Irrigation Scheduling and Evaluation of Tree Water Status in Deciduous Orchards

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I. INTRODUCTION

Irrigation is a major horticultural activity and is the most intensively practiced operation throughout the season. Its importance depends on the climate, and increases with progress from temperate to drier and to arid zones. Dryland orchards can survive and be productive in temperate zones without irrigation, whereas the survival of deciduous orchards in semi-arid zones depends on the availability of water for irrigation throughout most of the growing season. The performance of deciduous trees, i.e., crop yield, fruit size, fruit quality, storability, and long-term productivity are highly dependent on irrigation, and different species respond differently to irrigation. Worldwide, the amount of fresh water available for agricultural use is decreasing and, since shortages of fresh water are to be expected, there is a need to increase water use efficiency, either by improving genetic performance and horticultural practices, or by improving irrigation scheduling.

The level of irrigation of deciduous orchards depends on environmental factors that drive evaporative demand and transpiration, salinity, and electrolyte composition in the soil solution, the resistance of the soil to root penetration and moisture transport, soil aeration, tree hydraulic architecture, and crop load. Irrigation interacts indirectly with the susceptibility of deciduous orchards to diseases and pests, and through the effects of soil moisture on pests. The above-mentioned interactions are beyond the scope of the present review.

Irrigation affects the performance of deciduous trees through two major mechanisms: its effects on stomatal conductance and assimilation
rate; and its effects on turgor and expansive growth. This emphasizes the important role of tree-water relations in irrigation, and the reader may refer to a few reviews on that topic (Landsberg and Jones 1982; Jones et al. 1985; Flore and Lakso 1989; Lakso 2003).

Whereas earlier reviews covered older studies (Behboudian and Mills 1997; Fereres and Goldhamer 1990), the present review will focus mainly on recent publications. It is divided into two major topics: (1) The effects of deficit irrigation at different phenological stages on productivity and fruit quality and (2) factors affecting irrigation level, water stress assessment, and timing of irrigation.

II. THE MODERN IRRIGATION SCHEDULING CONCEPT

Minimum water stress may be the optimal tree water status in certain phenological stages, where a certain degree of stress would be optimal in other phenological stages. Irrigation is applied mainly to maintain optimal availability of assimilates, which is achieved through the control of stomatal aperture, and maintenance of an adequate turgor potential when expansive growth of either the canopy and/or the fruit is expected. The irrigation level used is intended to return to the soil profile the amount of water transpired by the tree and the cover crop (T) in addition to the amount evaporated from the soil surface (E). The sum of these components is called evapotranspiration (ET). Transpiration is a two-step process that starts with conversion of the water from the liquid to the gas phase, a process that requires a significant amount of energy (2.54 MJ kg\(^{-1}\) at 20°C). After the water is vaporized in the stomatal cavities, it diffuses into the free air at a rate controlled by vapor pressure deficit—the difference between saturated vapor pressure at the leaf temperature and the actual vapor pressure at the atmospheric temperature—which is determined by air and leaf temperatures and air humidity. The resistance to this transport process is the sum (in series) of stomatal resistance and the boundary layer resistance, the latter being determined by wind speed, leaf size and shape, and canopy structure. Day-to-day variations in ET are expected because of the significant role of changing weather conditions in transpiration.

The modern irrigation-scheduling concept (Allen et al. 1999) assumes:

1. ET of non-stressed crops, reference crop and evaporation from a free-water surface respond similarly to atmospheric evaporative demand.
2. ET increases linearly with intercepted radiation by the crop.
3. Further differences in ET between crops are due to differences in canopy conductance and canopy roughness.

Based on these assumptions, the ET of a specific crop under maximum moisture availability (ETₐ) is defined as ET₀·Kₖ, where ET₀ is the evapotranspiration of a reference crop that covers the whole surface area, and which can be replaced by the evaporation from a free water surface in a standard pan, and Kₖ (crop coefficient) is a proportion factor that depends on the fraction of the soil surface covered by the crop, the canopy conductance, and the canopy roughness. There are many models of calculating ET₀, from empirical to more mechanistic ones where the effect of wind speed on ET is based on empirical relationships. Pan evaporation rates are highly correlated with ET₀, but the slopes of these relationships are not unique and may change between types of evaporation pans and between operational standards. Detailed analysis of the methods of calculating ET₀, their correlation with data collected in lysimeters, and the relationships between ET₀ and pan evaporation rates can be found elsewhere (Jensen et al. 1990). Canopy conductance of deciduous trees during the dormant season is zero and they are not irrigated in spite the fact that the soil evaporation term of ETₐ is not zero. Kₖ of deciduous trees increases with increasing foliage coverage, and varies according to seasonal changes in canopy conductance that result from changes in tree-water relations and according to crop level (as will be discussed in detail below). Sets of seasonal crop coefficients are available for various crops; they are based on lysimeter or soil water balance measurements (Allen et al. 1999). Irrigation for maximum biomass production requires no stress, while in other crops, including trees, stress may not affect economic yields. In many cases, tree water status attains its optimal value from the horticultural point of view under a certain stress, and ETₐ must be multiplied by a stress factor (Kₛ), which is expected to change in the course of the season in accordance with the optimal tree water status. The actual irrigation level assuming no water depletion below the root zone (I) is the product of ET₀, Kₖ and Kₛ: I = ET₀·Kₖ·Kₛ. In cases where there is a risk of high salinity build up during the growing season, a leaching fraction is added. Two major aspects will be covered in the following: the response of deciduous trees to irrigation at different phenological stages, and issues related to timing of irrigation in relation to the degree of water stress. Also addressed will be the proper representation of water status in commercial orchards.
III. DEFICIT IRRIGATION

Growers have practiced deficit irrigation for decades. In the past, deficit irrigation was restricted to the postharvest period based on the belief that water stress introduces no problems during phenological stages when no fruit exist on the tree and additional vegetative growth is undesirable; an exception is early cultivars in which the desired shoot growth is not completed by harvest. The effect of severe postharvest water stress on the productivity of stone fruits was studied mainly in early-maturing species such as apricot. Deficit irrigation at phenological stages other than postharvest was proposed in the early 1980s (Chalmers et al. 1981, 1986) as a beneficial irrigation strategy, and since then has been studied extensively.

Several different processes are sensitive to water stress, and the times of occurrence of those processes may influence the sensitivity to deficit irrigation:

1. Reproductive cell division—lasts 30–40 days post anthesis.
2. Fruit drop—occurs usually during the first 40 days post anthesis.
3. Canopy growth—occurs mainly at the beginning of the season, but may continue longer if sufficient moisture is available and the crop load is low.
4. Flower bud differentiation and development—starts in midsummer and continues throughout the rest of the growing season.

The above-mentioned processes are expected to respond differently to moisture availability. Therefore, the effects of deficit irrigation at each phenological stage will be discussed separately. In the cited reports, different water stress indicators were used, the intensity and duration of deficit irrigation varied, and several different cultivars were studied. These differences among others may result sometimes in inconsistent and contradictory findings. Therefore, the interpretation of the results is not always straightforward and the discussion on the effects of water stress, in most cases, is restricted to general terms such as low, moderate, and severe water stress.

The post reproductive-cell division fruit growth stage in stone fruits can be divided into two parts, the pit-hardening stage and the final fruit growth stage, where in pip fruits there is practically a single post reproductive-cell division stage. Therefore, the post reproductive-cell division stage of stone fruits and pip fruits will be discussed separately.
A. Reproductive Cell Division Stage

Reproductive cell division lasts 30–40 days after full bloom (Westwood 1993) and is accompanied by initial fruit growth. Water stress in the reproductive cell division stage did not affect the number of cells in the fruits (Marsal et al. 2000) but at harvest the cells in the fruits of the stressed trees were smaller, which indicates that water stress during the reproductive cell division stage affects the potential cell size. The proportion of fruit drop in apple increased in response to early water stress (Powell 1974; A. Naor, unpubl.).


Early water stress led to smaller apple (Failla et al. 1992) and pear (Marsal et al. 2000, 2002a; Naor et al. 2000) fruits; fruit size decreased with decreasing midday stem water potential during the reproductive cell division stage (Marsal et al. 2000, 2002a), and the smaller fruit size persisted until harvest in apple and pear (Marsal et al. 2000; Naor et al. 2000). Early water stress decreased the fruit sizes attained in peach by the end of the reproductive cell division stage (Fig. 3.1) and at harvest (Girona et al. 2002, 2004; Goldhamer et al. 2002). Deficit irrigation during both the reproductive cell division and the pit hardening stages in apricot decreased fruit size at the end of the pit hardening stage, but a significant fruit size recovery was apparent after the water stress was relieved during the final fruit growth stage (Ruiz-Sanchez et al. 2000a; Torrecillas et al. 2000). However, the statistical analysis of final fruit size in these studies is insufficient to conclude that the decrease in fruit size in response to early stages water stress is fully reversible.

Contradicting results of increasing final fruit size in response to early water stress was reported for high-density pear (Mitchell et al. 1984; Chalmers et al. 1986), and it could be related to the higher midday leaf water potential in the pre-stressed treatment than in the control after resumption of irrigation (Chalmers et al. 1986). It seems that larger canopies in the control of high-density pear orchard, because of a significant increase in vegetative growth (Mitchell et al. 1984, 1986, 1989; Chalmers et al. 1986), may have increased water consumption and therefore decreased water potential. It may well be that in high-density orchards, the vegetative part invokes a significant competition for assim-
Fig. 3.1. Effects of withholding irrigation (WI) in the reproductive cell division (Stage I), pit hardening (Stage II), and final fruit growth (Stage III) stages on peach fruit fresh weight relative to unstressed trees (control). Fruit weights of the control were 41.2, 68.5, and 215 g at the end of stages I, II, and III, respectively (Source: Girona et al. 2002).

ilates, explaining the contradicting results of increased fruit size in early-stressed trees in high-density trees.

A multiseason test of the effects of early water stress resulted in increased numbers of pears per tree (Mitchell et al. 1989), similar to the effect of moderate postharvest water stress (Fig. 3.2). This may indicate that moderate water stress improves the completion of flower bud development, resulting in higher flower intensity and fruit set in subsequent seasons.

