4.1 Fruit trees and vines

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Olive

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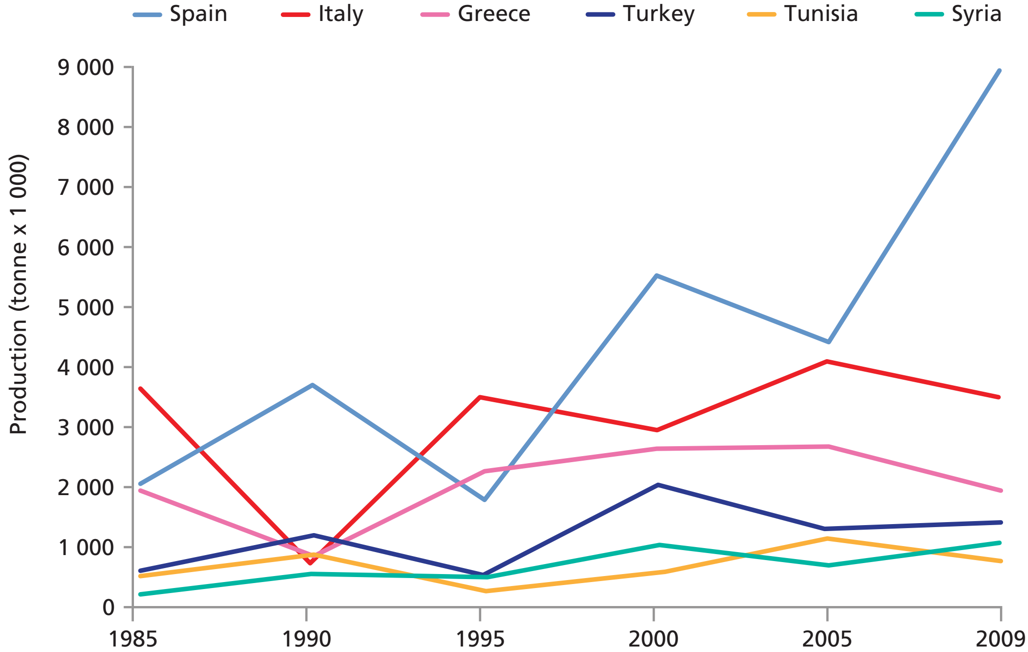
Olive

GENERAL DESCRIPTION

Olive (*Olea europaea L.*) is an evergreen tree grown primarily between 30 and 45° latitude in both hemispheres. In 2008 total harvested area was over 10 500 000 ha, 95.5 percent of which was concentrated in ten countries surrounding the Mediterranean Sea (FAO, 2011). Spain, Italy and Greece are the main producers of virgin oil followed by Tunisia, Syria, Turkey and Morocco (years 2002-2008). About 90 percent of the world production of olive fruit is for oil extraction, the remaining 10 percent for table olives. The world cultivated area of olives in 2009 was over 9.2 million ha with an average yield of 2.1 tonne/ha (FAO, 2011). Figure 1 shows the evolution of olive production over the last decades in the principal countries. European Union countries produce 78 percent and consume 68 percent of the world's olive oil.

Olive trees have been sparsely planted for centuries, without irrigation, on marginal lands in Mediterranean climate conditions because of their high resistance to drought, lime and salinity. Typical densities of traditional groves are between 50 and 100 tree/ha with trees severely pruned to stimulate vegetative growth and renewal of the fruiting surface, and the soil periodically tilled. Fruit yields are low, ranging from less than 1 up to 5 tonne/ha of olives. Although traditional groves vary in cultivar composition, tree density, training system, degree of mechanization and chemical inputs, they are still the most widespread production system and a landmark of Mediterranean landscapes. Intensive orchards have a density of between 200 and 550 tree/ha, which translates into a higher fraction of intercepted radiation that leads to higher productivity per unit land area than traditional systems, particularly during the first 10 years of production. Trees are trained to a single trunk for mechanical harvesting and the soil is often managed by temporary or permanent grass cover to reduce erosion and ease traffic in wet periods. In areas of annual rainfall higher than 600 mm, production can be maintained under rainfed conditions in soils with good water-holding capacity. However, irrigation plays an important role in the drier areas, and/or for soils with limited water storage. Elsewhere, irrigation plays an important role to stabilizing yields in the years of low rainfall. Irrigation is becoming common in the intensive orchards as it allows early onset of production (from the second to forth year after planting), high yields (averages up to 10-15 tonne/ha) under optimal conditions and less variability because of alternate bearing.

FIGURE 1 Production trends for olives in the principal countries (FAO, 2011).



Quality considerations

Of the several categories of olive oils, defined according by the European Union legislation (Reg. EEC 2568/91, UE 702/07 and 640/08), and widely accepted internationally, the concept of quality only pertains to virgin olive oil (VOO), the main product of the olive industry. In order to qualify as VOO, it is required that oils satisfy analytical parameters and be tested and approved for their sensory characteristics by a panel of experts. Moreover, the current perception of quality is mainly based on the sensory and health-related properties, which are closely related to the concentration and composition of the phenolic and volatile fractions, respectively. Oleic acid is the most abundant fatty acid followed by palmitic acid, linoleic acid and others that do not exceed 2 percent of fatty acid composition. Fatty acid composition is cultivar dependent and changes with climatic conditions and progression of ripening. The ratio between mono-unsaturated and poly-unsaturated fatty acids first increases, then it reaches a maximum and then decreases in overripe fruit. The concentration of phenolic compounds in the fruit, and consequently in the oil, is also cultivar dependent and reaches a maximum at the beginning of ripening, when the skin (epicarp) is still partially green, to decline sharply in overripe fruit. Qualitative features of table olives are similar to those of other stone fruit used for fresh consumption and include fruit size, pulp-to-pit ratio, pulp firmness, colour and soluble carbohydrate concentration.

Most of the world's olive area is composed of the two systems described above. However, in the last 15 years very high density, hedgerow type, olive orchards (from 1 000 to 2 000 tree ha) have been developed to further reduce harvesting costs using over-the tree harvesting machines. Because of the higher ET_c demand of the dense canopies and the low soil volume available for each tree, irrigation is needed. Average yields can be quite high (5-15 tonne/ha) in the first years of production (third to seventh year after planting) and may average 10-14 tonne/ha over a 10-year period, but there are questions about the sustainability of high yields in the long term, and about the adaptation of many cultivars to this production system. The area devoted to these super-intensive plantations is about 100 000 ha worldwide.

STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

Yield is the result of three main developmental processes that occur between flowering and harvest: fruit set, fruit growth and oil accumulation in the fruit pulp (mesocarp). Vegetative growth is critical in terms of olive fruit production, because flowering and fruit set originate in the axillary buds of past year's growth. The reproductive cycle from flower bud induction to fruit ripening takes 15-18 months depending on cultivar and growing conditions, as it starts in the summer and ends in the autumn of the following year. Flowers are usually borne in inflorescences at the axil of leaves of one-year old wood, whereas the terminal bud of the shoot is almost always vegetative (Rapoport, 2008). Shoot growth starts with bud break in spring and resumes when temperatures are above 12 °C, as long as it is not inhibited by temperatures above 35 °C, soil water deficit or other environmental stresses. A second flush of shoot growth is common after the summer. Olive trees are sensitive to waterlogging and temperatures below -10 °C.

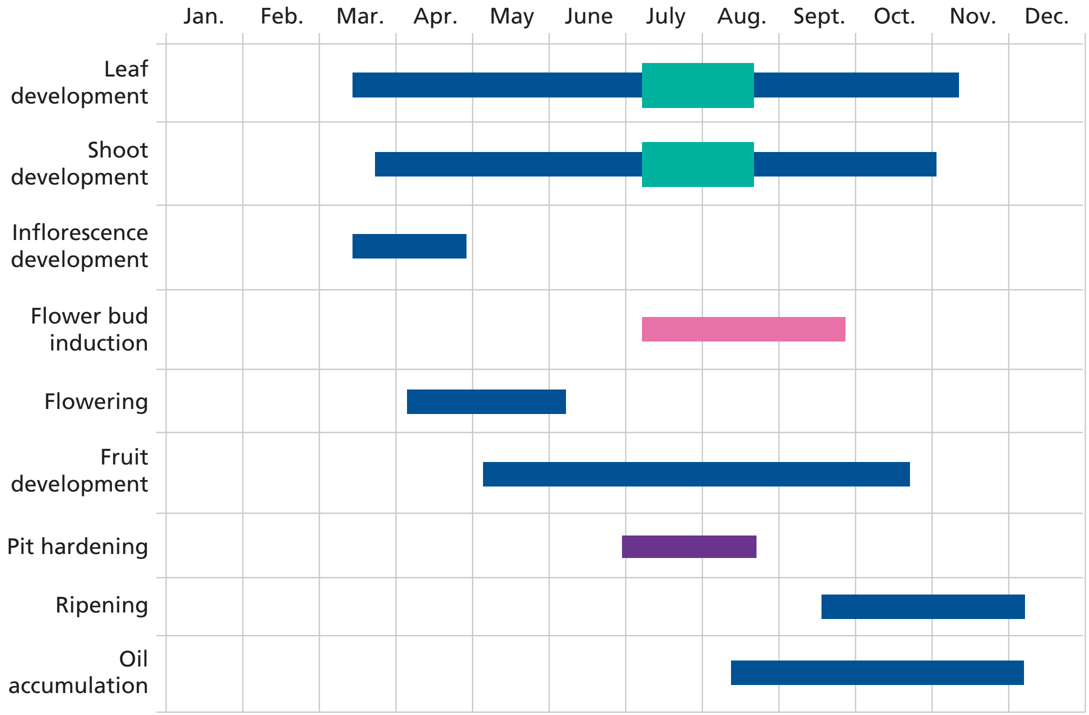
Chilling is needed for flower bud differentiation. Lack of chilling results in scarce and uneven formation of flower buds. Chilling requirements vary with the cultivar but at least 10 weeks below 12 °C are usually needed for abundant flowering. Main phenological stages for olive trees, described according to the two-digit Biologische Bundesanstalt, Bundessortenamt and Chemical industry (BBCH) scale, include bud break, bud development, leaf full expansion, beginning of flower cluster development, full elongation of flower clusters, full flowering, fruit set, fruit development, maturity and senescence. The time sequence of main developmental processes is reported in Figure 2.

Olives flower in late spring, a month or two later than to many deciduous trees; timing and duration depend on cultivar, temperature and soil water availability. Fruit set is generally low (less than 2 percent of flowers) but suboptimal conditions (temperature, rain, winds) can reduce it further. Fruit growth apparently follows the typical double-sigmoidal pattern of stone fruit, although there are some questions as to whether this pattern is inherent to olive fruit development or is a consequence of the interaction with environmental constraints in midsummer such as high temperature and low water availability. Fruit pit hardening occurs about two months after fruit set. Oil accumulation in the fruit is proportional to the intercepted solar radiation and becomes substantial in late summer for most cultivars, right after the end of massive pit lignification. At harvest, fruit contain between 10 and 25 percent oil on a fresh weight basis, depending on cultivar, crop load and growing conditions. Oil accumulation patterns in the mesocarp follow a simple sigmoid curve, but may vary with cultivar and environmental conditions.

RESPONSES TO WATER DEFICITS

Olive trees are very resistant to drought and show a high capacity to recover from prolonged drought periods. Trees can completely re-hydrate within three days of irrigation after a water deficit that reached a leaf water potential (LWP) of -4.0 MPa. Even during a severe drought that

FIGURE 2 Occurrence and duration of main phenological stages of olive trees during the growing season (n). Flower bud induction occurs during the summer of the previous year (n-1). Shoot and leaf development are often inhibited by high temperatures and water deficit during the summer (vertical shading). Modified from Sans-Cortes *et al.*, (2002).



lowered the LWP down to -8.0 MPa, the trees rehydrated in less than a week following the onset of rains (Connor and Fereres, 2005). Nevertheless, as for all terrestrial plants, expansive growth of olive leaves, branches, fruit, and trunk, is sensitive to water deficits. Water stress also affects stomatal opening and photosynthesis. It is well known that olive stomata close partially during the day (Fereres, 1984) in response to increases in vapour pressure deficit, even if the trees are well watered, with corresponding decreases in CO_2 assimilation. Leaf photosynthetic rate is relatively high, of the order of 12-20 μmol CO_2 m^{-2} s^{-1}, but is reduced under and following water stress because of stomatal closure. When water deficits are severe (LWP below -4 to -5 MPa), photosynthetic rate does not exceed one-third of normal values, reaching a maximum early in the morning and then declining as the day advances (Angelopulos *et al.*, 1996).

The olive root system is extensive and vigorous and, therefore, can explore the soil profile thoroughly after the first years of tree establishment. In general, it can be assumed that most of the absorbing roots are in the first 1 m depth. However, in deep alluvial soils, roots can reach 2-3 m depth or more, whereas in marginal soils the rooting depth may be less than 0.5 m. Given the capacity of olive trees to lower their LWP to -7 MPa or less, the soil water content in parts of the root zone can easily reach values below the standard permanent wilting point. Given the shape of the moisture release curve of most soils, the amount of additional water extracted would be small. Nevertheless, such small amounts may be critical for surviving extreme droughts.

Because olives flower late, the risk of low temperature damage is significantly reduced; however, the risk is increased of being affected by water and/or high temperature stress in the Mediterranean climate, and also fruit growth is delayed into the summer, normally an extended period of water shortage. It has been observed that for rainfed trees in years when winter rainfall has been very limited, that flowering and fruit set are processes that are quite sensitive to water deficits. Thus, water stress should be avoided from floral development to fruit set in spring. However, in relatively humid climates (e.g. central and northern Italy) stress seldom develops in spring and irrigation is usually unnecessary. Once the fruit is set, it grows more or less linearly by cell division and subsequent expansion, unless water deficits and high temperatures slow its growth rate. Initial rapid fruit growth (Stage I) and the period when oil is actively accumulated in the fruit (Stage III), are also sensitive to water deficit.

Given that water deficits reduce fruit growth, irrigation that avoids water deficits increases fruit size, although the effect is mediated by the amount fruit borne on the tree. Once the fruit is set, its growth rate may be slowed down by water deficits, but growth quickly resumes upon relief from stress by rainfall or irrigation. Complete recovery of endocarp growth occurs even after several weeks of deficit, whereas recovery of mesocarp growth is less certain. The pulp-to-pit ratio, an important quality feature for both table and olive oil fruit, is increased under irrigated conditions, but it has been observed that mild water deficits during fruit development have a positive effect on the pulp-to-pit ratio (Gucci *et al.*, 2007).

