Al-Saket and Aesheh (1987) reported young olive trees as tolerating an SAR of 18 in the growing medium. Loreti and Natali (1981) reported mature trees as tolerating irrigation with SAR less than 26. Leaching requirements for avoiding salt accumulation in the soil depend on the salt concentration in the irrigation water, on the rainfall regime and on the irrigation system. For water containing 0.014, 0.028 and  $0.069 \text{ mol L}^{-1}$  salt, leaching requirements have been calculated as 15, 30 and 70% of volume applied, respectively (Ayers and Westcot, 1985; FAO, 1993). These percentages may be lower if high-frequency irrigation is used, and in areas where rainfall in the wet season is enough for washing out the salts accumulated during the irrigation season.

The use of municipal wastewater for irrigating the olive tree is an interesting option. The volume of municipal wastewater treated as a result of regulations continues to increase, making enough available for the irrigation of many hectares. The olive seems to behave well when irrigated with municipal wastewater. Saavedra, Troncoso and Arambarri (1984) grew 1-year-old

'Manzanilla' plants in pots, irrigating them for eight months with untreated wastewater. No toxicity symptoms or any other anomaly was observed. For health reasons, however, municipal wastewater must be treated before it can be used for irrigation. Different countries have different quality standards for wastewater used for irrigation, which have to be taken into account.

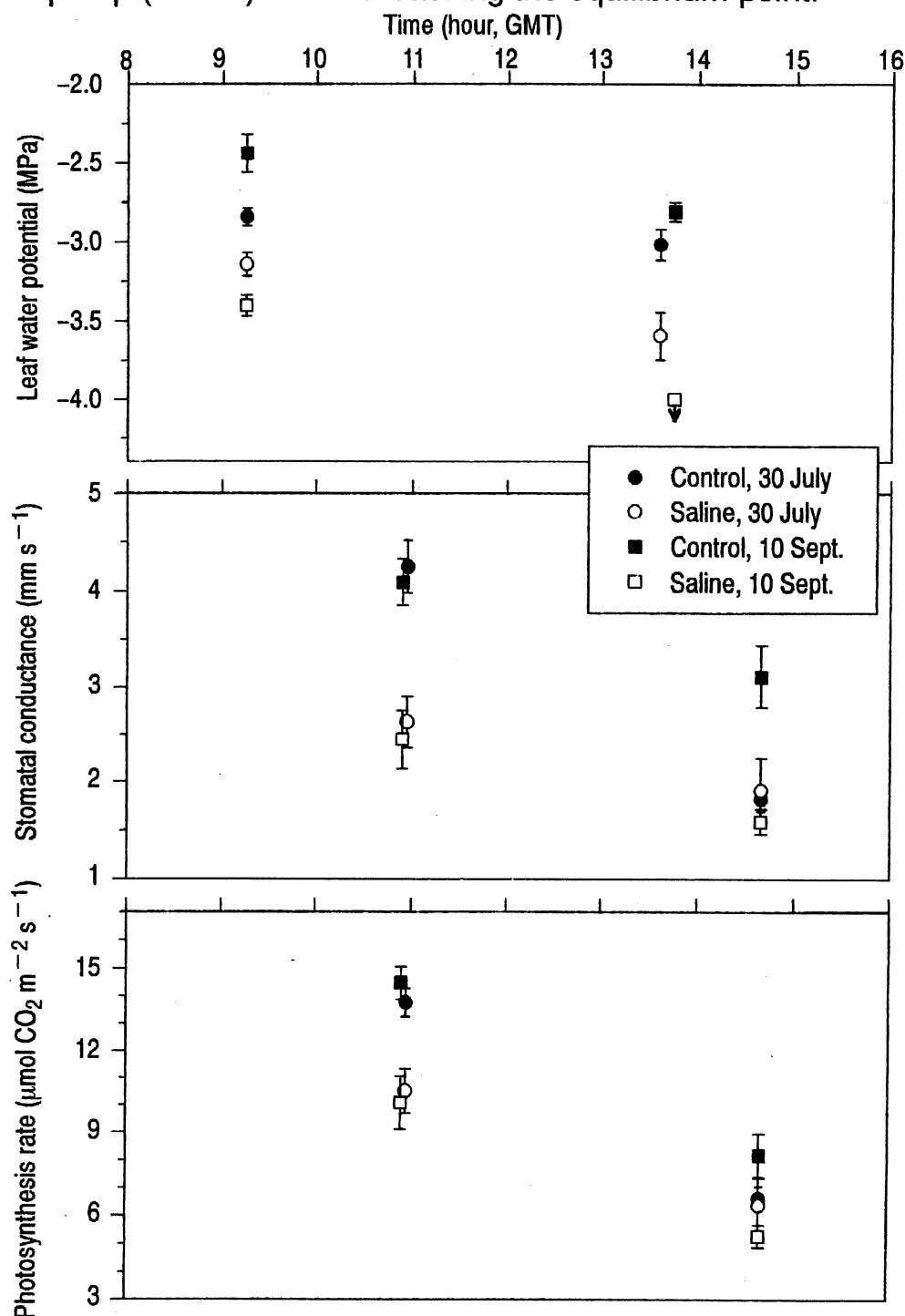
A significant amount of wastewater is produced every year by the olive industry, from both olive mills and factories processing olives for table consumption. Part of this water is used for irrigating olive orchards. Most of the existing literature refers to the use of olive mill wastewater (OMW). Generally, OMW contains 83-94% of water, 4-16% of organic matter, and 0.4-2.5% of mineral salts (Ramos-Cormenzana, 1986), though the chemical composition varies with the oil extraction procedure, the cultivar, and the degree of ripeness, among other factors. OMW has a high potential for causing pollution, but up to  $800 \text{ m}^3 \text{ ha}^{-1}$  can be used for direct irrigation of soil (Fiestas Ros de Ursinos, 1986; García-Ortíz et al., 1993). The current production of OMW in Mediterranean countries is estimated to be around  $10\text{-}12 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ , though this amount has tended to decrease with new extraction methods (Cabrera et al., 1996). The high content in organic matter may be a problem when using certain irrigation systems. However, OMW can even be used for drip irrigation if it is taken from the ponds where it is usually stored, diluted with fresh water, and minimum precautions are taken to prevent dripper blockage.