B. Pit Hardening Stage (Stone Fruits)

The duration of the pit hardening stage changes with harvest date: the later the harvest the longer the duration of this stage (Westwood 1993). In early-maturing cultivars, the fruits continue to grow during the pit hardening stage, but slightly more slowly, making it hard to distinguish among the different fruit growth stages. The extent of fruit growth in the pit hardening stage decreases with increasing its duration. In practice,
Figure 3.2. Effects of postharvest irrigation levels in 2001 and 2002 on next-season pear crop yield (cumulative for 2002 and 2003). Midday stem water potentials were -2.8 MPa, -2.4 MPa, and -1.5 MPa in the Low, Med. and High irrigation levels, respectively (A. Naor et al. unpubl.).

the duration of the pit hardening stage in early-maturing cultivars is too short for deficit irrigation to be considered.

Water stress during the pit hardening stage reduced fruit size at the end of the stage in peach (Girona et al. 2002) and nectarine (A. Naor, unpubl.), and water stress during both reproductive cell division and pit hardening stages also caused reductions in fruit size by the end of the latter stage in peach (Mitchell and Chalmers 1982) and apricot (Ruiz-Sanchez et al. 2000a; Torrecillas et al. 2000). In the above studies, fruit size recovered when irrigation was applied at a minimal-stressing level in the final fruit growth stage. An increase in fruit size in response to water stress in the pit hardening stage was reported in the third year, in a high-density peach orchard (Chalmers et al. 1981); this contradictory response could be a result of higher competition of the dense-shaded canopy for assimilates in minimum-stressed trees compared with stressed trees at that particular high-density orchard. Water stress dur-
ing the pit hardening stage in peach led to a lower percentage of large fruits (Goldhamer et al. 2002), in a study in which there was a 10-mm increase in fruit diameter during the stress period, which could have increased the sensitivity to water stress at this stage. If the designated end of the pit hardening stage in that study had been too late, that could also account for the smaller fruit size. Fruit expansive growth is affected by water stress, and the relative insensitivity of fruit size to water stress in the pit hardening stage is related to the limited fruit expansive growth that is usually apparent in this stage. The start of the pit hardening stage is easy to determine, whereas the end of this stage is not clear and in most cases it can be determined only post factum, on the basis of continuous measurements of fruit weight in the course of the season. In addition, the duration of the pit hardening stage and the date of its end change markedly from one season to another (Girona et al. 2003; A. Naor, unpubl.), therefore the use of a predetermined duration of deficit irrigation during this stage might be risky.

In shallow soils both the build-up and the relief of water stress are rapid (Goldhamer et al. 2002), but in a deep heavy soil profile the relief of water stress at the end of pit hardening may take a few weeks, unless a significant extra amount of irrigation water is provided, to fill the soil profile (Naor, unpubl.); this may reduce the amount of annual applied water that can be saved through deficit irrigation at that stage. Shoot growth in grown apricot is almost completed by the end of the reproductive cell division stage (Torrecillas et al. 2000), therefore using deficit irrigation in the pit hardening stage is not beneficial for vegetative control. In peach, on the other hand, active shoot growth continues into the pit hardening stage (Fig. 3.3), therefore water stress in that stage might be beneficial for canopy size control. Improved color in peach that resulted from deficit irrigation in the pit hardening stage was attributed to reduced shoot growth and an improved light regime around the fruit (Gelly et al. 2003, 2004).

C. Final Fruit Growth Stage (Stone Fruits)

Fruit growth in the final fruit growth stage is highly responsive to irrigation, as a significant proportion of dry and fresh weight is accumulated in the fruit (Pavel and DeJong 1993; Grossman and DeJong 1995a,b; Girona et al. 2004). Water stress in the final fruit growth stage significantly decreased the final fruit size in peach (Besset et al. 2001; Girona et al. 2002), nectarine (Naor et al. 1999, 2001), apricot (Torrecillas et al. 2000), and Japanese plum (Naor et al. 2004). Under water stress, reductions in average fruit weight and yield were found to increase with increasing numbers of fruits per tree in both nectarine (Naor et al. 1999, 2001) and apricot (Torrecillas et al. 2000).
2001) and Japanese plum (Naor et al. 2004). Under minimum water stress conditions, the nectarine fruit size distribution was shifted towards smaller fruits as the number of fruit per tree increased (Naor et al. 1999), indicating the magnitude of crop the canopy can support is limited and the crop level should not exceed this limit if large fruits are to be achieved. In Japanese plum under minimum stress conditions (Naor et al. 2004), the fruit size distribution was unaffected by the number of fruit per tree, probably because of lower crop yield, which did not introduce significant limitation of assimilates.

D. Preharvest Deficit Irrigation in Almonds

Preharvest deficit irrigation is a common practice in almond, for technical reasons: to reduce damage to the trunk caused by the shaker, and to simplify collection of the fruit. Withholding irrigation prior to harvest slightly decreased the shaker damage to the trunk (Gurusinghe and Shackel 1995; Goldhamer and Viveros 2000) but, on the other hand, severe water stress increased the proportion of the fruits that remained on the tree, delayed the opening of the hull, and increased the proportion of unopened hulls at harvest (Goldhamer et al. 2004).
Water stress in the final fruit growth stage of almond decreased (Goldhamer and Viveros 2000; Goldhamer et al. 2004; Romero et al. 2004) or did not affect kernel weight (Esparza et al. 2001a; Girona et al. 2005). The kernel size in almond decreased by <20% (Goldhamer and Viveros 2000; Goldhamer et al. 2004) in response to preharvest water stress, compared with reductions of up to 40% in fruit sizes (in peach, nectarine, plum, and apricot) (Naor et al. 1999, 2001, 2004; Besset et al. 2001). Most of the reduction in almond fruit size was restricted to the hull shell (Goldhamer et al. 2004), which is of no economic value.

Preharvest water stress in almond slightly increased the number of fruit per tree in subsequent years (Goldhamer and Viveros 2000; Goldhamer et al. 2004); the increase was probably caused by an increased proportion of not fully developed flower buds in well irrigated trees (Forshey and Elfving 1989), similar to the case of pear (Mitchell et al. 1989; Fig. 3.2). The longer the duration of withholding irrigation prior to harvest (or the higher the degree of water stress) the lower the fruit set in the following season, provided postharvest water stress was applied (Goldhamer and Viveros 2000). This may indicate that the functioning of the flowers was damaged, which could also be related to a decrease in non-structural carbohydrate accumulation caused by water stress (Esparza et al. 2001b).

Productivity of almond is highly correlated with canopy size in both young (Castel and Fereres 1982; Torrecillas et al. 1989; Girona et al. 1993a; Hutmacher et al. 1994) and grown trees (Esparza et al. 2001a; Romero et al. 2004). Productivity of almond is dependent on shoot growth, since some of the fruits are carried on 1-year-old shoots, and because of the high mortality rate of spurs (60% in three years), irrespective of irrigation level (Esparza et al. 2001a). Preharvest water stress in almond did not affect subsequent season productivity (Goldhamer and Viveros 2000), since most of the shoot growth occurs in earlier stages in the course of the season. On the other hand, preharvest water stress caused the productivity of a young orchard to decrease from year 4 to 7 (Fereres et al. 1981; Girona et al. 2005), because productivity is more dependent on canopy growth in young, not fully developed orchards.

E. Post Reproductive Cell Division Stage (Pip Fruits)

The fruit growth patterns of apple (Lakso et al. 1995) and pear (Naor et al. 2000) are expolinear—exponential increase during reproductive cell division stage followed by a linear growth pattern thereafter. In many studies the post-cell-division stage, which extends up to harvest, was arbitrarily divided into two sub-stages (early deficit and late deficit), so
only general information was obtained about the sensitivity to water stress in the course of that stage.

Moderate water stress up to 102 days after full bloom reduced canopy growth in apple (Behboudian et al. 1998), whereas water stress applied after this period had no effect. This indicates that shoot growth ends within 3 months after bloom (Irving and Drost 1987; Forshey and Elfving 1989). An early deficit created moderate water stress and resulted in a lower return bloom, whereas no reduction in return bloom was apparent in a late-deficit treatment (Kilili et al. 1996a; Behboudian et al. 1998). In another study, deficit irrigation throughout the season did not affect return bloom (Mills et al. 1994), but, in that particular case, water stress did not develop up to 100 days after bloom. Non-stress conditions decreased subsequent season productivity in pear (Mitchell et al. 1989; Fig. 3.2) and stone fruits (Larson et al. 1988; Johnson et al. 1992), probably by delaying flower bud development. Reductions in return bloom and productivity under severe water stress were found in pear (A. Naor et al. unpubl.) and apple (Ebel 1991), as well as in stone fruits (Brown 1953; Uriu 1964; Johnson et al. 1994; Ruiz-Sanchez et al. 1999; Goldhamer and Viveros 2000; Torrecillas et al. 2000; Girona et al. 2003; Naor et al. 2005); the above-mentioned apple studies that showed lower return bloom did not involve such a high level of water stress (Kilili et al. 1996a; Behboudian et al. 1998). The reduction in the proportion of return bloom in apple trees moderately stressed early in the season can be explained as follows: A vegetative bud (bourse shoot) emerges from apple flower buds, and the longer the bourse shoot the higher the probability for its terminal bud to flower the following year (Lauri et al. 1996; Lauri and Trottier 2004). There is a possibility that water stress in the early-deficit treatments reduced the length of the bourse shoots, which resulted in a lower proportion of return bloom, whereas the bourse shoots had already reached their final size by the time the late-deficit treatments were started.