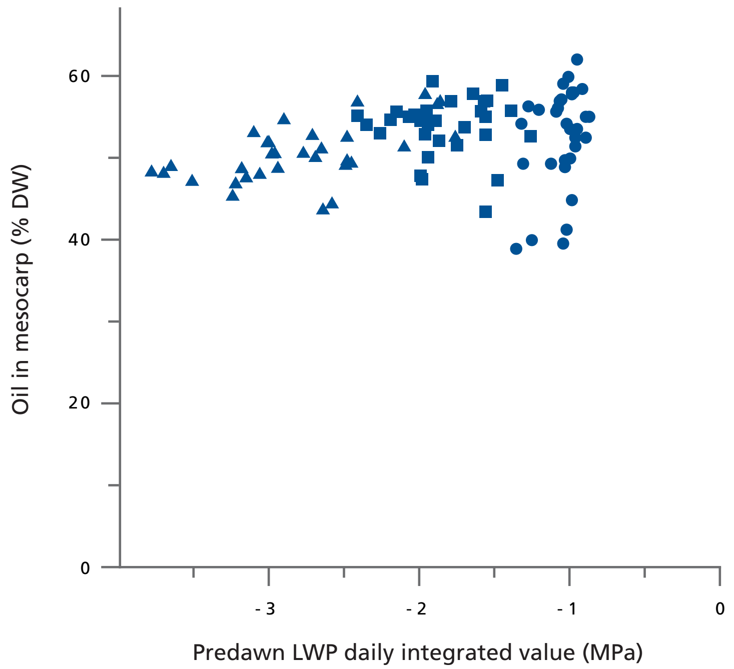
Soil water availability affects colour change and ripening of fruit. The effect of irrigation on oil content may be apparently contradictory as it affects water content and the process of oil accumulation in the fruit in different ways. It is well known that severe stress during the oil accumulation period (from mid-August through the end of October for most cultivars in the Northern Hemisphere), reduces the oil percentage on a dry weight basis at harvest. As stress becomes less intense the oil percentage increases, although at a relatively low rate. Under non-stress conditions the variability of data on the relationship between predawn LWP and oil content increases and oil concentration may be even less than for mildly stressed fruit (Figure 3).

While irrigation does not usually alter the fatty acid composition or basic parameters used for the classification of VOO (e.g. free acidity, peroxide value, spectrophotometric indexes), increasing volumes of water applied decrease the concentration of phenolic compounds in the oil, namely the concentration of secoiridoid derivatives of oils, such as 3,4-DHPEA-EDA, 3,4-DHPEA-EA and p-HPEA-EDA (Gomez-Rico *et al.*, 2007 and Servili *et al.*, 2007), which act as natural antioxidants during oil storage and play important functions in human diet and prevention of cardiovascular diseases. As a result, oils from irrigated orchards are usually less bitter and pungent that those from rainfed ones (Servili *et al.*, 2007).

Assessment of tree water status

The established method of measuring tree-water status is the measurement of stem-water potential or leaf-water potential. Exposed leaves are used for the latter while shaded or covered leaves are used for SWP; in some cases, small terminal branches have been used to characterize tree water status. Predawn LWP is a reliable indicator of tree water status in mature trees, but it is inconvenient in practice because of the need for early morning measurement.

FIGURE 3 The relationship between oil in the mesocarp on a dry weight basis measured at harvest and predawn leaf water potential (LWP) for olive trees cv. Leccino grown under three irrigation regimes over two consecutive years (modified from Gucci *et al.*, 2007).



The LWP measured on exposed leaves at midday depends not only on soil water availability but also on environmental conditions that influence canopy conductance during the day. Water potential values of exposed leaves are more variable as they are affected by the degree of stomatal opening. With stomata fully open, the gradient between stem and sunlit LWP is about 0.5 MPa when water supply is adequate. Such value may increase (up to 1 MPa) as water stress increases, but it tends to decrease again as stomata close.

Stem-water potential (SWP) is considered a more reliable indicator of tree-water status than midday LWP, because it is less dependent on diurnal changes in radiation and humidity. The midday SWP of olive trees grown under adequate soil water supply, ranges between -0.5 and –1.2 MPa, depending on the evaporative demand, with a tendency to decrease even to lower values in mid- to late summer under conditions of high evapotranspirative demand (Gimenez *et al.*, 1997). SWP values for olive are higher than -0.5 MPa have been only occasionally measured. Typical reference values for midday SWP for mature, fully-productive olive trees vary between -1.0 and -1.2 MPa for summer, sunny days with an ET_o of 5-6 mm/day.

Under water deficit conditions, stress develops and SWP values decrease. Typical values of SWP for moderately-stressed trees are between –1.7 and -2.5 MPa, and become severe when values approach -3.5 to -4.0 MPa. Although olive trees have exceptional resistance to drought, and SWP or LWP values as low as –7.0 to -8.0 MPa have been measured in rainfed olive trees during severe drought periods (Fereres, 1984), these values should be considered exceptional and close to a survival state rather than acceptable for satisfactory yields.

The use of displacement sensors to monitor olive trunk growth and trunk diameter fluctuations has yielded information that confirms the high sensitivity of expansive growth to water deficits. These highly sensitive sensors could be used in young, intensive plantations where the objective is to maximize canopy growth and reach full production as early as possible. Sap flow sensors have also been used to determine changes in sap velocity, which are indicative of transpiration rate and of its changes in response to water deficits. All these instruments are still in the research and development stages and are not yet used commercially for irrigation scheduling.

WATER REQUIREMENTS

Olive trees withstand long periods of drought and can survive in very sparse plantings even in climates with only 150-200 mm annual rainfall. However, economic production requires much higher annual precipitation or irrigation. Table 1a summarizes the crop coefficient (K_c) values proposed by various authors that have been developed in different environments. The range of K_c values is quite wide, varying from less than 0.5 to about 0.75, average values varying

TABLE 1a Monthly crop coefficients (K_c) used for olive orchards in different olive-growing regions and recommended average values.

Site, region	Latitude	ET_o (mm)	Rainfall (mm)	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
Bibbona, Tuscany	43° 16 N	1 000	772 (30-year mean)	-	-	-	0.60	0.55	0.65	0.65	-	-
Metaponto, Basilicata	40° 22 N	1 270	492	0.7	0.65	0.6	0.55	0.5	0.5	0.6	0.65	-
Sassari, Sardinia	40° 42 N	-	-	-	0.55	0.5	0.5	0.5	0.5	0.5	0.55	-
Cordoba, Andalusia	37° 50 N	1 420 (mean of 3 years)	639 (mean of 3 years)	0.65	0.6	0.55	0.55	0.5	0.5	0.55	0.6	0.65
Fresno, California	36° 44	-	-	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	-
Benevento, Campania	41° 06 N	1 240 (20-year mean)	714 (20-year mean)	-	-	-	0.65	0.65	0.65	0.65	-	-
Recommended values, clean cultivated	-	-	0.45 * to 0.75	0.45 to 0.75	0.5 * to 0.65	0.55	0.55	0.5 to 0.55	0.5 to 0.55	0.55 to 0.6	0.6 to 0.65	0.6 to 0.65

** In winter and spring only, the low K_c applies to dry, cold climates, while the high K_c applies to areas frequently wetted by rainfall.*

TABLE 1b Summary of recommended olive K_c values.

Climate*	Semi-arid	Arid
Spring	0.65-0.75	0.45-0.55
Summer	0.50-0.55	0.50-0.55
Fall	0.60-0.70	0.55-0.65
Winter	0.65-0.75	0.40-0.55

** Mediterranean-type climates; the one labelled semi-arid has seasonal rainfall values around 500 mm or more, mostly between autumn and spring, while the arid climate would have less than 400 mm rainfall and is more continental, with relatively cold winters. The higher K_c values of the range should be used for high rainfall situations. K_c values to be used with ET_o calculated following FAO I&D Paper No. 56.*

from 0.55 to 0.65, depending on the season. A synthesis of current estimates of K_c developed recently (Fereres *et al.*, 2011) is given at the end of Table 1b.

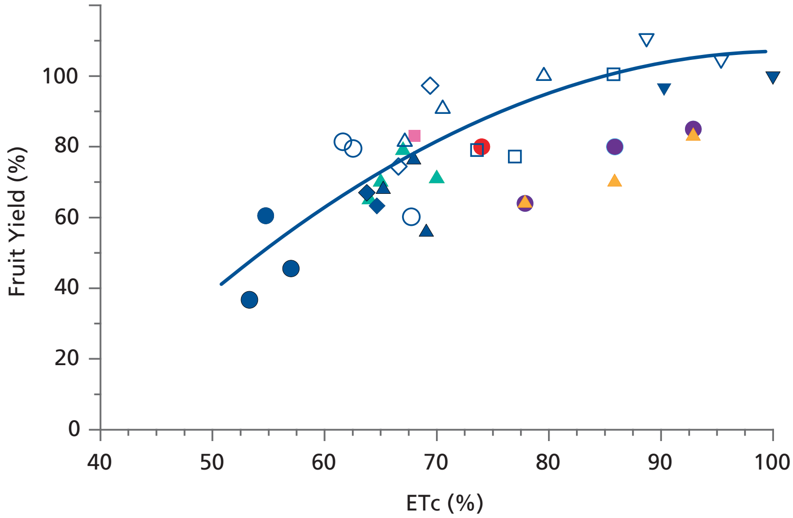
Despite the evergreen nature of the olive, the K_c is not constant throughout the year, because of tree transpiration responses to environmental and endogenous factors. Measurements have shown that relative transpiration is lowest in spring and highest in early autumn. However, the K_c also must reflect the rate of evaporation from the soil surface, which is quite high in spring in many Mediterranean environments. Thus, K_c values reflecting olive orchard water use do not differ as much between spring and autumn (see Table 1). In midsummer relatively low values of K_c are found because of partial stomatal closure in response to high vapour pressure deficit.

If more precise estimates of water use are needed, an alternative method has been proposed to calculate transpiration and evaporation independently (Orgaz *et al.*, 2006) (See Chapter 4, Box 5). For table or canning fruit production, the higher range of K_c values is recommended. Crop coefficients should be further increased (up to about 0.8 to 1.0 in winter and early spring, depending on the type of the cover crop and its density) if the orchard floor has a permanent grass cover.

WATER PRODUCTION FUNCTION

Olive fruit yield decreases as ET_c decreases below its maximum. However, it has been found that the decline in production is hardly detectable with small reductions in ET_c (Figure 4). As ET_c is further reduced, however, yields decline more. Thus, the response curve of yield (fruit or oil) to ET_c is almost linear at low levels of consumptive water use, but levels off when water consumption is high. As a result, the overall response curves are parabolic and can be described by second order equations, such as the one presented in Figure 4. The shape of the curve implies that the water productivity (WP) increases as ET decreases and, therefore, one can find an economic optimum, in terms of ET and therefore of irrigation amount, if the price of oil and the irrigation water costs are taken into consideration. The curve shown in Figure 4 is the best fit line to a dataset obtained for the cv. Picual at Cordoba, Spain (Moriana *et al.*, 2003). Additional data published for the cvs. Arbequina, Morisca, Mulhasan, Frantoio, Leccino, and also for the cv. Picual collected at another location, are also plotted in Figure 4. It appears that the data from other varieties/locations fall within the margins of error, on the curve originally obtained at Cordoba, with perhaps the cv. Morisca showing higher sensitivity

FIGURE 4 Relationship between relative fruit yield and relative ET_c for olive. Curve was obtained for the cv. Picual in Cordoba, Spain (Moriana *et al.*, 2003), and data points obtained from additional studies (Lavee *et al.*, 2007; Iniesta *et al.*, 2009; Martin-Vertedor *et al.*, 2011; Gucci *et al.*, 2007 and Caruso *et al.*, 2011) for different cultivars, as shown in the graph.



to mild ET_c deficits than the cv. Picual. More research is needed to characterize the response of the other cultivars in different environments. From the original data sets and equations in Figure 4 for Cordoba, Spain, over 700 mm of water consumed in ET_c are needed to reach the maximum olive fruit yield in that particular environment. If the effective rainfall is 400 mm, at least 300 mm would have to be supplied by irrigation to achieve maximum yields in that particular location. However, because of the shape of the yield response to ET_c, olive production responds very well when small irrigation amounts are applied to rainfed orchards. In different locations in southern and northeastern Spain (between 350-500 mm of annual rainfall), farmers are achieving WP values of up to 30 kg/ha/mm (fresh fruit) with seasonal irrigation applications of 100 to 150 mm in orchards that were previously rainfed. In coastal, central Italy (about 600 mm annual precipitation), less than 100 mm of irrigation water are sufficient to obtain yields that are over 80 percent of those of fully irrigated orchards (Gucci *et al.*, 2007). Significant increases in yield were obtained in Israel using a single irrigation of 75 mm in the middle of the summer (Lavee *et al.*, 2007).

The yield response curve to applied irrigation water is similar to Figure 4 but flatter at high irrigation levels, because the olive is capable of extracting substantial stored soil water and can compensate for reductions in applied water, as long as there is sufficient water in the root zone. The level of irrigation savings depends on the storage capacity of the soil and on the amount of rainfall needed for the sustainable replenishment of stored soil water. The response of oil production is similar to that of the response of fruit production, and the responses of oil quality are discussed below.

The yield response of table olives to a reduction in applied water (AW) is shown in Table 2 from one study (Goldhamer *et al.*, 1994). A reduction in AW of 21 percent did not affect fruit yield or revenue. A further reduction down to 62 percent of maximum AW, decreased relative fruit yield by 10 percent, and relative revenue by 25 percent. The more drastic reduction in revenue was associated with a lower price due to the reduction in fruit size.

TABLE 2 Relative yield and gross revenue of table olives under deficit irrigation (Goldhamer *et al.*, 1994).

Regulated deficit irrigation regime	Consumptive use (mm)	Gross fruit yield (t/ha)	Gross revenue (US$/ha)	Relative ET_c (%)	Relative yield (%)	Relative gross revenue (%)
Control	881	12.0	6725	100	100	100
T2	759	12.3	6750	83.9	103.1	100.4
T3	693	12.5	6700	75.4	103.7	99.6
T5	546	10.8	5050	56.3	90.0	75.1

SUGGESTED RDI REGIMES

Several specific cases are developed below for different environments and water supply situations. Table 3 illustrates an example of the water budget approach for irrigation scheduling of a young olive orchard in central Italy. Values are reported on a monthly basis, but during normal irrigation practice water budgets are calculated weekly. Two irrigation levels are used, full irrigation and 50 percent deficit irrigation. It should be noted that the early water deficit that occurred in April was unusual for this location, where the irrigation season normally starts in June. In more arid climates it is normal that irrigation starts in spring and may extend well into the fall season. Water is preferably applied to satisfy tree daily needs by microirrigation, but in poorly-drained soils it is desirable to reduce the frequency of irrigation to 1-2 times a week. The use of longer intervals with microirrigation is often inefficient because there may be significant losses to deep percolation. When water agencies supply water at longer intervals (2-4 weeks), it is desirable to build on-farm storage facilities to irrigate as frequently as needed.

Three different RDI strategies have been successfully demonstrated for olive irrigation. In the first, the planned deficit is distributed evenly throughout the whole irrigation season (sustained deficit irrigation or SDI). In the second, the deficit is concentrated in the summer period, from pit hardening until the end of the summer (RDI_1). The third strategy (RDI_2) which is intermediate between the previous two, alternates short cycles of stress and relief during the irrigation period, maintaining the SWP or predawn LWP at variable levels which are moderately low during the fruit development period. The hypothetical seasonal course of tree water status under the three different DI strategies is represented schematically in Figure 5.