We have not found any published work on irrigation of olive orchards with table olive industry wastewater (TOW). We are currently involved in a research project designed to evaluate the use of TOW for irrigating olive orchards. Some preliminary results on the effects on leaf water relations and photosynthesis of mature olive trees irrigated with TOW are shown in Figure 15. An immediate decrease in the values of  $\Psi_l$ ,  $g$  and  $A$  was observed in the trees irrigated with TOW as compared with those irrigated with fresh water. A reduction in yield of about 30% was also recorded. EC values of the TOW used were between 4 and  $6 \text{ dS m}^{-1}$ , which is about the limit for a reduction in olive performance, and the sodium adsorption ratio was between 70 and 80, very much over the permitted limit. We observed a high temporal variability in the TOW composition, even when the water came from the same factory, which is not uncommon (Kopsidas, 1994). Though we analyzed TOW regularly, such variability could cause peak values of EC and SAR—or any other water characteristic affecting the results—to be undetected.

### MANAGING IRRIGATED ORCHARDS

It is clear that irrigation is a required practice in intensive orchards where maximum productivity is the aim. The positive effects of irrigation are not

FIGURE 15. Leaf water potential, stomatal conductance, and photosynthesis rate measured in July and September in leaves of 20-year-old 'Manzanilla' olive trees near Morón de la Frontera (Seville, Spain). The trees were drip irrigated, some of them with good quality water and some with waste water from the table olive industry with electrical conductivity values from 4 to 6 dS m<sup>-1</sup> and sodium adsorption ratio between 70 and 80. The irrigation season lasted from the beginning of July to mid-September. Two measurement sets per day were taken on July 30 and September 10, one in the morning and the other in the afternoon. Each point represents the mean of 10 values per treatment. Vertical bars indicate twice the standard error. The arrow in the more negative value of leaf water potential means that we reached the maximum pressure in our pressure pump (4 MPa) without reaching the equilibrium point.



going to be fully achieved, however, if fertilization, pruning, or any other agricultural practice in the orchard is carried out incorrectly. Recommended practices for a correct design and management of intensive olive orchards are summarized below.

The cultivar must be well adapted to the environmental conditions in the orchard and must produce high quality products, either fruit for table consumption or oil. Plants of about 1 year old from self-rooted cuttings raised in mist houses are recommendable for propagation. More than one cultivar with concurrent anthesis must be planted in the orchard for increasing yield by cross-pollination. Plant density must range from 250 to 400 trees ha<sup>-1</sup>, depending on vigor and plant formation. Current experiments with higher plant densities are giving good results in the first years of the orchard life, but they have not been long enough for definitive conclusions. Tree rows must follow the east-west direction. Trees must have a single trunk with main branches at a minimum height of 0.8-1 m above the ground surface, to allow for machine-harvesting. Canopy shape must favor leaf illumination. Reduced tillage is recommendable, especially for orchards in sloping areas. This not only reduces erosion, but also, combined with a correct weed management by the use of herbicides, reduces runoff and increases water stored in the soil. Pruning must be done every year, when growth has ceased. The height of the trees must be controlled by pruning, especially for the table cultivars, which cannot be machine-harvested. Mechanical pruning is an option. The orchard must be fertirrigated. A high-frequency localized irrigation system is recommendable, perhaps with one pipe per row of trees and 4-6 emitters per tree. Drippers are preferred to microjets in most cases. If enough water is available for irrigation, the volume of soil wetted by the irrigation system must be as great as possible, to avoid restrictions in crop performance due to root signaling. Fertilizers can be added to the irrigation water once or twice per week throughout the irrigation season. Programmable devices can be used for controlling fertirrigation. The nutrient status of the trees can be monitored by leaf analysis every 1-2 years in mid-summer. Soil analysis is advisable only at the beginning of planting, except in cases of difficult soils. Pest control must be carried out always under technical advice. The use of models for the evaluation of pest populations and disease conditions is helpful. The incidence of diseases associated with a high plant density (*Cycloconium oleaginum*) or with high soil water content (*Verticillium dahliae*) must be especially considered.

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