Early water deficit (for about 2 months post reproductive cell division) reduced apple fruit size (Kilili et al. 1996a; Mpelasoka et al. 2000, 2001a), similar to the effect when late deficit was imposed on pear (Ramos et al. 1994; Naor et al. 1999; Marsal et al. 2000) or apple (Failla et al. 1992; Naor et al. 1995, 1997a, b; Mpelasoka et al. 2000, 2001a; Ebel et al. 2001). In a few studies, post-cell-division water deficit did not reduce fruit size (Behboudian et al. 1998; Mpelasoka et al. 2001a). Caspari et al. (1994) found that the average fruit weight of Asian pear at harvest was unaffected by either early or late water deficit, whereas fruit growth (measured on selected fruit) under the late-deficit treatment was smaller.
The effect of late deficit on fruit size interacted with the number of fruit per tree with both apple (Naor et al. 1997a) and pear (Naor et al. 2000), as well as with stone fruits (Naor et al. 1999, 2001, 2004): the more fruit per tree, the greater the water-stress-induced reduction in fruit size (Fig. 3.4), but when there were few fruits per tree their size was unaffected by water stress. It may suggest that the reduction in assimilation rate in response to tree water stress does not invoke limitation of assimilates at low crop yields.

### F. Flower Bud Differentiation and Development Stage

In many cases the initial stages of bud development are noted before harvest (Tufts and Morrow 1925; Westwood 1993), and the development continues throughout the rest of the season. Water stress is known to affect flower bud development, but past research on this topic was restricted to the postharvest period because of the high sensitivity of expansive fruit growth to preharvest water stress. Application of preharvest water stress is now considered normal for almond and processing prunes, therefore study of the effect of water stress on bud development in deciduous trees is no longer restricted to the postharvest stage.

![Diagram](image-url)  
**Fig. 3.4.** Effect of the number of fruits per tree on apple crop yield >70 mm at five irrigation levels prior to harvest (Naor et al. 1997a).
The occurrence of twin fruits in peach and nectarine is related to postharvest water stress (Larson et al. 1988; Johnson et al. 1992; Handley and Johnson 2000; Naor et al. 2005). Both twin fruits and those with deep sutures result from postharvest water stress (Handley and Johnson 2000; Naor et al. 2005). The percentage of twins in nectarine increased with decreasing average midday stem water potential in August (Fig. 3.5), and a lower limit of -2.0 MPa can be set for postharvest irrigation scheduling, as lower values cause a significant increase in fruit twinning. In nectarine, more twin fruit were formed in response to severe postharvest water stress that occurred before Sept. 1, than to that which occurred later (Naor et al. 2005), and this is consistent with the finding of a significant decrease in the occurrence of twin fruits in peach when postharvest water stress was relieved at the end of August (Handley and Johnson 2000).

Severe postharvest water stress at 25°C did not cause fruit twinning in cherry (Beppu and Kataoka 1999), which suggests the responses of cherry

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**Fig. 3.5.** The relationship between average midday stem water potential in August and next-season occurrence of double fruits (30 days after full bloom) in Snow Queen nectarine (Naor et al. 2005).
and peach to postharvest water stress are different; the difference could be related to cherry fruit carried on spurs and nectarines on one-year-old shoots, which may alter the timing and dynamics of flower bud development. This hypothesis might be supported by the fact that no twins were reported to result from severe postharvest water stress in spur-type Japanese plum cultivars (Johnson et al. 1994; Naor et al. 2004). The percentage of twin fruit in cherry increased with increasing temperature above 30°C (Beppu and Kataoka 1999; Beppu et al. 2001) in a controlled environment, and it decreased in field-grown trees under shade netting that reduced the air temperature (Beppu and Kataoka 2000). These findings are in agreement with those for peach (Johnson et al. 1992; Naor et al. in press), in which the percentages of twin fruit were much higher when high postharvest temperatures were apparent in a former season. Both temperature (Beppu and Kataoka 1999; Beppu et al. 2001; Johnson et al. 1992; Naor et al. in press) and postharvest water stress (Larson et al. 1988; Johnson et al. 1992; Handley and Johnson 2000; Naor et al. in press) are responsible for the occurrence of double fruits. It seems that flower buds exposed to high temperature during the bud development stage acquire the potential to form twin fruits, but that the proportion of buds that realized this potential was strongly affected by postharvest water stress. Beppu et al. (2001) suggested the sensitivity to double pistil formation occurs during the transition from sepal to petal differentiation.

Severe postharvest water stress decreased the productivity in the subsequent year, in apricot (Brown 1953; Uriu 1964; Ruiz-Sanchez et al. 1999; Torrecillas et al. 2000), peach (Girona et al. 2003; Naor et al. 2005), Japanese plum (Johnson et al. 1994), almond (Goldhamer and Viveros 2000), and pear (Fig. 3.2), and contrary findings of increased productivity in the season following postharvest water stress (Larson et al. 1988; Johnson et al. 1992) were related to a lower level of stress and to pre-winter irrigation that had shortened the duration of the postharvest water stress. A moderate level of postharvest water stress resulted in the highest pear crop yield in the following season (Fig. 3.2) due to increased number of fruits per tree, which appears to indicate that minimal water stress conditions slow flower bud development so that some of the buds are not fully matured in time for the subsequent season bud break.

The decrease in productivity caused by severe postharvest water stress was due to reduced flowering intensity (Brown 1953; Girona et al. 2003) and lower fruit set (Ruiz-Sanchez et al. 1999; Goldhamer and Viveros 2000; Torrecillas et al. 2000; Girona et al. 2003). The lower fruit set in apricot was attributed to reduced pollen vitality (Ruiz-Sanchez et al. 1999). Severe postharvest water stress delayed flower bud development (Brown 1953; Naor et al. 2005), and the resulting buds had smaller
leaves surrounding the fruit, and smaller stones, and their harvest was delayed (Brown 1953).

Sporadic flowering of terminal buds occurs in pear after harvest. A significant autumn flowering (including spurs) occurred in pears as a consequence of severe postharvest water stress that was relieved at the beginning of October (60 mm irrigation in 6 days) (A. Naor et al. unpubl.); unstressed and moderately stressed trees had higher midday stem water potentials and they did not flower in response to 60 mm of irrigation at the beginning of October (Fig. 3.6). This raises the possibility that severely stressed pears may respond to heavy autumn rains by massive flowering.

G. Deficit Irrigation and Fruit Quality in Deciduous Fruit Trees

In general, deficit irrigation advances maturity, increases total soluble solids content and firmness, improves red color, and decreases the background color. It also affects volatile aroma compounds.

Many past studies found higher firmness as a result of deficit irrigation. However, it was argued (Behboudian and Mills 1997) that the

![Figure 3.6](image.png)

**Fig. 3.6.** Effect of midday stem water potential at the end of September (prior to the application of 60 mm of irrigation in ten days) on the cumulative number of Spadona pear flowers counted up to mid-November (A. Naor et al. unpubl.).
increased fruit firmness in stressed trees could be an artifact because fruit size decreases as a direct result of deficit irrigation, and the firmness of apples increases with decreasing fruit weight (Ebel et al. 1993). In different studies, post-cell-division water stress increased (Mpelasoka et al. 2000, 2001a,b), did not affect (Ebel et al. 1993; Behboudian et al. 1998), or decreased (Mills et al. 1994) apple firmness at harvest. Pear firmness was unaffected by tree water status (Ramos et al. 1994), and deficit irrigation did not affect fruit firmness in peach (Gelly et al. 2003). In another apple study, fruit firmness increased by the end of the early-deficit treatment, but the differences had disappeared by harvest time (Kilili et al. 1996a). The dynamics of fruit firmness in cold storage were examined in two studies in apple (Kilili et al. 1996b; Mpelasoka et al. 2001a). The differences in firmness between fruits from different water-stress treatments remained the same during 12 weeks (Kilili et al. 1996b) and 10 weeks (Mpelasoka et al. 2001a) in cold storage; they diminished after 10 weeks and reached similar levels by 17 weeks (Mpelasoka et al. 2001a). During a shelf life study (Mpelasoka et al. 2001a), the higher firmness imparted by a deficit irrigation treatment was retained for 6 days, after which the differences diminished and disappeared. Data collected in the past decade suggest firmness increases in response to post-cell-division water stress, but that the increase is often temporary.

Many studies found that deficit irrigation increased ethylene concentrations in apple, at harvest or during storage (Ebel et al. 1993; Kilili et al. 1996b; Behboudian et al. 1998; Mpelasoka et al. 2000, 2001a, 2002); a similar response was reported for peach (Gelly et al. 2003, 2004); deficit irrigation increased also the proportion of mature fruits in Asian pear (Caspari et al. 1996) and apple (Mpelasoka et al. 2002) at harvest. Background color is an indicator of maturity in apple and it was reported to either decrease (Kilili et al. 1996a,b) or to remain unchanged (Mpelasoka et al. 2001b) in response to deficit irrigation. These findings indicate deficit irrigation advances maturity in most cases.

Studies on the effect of deficit irrigation on aroma volatiles yielded inconsistent results (Behboudian et al. 1998; Mpelasoka et al. 2002) probably because of the dramatic rise of those compounds at a certain point, together with the fact that there is not a distinct definition of maturation and the advancement of maturity in response to deficit irrigation. Water deficit was reported to increase emissions of volatile compounds from other tree organs in apple (Ebel et al. 1995), therefore, in spite of the inconsistent findings, a direct effect of deficit irrigation on volatile compounds in the fruit cannot be ruled out.

Deficit irrigation increased total soluble solids in apple at harvest (Ebel et al. 1993; Behboudian et al. 1994, 1998; Mills et al. 1994; Kilili
et al. 1996a,b; Mpelasoka and Behboudian 2000, 2001a,b, 2002), and the differences were retained during storage (Ebel et al. 1993; Kilili et al. 1996b; Behboudian et al. 1998; Mpelasoka et al. 2000, 2001a, 2002). Deficit irrigation increased total soluble solids at harvest in peach (Crisosto et al. 1994; Gelly et al. 2003) but not in apricot (Torrecillas et al. 2000) or Asian pear (Behboudian et al. 1998). The increased total soluble solids content was accompanied by an increased percentage of dry matter (Mills et al. 1994; Kilili et al. 1996a; Mpelasoka et al. 2001a), suggesting part of the increase in soluble solids was due to water losses from the fruit. However, deficit irrigation elicited specific metabolic effects that were manifested in changed proportions of specific sugars—increased fructose (Mpelasoka et al. 2000) or sorbitol content (Mills et al. 1994)—under deficit irrigation compared with unstressed treatments.