There is no evidence to demonstrate the superiority of one RDI strategy over the others, as they all seem to give good results (see below). In areas where rainfall patterns are typically Mediterranean, and where soils have a reasonable water storage capacity (over 100 mm of extractable water), the RDI strategies are easily implemented with irrigation systems that have limited (below the ET needs) and fixed capacity (i.e. two emitters per tree). The irrigation system is run for the same period more or less throughout the entire season. In late spring,

TABLE 3 Sample calculation of monthly water budget for irrigation scheduling in a high density (510 tree/ha), 5-year-old olive orchard grown in a loam soil at Venturina (central Italy). Two levels (full, deficit) of irrigation are reported yearly ET_o = 965 mm; precipitation 708 mm. Flowering occurred on 13 May 2007. The crop coefficient was 0.55, the coefficient of ground cover 0.8. Average monthly min and max temperatures and ET_o are reported. Effective rainfall (ERain) was calculated as 70 percent of total rainfall (Rain), excluding precipitations less than 4 mm. (Caruso *et al.*, 2011)

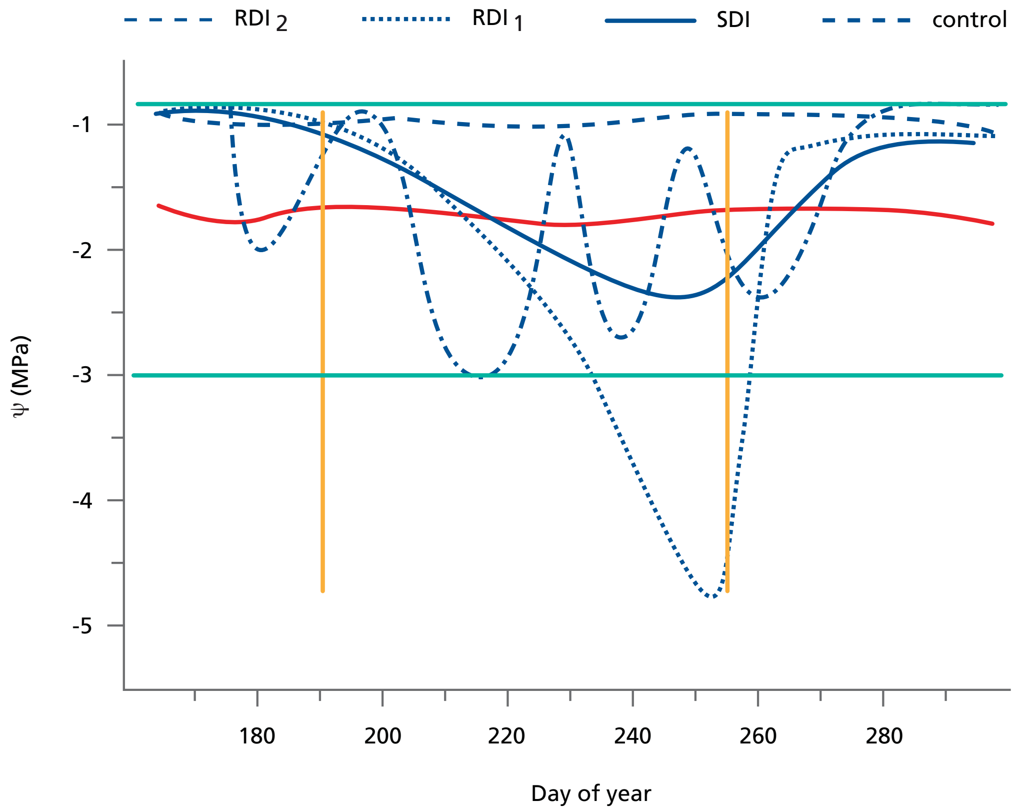
Month	T_{max} (°C)	T_{min} (°C)	ET_o (mm/day)	ET_c (mm/ month)	Rain (mm/ month)	ERain (mm/ month)	ET_c - ERain (mm/ month)	Full irrigation (mm/ month)	Deficit irrigation (mm/ month)
J	14.7	5.5	0.7	9.6	30	21	-11.4		
F	15.6	4.6	1	12.3	96.6	67.62	-55.32		
M	16.4	5.3	1.9	25.9	76.6	53.62	-27.72		
A	22.3	6.9	3.3	43.6	6.8	4.76	38.84	2.8	2.8
M	24.2	10.6	4.3	58.7	130.8	91.56	-32.86	2.8	2.8
J	27	14	4.8	63.4	68.8	48.16	15.24	3.9	3.9
J	30.3	14.6	5.4	73.7	0.6	0.42	73.28	58.9	19.7
A	29.8	12.9	4.3	58.7	36.2	25.34	33.36	36	13
S	26.7	10.2	2.8	37	19	13.3	23.7	30.4	30.4
O	22.5	7.9	1.5	20.5	88	61.6	-41.1		
N	16.8	4.7	0.9	11.9	102.6	71.82	-59.92		
D	18.1	-1.6	0.7	9.24	52.2	36.54	-27.3		

the water supply is normally adequate to meet the full ET needs, but as the summer starts and the ET_o increases, supply from the drip system is insufficient and water is extracted from the soil reservoir to meet the demand.

As the season progresses, water deficits set in, to increase in severity as the summer advances, but by the end of summer ET_o start to decline and the rains may arrive. At this time, the level of stress is reduced or eliminated, which is desirable during the fruit growth and maturation period. By manipulating irrigation frequency, the grower can run the system a fixed time (normally at its maximum capacity) and scheduling becomes straightforward. The RDI_2 approach permits the installation of irrigation systems designed to cope with situations of very limited water allocation, for instance in cases when water is drastically restricted during midsummer (mid-July, end of August) for conflicting urban uses (e.g. tourism in Liguria, Italy). A key factor for success with the RDI_2 approach is to start irrigating early enough to conserve the soil water reserve for when the ET_o demand is high.

The sustained deficit irrigation strategy (SDI) is planned by distributing the water deficit proportionally to the monthly ET requirements. In this case, for the same amount of water, the anticipated water deficits are of less magnitude at midsummer than in RDI_1, while the stress that develops earlier and later in SDI, should be of greater magnitude than in the RDI_1.

FIGURE 5 Hypothetical seasonal course of leaf or stem-water potential for olive trees subjected to different strategies of deficit irrigation. Green horizontal lines bracket the range between fully hydrated trees and turgor loss point, vertical orange lines limit the interval of water deficit. Values will vary in different climate and soil conditions. Legend: broken line, fully-irrigated baseline; solid line, SDI; dotted line, RDI_1; broken and dotted line, RDI_2.



The RDI_2 strategy may be useful in soils with a high clay percentage to allow the root system not to be exposed to high humidity for long periods.

Other RDI strategies that have been sought include the concentration of the water deficit in the 'off' year, when the crop load is so low that vegetative growth in not affected much by the water deficits. In the 'on' year, the water saved in the previous year is applied to maximize fruit production with minimum water deficits. The only published test performed with this strategy (Moriana *et al.*, 2003) did not give as good results as the previous three strategies described above. Also, the management of water supply under this strategy is not easy, and it will require commitments of water supply that exceed the current season and that, therefore, may be hard to implement by many water agencies.

Because olive irrigation is a relatively new practice, often irrigation authorities cannot deliver sufficient water to meet the full orchard requirements and are promoting deficit irrigation practices. Reasons include lack of sufficient water supply, equity considerations, the limitations imposed by the original tree spacing of the rainfed orchards, and priority for urban uses. When supply is limited to such levels, use of drip irrigation is a must, with as few emitters per tree as possible. Also, growers should irrigate as infrequently as feasible (once or twice a week) to minimize E losses and avoid prolonged exposure of olive roots to high soil-water levels in clayey soils. If supply is very limited, and a new irrigation system is going to be installed, one option would be to use subsurface drip as E losses would then be negligible.

The goals of water saving using RDI in olive orchards appear particularly interesting. Most documented evidence indicates that RDI strategies supply only 30 to 70 percent of the volume needed for fully-irrigated trees. Seasonal water volumes of as little as 50 mm are sufficient to increase yields significantly in subhumid climates, whereas about 100 mm are needed in drier climates. These amounts are definitely much less than that used in most other crops.

Today, an important issue is the use of RDI to optimize oil quality. Recent evidence shows that the concentration of phenolic compounds and volatile compounds with sensory impact can be optimized using RDI strategies rather than by applying full irrigation or under rainfed (Gomez-Rico *et al.*, 2007; Motilva *et al.*, 2000 and Servili *et al.*, 2007). The beneficial effects of moderate water deficits that are imposed by RDI on olive oil composition stemmed the term 'qualitative irrigation', an aspect which will probably be more important. There are some reports that recommend restricting irrigation before harvest to limit or avoid trunk damage during mechanical harvesting by trunk shakers and/or problems of oil extractability during processing in the mill. Deficit irrigation appears to be beneficial for optimizing the pulp-to-pit ratio in of table olives (Gucci *et al.*, 2009).

Additional considerations

Introducing irrigation to rainfed olive growing involves a number of potential side effects. Increasing incidence of Verticillium wilt (*Verticillium dahliae*) disease has been reported, especially for young orchards. There is documented evidence that inoculum density of the pathogen is higher in wet areas than in dry. Although the cause of greater incidence of Verticillium wilt in irrigated orchards is unclear, it is likely that susceptible secondary olive roots increase close to the drippers where the soil may be quite wet favouring infection, weeds survive longer and temporarily host the pathogen, and infected leaves decompose quicker under high humidity conditions (Lopez-Escudero and Blanco-Lopez, 2005). The Verticillium wilt disease is a limiting factor for irrigated orchards in some areas where localized, low-frequency irrigation is recommended as a management technique.

Further, reportedly here is an increasing damage by the olive fruit fly (*Bactrocera oleae* Gmel.) in irrigated orchards, but supporting evidence is not strong. The olive fruit fly preferably damages large fruit (cultivars of large fruit size and olive fruit with high water content are more susceptible than small), so its effect may be indirect because irrigation increases fruit size. However, it is likely that the fruit fly also enjoys more favourable conditions when humidity is higher because of irrigation in the olive orchard.

Problems of the low oil yield of fruit from fully-irrigated, very high density orchards of some cultivars have been reported, but they appear to be related to technological problems in oil extraction when fruit is highly hydrated rather than to less oil in the fruit itself. Because of the relatively high resistance to salinity, olive trees yield well when irrigated with saline waters (Gucci and Tattini, 1997).

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Citrus

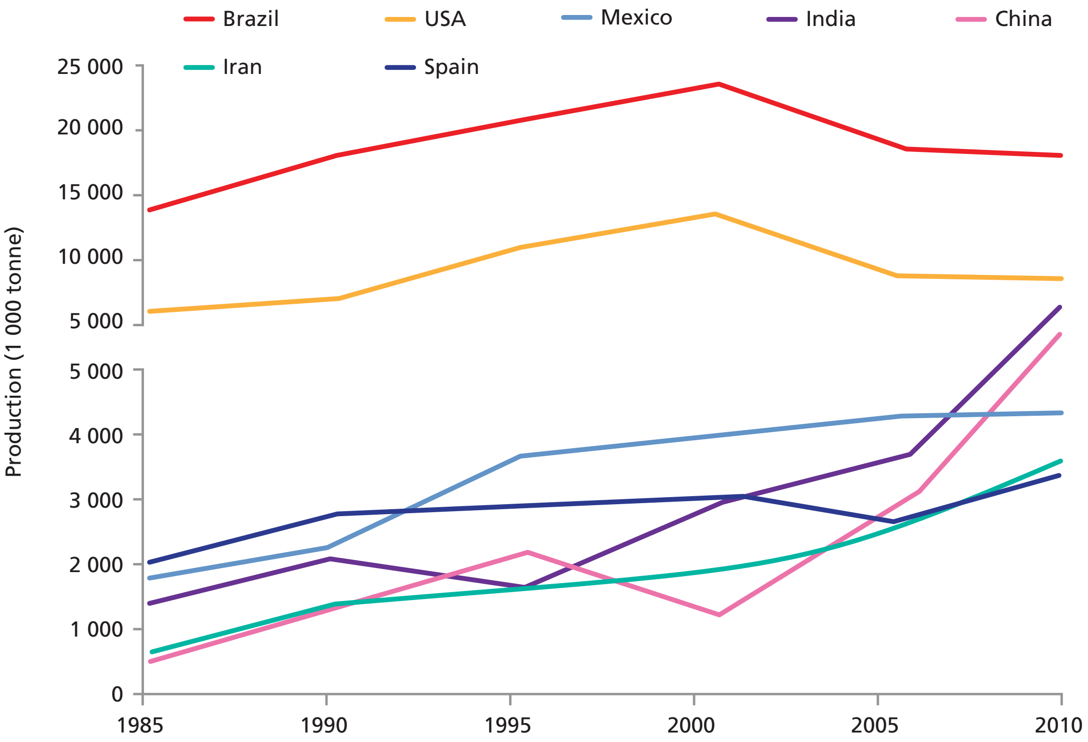
INTRODUCTION AND BACKGROUND

Citrus fruit include oranges, which account for about 70 percent of worldwide production, small citrus fruit, such as mandarins, tangerines, tangelos, clementines, satsumas, lemons, limes and grapefruit. Oranges are produced for both the fresh market and for juice — chilled single strength and concentrate. Until the middle of the twentieth century, citrus was almost exclusively cultivated locally. Speed and care when shipping the perishable fruit was of great concern. However, the development of citrus concentrate had a lasting impact on the citrus industry worldwide. Concentrating the fruit permitted the storage, transportation, and transformation of the product far from the groves. In addition to fresh fruit and juice, there are citrus by-products such as food additives, pectin, marmalade, cattle feed (from the peel), cosmetics, essential oils, chemicals and medicines.

Because citrus is an evergreen crop sensitive to low temperatures, subtropical regions produce the bulk of the world's citrus. Tropical cultivation is not as productive since seasonal changes in temperature favour adequate blooming patterns, fruit growth and fruit colour development during ripening. In fact, the high temperatures of the tropics induce fast development and production of large fruit that ripen quickly, remaining marketable for a very short time. In contrast, growth in the subtropical zones slows in the winter and fruit can remain mature on the tree for longer before it is harvested and marketed. Frost damages citrus fruit although the trees can withstand short periods of light frost. However, hard frosts of long duration kill trees and can be devastating.

Citrus fruit value ranks first in international fruit trade. In 2009, there were over 5.4 million ha of citrus (4.1 million ha of oranges) with an average yield of 16.3 tonne/ha. Figure 1 presents the trends since 1985 of the production of the world principal countries (FAO, 2011). As a result of trade liberalization and technological advances in fruit transport and storage, the citrus fruit industry is becoming more global. During the last decades, citrus production and trade have increased steadily; although the intensity of growth varied according to the type of fruit (it has been stronger for small fruit and juice). Citrus production is evolving in a context of highly competitive global markets. There is an apparent ever-increasing focus on the quality and the value-added aspects of the products. Citrus is often promoted for its health and nutritive properties; rich in Vitamin C, folic acid, and fibre.

FIGURE 1 Production trends for citrus in the principal countries (FAO, 2011).



Quality considerations

The goal of citrus production is to harvest as large and as high-quality crop as possible. In this case, quality refers to fruit size, peel colour and appearance, chemical constituents, and taste. Fruit size is usually the primary factor in determining fruit value. In general, larger fruit is more valuable than smaller. However, cultivars, harvest time, local preferences, and market factors can exhibit extreme influences on fruit value. Of the quality factors, peel appearance is usually most important with a smooth, deep coloured and blemish-free peel being most desirable. One limitation of citrus production in the tropics is that fruit remain green and do not change colour when mature. In terms of taste, most people prefer a balance between sweetness and tartness, as measured by the soluble solids-acid ratio (TSS/TA). Juice content is another quality factor, particularly for lemons and limes. In general, citrus fruit have a high postharvest storage potential; from weeks for mandarins and up to six months or more for lemons.

GROWTH AND DEVELOPMENT IN RELATION TO YIELD DETERMINATION

The growth of citrus trees can be divided into vegetative and reproductive stages. Vegetative growth includes the growth of roots, stems, leaves and new flushes. Reproductive growth includes flower bud initiation, differentiation, flowering, fruit set, fruit development and fruit maturity.

Early vegetative and reproductive growth

Under subtropical climate conditions in the Northern Hemisphere (California, for example), the main vegetative growth flush occurs in late February and March. There are normally additional growth flushes in the summer and autumn. Leaves are viable for about two years. Leaves are continuously replenished although leaf drop is generally highest during the spring.

Most citrus cultivars produce flowers in the spring and are self-compatible; they may be fertilized by their own pollen. In cool, coastal climates, flowers may be produced throughout the year but maximum flowering is also in the spring. Flowers develop in leaf axils on older shoots as opposed to shoots developing in growth flushes.

Citrus trees produce a large amount of flowers resulting in small fruit. However, a large percentage of these small fruit drop from the tree apparently because of a combination of physiological and environmental factors. There appears to be a hierarchy of flowers relative to fruit drop; flower in locations with a higher flower/leaf ratio are more subject to drop. Flowers that open late in the bloom period are more likely to set fruit that survives to harvest than fruit set from early flowers. Likewise, faster growing fruit is less apt to drop than slow growing fruit.

The primary factor controlling the dropping of flowers and young fruit is a weakening of tissue in a preformed abscission zone at the point of attachment at the base of the ovary to the disk or of the pedicel to the stem. The actual mechanism of the process is not well understood but is believed to be triggered by growth regulators in response to either external or internal changes. Young fruit that remain after the first period of dropping presumably are capable of developing to maturity if the weather is favourable. Nevertheless, some dropping of fruit occurs throughout the season. As the weather becomes hotter in the early summer months, there is generally a period of accelerated fruit drop, which is often referred to as the 'June drop' period. If the heat is severe and prolonged for several days, fruit drop can be heavy, resulting in a greatly reduced crop. This has been observed in several cultivars of the navel and Valencia types. Some cultivars, notably Valencia and mandarins, have an alternate bearing cycle; light crop years following heavy crop years.

Fruit development stage

Following early season fruit drop, and after the leaves of new flushes have fully expanded, the remaining fruit begin to develop initially by rapid cell division. At this point, a cross-section of the fruit clearly reveals its component parts:

- **Flavedo** (*epicarp*) – a rough, robust and bright colour (from yellow to orange) skin or rind that covers the fruit and protects it from damage. Its glands contain the essential oils that give the fruit its typical citrus fragrance.

- **Albedo** (*mesocarp*) – a white, spongy tissue that, together with the flavedo, forms the peel (pericarp) of the fruit.

- **Pulp** (*endocarp*) – the internal part is comprised of individual segments or juice sacs. This is the edible part of the fruit and the source of the juice.

Fruit growth during this stage is temperature dependent; extremely high or low temperature can slow growth. Cell division is followed by cell enlargement. It is during this period that the peel reaches maximum thickness. Later, as the pulp expands, the peel becomes thinner. The fruit continues to grow as long as it is on the tree, albeit slower as temperatures fall.

The potential fruit size at harvest is highly dependent on environmental factors that exist during cell division. The conventional wisdom is that any decrease in the rate of cell division will directly translate into reduced potential fruit size at harvest. Once the fruit growth cycle passes from a predominant cell division phase to a primarily cell expansion phase, fruit size at harvest is not as susceptible to growing conditions. As for other fruit crops, there are trade-offs in citrus between fruit number and size; large numbers per tree leads to small individual size. Both very small and very large fruit fetch lower prices in most fresh markets but there is a wide range of acceptable sizes for citrus. When citrus are grown for juice, fruit size is relatively unimportant.

Fruit maturation stage

The beginning of this stage is usually characterized by the onset of fruit colour change, triggered by the cooler night temperatures in the subtropical regions. The fruit is still increasing in size but at a much slower rate than previously. During fruit maturation, the juice content of the pulp increases. The acid content of the fruit decreases as the sugar content increases. Unlike many deciduous fruit, there is no precise point that indicates maturity in citrus. In California, the basis for legal maturity of oranges is a ratio of 8-to-1 for total soluble solids to titratable acidity (TSS/TA); the so-called sugar-acid ratio. The balance between sugars, which accounts for about 75 percent of the total soluble solids, and the sourness produced by acidity is the best criterion in correlating fruit quality with consumer acceptance.

Peel colour is also used as a maturity index but this approach is not reliable since peel colour depends on temperature. Moreover, harvest timing is highly influenced by market prices and processor availability. Hormonal sprays, such as gibberellic acid, are used to prolong the viability of fruit on the tree. If left on the tree too long, the fruit is subject to drop, insect/ disease damage, and breakdown of the acid and flavor components.

RESPONSES TO WATER DEFICITS

There is a large body of work on the responses of different citrus physiological processes to water stress. Many species, cultivars, and growing conditions have been studied. Since responses vary with the timing of stress during the season, the year was divided into seasons and unless otherwise noted the information focused on orange response.

Spring stress

In terms of eventual impact on yields, the flowering and fruit set period has been repeatedly identified as the most sensitive to stress for small citrus, such as clementines (Gonzalez-Altozano and Castel, 1999) and oranges (Pérez-Pérez *et al.*, 2007). This resulted in the increased abortion of small fruit (June drop). On the other hand, there are reports indicating that early season stress significantly reduced peel creasing in a particularly vulnerable navel cv. (Frost Nucellar) without negative impacts on harvest fruit load or size (Goldhamer and Salinas, 2000).

Summer stress

During this period of cell expansion in the fruit, deficit irrigation can reduce the fruit growth rate. In fact, severe stress can result in fruit shrinkage. However, reintroduction of full irrigation can increase the fruit growth rate, such that harvest fruit size is unaffected (Goldhamer and Salinas, 2000). This has been attributed to the maintenance of dry matter accumulation in the fruit during the stress period and/or full rehydration of the fruit upon reirrigation. Under the experimental conditions on the east coast of Spain (Gonzalez-Altozano and Castel, 1999), summer stress had no impact on clementine yield as long as predawn leaf water potential (LWP) was not reduced below -1.3 MPa. However, severe stress for a prolonged duration during the summer can reduce harvest fruit size, tree growth and increase sugars (Mantell, 1977). Harvest sugar concentration can increase because of summer stress, presumably the result of fruit dehydration. Of the two primary yield components, fruit size is more susceptible to reduction than fruit load as a result of summer stress. Working with cv. Valencia, it was found that moderate stress in the summer and fall did not reduce yields in Arizona (Hilgeman and Sharp, 1970).

It should be noted that the imposition of severe stress during the summer has been used with lemons to induce an off-season bloom and resulting summer harvest fruit. This is known as the Forzatura technique or the Verdelli effect. In one study that withdrew irrigation for nine weeks starting in June, predawn LWP reached - 2.7 MPa (Barbera and Carimi, 1988). This regime yielded 30 kg/tree in each of the summer and winter harvests. They found that insufficient stress resulted in the lack of off-season flowering but that when stress was too severe, it produced excessive leaf drop, higher flower abortion, winter fruit drop and reduced winter harvest fruit quality (Barbera and Carimi, 1988).

Autumn stress

As opposed to stress-induced reductions in fruit growth being overcome upon the reintroduction of full irrigation, reducing fruit growth in the autumn usually results in smaller fruit at harvest. Irrigation of clementines at 25 and 50 percent ET_c during late summer/early fall reduced harvest fruit size by 11 and 25 percent, respectively (Gonzalez-Altozano and Castel, 1999) and produced more fruit peel creasing, as has been found with navel oranges (Goldhamer and Salinas, 2000). Both studies found no influence of autumn stress on fruit load.

In addition to reducing fruit size, numerous studies have shown that autumn stress can increase both the sugar and acid content of the fruit as well as increase the peel thickness.

Winter stress

In most citrus producing areas of the world, winter soil water deficits are unlikely to occur because of rainfall. However, in Florida, water restrictions applied to Valencia oranges, during the winter were used to modify the timing of flowering, delaying bloom dates by two to four weeks (Melgar *et al.*, 2010). The fruit were able to overcome a fruit size reduction during the following spring when irrigation was restored to full crop water needs. This was because Valencia is a very late-season cultivar and fruit had three to four months to recover to the optimum size. In this case, winter stress was used to reduce immature fruit drop for the next season's crop during mechanical harvesting with trunk shakers.

Season-long stress

Several studies have imposed deficit irrigation throughout the season. Some of these imposed irrigation regimes based on tensiometer readings. A value of 70 kPa as a threshold was used which caused delayed bloom, flower opening, and decreased fruit set with cv. Valencia (Davies and Bower, 1994). In a study with the cv. Shamouti where tensiometers were used, with 35 percent less applied water than fully irrigated trees, flowers per tree increased by 52 percent but the flower abscission rate was high. This resulted in a 20 percent lower yield but higher sugars and acid (Moreshet *et al.*, 1983). Another study showed that allowing 80 percent depletion of available water in the surface 1 m in the summer and winter and 60 percent depletion in spring and autumn did not reduced yields with navels (Wiegand and Swanson, 1982). The same regime reduced fruit weight in cv. Valencia. No applied water data was given and it was difficult to judge the level of stress that the depletion of soil water induced in the trees. Another approach to produce season-long stress is to irrigate at fractions of ET_c. For grapefruit, applying 35 percent less than full ET_c delayed maturity and reduced yield by 13 percent due to both smaller fruit and lower fruit load. The sugar and acid content was higher while there was no impact on the sugar/acid ratio (Eliades, 1994). For navels, irrigating with 22 and 46 percent less than full ET_c reduced yields by 7 and 22 percent, respectively (Brych and Luedders, 1988). Finally, for clementines the application of 55 percent of tree water needs during the entire season reduced yields by only 17 percent (Gonzalez-Altozano and Castel, 1999).

Indicators of tree water status

The established indicator of tree water status is the stem-water potential (SWP) as measured with the pressure chamber. A simpler and less time-consuming approach is to measure the water potential of shaded leaves. Both Goldhamer with navels, and Castel with clementines, found the slope of regression lines very close to unity and high correlations between this measurement and SWP (slopes of 0.97 and 0.98; R^2 of 0.95 and 0.96, respectively). Midday SWP values above – 1.0 MPa indicate the absence of water stress for a typical summer day of ET_o about 6-7 mm/day. Values between – 1.0 and -1.5 MPA are indicative of mild stress. Citrus can withstand more negative SWP than other fruit trees and vines. Trees show hardly any visual symptoms of stress with SWP of -2.0 to -2.5 MPa. Severely stressed orange trees that had predawn LWP around -6.5 MPa recovered their water status within a week of rewatering although they experienced severe defoliation and took several weeks more for complete functional recovery (Fereres *et al.*, 1979).

WATER USE REQUIREMENTS

Orchard transpiration, the primary component of ET_c, depends directly on stomatal conductance and scientists recognized early on that the stomatal behaviour of citrus differs significantly from that of most other crop plants. An early comparative study found that maximum stomatal conductance (Gl) of soybean, wheat, and orange under fully irrigated conditions was 1.0, 0.60, and 0.48 cm/s, respectively, and occurred at about 09:00 hours. They attributed this to differences in stomatal opening and densities (Meyer and Green, 1981). A comparison of citrus Gl against that of almond and pistachio under similar conditions in the San Joaquin Valley of California carried out by Goldhamer showed that citrus reached a Gl maximum of around 0.4 cm/s at 08:00 hours and declined steadily thereafter. By contrast, almond had its highest Gl of close to 1 cm/s at 12:00 hours, and pistachio reached an even greater Gl value of 1.15 cm/s at 10:00 hours, more than twice the maximum citrus Gl. Both pistachio and almond maintained similar high values throughout most of the day.

Since citrus is an evergreen plant, many water use studies report a single crop coefficient (K_c) value. These include 0.62 for Valencia in Sunraysia (Grieve, 1989), 0.44 for clementines in Mazagon, Spain (Villalobos *et al.*, 2009), and 0.52 for lemons in Ventura, California (Grismer, 2000). Others have divided the season into winter and summer and suggested that the K_c was 0.70 and 0.65, respectively. They suggested increasing these values by 0.1 or 0.2 for humid and semi humid regions (Allen *et al.*, 1998).

Many studies indicate that, compared to the summer, the citrus K_c is slightly higher in the winter and early spring and appreciably higher in the autumn. This is generally attributed to the citrus stomata being sensitive to evaporative demand (the air vapour pressure deficit, VPD), closing under dry, hot, windy conditions and opening under the opposite conditions. Thus, the K_c in the mild Mediterranean and coastal climates should be higher than those of more arid, inland valleys. In addition, in Mediterranean environments, high K_c values in winter reflect high soil evaporation rates from frequent rainfall during that part of the season. Not all studies found that the K_c was minimum in the summer. One study for cv. Valencia (Hoffman *et al.*, 1982) and another for navels (Chartzoulakis *et al.*, 1999) reported just the opposite.

The monthly K_c values published in six studies are summarized in Table 1. These include the cvs. Salustiana and Valencia under a variety of different climatic conditions. Spring K_c ranged from 0.49 in Valencia, Spain (navel) to 0.77 (Valencia) in Kiyú, Uruguay with a mean value of 0.63. For the summer, minimum and maximum values were 0.52 for cv. Shamouti in Rehovot, Israel and 0.87 for cv. Valencia in Kiyú, Uruguay, respectively, with a mean value of 0.66. Autumn minimum and maximum values were 0.58 for Shamouti in Rehovot, Israel and 0.85 for navels in Tempe, Arizona, respectively, with a mean value of 0.73.

Working with drip irrigated clementines in a precise weighing lysimeter in Valencia, Spain, Castel found that the annual K_c was linearly related to ground cover and reported the following relationship:

$$K_c = 0.006 \text{ ground cover} + 0.272 \quad (R^2 = 0.96)$$

He also emphasized that the K_c will depend on the frequency of wetting of the orchard floor; he found that without rain, surface evaporation for young drip irrigated trees varied between 8 to 30 percent of total ET_c while after a rain, it reached 30 to 50 percent of total (Castel, 1997).

Actual annual ET_c values will, of course, depend not only on the K_c but on evaporative demand and, to some degree, irrigation frequency and the amount of wetted surface area. The range of reported ET_c worldwide include 820-1 200 mm in Florida and 1 080-1 500 mm in Arizona, Unites States, 1 300 mm in South Africa, and 800- 850 mm for the coastal areas of East Spain and Israel.

TABLE 1 Published monthly crop coefficients (K_c) for different mature orange cultivars from different locations. All studies used the water budget to determine consumptive use.