Deficit irrigation increased the color intensity in apricot (Torrecillas et al. 2000) and peach (Gelly et al. 2003, 2004), but different researchers found it increased the red color (Mills et al. 1994; Kilili et al. 1996a,b) or did not affect it in apple (Mpelasoka et al. 2001) and European pear (Caspari et al. 1996). Enhancement of the red color could be an indirect effect of deficit irrigation, via a reduction in vegetative growth, which affects light regime within the canopy.

Irrigation of previously water-stressed prune has been found to induce fruit-end cracking (Uriu et al. 1962); the formation of cracks was accompanied by increased osmotic potential gradients along the fruit in re-watered trees (Milad and Shackel 1992), which probably was accompanied by a gradient in turgor potential.

H. Partial Root Drying

The use of both high and low soil moisture regimes within the root zone of a single tree was proposed to manipulate tree water relations and tree performance (Loveys et al. 2000). This technique was tested in both winegrapes and deciduous fruit trees.

1. Physiological Basis. It is now well established that the control of the stomatal opening under light saturation conditions is influenced by root water status (e.g., Gollan et al. 1986; Davis and Zhang 1991) through root signals, and that ABA seems to be involved in this process. Stomatal conductance was found to respond both to root signals and to leaf water potential, and the responsiveness of stomatal conductance to ABA decreased with decreasing leaf water potential (Tardieu and Davies 1993; Tardieu et al. 1993). Root signals also decreased shoot growth in apple under non-stressed conditions (Gowing et al. 1990).
In light of the above-mentioned responses, the possible use of partial root drying was examined. Stomatal conductance of container-grown wine-grapes decreased in response to withholding of irrigation in half of the root zone, but after 8 days it started to recover (Loveys et al. 2000; Stoll et al. 2000). Shoot growth of container-grown wine-grapes was reduced under partial root zone drying (Loveys et al. 2000). In a partial root zone drying experiment with container-grown apple (Gowing et al. 1990), shoot growth recovered in response to both re-watering and to elimination of the dried part of the root zone.

Partial root zone drying has the potential to manipulate tree-water relations so as to combine high turgor with low stomatal conductance and low shoot growth. However, the ability of partial root zone drying to manipulate fruit growth was not examined in details.

2. Field Examination. Partial root zone drying did not affect stomatal conductance in pear (O’Connell and Goodwin, 2004) and apple (Caspari et al. 2004a; Einhorn and Caspari, 2004). Similar crop yields and fruit sizes were measured in apple both under regular deficit irrigation and with partial root zone drying at the same irrigation levels (Caspari et al. 2004b; Einhorn and Caspari 2004; Leib et al. in press), but in one study there were larger fruit in the partial root zone drying treatment in one of two seasons (Caspari et al. 2004). Similar crop yields, fruit sizes, and fruit color were obtained in peach under both regular deficit irrigation and partial root zone drying at the same irrigation levels (Goldhamer et al. 2002).

In summary, the physiological responses to partial root drying were obtained in container-grown wine-grapes (Stoll et al. 2000) and apple (Gowing et al. 1990) and in semi-controlled conditions in wine-grapes (Loveys et al. 2000). However, no responses were obtained to partial root zone drying under commercial-scale conditions. It seems as if the size of the root zone in commercial plots and the non-uniformity of moisture content created different dynamics of root water status development in the drying side compare to the experiments that were performed in containers; this was probably responsible for the failure to reproduce the effects found in a controlled root zone under commercial field scale conditions.

IV. WATER STRESS ASSESSMENT AND TIMING OF IRRIGATION

Commercial orchards consist of numerous combinations of many factors that may require adjustment of the published $K_c$ and $K_s$ values to suit the actual conditions. These factors include rootstock, training system,
row spacing, cultivar, the number of fruit per tree, crop load (the ability of the canopy to support the crop), and potential fruit size. In addition, the irrigation level is calculated on the assumption that application efficiency is 1, which is not the case in commercial orchards: it may vary with the combination of soil depth and soil hydraulic properties, irrigation equipment and spacing of emitters, irrigation level, and irrigation intervals, and therefore may require site-specific corrections. There are also some concerns about the assumption that fruit trees and the reference crop respond similarly to evaporative demand under all weather conditions (Johnson et al. 2004). The above-mentioned limitations leave growers with uncertainty about optimal day-to-day decisions on irrigation scheduling. Those uncertainties and ways to minimize them are discussed below.

A. Factors Affecting Transpiration and Irrigation Level

Irrigation level is affected by the amount of intercepted radiation by the canopy and the presence of crop, which directly affect tree transpiration rate. The demand for assimilates increases with increasing the expected crop yield and it may affect irrigation level as well. Potential fruit size may affect the optimal tree water status needed to achieve the target fruit size and therefore it affects irrigation level. These aspects and the attention that should be paid to application efficiency of the irrigation water will be discussed in the following.

1. Intercepted Radiation and Canopy Size. The transpiration rate is proportional to leaf area (Angelocci and Valancogne 1993) and it dictates the amount of light intercepted by the canopy (Johnson et al. 2000; Ayars et al. 2003) to supply latent heat flux that drives the evaporation of water from the canopy (Green et al. 2003). Canopy size and light interception varied with the training system in apple (Robinson and Lakso 1991; Wunsche et al. 1995) and peach (Giuliani et al. 1998), and with cultivars in apple (Robinson and Lakso 1991). These findings suggest that the effects of canopy size on transpiration and, therefore, on irrigation level should be evaluated for each specific plot. Light interception can be measured quite accurately, but most procedures are not suitable for use by growers (Pearcy 1989; Wunsche et al. 1995; Welles and Cohen 1996). High correlations were found between percentage shade at midday (whose measurement requires a simple procedure that growers could perform) and $K_c$ for young almonds (Fig. 33-4 in Fereres and Goldhamer 1990) and peach (Ayars et al. 2003; Goodwin and Connor, in press). However, there is no unique relationship between midday light
interception and daily light interception that is valid for every combi-
nation of training system and row orientation (Palmer 1993). There is a
need for modeling the relationships between midday and daily light
interception for combinations of training systems, rootstocks, cultivars
and row orientation; and such a model might reduce the uncertainty in
evaluating the effect of canopy size on the crop coefficient in each par-
ticular plot. Tree size is correlated with trunk cross-section area and light
interception in the first years, before significant pruning is performed,
and growers can then utilize this measurement to adjust $K_c$ for orchards
of different ages. However, care should be taken as the slope of this rela-
tionship may vary with rootstock and training system and cultivars.

2. Crop Yield. Two aspects of the effect of crop yield on irrigation level
should be considered: the direct effect of cropping on stomatal conduc-
tance and hence on transpiration and water consumption; and the
increasing demand for assimilates as crop yield increases.

Direct Effect of Cropping on Transpiration. Leaf photosynthesis and
stomatal conductance of deciduous trees have been found to increase
with the presence of a crop (Hansen 1971; Fuji and Kennedy 1985;
Dejong 1986; Erf and Proctor 1989; Gucci et al. 1991, 1994; Wibbe and
Blanke 1995; Giuliani et al. 1997; Wunsche et al. 2000; Marsal et al.
2005), although in a few cases no effect (Palmer 1986, 1992; McFayden
et al. 1996) or the opposite effect (Fuji and Kennedy 1985; Schechter
et al. 1991; Mpelasoka et al. 2001b) was apparent. The effect of cropping
on assimilation rate was found to change in the course of the season (Fuji
and Kennedy 1985; Palmer 1992; Wibbe et al. 1993; Gucci et al. 1994;
Giuliani et al. 1997; Wunsche and Palmer 1997; Wunsche et al. 2000),
with the maximum effect occurring at midsummer and diminishing
after harvest. In general, the contradictory results have been attributed
to changing responses in the course of the season, changes in the
response after fruit thinning (Gucci et al. 1991), differing morning and
afternoon responses (Gucci et al. 1991), or the existence of sinks other
than fruit. Cropping in plum increased leaf water use efficiency (Gucci
et al. 1991), but did not affect it in apple (Wunsche et al. 2000).

Assimilation rate increases with increasing crop load and it starts to
level off at daily demand of $\sim 15$ mg carbon per leaf in peach (Ben
Mimoun et al. 1996) or up to about 15 fruits per square meter of leaf area
in apple (Palmer et al. 1997). In the latter case, the crop load was equiv-
alent to $\sim 30$ ton/ha, whereas the whole-tree assimilation rate has been
found to respond to crop loads as high as 45 ton/ha (Wunsche et al.
2000). In another study (Giuliani et al. 1997), all crop loads were in
the range in which leaf assimilation rate does not respond any more to crop load.

Studies with containerized (Lenz 1986) and lysimeter trees (Buwalda and Lenz 1992; Buwalda and Lenz 1995; Mpelasoka et al. 2001), and with whole-tree gas-exchange systems (Wibbe et al. 1993; Wunsche et al. 2000) demonstrated that cropping trees use more water. A 36% increase in transpiration in high crop loaded relative to defruited field grown apple trees in whole-tree gas-exchange system (Wunsche et al. 2000) is the closest available estimate to commercial field conditions. Cropping also decreased water potential (Erf and Proctor 1989; Berman and Dejong 1996; Naor et al. 1997b, 2001, 2004; Mpelasoka et al. 2001b), and thus indirectly supports increased transpiration in cropping trees. The data collected in the past two decades generally show a direct effect of increased transpiration caused by cropping, and irrigation levels should be adjusted to account for this effect.

*Annual Irrigation Level Adjustment According to Crop Yield Estimates.* The higher the yield the higher the demand for assimilates, and, since the assimilation rate is affected by water stress and therefore by the irrigation rate, there is a need for a quantitative evaluation of the effect of crop yield on irrigation level. Naschitz and Naor (2005) proposed an operative model that may enable the adjustment of the annual irrigation level according to crop yield predictions, and the evaluation of relative water use efficiency on the orchard scale.

Fruit diameter increases with increasing specific reproductive water use, i.e.,

\[
\frac{\text{annual irrigation rate} - \text{annual vegetative water use}}{\text{total crop yield}}
\]

until it reaches a maximum (Fig. 3.7) and the maximum fruit diameter changes from year to year because of changes in the potential fruit size. The "vegetative water use" is estimated by extrapolating the model to zero fruit diameter. The cost in terms of water use for the production of 1 tonne (fresh weight) of apple fruits would be approximately 47 m$^3$ (Naschitz and Naor 2005), which might differ between climatic regions because of the effect of humidity on the water use efficiency (Jones 1992) and the effect of air temperature on respiration. Consistent application of specific reproductive use levels either higher or lower than 47 m$^3$ t$^{-1}$ for a few years would result in the adjustment of the tree structure (increase or decrease) so as to change vegetative water use until the
actual specific reproductive use approaches 47 m\(^3\) t\(^{-1}\) in a new steady-state condition. The cost in terms of water use for the production of 1 t (fresh weight) should be determined for each species on a regional basis, as it is affected by climatic conditions, and the resulting value could then serve for planning irrigation levels once good estimates of crop yield are available. Water use efficiency on an orchard scale could be evaluated once a regional response curve (as in Fig. 3.7) was constructed. Commercial plots whose data lie on the model curve (Fig. 3.7) are considered efficient plots, whereas if the data of a specific plot lie below the model line it indicates that the specific plot is inefficient.

3. Potential Fruit Size. The number of cells in the flesh determines the potential fruit size, and the fulfillment of that potential is dependent on irrigation and the crop load, and different potential fruit sizes may require different irrigation levels to reach the target fruit size (Fig. 3.7). Therefore, early predictions of potential fruit size are essential to enable growers to optimize fruit size by either fruit thinning or irrigation.

![Fig. 3.7. The effects of irrigation rate per tonne of fresh weight (in addition to a constant irrigation level for the maintenance of the canopy structure and foliage) on 'Golden Delicious' apple fruit diameter in 1995 (n = 79) and in 1996 (n = 92) (Source: Naschitz and Naor 2005).](image)
The reproductive cell division lasts up to 40 days post bloom (Westwood 1993). Temperatures lower than 25°C during the reproductive cell division phase reduced apple fruit size (Tromp 1997; Warrington et al. 1999), but, on the other hand, the number of cells in apples decreased when the trees were grown at 35/15°C (day/night) rather than 25/15°C (M. Flaishman and A. Naor, unpubl.). It suggests that there is an optimum temperature for reproductive cell division, and limitations in potential fruit size are expected in both cold and hot climates. The previous-year crop yield (Bergh 1985) affects the initial cell number in the pedicle of the apple at bloom time: the greater the previous yield, the smaller the number of cells in the receptacle in the current year. The current-year crop level affects the number of cells, and the timing of fruit thinning affects the number of cells and the potential fruit size in apple (Quinlan and Preston 1968; Goffinet et al. 1995). Thus, potential fruit size is expected to vary from year to year according to the temperature regime during the reproductive cell division phase, the previous- and current-year crop levels, and the timing of fruit thinning.

Models based on the effect of temperature on reproductive cell division were proposed as a tool for predicting final fruit size in apple (Austin et al. 1999; Stanley et al. 2000, 2001); such models might enable the grower to adjust his irrigation level and thinning strategy early in the season. Other models, which assume a given seasonal pattern of fruit growth (Assaf et al. 1982; Lakso et al. 1995) can also be utilized for that purpose, but the first relevant predictions can be expected only two or three weeks into the main fruit growth phase.

4. Application Efficiency. Application efficiency is the fraction of the irrigation water that remains in the main root zone and is available for the plant use, and is rarely close to 1. Its accurate evaluation requires intensive measurement of the soil moisture distribution in the soil profile, and the less uniform the soil, the greater the number of measurements required for proper assessment. Spatial variability of soil depth and of soil hydraulic properties may cause non-uniform application efficiency, with the lowest value expected at the shallowest levels. Maximum application efficiency can be attained through appropriate choices of emitter density and of recharge and irrigation intervals. Further increases in application efficiency can be achieved by combining blocks of uniform soil depth and soil hydraulic properties for a given irrigation operation. The irrigation should be increased by the proportion of inefficiency, but under commercial field conditions there is always uncertainty about the actual value of application efficiency.
B. The Grower's Dilemma

In commercial orchards, there is a wide diversity of combinations of cultivars, rootstocks, training systems, crop loads, potential fruit sizes, and irrigation efficiencies, and, since each combination can affect irrigation requirements differently, there is a need to adjust the general set of crop coefficients for each particular plot. The growers have limited possibilities to quantitatively estimate the effect of each of the above-mentioned factors on the crop coefficient, and they are left with uncertainty about how to determine the irrigation amount for each specific plot.

In order to visualize the grower's dilemma, consider the response of marketable yield to irrigation level, as depicted in Fig. 3.8. A reasonable grower would choose irrigation level A and expect it to elicit a marketable yield level B. However, if the canopy size and crop level in a particular orchard were greater, and application efficiency lower than the experimental site where the response curve was determined, the actual response curve might shift to the right (dashed line), so the choice of irrigation level A would lead to a significantly lower marketable yield (C). The response of a reasonable grower would be to apply a safety factor and increase irrigation in order to get high marketable yield (D) and would hope not to reach E, which could happen if fruit development were in phenological stages in which deficit irrigation was beneficial.
C. The Use of Water Stress Indicators

A curve that depicts the response of marketable yield to plant water status (e.g., Fig. 3.9A, B), rather than to irrigation level (Fig. 3.8), might provide a partial solution to the grower’s irrigation dilemma. A threshold value of water status could be determined from the response curves (e.g., Fig. 3.9) and the product of crop and stress coefficients would be adjusted by trial and error until the threshold water status was reached. Setting a threshold is composed of physiological and horticultural response to the water stress indicator reading and economical considerations such as the amount of water that can be saved and the costs of water stress monitoring—the closer the threshold to the point where a damage can occur the more frequent and intensive water stress assessment should be performed. The use of a water status threshold based on the response curves (e.g., Fig. 3.9A, B) eliminates the uncertainties related to application efficiency, canopy size, and, to a certain extent, crop level. However, thresholds may change from year to year according to potential fruit size (Fig. 3.7); they may also differ in plots where the crop load is extremely high. The response curves (e.g., Fig. 3.9) might also differ among cultivars according to their tendency to produce large fruit, and among rootstocks, which could affect tree hydraulic architecture. Different thresholds might be needed for different climatic regions, because of differences in light intensity and temperature, which could alter the relationships between tree water status and the amount of assimilates available for the accumulation of dry matter. However, the

![Fig. 3.9.](image-url) Relative yield of nectarine (A) (Naor et al. 2001) and apple (B) (A. Naor, unpubl.) as a function of midday stem water potential. Bars denote SE.
question of the transferability of thresholds for irrigation scheduling has not yet been addressed experimentally in any water stress indicator.

In the following sections, the relevance and applicability of water stress indicators, as well as their limitations, are discussed in detail. The discussion includes issues such as responses to moisture availability and variability, and correlation with yield and quality attributes.

1. General Requirements for a Water Stress Indicator. The choice of a good water stress indicator for irrigation scheduling involves the following requirements:

1. Readings of water stress indicator should be correlated and consistent with horticultural parameters of economic importance: crop yield, fruit size, fruit growth rate, fruit quality, etc. In light of these relationships, a threshold for irrigation scheduling can be set, taking into account economical aspects. Water stress indicator readings should be correlated with assimilation rate or stomatal conductance, since optimizing the availability of assimilates is a major goal of irrigation. High correlation of the water stress indicator with horticultural parameters of economic importance is a prerequisite, and once it has been met the following requirements should be examined.

2. Response to moisture and irrigation regime—water stress indicator values should respond to the irrigation regime, especially near optimal conditions.

3. General applicability—thresholds for irrigation scheduling are usually based on controlled irrigation experiments. The transferability of thresholds to each commercial plot and the procedure for adjusting thresholds need to be straightforward.

4. Variability of the readings—this is an important issue since it determines how many measurements should be taken in order to properly represent the water status of a commercial plot. The number of measurements and the ease of operation and interpretation, as well as cost, may determine (on an economic basis) the efforts that should be invested in water status assessment in commercial orchards.

5. Early detection of water stress may allow the grower to respond by adjusting the irrigation regime before a significant irreversible damage occurs.

There are many good water stress indicators, such as stomatal conductance and assimilation rate, or tree transpiration rate, that are useful for research but are not applicable for irrigation scheduling because
of cost, and the complexity of operation and/or interpretation of the data. Therefore, only water stress indicators that have been proposed for or have potential for use in irrigation scheduling in commercial orchards are reviewed.

2. Types of Water Stress Indicators Available for Commercial Use. There are three major groups of water stress indicators in terms of the practical meaning of the measurement. (1) Those that estimate moisture availability—the ability of the soil to supply the water at an adequate rate—where the desired rate is dictated by the changing evaporative demand. Soil water stress indicators and predawn leaf water potential belong to this group. (2) Those that estimate peak daily water stress, including midday stem water potential, midday leaf water potential, and daily trunk shrinkage. (3) Those that provide information related to average daily water stress—daily transpiration, daily growth of fruit or trunk or other plant tissues.

3. The Relevance of Plant Water Stress Indicators. The relevance of a water stress indicator is determined by either direct correlation with horticultural attributes having an economical value, such as crop yield, fruit size, and fruit quality, or correlation with physiological parameters that are indirectly related to horticultural attributes having an economical value, such as stomatal conductance, assimilation rate, or shoot growth.