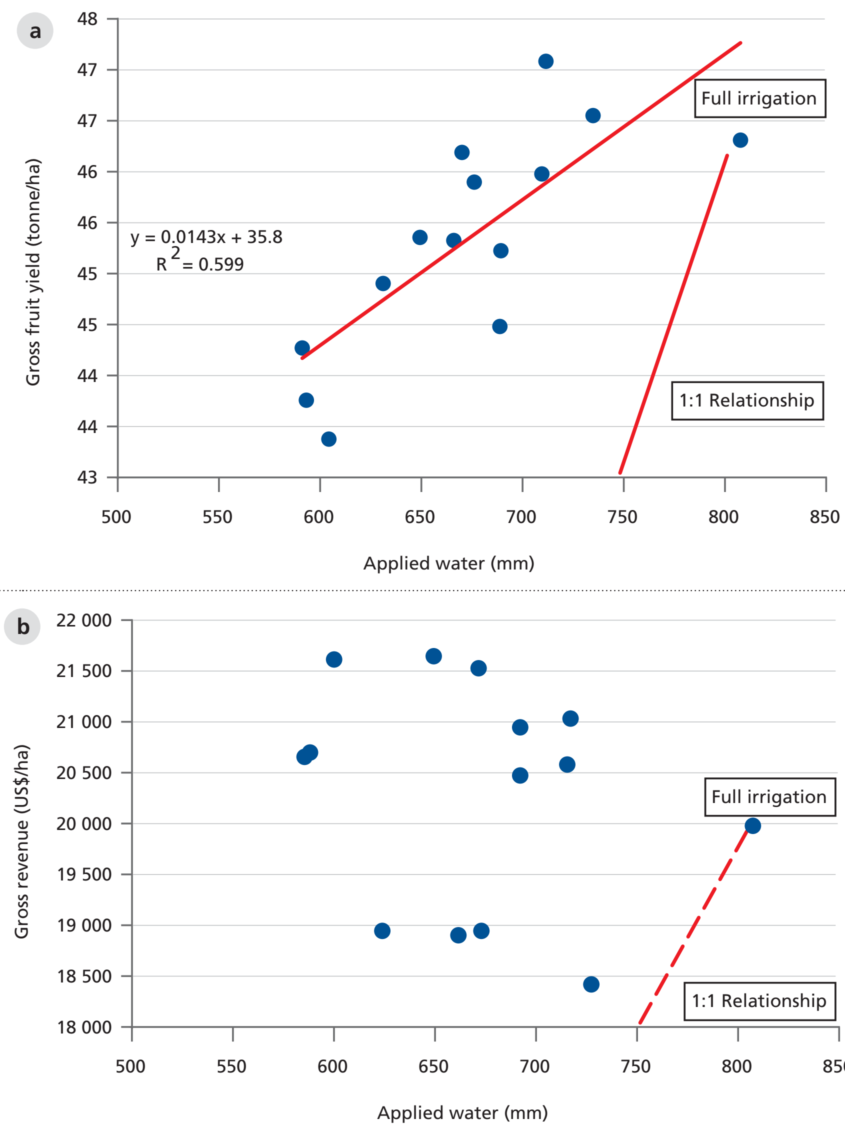
Source:	**Castel & Buj, 1989**	**Castel *et al.*, 1987**	**Van Bavel *et al.*,1967**	**Hoffman *et al.*, 1982**	**Kalma and Stanhill, 1969**	**García-Petillo and Castel, 2007**
Cultivar:	Salustiana	Washington Navel	Washington Navel	Valencia	Shamouti	Valencia
Location:	Valencia, Spain	Valencia, Spain	Tempe, Arizona	Yuma, Arizona	Rehovot, Israel	Kiyú, Uruguay
January	0.66	0.54	0.57	0.43	1.08	0.51
February	0.65	0.63	0.46	0.42	1.37	0.62
March	0.66	0.47	0.43	0.66	0.73	0.71
April	0.62	0.53	0.55	0.56	0.63	0.78
May	0.55	0.48	0.72	0.69	0.70	0.83
June	0.62	0.57	0.74	0.74	0.56	0.86
July	0.68	0.59	0.75	0.78	0.56	0.88
Aug.	0.79	0.68	0.76	0.87	0.45	0.87
Sept.	0.74	0.62	0.76	0.87	0.41	0.85
Oct.	0.84	0.68	0.85	0.79	0.62	0.81
Nov.	0.73	0.75	0.93	0.45	0.70	0.75
Dec.	0.63	0.79	0.75	0.34	1.34	0.67
Mean	0.68	0.61	0.69	0.63	0.76	0.76
Dec., Jan., Feb.	0.65	0.65	0.59	0.40	1.27*	0.87
March, April, May	0.61	0.49	0.57	0.64	0.69	0.80
June, July, Aug.	0.70	0.61	0.75	0.80	0.52	0.60
Sept., Oct., Nov.	0.77	0.68	0.85	0.70	0.58	0.77

* *High K_c values in winter re ect high soil evaporation rates from seasonal rainfall in a Mediterranean environment.*

WATER PRODUCTION FUNCTIONS

The two primary yield components of citrus are fruit load and individual fruit weight. Visual appearance and the market values of different size fruit play a large role in determining the net worth of a citrus crop, as they are in many tree and vine crops. This is illustrated with two examples from orange navels in the San Joaquin Valley, California (Goldhamer and Salinas, 2000 and Goldhamer, 2007). The mean gross tonnage from the final three years of a four-year experiment where 13 different RDI regimes of various stress timings and durations were imposed is shown versus applied water in Figure 2a. A linear expression fairly well describes the relationship (R^2=0.59) with a slope of about 2:1 in terms of reduced applied water: gross tonnage reduction. The primary difference in crop performance between the RDI regimes was

FIGURE 2 (a) Crop, and (b) Gross revenue versus applied irrigation water for Frost Nucellar navels grown in the southern San Joaquin Valley of CA, USA. Data are mean values of the final three years of a four year RDI study (adapted from Goldhamer and Salinas, 2000).



that early stress significantly reduced creasing; the primary peel defect. There was relatively little impact of any of the regimes on fruit size and fruit load. The reduced creasing resulted in a higher percentage of the fruit being graded as Fancy and thus, highly marketable in the fresh market, rather than being designated as Choice that has much less value to the grower. This caused the value of the fruit in the early stress regimes to be significantly higher than the fully irrigated trees. This materially changed the relationship between gross grower revenue and applied water, as shown in Figure 2b, as compared with the yield-applied water relationship (Figure 2a).

Fruit size plays an important role in determining the value of fresh market fruit. Generally, large size fruit is preferred – very large size fruit as well as smaller fruit is normally worth less. However, the prices paid in the United States market for different fruit sizes can vary widely over the season for both grades of marketable fruit – Fancy and Choice (Table 2). For early harvest fruit where sizes tend to be smaller, the most desirable size is large (40 to 48 fruit/box). However, as the harvest period progresses and the fruit on the tree continues to grow, large fruit becomes the dominant size and the value of the scarcer smaller fruit increases. With the very late harvest varieties, fruit may became very large, which makes it almost worthless; in the example provided, the value is only US$5.00/box for the 24-36 fruit/box size compared with over US$14/box for the medium fruit size of 56-72 fruit/box (Table 2). On the other hand, this same very large size category (24-23 fruit/box) is worth twice that with the early harvest. Because of the desirability of having smaller fruit for the late harvest varieties, RDI can be an effective tool if the fruit size distribution can be shifted toward smaller sizes and there is no concomitant negative impact on other yield components.

The classical water production function relates yield to consumptive use. There are two issues with citrus that limit the usefulness of this relationship. First, crop revenue (US$/ha) depends not only on yield (kg/ha) but also on fruit value (US$/kg), which, in turn, is a function of fruit size, peel appearance, and fresh market prices. Second, most published studies of the impact of irrigation on production only report applied water, (many do not even report that), and do not attempt to quantify consumptive use (ET_c), limiting the applicability of the reports.

TABLE 2 Typical early (Frost Nucellar) and late (Lane Late) harvest fresh market fruit values to the packer for different navel fruit sizes in the southern San Joaquin Valley, California. Values are shown as US$/box (Goldhamer *et al.*, 1994).

		Fruit size category			
		88-163	56-72	40-48	24-36
		(fruit/box)	(fruit/box)	(fruit/box)	(fruit/box)
Early harvest	Fancy	7.50	12.00	12.50	10.00
Frost Nucellar	Choice	6.64	7.87	8.00	5.17
Late harvest	Fancy	12.26	14.15	7.50	5.00
Lane Late	Choice	7.62	8.44	5.72	3.00

Four crop-water-production functions are shown in Figure 3a, each for a different cultivar. Three are from California and one from Spain. Each of the data sets involved field experiments on mature trees that were conducted over at least four years. First order best fit lines for all studies show fairly strong correlations with correlation coefficients ranging from 0.68 to 0.98. The best fit linear expressions for the Frost Nucellar and the Lane Late studies in California have slopes less than one; the Parent Washington study in California has a slope of almost exactly one, and the Clementine study in Spain has a slope greater than one, suggesting that this cultivar may be more sensitive to water deficits than navel oranges.

The revenue-water-production functions (Figure 3b) generated from three of these studies (the Clementine study did not include revenue data) have a much different appearance than their companion crop-water-production functions. With the exception of the Parent Washington study, it is obvious that the relationships between gross revenue and consumptive use are not linear. The Lane Late study shows that revenues can be increased by about 80 percent with RDI regimes that reduce consumptive use by either 10 (late season stress) or 40 percent (season-long stress). On the other hand, a less successful RDI regime (midseason stress) reduced revenue by 15 percent with a 23 percent reduction in consumptive use. This large range in relative gross revenues for different RDI regimes clearly illustrates the importance of stress timing in some citrus varieties.

Both the Lane Late and Frost Nucellar orange studies show that gross revenue can be increased and/or consumptive use dramatically reduced with optimal RDI regimes. The results from these cultivars differ markedly than that of Parent Washington. The reason is that both of the former cultivars had production problems that were lessened with the successful RDI regimes — peel creasing with Frost Nucellar and excessively large fruit with Lane Late. There were no identifiable issues of peel appearance and/or fruit size with the Parent Washington. Nevertheless, the Parent Washington data show that consumptive use can be reduced by 7 percent with no impact on gross revenue or 18 percent with only a 6 percent decrease in gross revenue (Figure 3b).

SUGGESTED RDI REGIMES

Soil water instrumentation has been used for many years to monitor irrigation and impose water deficits in citrus. Hilgeman and Sharp (1970) used tensiometers in their RDI work with Valencia oranges. They recommend full irrigation from March through mid-July, then irrigating when tensiometers reach 75 cbar. This regime reduced irrigation by 66 percent relative to fully irrigated trees. Yield was not reduced, sugars were higher, and the resulting smaller trees were easier to pick. However, since fruit value depends on many factors discussed previously, it must be emphasized that a successful RDI approach on a given cultivar in a given location will not likely be optimal for other cropping situations. Additionally, it is dangerous to recommend soil-based stress thresholds because of differences in soils, placement of the instrument (depth and location), irrigation methods, and varieties/cultivars.

The easiest approach to imposing RDI regimes is to irrigate at given percentages of maximum ET_c at specific periods of the season. For the Frost Nucellar cv., it is recommended to irrigate at 50 percent ET_c from mid-May through early July (Goldhamer and Salinas, 2000). Goldhamer found that a late summer/early autumn stress was optimal with Lane Late in shifting the fruit

FIGURE 3a Crop-water production functions for four studies of different orange cultivars from Spain (Castel and Buj, 1989) and CA, USA (Goldhamer and Salinas, 2000; and Goldhamer *et al.*, 2007). Each study was at least four years in duration. Slopes, intercepts, and correlations coefficients for the best fit lines are shown in Table 3.

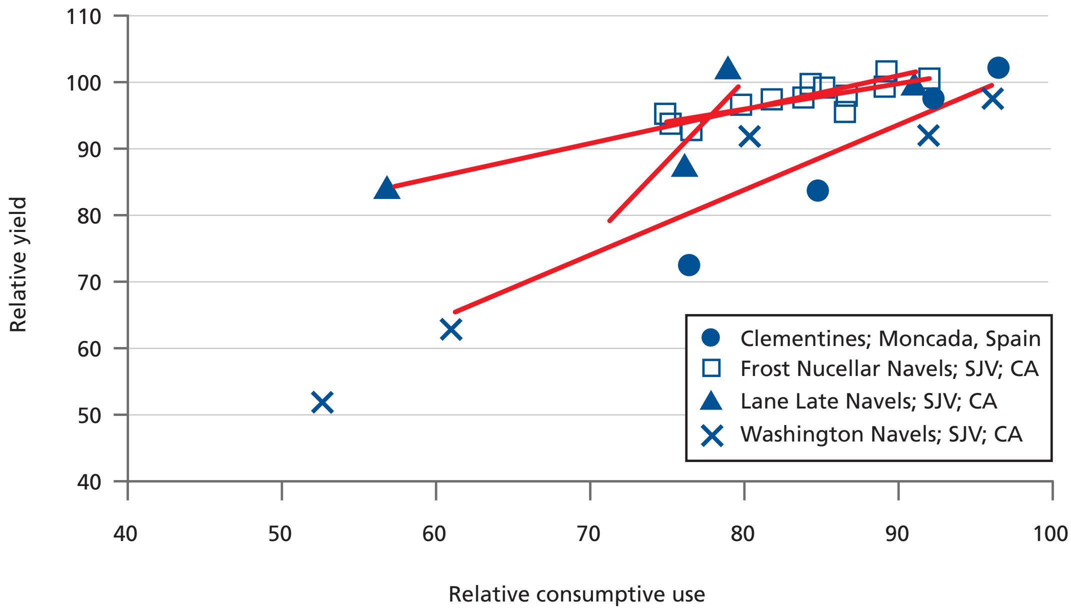
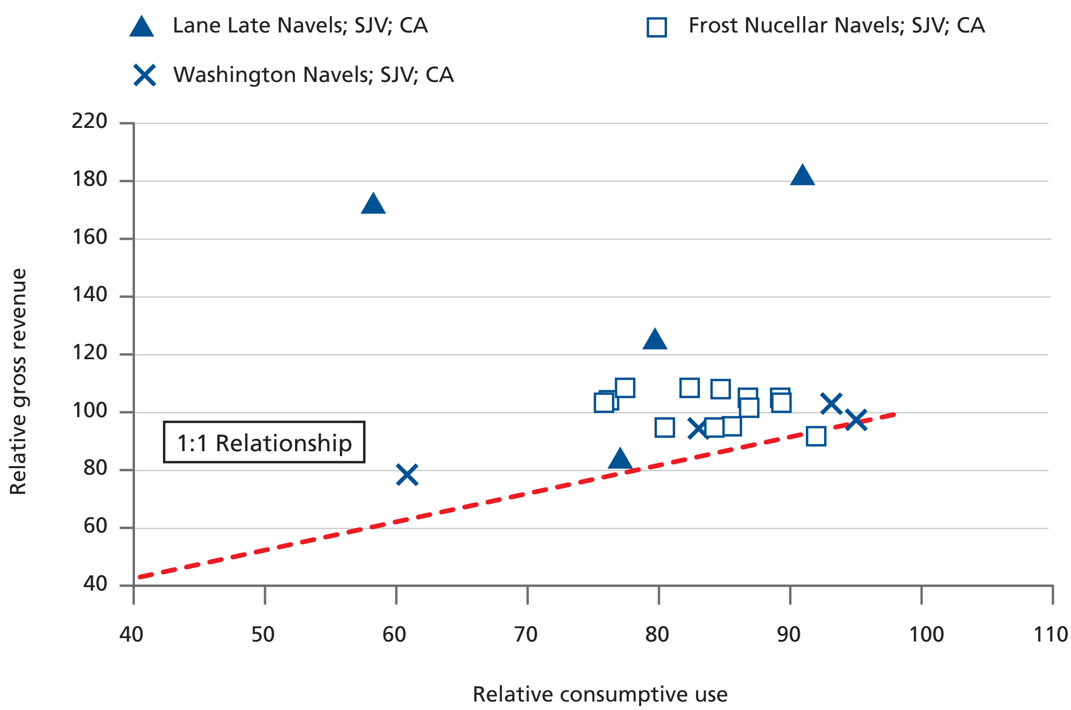


FIGURE 3b Gross revenue-water production functions for three of the studies shown in Figure 3a.



size distribution toward more favourable fruit value and thus, increasing grower revenue. On the other hand, in a small citrus fruit such as Clementina de Nules, it was concluded that the best RDI strategy was irrigation at around 50 percent ET_c from July (after June fruit drop) to the beginning of September when late summer autumn rainfall helped to quickly release plant water stress (Gonzalez-Altozano and Castel, 1999). The usefulness of this strategy has also been recently corroborated in commercial situations (Ballester *et al.*, 2011).

It should be noted that the utility of ET_c-based RDI regimes depends, in part, on soil conditions and the amount and storage of winter rainfall in the root zone, especially early in the season. For example, with relatively high winter rainfall, deep soils, and a full coverage irrigation system that promotes roots in the entire potential root zone, reducing applied water early in the season may not induce tree water deficits and will not have much impact on tree water status. On the other hand, with the opposite conditions — low winter rainfall, shallow soils, and localized (drip, microsprinkler) irrigation, there will likely be a rapid decline in tree water status in response to deficit irrigation soon after is imposed.

For this reason, the use of a plant-based indicator of tree water status is highly recommended when applying RDI for validating that the desired stress level is being achieved in the tree. In conclusion, given the very wide diversity of combinations of species, cultivars, market and growing conditions that exist in citrus, the need to tailor RDI strategies to specific conditions is even more pressing that for other fruit trees and makes it difficult to recommend generalized RDI programmes.

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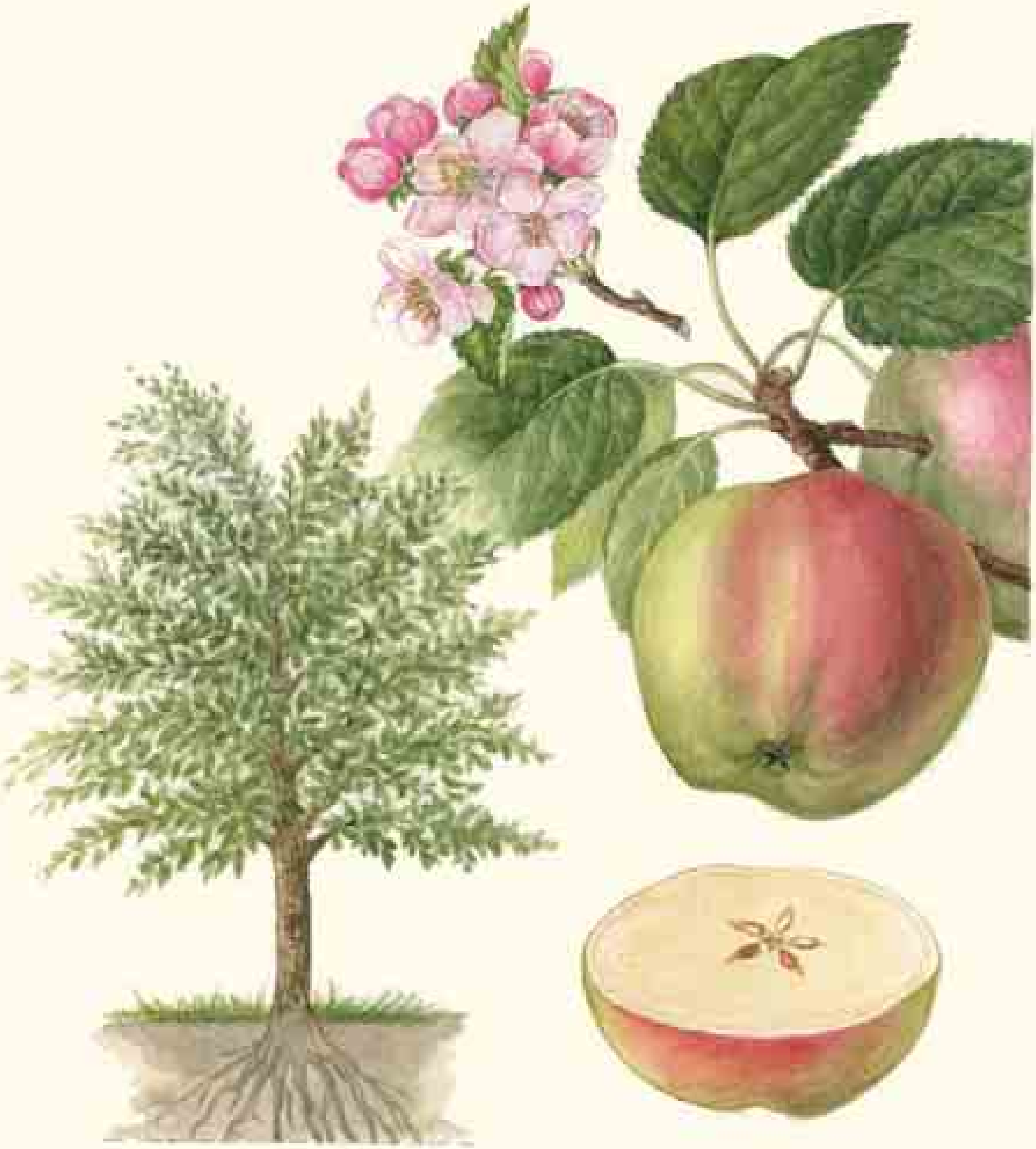

Apple

Apple

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INTRODUCTION AND BACKGROUND

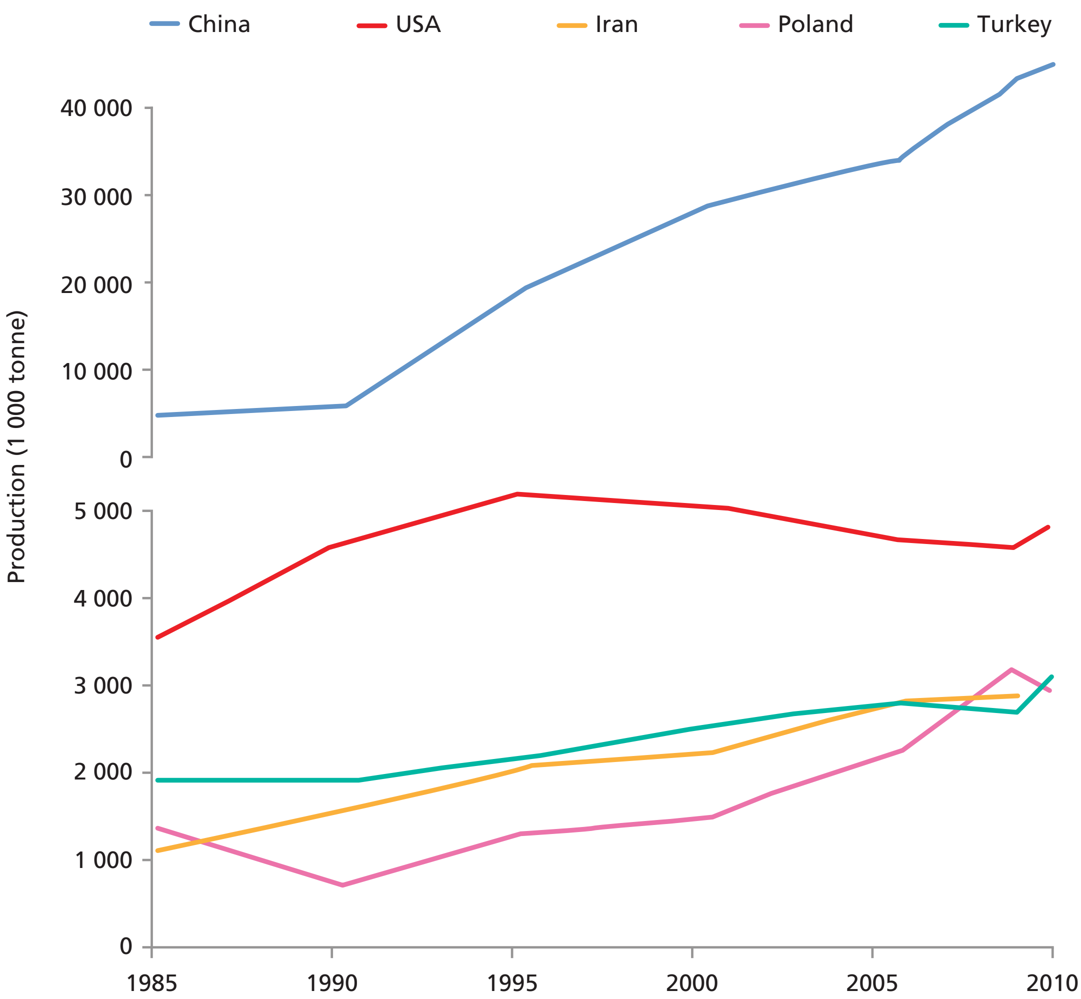
Apple (*Malus domestica* Mill.) is one of the most widely cultivated fruit crops and is produced commercially in over 80 countries around the world (FAO, 2011). Its production is the third highest fruit crop in the world after banana and grape and is ranked second behind grape for area. Most apples are grown in temperate zones because of the high chilling requirements for proper bud break in the spring. The development of apple varieties with low chilling requirement and the use of dormancy-breaking chemicals has enabled the migration of apples towards warmer regions. Production areas have increased significantly in recent decades until 2000, when China took the lead in production. Total production of apples stabilized during 2000-2010 at 60 to 70 million tonne/year. In 2009, the harvested area exceeded 4.9 million ha with an average yield of 14.7 tonne/ha (FAO, 2011). Figure 1 shows the production trends of the principal countries. China is the largest apple-producing country (42 percent of world production) and its production is six-fold larger than the second country (United States, 7 percent).

The duration of the season from bud break to harvest varies widely among varieties, from 70 days up to 210 days (Westwood, 1993) and it is correlated with the storability duration.

Apple originated in Central Asia, where its wild ancestor is still found today. There are more than 7 500 known cultivars resulting in a wide-range of fruit characteristics. Cultivars vary in their yield, fruit size, colour, taste, and the ultimate size of the tree, even when grown on the same rootstock. Apple is grown in a wide-range of environments, in many areas of Asia and other continents. In Europe from Scandinavian countries in the north to Italy in the south, in South Africa, Australia and New Zealand, United States and Canada, and in the southern countries of South America. The optimum climatic requirements might be characterized as cool to cold winters followed by a rapid rise in temperature in spring.

Apple has two types of buds, pure vegetative and mixed buds containing a floral bud that has several vegetative buds at its base. The floral bud generates an inflorescence that usually has five flowers. Flower buds are borne terminally on shoots and spurs and, to some extent, on lateral buds of one year-old shoots. Most apple varieties have self-incompatibility (Goldway *et al.*, 2007) thus growers usually include more than one variety within each plot, and some orchard growers use crab apples as pollinators.

FIGURE 1 Production trends for apples in the principal countries (FAO, 2011).



Quality considerations

There are many features that affect apple fruit quality for the fresh market. External features such as size, colour, shape and appearance are very important. For many markets, fruit that is smaller than 65-70 mm in diameter have a price penalty. Depending on the variety, the background and superficial skin colours, whether green, yellow, red or red striped play an important role in fruit appearance, and therefore its fresh market value. Skin blemishes such as sunburn, russeting and other markings negatively affect fresh quality. Flesh texture and firmness are important attributes, and are affected by environmental factors, cell wall properties and calcium content. Fruit composition in terms of sugars, acids and different aromas is variety dependant and has a strong influence on fruit taste and quality. Postharvest handling in controlled atmospheres, now commonly for this fruit months after harvest, is critical in terms of maintaining fruit quality and to limit the numerous physiological disorders that may appear during storage.

Apples tend to have a biennial bearing pattern where the degree of biennial bearing varies with varieties (Lauri *et al.*, 1996) and potential crop yield is highly affected by the timing of fruit thinning and the crop load in the previous season.

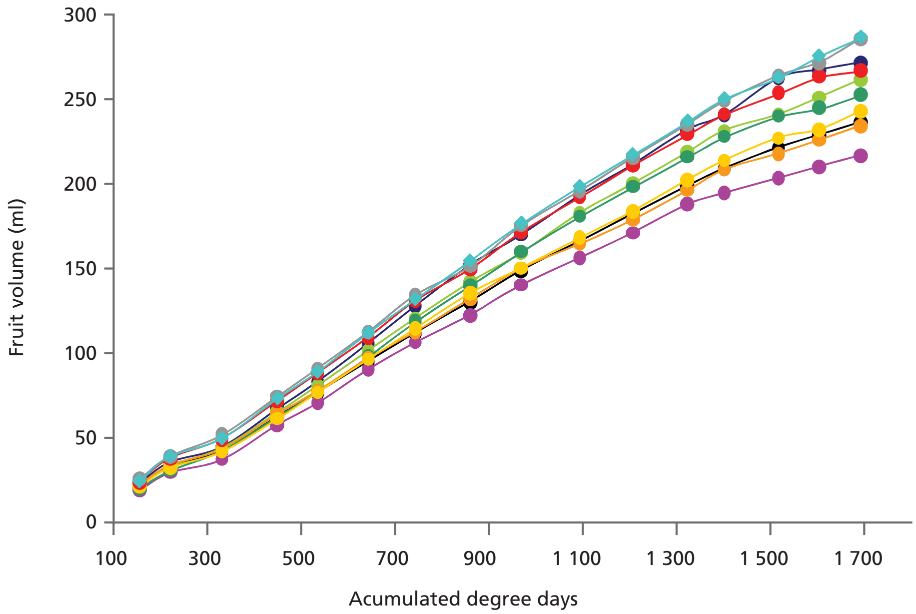
STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

Bloom date varies with varieties and climatic regions. Most varieties flower in April (Northern Hemisphere), whereas early (low chilling requirement) varieties can bloom at the end of February and early March. Apple fruit has an expo-linear growth pattern where much of the dry mass accumulation occurs in the linear phase that starts ~30 days after full bloom in some varieties while in others the linear phase starts ~60 days after full bloom (Goffinet *et al.*, 1995) Figure 2 shows the patterns of fruit growth as affected by different irrigation treatments. The reproductive cell division phase lasts 40-50 days post bloom (Westwood, 1993).

Fruit size is a major determinant of fresh fruit quality and is highly dependent on tree water status and irrigation. However, there are many other factors that will affect the response of fruit size to irrigation including the number of cells in the fruit pericarp, crop load, the number of seeds per fruit, factors that interact with each other.

Temperatures lower than 25 °C during the reproductive cell division phase reduce apple fruit size (Tromp, 1997 and Warrington *et al.*, 1999); on the other hand, it has been found that the number of cells in apples decreased when the trees were grown at 35/15 °C (day/night) rather than at 25/15 °C. This suggests that there is an optimum temperature for reproductive cell

FIGURE 2 Seasonal patterns of apple fruit growth in response to various irrigation treatments: Dark and light blue, grey and red – 100 percent of estimated ET_c for various drip irrigation arrangements; Dark and light green – 100 percent of estimated ET_c applied after two years of severe water restrictions (between 50 to 70 percent of estimated ET_c); Light and dark orange, black and violet - Different water restriction levels (50 - 70 percent of estimated ET_c) (Girona *et al.*, 2011 and unpublished data).