Direct Correlation. Midday stem water potential prior to harvest was highly correlated with fruit size in apple (Naor et al. 1995, 1997b; Ebel et al. 2001; Fig. 3.8), nectarine (Naor et al. 1999, 2001), pear (Ramos et al. 1994; Naor et al. 2000; Naor 2001), and Japanese plum (Intrigliolo and Castel 2005; Naor 2004), whereas practically no correlation was apparent between midday leaf water potential and fruit size in one experiment in apple (Naor et al. 1995). Fruit growth rate was correlated with daily trunk shrinkage, predawn leaf water potential, and midday stem water potential in apple (Bonany et al. 2000); and the highest, medium and lowest correlations were exhibited by the daily trunk shrinkage, the predawn leaf water potential, and the midday stem water potential, respectively. Midday stem water potential was highly correlated with pear fruit growth rate (Marsal et al. 2002a), and the faster the growth rate the higher the correlation. The postharvest midday stem water potential was correlated with the following season's crop yields of nectarine (Naor et al. 2005) and Japanese plum (Johnson et al. 1994), and postharvest midday leaf water potential was correlated with the following season's fruit set in peach (Girona et al. 2003). Postharvest midday stem water
Indirect Correlation. Stem water potential was highly correlated with stomatal conductance or assimilation rate in apple (Naor et al. 1995; Naor 1998), nectarine (Naor 1998), pear (Naor 2001; Marsal et al. 2002a), plum (Naor 2004), and prune (Lampinen et al. 2004). Leaf water potential was correlated with stomatal conductance or assimilation rate in apple (Naor 1998), pear (Naor 2001), nectarine (Naor 1998), peach (Garnier and Berger 1987; Escobar-Guttierez et al. 1998), and plum (Naor 2004). The correlation of midday stem water potential with stomatal conductance was better than that of midday leaf water potential with stomatal conductance in apple, pear, nectarine, and plum (Naor 1998, 2001, 2004), and this applied whether the leaves were covered before or after excision (Naor 2004), a finding that eliminates the possibility that the better correlation of stem water potential with stomatal conductance was due to measurement error (Williams and Araujo 2002). The response of stomatal conductance to water potential changed in the course of the season (Marsal and Girona 1997; Marsal et al. 2002a), which may affect thresholds for irrigation scheduling.

D. Response to Moisture and Irrigation Regimes

Most studies have compared extreme water regimes and there are very few that enable the construction of curves that describe the response of plant water status to irrigation levels (Lampinen et al. 1995; Naor et al. 1997b, 1999, 2000, 2001, 2004; Goldhamer and Viveros 2000; Shackel et al. 2000b). Predawn leaf water potential was highly correlated with the preharvest irrigation level (Goldhamer and Viveros 2000) in almond (Fig. 3.10); midday stem water potential was highly correlated with the irrigation level during the main fruit growth phase (Naor et al. 2000) in pear (Fig. 3.10). In prune, the seasonal average of midday stem water potential was highly correlated with annual irrigation level (Lampinen et al. 1995) when different irrigation regimes were applied at different phenological stages, which may indicate that plant water status responds similarly to irrigation level at all phenological stages.

Significant reductions in soil moisture content have been observed before the occurrence of reductions in predawn leaf water potential (Garnier and Berger 1987; Girona et al. 1993b; Ruiz-Sanchez et al. 2004), midday stem water potential (Shackel et al. 2000a; Ebel et al. 2001; Romero et al. 2004), and relative transpiration (Ferreira et al. 1997). It may suggest that a significant reduction in moisture content should occur before soil moisture availability starts to decrease.
Relative transpiration was highly correlated with predawn leaf water potential in a drying cycle in peach (Ferreira et al. 1997; Valancogne et al. 1997), plum, apple, and walnut (Valancogne et al. 1997). However, the relationships between relative transpiration and predawn leaf water potential changed in the course of the season (Valancogne et al. 1997), suggesting that thresholds for irrigation scheduling might change along the season as well.

In spite of the high responsiveness of predawn leaf water potential to the irrigation regime and to soil moisture content in the range within which it affects transpiration, setting a threshold might be a problem under nonhomogenous soil conditions, which are commonly found in commercial orchards. It was argued that predawn leaf water potential equilibrates with the wettest parts of the root zone (Dirksen and Raats...
Ameglio et al. (1999) demonstrated that relative transpiration was highly correlated with predawn leaf water potential in homogenous soils but not in heterogeneous soil profiles. This suggests that the predawn leaf water potential in heterogeneous soils does not correlate with average soil moisture content in the entire root zone, and therefore does not properly represent the soil moisture availability—the ability of the soil to meet the peak demand for water by the trees. The predawn leaf water potential of soybean grown in compartmented nutrition solutions of differing osmotic potential was equal to the average of the water potentials of the two compartments (Maertens and Blanchet 1981; Cited by Ameglio et al. 1999); as nutrition solutions introduce no hydraulic limitations in the growing medium, this suggests the responses of transpiration to predawn leaf water potential is dependent on the soil hydraulic properties. Therefore, different thresholds would be needed for different soil hydraulic properties and it may limit the transferability of predawn leaf water potential thresholds for irrigation scheduling from one site to another. There is a possibility that under extremely heterogeneous soil hydraulic properties conditions, predawn leaf water potential will not represent properly the average soil moisture availability (Ameglio et al. 1999).

**E. Sensitivity of Water Stress Indicators**

The sensitivity of a water stress indicator relates to the degree of change in water status that can be detected statistically, i.e., the least significant difference for a given number of measurements. The sensitivity of a water stress indicator is expected to increase with the level of response of the sensor to changes in water status, and to decrease with increasing variability between sensors/readings. Goldhamer et al. (2000) employed the following terminology to compare sensitivity of different water stress indicators: “signal”—is the extent of response of the water stress indicator to changes in water status or water availability; “noise”—is the variability between readings of different sensors; and “sensitivity” is the signal/noise ratio.

Midday stem water potential was more sensitive than midday leaf water potential in many deciduous trees (Garnier and Berger 1985; Higgs and Jones 1991; McCutchan and Shackel 1992; Behboudian et al. 1994; Naor et al. 1995; Naor 1998; Marsal et al. 2000; Girona et al. 2004). This suggests midday leaf water potential is inferior to midday stem water potential as a water stress indicator (Fig. 3.11).
Daily trunk shrinkage gave a stronger signal than midday stem water potential (Goldhamer et al. 2000; Goldhamer and Fereres 2001; Fereres and Goldhamer 2003; Naor and Cohen 2003; Intrigliolo and Castel 2004), but the noise (variability) of the daily trunk shrinkage was higher than that of midday stem water potential (Goldhamer et al. 2000; Goldhamer and Fereres 2001; Fereres and Goldhamer 2003; Naor and Cohen 2003; Intrigliolo and Castel 2004; Fig. 3.12). The sensitivity (signal/noise ratio) of daily trunk shrinkage was found to be higher than that of midday stem water potential in some studies (Goldhamer and Fereres 2001; Goldhamer et al. 1999), but the opposite was found in other studies (Naor and Cohen 2003; Intrigliolo and Castel 2004).
Midday stem water potential - SWP (MPa)

Daily trunk shrinkage - DTS (μm)

Relative differences between stressed and control trees (% of control)

Fig. 3.12. The responses of midday stem water potential (SWP) and daily trunk shrinkage (DTS) to withholding of irrigation for 17 days (bold horizontal bar) in apple. Bars denote SE (Source: Naor and Cohen 2003).

F. Early Detection of Water Stress

Use of predawn leaf water potential, midday stem water potential, and cumulative transpiration rate enabled the detection of water stress earlier than the use of midday leaf water potential and canopy temperature (Remorini and Massai 2003). Water stress was detected earlier by using midday stem water potential than by using midday leaf water potential (Selles and Berger 1990), daily trunk shrinkage (Goldhamer et al. 2000; Naor and Cohen 2003), and daily transpiration (Naor and Cohen 2003). In other studies, water stress was detected earlier by using daily trunk shrinkage than by using midday stem water potential (Intrigliolo and Castel 2004), predawn leaf water potential, midday leaf water potential, or midday stem water potential (Goldhamer et al. 1999). Use of predawn leaf water potential enabled the detection of water stress earlier than the use of midday leaf water potential (Girona et al. 1993b; Goldhamer and Viveros 2000; Ruiz-Sanchez et al. 2000b).

It can be concluded that midday leaf water potential and canopy temperature were inferior to other parameters as indicators of water stress. However, the relative merits of daily trunk shrinkage, midday stem water potential, and predawn leaf water potential in early water stress detection are not clear.

G. Representing Water Status on an Orchard Basis

This section deals with the efforts in terms of the number of measurements that are required for representing tree water status on an orchard
basis within acceptable uncertainty; this topic covers the within-tree and root-zone variability and the orchard-wide spatial variability. An acceptable variability depends on how close the threshold is to a point at which damage can occur and the probability of the actual tree water status to be beyond that point.

1. Within Tree and Root Zone Variability. The thresholds of soil water stress indicators are intended for evaluating the ability of the soil to meet the peak demand for water by the tree. Moisture availability is dependent on: the distribution of the sink strength of the water-absorbing roots; the soil moisture distribution; and the distribution of soil hydraulic properties, including those in close proximity to the roots. The average soil moisture availability within the root zone can be evaluated by using three-dimensional water transport models, assuming those distributions are available. However, the root-zones of perennial trees are irregular and usually occupy a non-uniform soil volume that is larger than the irrigated volume. Therefore, modeling moisture availability is not practical, and the choice of locations to monitor the soil water status remains problematic, and the ability to determine thresholds for soil water stress indicators is limited.

Soil water stress indicators were reported to have greater variability than daily trunk shrinkage and midday stem water potential (Naor et al. 1995, 1999, 2000, 2005; Goldhamer and Fereres 2001; Intrigliolo and Castel 2004; Fig. 3.13). The tree responds to average soil moisture availability and the tree water status indicators readings reflect the response to the average soil moisture conditions in terms of tree water status, thus avoiding the within root zone variability; this may account for the consistently greater variability of soil-based water stress indicators than of plant-based ones.

In spite of the above-mentioned limitations, soil water status sensors are the most popular water stress indicators for irrigation scheduling (Phene et al. 1990; Howell 1996), including that of perennial trees. In general, these indicators are easy to use and most of them provide analog outputs that enable continuous on-line monitoring. Thus, growers need to apply only empirical, site-specific calibration when they rely on soil water stress indicators to guide the decision on when to irrigate.