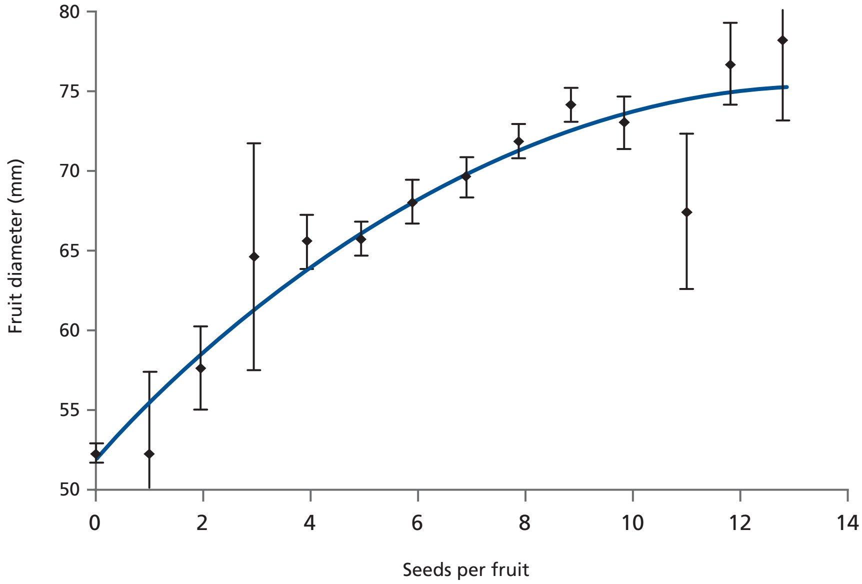
division, and that limitation of potential fruit size should be expected in both cold and hot climates. The previous-year crop yield (Bergh, 1985), the current-year crop level, and the timing of fruit thinning affect the number of cells and therefore potential fruit size (Goffinet, 1995 and Quinlan and Preston, 1968). The number of seeds per fruit has a dramatic effect on final fruit size as shown in Figure 3 where, for the cv. Golden Delicious, the fruit diameter when no seeds were apparent was ~52 mm, while it reached ~73 mm when ten seeds per fruit were apparent. There is the perception that water stress affects cell division, however, studies of other fruit trees (olives and pears) showed no effect of water stress on fruit cell numbers even where predawn leaf water potential (LWP) reached -4.0 MPa in olive (Rapoport *et al.*, 2004).

Crop load in the current season affects the fulfillment of potential fruit size and it interacts with irrigation and fruit water status, which is discussed later. Information about the positive or negative effects of postharvest water deficits on the yield and quality responses of apple in the following growing season is limited, but it appears that severe stress can have negative effects on return bloom.

RESPONSES TO WATER DEFICITS

Irrigation is a major horticultural activity and is the most intensively practiced operation throughout the season. Its importance depends on the climate, and increases as one moves from temperate to drier and to arid zones. Rainfed apple orchards can survive and be productive in temperate zones without irrigation, whereas the survival of apple orchards in arid and semi-arid zones depends on the availability of water for irrigation throughout most of the growing season. The performance of apple in terms of crop yield, fruit size, fruit quality, storability, and long-term productivity are highly dependent on irrigation and irrigation management. Irrigation level and water status are known to affect yield and yield components: crop yield, fruit size and quality, growth habit, precocity, and long-term productivity. Apple fruit size is very sensitive to

FIGURE 3 The effect of the number of seeds per fruit on fruit size at harvest for Golden Delicious apples in Israel (Naor, unpublished).



water stress and thus highly responsive to irrigation (Naor, 2006; Naor *et al.*, 1995 and Girona *et al.*, 2010). It is also highly responsive to crop load (Naor *et al.*, 2008). Assimilate availability is thus the limiting factor for fulfilling potential fruit size (Naschitz *et al.*, 2010). Water stress not only limits cell and fruit expansion but also reduces photosynthesis (the source for assimilates), while primarily crop load determines the demand for assimilates and to a certain extent the photosynthetic rate.

Unlike peach, apple does not have distinct stages of fruit growth and a large part of vegetative and reproductive growth overlap during the growing season. For this reason, deficit irrigation researchers normally use the terms 'early-season' or 'late-season' to describe the timing of their treatment application. Early season normally indicates the time period before flowering buds are formed for the next season fruit. For most varieties, early season will be before July in the Northern Hemisphere and before January in the Southern Hemisphere.

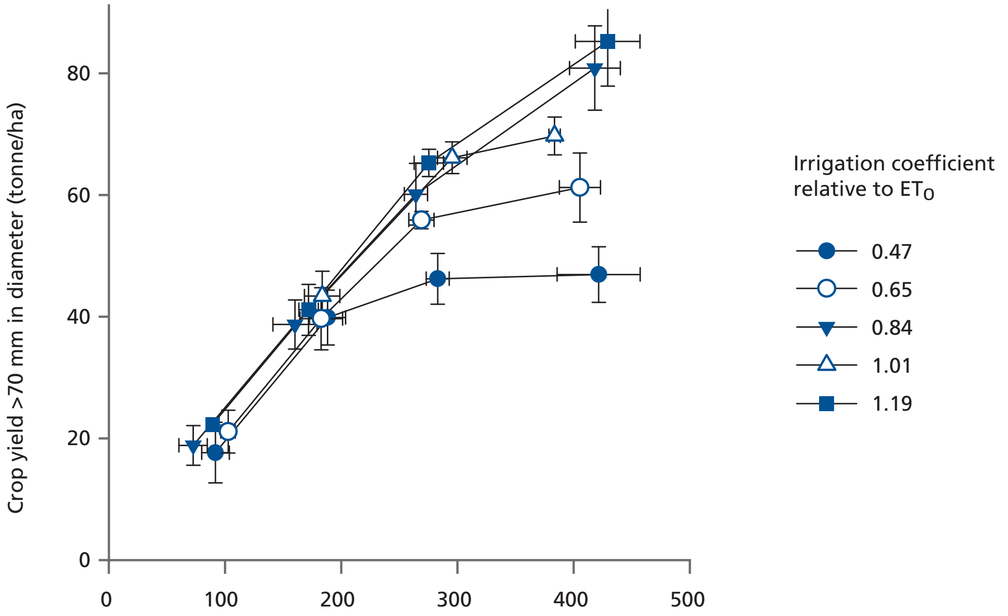
Early-season water stress reduces apple fruit size (Failla *et al.*, 1992 and Rufat *et al.*, 2003). It also reduces fruit set by dramatically increasing fruitlet drop in temperate zones; in one experiment (Powell, 1974), final fruit set decreased from 24 percent for irrigated trees to 8.7 percent for non-irrigated trees. In a semi-arid area of Israel, final fruit set of fully-irrigated trees was 15 percent decreased to 8 percent in severely stressed trees. Water storage from winter precipitation avoids rapid development of severe water stress in most temperate climatic conditions, but for containerized apples with a limited rooting zone, severe water stress may cause up to 100 percent fruitlet drop. This suggests that growers should be aware of the risk of severe water stress development early in the season especially during drought years, and/or in very shallow soils having low water-holding capacity.

Late-season water stress that occurs in the post-reproductive cell division stage affects apple depending on the degree of severity. Moderate water stress up to 102 days after full bloom reduced canopy growth (Behboudian *et al.*, 1998), whereas water stress after this period had no effect. This indicates that shoot growth ends within three months after bloom (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 (Behboudian *et al.*, 1998). However, if water stress is severe during these later stages it may affect next year's growth (Ebel, 1991 and Girona, 2010a). Reductions in return bloom and productivity under severe water stress have been found in apple. Fruit numbers in the following years were affected by severe stress the previous year generated by terminating irrigation in early summer. This was particularly evident in early varieties (Ebel, 1991).

The other, above-mentioned studies, where return bloom was not reduced, did not involve such a severe level of water stress (Behboudian *et al.*, 1998). The reduction in the proportion of return bloom of apple trees that were moderately stressed early in the season could reduce the size of the bourse shoot that emerges from apple flower buds below the threshold required for its terminal bud to produce a viable flower bud (Lauri *et al.*, 1996). It may well be that bourse shoots had already reached the threshold length prior to the start of late-deficit treatments thus no effect on return bloom during late water stress was apparent. It has been observed that excessive shading by a dense canopy can also negatively affect return bloom.

In most studies early water deficits (for about 2 months post reproductive cell division) reduced apple fruit size (Naor, 2006 and Rufat *et al.*, 2003). In general, total crop yield increases with both irrigation level and crop load. However, as fruit size is a major attribute of fruit quality, growers are interested in larger fruit up to a certain limit, where oversize apples will fetch a lower price. The yield of large fruit is affected by both irrigation and crop load (Figure 4). At low crop loads, there is no advantage of increasing irrigation, as similar crop yields were obtained in one experiment where irrigation levels between June and harvest ranged from 46 percent to 119 percent of ET_o (Naor *et al.*, 1997).

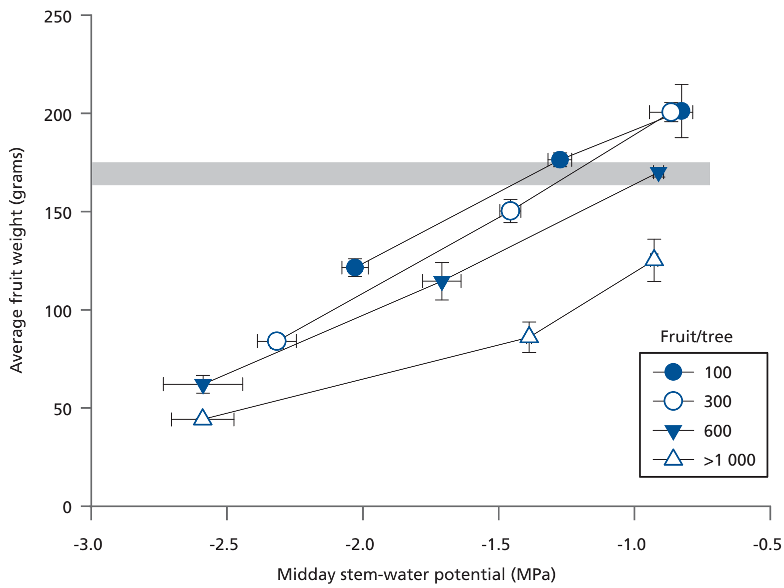
FIGURE 4 Effect of the number of fruit per tree (1 250 trees/ha) on apple yield (>70 mm in diameter) at different irrigation levels (ET_o) from mid-June to harvest. Bars denote Standard Error (Naor *et al.*, 1997).



The water deficits may reduce tree size in the following year, but do not negatively affect flower bud number or fruit load (Girona *et al.*, 2008). As crop load increased (double number of fruit per tree), yield of large fruit increased with increasing irrigation levels. This indicates an increased limitation in assimilate availability that cannot be overcome by supplying additional water above full requirements. At the highest crop load, yield of large fruit did not respond to a seasonal irrigation level above 84 percent of ET_o, which is more or less equivalent to apple ET_c during the irrigation period (see below).

Fruit size increased with increasing midday stem-water potential (SWP: Figure 5) where different response curves were observed for different crop loads. The threshold of midday SWP to reach marketable size fruit shifted to higher stem-water potentials with increasing crop load. For crop loads up to medium levels, maximum fruit size can be achevied by improving tree water status. However, at extremely high crop load, marketable size fruit cannot be reached even under non-stress conditions. Therefore, there is an upper limit of crop load that would enable large fruit size, suggesting that both irrigation and fruit-thinning practices should be employed to maximize crop yield of large, marketable fruit. In some cases, summer pruning can help achieve marketable sizes, as for peach.

FIGURE 5 The effect of midday stem-water potential on average fruit weight at various crop loads 1 250 trees/ha for Golden Delicious apple in Israel (Naschitz, unpublished). The grey rectangle represents the optimal fruit size. The four lower water potentials represent low irrigation rate (1 mm/day) and the four highest water potentials represent high irrigation rate (7 mm/day). The other points represent medium irrigation rate (3 mm/day).



Water deficits and fruit quality in apple

In general, mild water deficits during fruit development advance maturity, increase total soluble solids content and firmness, and may improve red colour and decrease the background colour. 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 increased fruit firmness of 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, water stress after the cell division phase increased (Mpelasoka *et al.*, 2001), did not affect (Ebel *et al.*, 1993), or decreased (Mills *et al.*, 1994) apple firmness at harvest.

The dynamics of fruit firmness in cold storage, as affected by water deficits, were examined in two studies on apple (Mpelasoka *et al.*, 2001. and Kilili *et al.*, 1996). The difference in firmness between fruit from different water-stress treatments remained the same during 10 and 12 weeks in cold storage; they diminished after 10 weeks and reached similar levels by 17 weeks (Mpelasoka *et al.*, 2001). During a shelf-life study (Mpelasoka *et al.*, 2001) the higher firmness imparted by a deficit irrigation treatment was retained for six days, after which the differences diminished and disappeared. Data collected over the past decade suggest that firmness increases in response to post-cell-division water stress, but that the increase is often temporary, around 10 weeks in some studies.

Many studies found that deficit irrigation increased ethylene concentrations in apple, at harvest or during storage (Ebel *et al.*, 1993; Kilili *et al.*, 1996; Behboudian *et al.*, 1998; Mpelasoka *et al.*, 2001 and Mpelasoka *et al.*, 2002). Background colour is an indicator of maturity in apple and it was reported to either decrease or to remain unchanged in response to deficit irrigation. These findings indicate that deficit irrigation advances maturity (and related red colour) in most cases. Studies on the effect of deficit irrigation on aroma volatiles yielded inconsistent results (Behboudian *et al.*, 1998 and Mpelasoka *et al.*, 2002) probably because of a dramatic rise of these compounds at a certain point together with the fact that there is no distinct definition of maturation and the advancement of maturity in response to deficit irrigation. Deficit irrigation increased total soluble solids in apple at harvest (Ebel *et al.*, 1993; Behboudian *et al.*, 1994; Behboudian *et al.*, 1998; Mills *et al.*, 1994; Kilili *et al.*, 1996; Mpelasoka *et al.*, 2001a and Mpelasoka *et al.*, 2002), and the differences were retained during storage. The increased total soluble solids content was accompanied by an increased percentage of dry matter, suggesting part of the increase in soluble solids resulted from to water losses from the fruit. However, deficit irrigation elicited specific metabolic effects that were manifested in changed proportions of specific sugars by increasing fructose or sorbitol content (Mills *et al.*, 1994) compared with unstressed treatments.

Deficit irrigation increased the red colour (Mills *et al.*, 1994 and Kilili *et al.*, 1996) or did not affect it in apple. Enhancement of the red colour could be an indirect effect of deficit irrigation, via a reduction in vegetative growth, which affects light regime within the canopy. It could also be associated with the advancement of maturity induced by the water deficit. More details of the effects of reduced irrigation on fruit quality for important deciduous fruit, including apple, have been recently published (Behboudian *et al.*, 2011).

WATER REQUIREMENTS

Two key factors determining apple tree water consumption are the evaporative demand of the atmosphere and the canopy size that determines the amount of energy intercepted by the canopy. A recent lysimeter study (Girona *et al.*, 2011) showed that the crop coefficient increases from bud break parallel with the development of canopy coverage where canopy coverage reaches a maximum ~60 days after full bloom (Figure 6). A slight increase in K_c was apparent closer to harvest followed by a sharp decline right after harvest. This decline was first probably the result of crop removal, which is known to affect transpiration, while the additional decrease thereafter was related to leaf senescence. The sharp decline in K_c right after harvest, from 1.0 to 0.6 in 2-3 weeks without evidence of leaf senescence (Figure 6) repeats every season (Girona *et al.*, 2011) because fruit is a very important carbon sink and removal feeds back to carbon assimilation and reduces stomatal conductance and transpiration. Trees with very low crop loads therefore use less water than trees with commercial loads, which indicates that the K_c values should be adjusted downward from the values of Figure 6 for low to negligible crop loads. Excessive vegetative growth is expected in the spring in low crop loaded trees and its suppression is difficult because of the low ET in the spring, thus summer pruning should be employed.

Recommended K_c values for various locations in the world are presented in Table 1. The K_c values for apple orchards depend on the intercepted radiation and may vary with different orchard conditions (row and tree spacing, tree age and size, training system, row orientation, etc.). For intensive, hedgerows plantations, a relationship between K_c and midday light interception (Girona *et al.*, 2011) is presented in Figure 7. Given that maximum K_c is around 1.0 (Figure 6), the relationship shown in Figure 7 may be used to determine the specific K_c values for apple orchards that have not achieved maturity.