Within-tree variability should be taken into account for proper representation of tree water status: the stem water potential decreases along the transport pathway, and the gradient increases with increasing transpiration rate. Gradients of stem water potential of 0.08–0.09 MPa.m\(^{-1}\) (Olien and Lakso 1986) and of 0.2 MPa.m\(^{-1}\) (Jones et al. 1991) were reported for apple, and of 0.15 MPa.m\(^{-1}\) for peach (Garnier and Berger
3. IRRIGATION SCHEDULING OF DECIDUOUS ORCHARDS

Fig. 3.13. Standard error of midday leaf (LWP) and stem (SWP) water potential, daily trunk shrinkage (TS), and soil water tension at 30, 60, and 90 cm depth, in apple, nectarine, and pear (Naor et al. in press). A set of 27, 27, and 30 trees in close vicinity were selected in apple, nectarine, and pear, respectively, and a single measurement of each of the water stress indicators was taken in each tree.

In semi-arid zones, where transpiration rates are higher, these gradients are expected to be greater. These findings suggest that, in order to represent the average tree water status properly and to minimize variability, measurements should be taken in the middle of the canopy close to the trunk.

Inconsistent procedures such as the duration needed for covered leaves to reach equilibrium with stem water potential (Fulton et al. 2001) or the pressure increase rate (Naor and Peres 2001) may affect variability.

2. Spatial Variability. Soil water content is spatially variable within an orchard; therefore, one would need dozens of measurements in order to represent the soil water status properly on an orchard scale (e.g., Warrick and Nielsen 1980; Russo and Bresler 1982).

A test case—Midday stem water potential as measured by growers using five-leaf samples in a few commercial apple orchards were compared with those obtained by using randomly selected 25-leaf samples in each of the commercial orchards under study (Naor et al. in press); the differences between the two sets of measurements ranged from 0.03 to 0.21 MPa (Table 3.1). The minimum sample size for each plot for different acceptable deviations was calculated from the variability of the
Table 3.1. The differences between apple midday stem water potential on a five-leaf sample selected by the grower and a 25-leaf sample randomly selected in a commercial orchard.

<table>
<thead>
<tr>
<th>Orchard</th>
<th>Sample size for differences in SWP (MPa) lower than:</th>
<th>Absolute difference in SWP (MPa) between experimental sets and commercial sets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.075</td>
<td>0.1</td>
</tr>
<tr>
<td>El-1</td>
<td>27</td>
<td>15</td>
</tr>
<tr>
<td>El-2</td>
<td>27</td>
<td>15</td>
</tr>
<tr>
<td>If-1</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>If-2</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>Me-1</td>
<td>28</td>
<td>16</td>
</tr>
<tr>
<td>MG-1</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>MG2</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>EZ-1</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>EZ-2</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

Source: Naor et al. in press.

25-leaf samples, and it ranged from four to 15 leaves, depending on the specific variability of each plot. This indicates that growers could evaluate the variability of each plot to determine the sample size needed for water stress assessment.

Soil hydraulic properties have a statistical structure, i.e., the correlation between measurements increases as the distance between them decreases (Warrick and Nielsen 1980). The number of measurements a grower can take in a single plot is economically limited, and the statistical structure of the hydraulic properties may serve to determine the minimum distance between neighboring measurement locations (Or 1995; Plana et al. 2002).

Mapping relative tree water stress by using remote sensing of canopy temperature (e.g., Meron et al. 2003) might provide the growers with a means of selecting representative sites within an orchard; such a tool could help reduce sample size and the cost of water stress monitoring. In addition, the pattern of canopy temperature distribution might provide the grower with information about extreme conditions related to malfunctioning of the irrigation system, variable irrigation efficiencies, or other factors.

H. Considerations in Setting Thresholds

The effects of irrigation on horticultural yields and quality are complex: the dominant effect is on the availability of assimilates, which is known
to limit production (Grossman and DeJong 1995a,b), whereas other factors, such as canopy temperature, nutritional status, and plant growth regulators may interact with the availability of assimilates and the vegetative-to-reproductive growth ratio. Water stress indicators do not evaluate the above-mentioned processes directly, but do so only through variables that correlate with them. Therefore, thresholds for irrigation scheduling might change from one site to another because of factors such as cultivars, rootstocks, crop loads, and climatic conditions that may influence the availability of assimilates.

The factors to be considered in setting thresholds for minimum stress conditions, which is the simplest situation, as well as for deficit conditions, are discussed below.

1. Minimum Stress Conditions

Account for Evaporative Demand. The midday stem water potential of well irrigated trees decreases with increasing evaporative demand, because of the high resistance to water flow from the bulk soil to the tree xylem vessels. As a result, the water balance (the amount of water absorbed minus the amount of water transpired) becomes more negative with increasing evaporative demand, leading to a lowering of the midday stem water potential. McCutchan and Shackel (1992) developed relationships between midday stem water potential of well irrigated prune trees and daily maximum vapor pressure deficit, whereby the threshold of midday stem water potential should be adjusted by 0.12 MPa for each change of 1 kPa in maximum vapor pressure deficit. A similar response of midday stem water potential to maximum vapor pressure deficit was found for almond (Shackel et al. 1997, 1998), but a slightly lower response (Fereres and Goldhamer 2003); no correlation was found between midday stem water potential and maximum vapor pressure deficit (Goldhamer et al. 2000) probably because all the treatments were under stress conditions. A change of midday stem water potential by 0.1 MPa per 1-kPa change in maximum vapor pressure deficit was found for apple (A. Naor, unpubl.). The above-mentioned response of midday stem water potential to maximum vapor pressure deficit can be utilized to adjust the thresholds and thus avoid unnecessary irrigations on days of high evaporative demand.

Daily trunk shrinkage was found to be highly responsive to maximum daily vapor pressure deficit in almond (Goldhamer et al. 2000; Fereres and Goldhamer 2003; Goldhamer and Fereres 2004) and apple (A. Naor, unpubl.), for which the correlation with vapor pressure deficit was higher than that of midday stem water potential with vapor pressure
deficit. Changes of 0.03 to 0.08 mm in daily trunk shrinkage per unit change in maximum vapor pressure deficit were reported for almond (Goldhamer et al. 2000; Fereres and Goldhamer 2003; Goldhamer and Fereres 2004). Corrections for the response of daily trunk shrinkage to maximum daily vapor pressure deficit were used in scheduling irrigation of almonds (Goldhamer and Fereres 2004) where quite stable midday stem water potentials were apparent for each of the two daily shrinkage thresholds that were examined.

In diurnal measurements, leaf water potential had lower correlation with whole trunk contraction than with trunk xylem contraction (excluding the bark) (Ueda and Shibata 2001). Similar responses of the trunk xylem contraction to leaf water potential were apparent for four consecutive days (Ueda and Shibata 2001), whereas the response of the contraction of the whole trunk varied from one day to another. The high resistance to water transport from bark to xylem, which is exhibited as a lag of trunk diameter changes behind stem water potential (Cohen et al. 2001), may explain the day-to-day variability in the relationships between trunk diameter changes and leaf water potential. It may also account for the higher dependence of daily trunk shrinkage on maximum daily vapor pressure deficit than midday stem water potential (Goldhamer et al. 2000; Fereres and Goldhamer 2003; Goldhamer and Fereres 2004).

Diurnal changes in leaf thickness in apple did not lag at all behind the changes in stem water potential, unlike trunk contraction (A. Naor, unpubl.) and it was highly correlated with leaf water potential (Syvertsen and Levy 1982), indicating that it might offer an advantage over trunk contraction measurements. However, the response of leaf thickness to water status varies between leaves (McBurney 1992), and calibration of the threshold would be required.

It should be emphasized that consideration of trunk xylem contraction and leaf thickness contraction for irrigation scheduling are in the very early stages of examination. In addition, based on the small daily trunk xylem contraction, errors from a significant thermal contraction may arise (Irvine and Grace 1997).

Seasonal Drift in Tree Water Status. There are a few examples of seasonal decrease in tree water status when minimum water stress was expected, irrespective of the effect of evaporative demand (Lampinen et al. 1995; Shackel et al. 1998; Goldhamer and Fereres 2001; Intrigliolo and Castel 2004). It could be that a higher value of $K_c$ should be used, to take into account different seasonal dynamics of canopy size, greater
crop load, and lower application efficiency in the above-mentioned reports than in the experiments used for the determination of $K_c$ values, raising a possibility of insufficient irrigation. At the beginning of the season, the soil profile retains enough moisture from winter precipitation to compensate for unsatisfactory irrigation, but as the season progresses the initial reservoir is exhausted, which may result in a decrease in midday stem water potential. The root volume at the beginning of the season is larger than the irrigated volume as roots are absorbing moisture that remained from winter precipitation, but as the season progresses the effective root volume decreases and converges to the irrigated soil volume; this may decrease the water absorption capacity (Naor et al. 2000) due to increased root resistance to water transport, which, in turn, may affect the midday stem water potential.

2. Setting Thresholds for Daily Trunk Shrinkage. The seasonal pattern of daily trunk shrinkage was found to be less stable than that of midday stem water potential (Goldhamster and Fereres 2001; Intrigliolo and Castel 2004; J. Marsal et al. unpubl.; A. Naor, unpubl.), and the high correlation between daily trunk shrinkage and the daily maximum vapor pressure deficit (Goldhamer et al. 1999, 2000, 2001) only partially accounts for this instability. To account for such instability Genard and Huguet (1999) used well-irrigated peach trees as an internal reference to calculate relative daily trunk shrinkage, which provided good predictions of the effects of water stress on fruit growth. Goldhamer and Fereres (2001, 2004) proposed the use of internal references of well-irrigated trees for irrigation scheduling to correct for the response of daily trunk shrinkage to vapor pressure deficit, and they discussed a few considerations relating to the internal reference. The number of dendrometers to be installed in the well-irrigated reference plot must be considered, because of the variability of daily trunk shrinkage. Possible changes in tree size and therefore in water consumption and daily trunk shrinkage caused by long-term excessive irrigation of the reference plot should also be taken into account—it may create a situation in which the reference trees and the orchard trees are not similar anymore, thus a change of the reference trees might be required along the season.

Combined Use of Midday Stem Water Potential and Daily Trunk Shrinkage. Midday stem water potential has been found to be a relevant and reliable water stress indicator, but its use is labor intensive, and measurements are limited to about two hours a day around midday. In addition, the measurements do not yield an analog output, and therefore are
not amenable to automatic data acquisition. Daily trunk shrinkage, on the other hand, is highly responsive, easy to use, and yields an analog output, but setting a threshold is problematic. Therefore, calibration of daily trunk shrinkage against stem water potential may provide thresholds for the use of daily trunk shrinkage for irrigation scheduling. Daily trunk shrinkage is highly correlated with stem water potential (Goldhamer et al. 1999, 2000, 2003; Bonany et al. 2000), but the relationships change during the season (Marsal et al. 2002b; Fereres and Goldhamer 2003; Intrigliolo and Castel 2004). This may necessitate periodical recalibration of the relationships, but the necessary frequency of recalibration against stem water potential is yet to be determined experimentally. The above-mentioned combined use of midday stem water potential and daily trunk shrinkage could be adapted to other easy-to-use water stress indicators that have difficulties in setting thresholds for irrigation.

3. Setting Thresholds Under Deficit Irrigation Conditions. Deficit irrigation is a common irrigation practice during some phenological stages, and it introduces some major difficulties in the use of several water stress indicators.

Thresholds for irrigation scheduling in stressed conditions may be determined in regional experiments that produce response curves. For example, in the case of postharvest irrigation of nectarines the optimal midday stem water potential would be about -2.0 MPa (Fig. 3.5), which is a value that allows water saving without risking the occurrence of twin fruits.

Except for one study (Goldhamer et al. 2000), the variability of all water stress indicators increases with increasing water stress (Johnson et al. 1994; Naor et al. 1995, 2000, 2004; Ruiz-Sanchez et al. 2000b; Naor and Cohen 2003) and therefore more measurements will be needed for water stress assessment under deficit irrigation.

The use of reference trees for setting thresholds for irrigation scheduling according to daily trunk shrinkage does not apply under deficit (stressed) conditions. The response of daily trunk shrinkage to midday stem water potential decreases under high water stress conditions (Bonany et al. 2000; Goldhamer et al. 2000), probably as a result of a significant decrease in the morning readings (maximum values). For the same reason, the daily trunk shrinkage under severe water stress might be less than that under less severe stress (Besset et al. 2001), and this could result in a misleading interpretation. Both predawn leaf water potential and midday stem water potential provided clear distinctions between different stress
conditions (Fig. 3.10), including severe water stress (Johnson et al. 1994; Naor et al., 2005; Ruiz-Sanchez et al. 2000b).

I. Conditions of Limited Response to Irrigation

There are significant resistances along the flow path of the water from the soil into the tree and also in specific places within the tree (Jones 1992). Therefore, diurnal water transport in the tree is under non-steady-state conditions, and when there is high evaporative demand and conductance is low, the response to irrigation might be limited.

1. Soil-root Zone Limitations. Midday stem water potential under high soil-moisture availability decreases with increasing vapor pressure deficit (McCutchan and Shackel 1992), because of the high resistance to water flow in the soil-root zone. In soils with high clay contents, the midday stem water potential is lower than in soils with low clay content (Naor et al. 2000; O'Connell and Goodwin 2004), even under full irrigation; this indicates that there may be some limitation to the water absorption capacity of the root system in these soils. Such a limitation could be related to lower oxygen fluxes into the root zone, or to mechanical resistance to root growth (Taylor 1983) or low soil hydraulic conductivity. The choice of an appropriate rootstock could improve water absorption capacity (Atkinson 1980): for instance, a higher midday stem water potential was found in pear grafted on Betulifolia than on Quince C (R. A. Stern and A. Naor, unpubl.).

2. Fruit Pedicle Limitations

Early Season Limitation. Water stress affects fruit set and abscission of fruitlets in apple (A. Naor, unpubl.; Powell 1974). The pedicle water conductance in apple is low for the first two weeks after bloom (Drazeta et al. 2004a), but a dramatic increase occurs at the end of the second week after bloom, and a further slight increase a couple of weeks later. The diameter of the xylem vessels and, therefore, their conductance decreases towards the end of the pedicle adjacent to the abscission zone. Under conditions of high evaporative demand and, therefore, of high fruit transpiration rate, pedicle conductance could impose a limitation that would limit the possibility of relieving fruit water stress by increasing the irrigation rate.

Preharvest Limitation. The conductance of the peach fruit surface was found to increase in the course of the season, and in most cultivars the
increase occurred close to harvest (Lescourret et al. 2001), therefore fruit transpiration is expected to increase along the season. In contrast, in apples fruit transpiration decreased during the season (Tromp 1984). Fruit surface conductance was found to be much higher in peach, nectarine (Lescourret et al. 2001), and pepper (Aloni et al. 1998) than in apple (Lang 1990), grape (Lang and Thorpe 1989), or tomato (Lee 1990); and in peach and pepper (Aloni et al. 1998; Lescourret et al. 2001) its increase towards harvest was attributed to the increased size of microcracks with increasing fruit surface area. Maguire et al. (1999) showed that the proportion of Braeburn apples showing microcracks increased with increasing fruit surface conductance. Lescourret et al. (2001) showed by means of a model simulation (Fishman and Genard 1998) that towards harvest fruit growth decreases as surface conductance increases, because the high tree water status could not compensate for the increased fruit water loss through the highly permeable fruit surfaces. The growth rate of Japanese plum fruits decreased dramatically under high evaporative demand (Naor et al. 2004), and the decrease was greater than could be accounted for by the parallel decrease in stem water potential. A decrease in net water transport through the xylem vessels to the fruits was reported for apples (Lang 1990); it was accounted for by a reduction in the conductance of the xylem vessels in the course of the season (Lang 1990; Lang and Ryan 1994; Drazeta et al. 2004b). It seems that partial blockage of xylem vessels may reduce the capability of high irrigation rates to compensate for the increased water losses through the fruit surface that are caused by high surface conductance, especially under conditions of high vapor pressure deficit. Therefore, high evaporative demand close to harvest is expected to decrease fruit size in conditions of high fruit surface conductance.

V. CONCLUDING REMARKS

Research in the past two decades has clearly shown that growers may benefit from deficit irrigation in certain phenological stages. This may be accomplished both by saving water and by improving productivity and fruit quality.

Stone fruits in the pit hardening stage are not sensitive to moderate water stress, however, the duration of the pit hardening stage varies with harvest date and there is a risk of missing the end of this stage and then decreasing fruit size by extending the water stress well into the final fruit growth stage; therefore it seems that in many cases the potential bene-
fit will not justify the risk. In early-maturing cultivars, the duration of the pit hardening stage is too short for deficit irrigation to be considered.

Excessive canopy growth due to high irrigation levels decreases subsequent season productivity both early in the season and post harvest; severe water stress decreased subsequent season productivity as well. Thus, moderate water stress, which controls canopy growth and avoids damage to the developing reproductive buds, seems to be optimal in terms of subsequent season productivity. Deficit irrigation in the reproductive cell division stage and in the final fruit growth stage decreases fruit size at harvest. Therefore, water stress should be avoided during the main fruit growth stages unless extreme conditions of high vigorous trees are apparent or in high-density orchards. In order to avoid the risk of decreasing fruit size in those extreme situations, other practices of controlling shoot growth such as shoot bending or the use of plant growth retardant should be considered.

Water stress during fruit growth accelerates maturation and improves fruit firmness, total soluble solids content, and fruit color, but it decreases fruit size, which is a major attribute of fruit quality. It seems that one would be able to benefit from deficit irrigation during the fruit growth stage only when potential fruit size is higher than the optimal marketable size; thus, both optimal fruit size and improved fruit quality can be gained in such conditions. Evidence for any effects of deficit irrigation on aroma compounds is inconclusive. Severe water stress in the bud development stage increases the proportions of twin fruits and of fruits with deep sutures in peach and nectarine.

The present review indicates that the process of making decisions on irrigation is complex because it involves many factors (physiological, phenological, agronomical, meteorological, and economic). Unfortunately, each of these factors is subject to uncertainty; therefore, the grower has to monitor the response of each specific orchard to a given irrigation regime and to adjust the latter accordingly. The use of water stress indicators may enable the grower to adjust irrigation and to compensate for the effects of canopy size, application efficiency, and (partly) of crop load on irrigation level.

Data collected in the past decade suggest that soil water stress indicators are more variable than plant water stress indicators; midday leaf water potential was found to be inferior as an indicator to midday stem water potential, predawn leaf water potential, and daily trunk shrinkage. Setting thresholds is more complicated for soil water stress indicators and for daily trunk shrinkage in general, especially under deficit irrigation conditions, and for predawn leaf water potential in heterogeneous soils.
The issue of transferability of threshold of water stress indicators for irrigation scheduling from one region to another is an extremely important issue that was not addressed experimentally yet for all the water stress indicators. The use of an unstressed internal reference might avoid the need to set thresholds for daily trunk shrinkage in some cases when no deficit irrigation is applied.

There is room for decision support systems that would handle the decision-making process and simplify it for the grower. The development of a decision support system would not involve new research, but would necessitate the manipulation of existing physiological and horticultural knowledge, together with cumulative regional experience and the experience of the specific grower who is to use the decision support system. The use of the cumulative experience could reduce the uncertainty and compensate for the gaps in scientific knowledge for specific orchard conditions. The input to a decision support system could include meteorological data from which \( ET_0 \) and vapor pressure deficit could be calculated, water meter data from which actual irrigation levels and actual irrigation coefficients could be calculated, seasonal dynamics of fruit size from which the expected fruit size at harvest could be calculated, tree water status and soil water status. A decision support system would be able to compare the performance of each particular plot with that of neighboring plots. In addition, the use of historical information could facilitate comparisons between the actual, present-day performance with that under similar conditions (e.g., meteorological, crop load) in the past.

Commercial orchards are spatially variable with respect to soil hydraulic properties, soil depth, irrigation application and crop load, all which may affect the optimal irrigation level for each specific tree or sub-plot. Remote sensing of canopy temperature already enables the grower to produce maps of relative water stress, and further developments might enable him to map canopy size and crop load. Based on such maps, growers might be able to produce high-resolution maps of irrigation level. The limit to the resolution of such maps would be the ability to adjust the irrigation level at high spatial resolution in commercial orchards; and this introduces a challenge to the irrigation equipment industry.

**LITERATURE CITED**

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