FIGURE 6 Seasonal reference ET_o crop coefficients for apple. Data from a weighing lysimeter study of commercial size trees within an orchard in Mollerussa (Lleida, Spain) (Girona *et al.*, 2011).

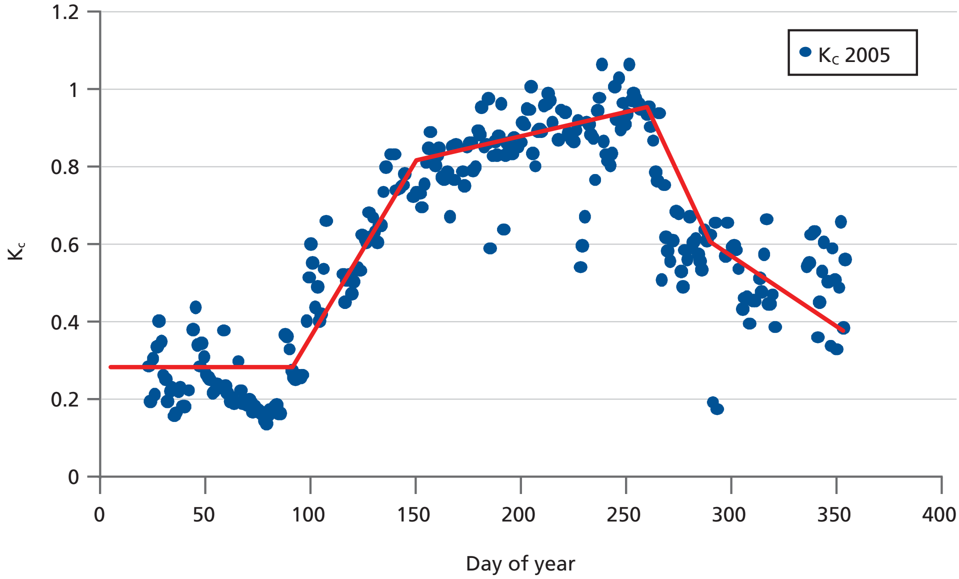


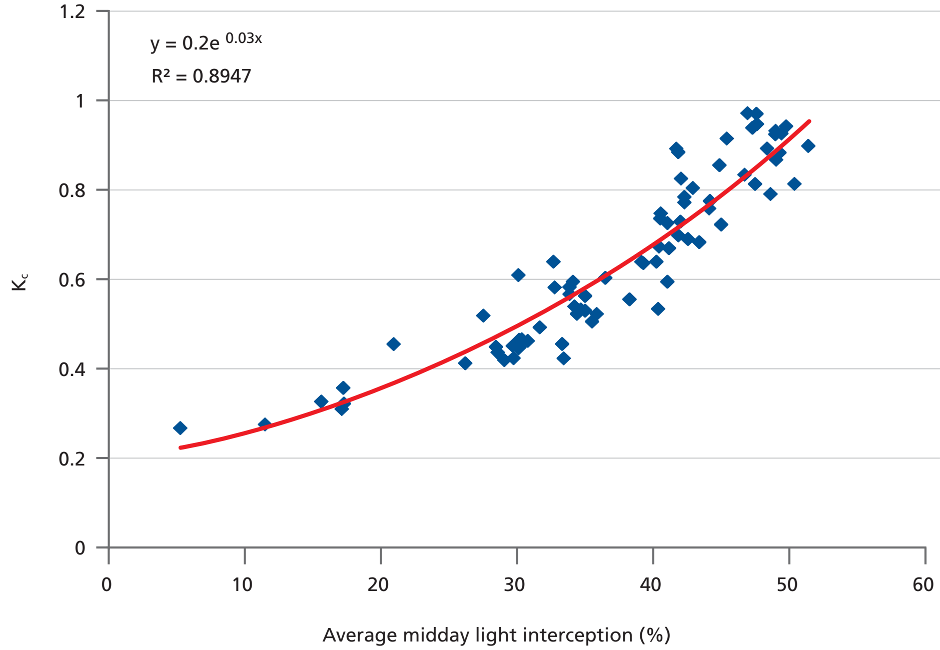
TABLE 1 Common sets of seasonal reference ET_o crop coefficients (monthly averages) from various countries throughout the world (Australia, Israel, and Spain).

Month	Spain (fraction of ET_o)	Israel (fraction of ET_o)	Month	Australia
Mar.	0.30/0.30		Sep.	
Apr.	0.40/0.45	*	Oct.	0.64
May	0.60/0.75	0.42	Nov.	0.64
June	0.82/0.87	0.73	Dec.	0.74
July	0.92/0.93	0.98	Jan.	0.95
Aug.	0.93/0.94	1.05	Feb.	0.95
Sept.	0.95/0.75**	1.05/0.48**	Mar.	0.95/0.42**
Oct.	0.60/0.55	0.32	Apr.	0.42

** irrigation based on soil moisture measurements*

*** preharvest/postharvest*

FIGURE 7 Effect of midday light interception of apples on their K_c values - data from a weighing lysimeter study of commercial size trees within an orchard in Mollerussa (Lleida, Spain) (Girona *et al*., 2011).



WATER PRODUCTION FUNCTIONS

Water production functions for apple are difficult to generalize because they are affected by many factors such as training system, crop load, pruning and thinning practices, and whether the target is total (as for juice production) or fresh marketable yields.

Figures 8 and 9 present the response of total and marketable yield to a decrease in ET_c determined in Lleida, Spain. In both cases, it seems that relative ET_c may be reduced by about 15- 20 percent without having a negative impact on final yield. Similar results were found in Israel where fruit yield >70 mm was unaffected by increasing K_c above 0.84 (Figure 10).

Water management of fresh market apple production should take into account that: 1) fruit size is highly dependent on crop load thus it should be optimized to maximize yield of marketable size fruit; 2) apples tend to have a biennial bearing pattern in response to high crop load, thus crop load should be optimized to allow stable production for each season. In one specific experiment with Golden Delicious (Figure 10), crop yield of marketable size (>70 mm) increased with both annual irrigation level and crop load, and the maximum crop yield was achieved at the highest load at maximum apple ET_c (equivalent to 84 percent of the seasonal ET_o). It should be emphasized that potential fruit size was high during this season and, although the threshold of maximum commercial crop yield could be higher; optimal crop load that avoids biennial bearing lies between the two highest crop loads (Figure 10) and may change with climatic conditions.

FIGURE 8 Water production function for apple (cv. Golden Smoothee) based on total yield obtained in Lleida, Spain (Girona, unpublished).

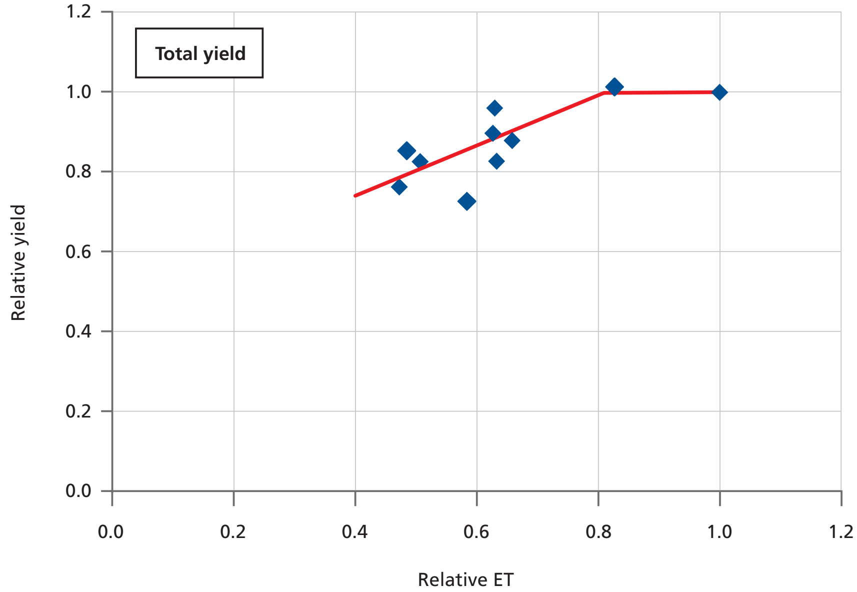


FIGURE 9 Water production function for apple (cv. Golden Smoothee) based on marketable yield obtained in Lleida, Spain (Girona, unpublished).

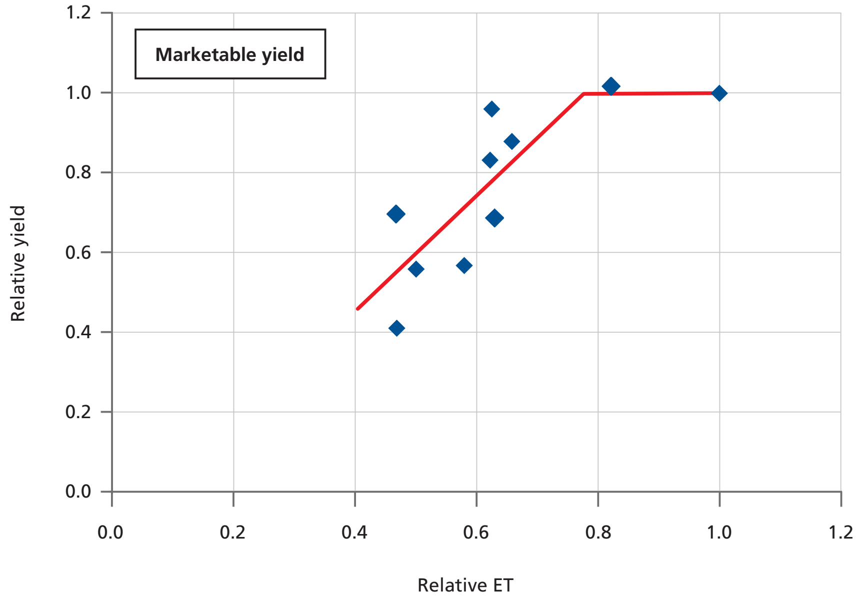
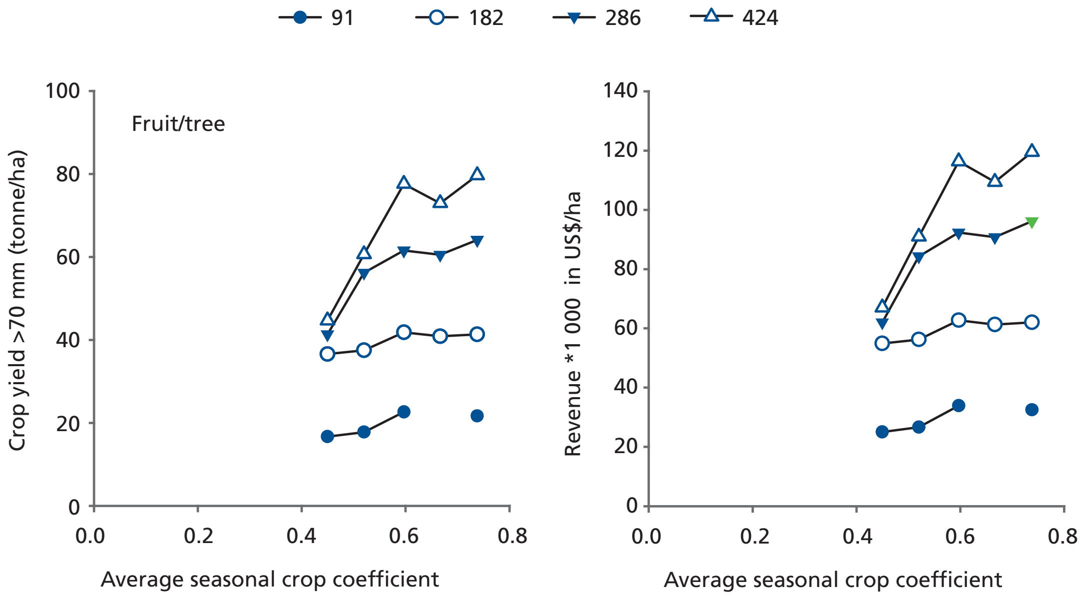


FIGURE 10 Response of marketable fruit yield (>70 mm) and revenue of Golden Delicious apple to irrigation rates (average seasonal reference ET_o K_c) at various crop levels (1 250 tree/ha). Different irrigation rates were applied from mid-June to harvest – K_c values were 0.44, 0.65, 0.84, 1.01, and 1.19; seasonal ET_o (1/5-1/11) was 1 172 mm.



SUGGESTED RDI REGIMES

Given the growth patterns of the apple, and the sensitivity of fruit size to water deficits, it appears that only mild water deficits may be applied to this crop, when grown for fresh market, without impacting negatively on farmers' income. However, RDI has some positive effects on quality that should be exploited, in particular in water scarcity situations. The objective of apple irrigation management under suboptimal water allocation would be to minimize damage and maximize irrigation water productivity. If a small reduction in supply is considered, it should occur preferably during the postharvest period. In common varieties that are harvested in September (Northern Hemisphere) it leaves some period of irrigation up to the start of leaf senescence, a period that will be shorter with increasing latitude. In water shortage conditions one can skip the postharvest irrigation for common varieties but that should not be done in early maturing varieties that have long postharvest period. If water shortages exceed the level equivalent to the amount used for postharvest irrigation, growers should apply the deficit on a continuous basis after the early fruit growth period (avoid stress in the first 30 to 60 days after fruit set, depending on variety), and adjust the crop load by thinning to ensure that the remaining fruit will reach commercial size. A recommendation on irrigation for different water allocations and optimal crop loads for production in warm climates is presented in Table 2.

It is important to monitor soil or tree water status when applying RDI (see Chapter 4). Climate control for apple (frost protection and/or cooling for sunburn protection or to enhance red colour in warm areas) is carried out using sprinkler irrigation and its use, in the case of cooling, may disrupt the RDI programme. Evaporative cooling reduces actual ET on the order of 20 percent, but total seasonal irrigation water requirements would be much higher than the full orchard ET_c, as calculated in Chapter 4.

TABLE 2 Apple orchard water requirements, based on an orchard planted at 4 x 1.6 m, trained with a central leader and with a ground cover about 45-50 percent and tree heights > 3.5 m. Located in Mollerussa (Lleida, Spain). ET_o values used are the average daily data from the last 8 years (2002-2009).

			FULL IRRIGATION		MODERATE RDI		SEVERE RDI	
		ET_o (mm/day)	K_c	ET_c (mm/day)	K_c	ET_c (mm/day)	K_c	ET_c (mm/day)
March	1-15	2.19	0.30	0.66	0.30	0.66	0.30	0.66
March	16-31	2.61	0.30	0.78	0.30	0.78	0.30	0.78
April	1-15	2.70	0.40	1.08	0.40	1.08	0.30	0.81
April	16-30	3.75	0.45	1.69	0.45	1.69	0.30	1.13
May	1-15	3.95	0.60	2.37	0.60	2.37	0.40	1.58
May	16-31	4.64	0.75	3.48	0.75	3.48	0.40	1.86
June	1-15	5.08	0.82	4.17	0.82	4.17	0.50	2.54
June	16-30	5.45	0.87	4.74	0.87	4.74	0.50	2.73
July	1-15	5.40	0.92	4.97	0.90	4.86	0.50	2.70
July	16-31	5.47	0.93	5.09	0.70	2.74	0.45	2.46
August	1-15	4.90	0.93	4.56	0.50	2.45	0.45	2.21
August	16-31	4.45	0.94	4.18	0.50	2.22	0.45	2.00
September	1-15	3.57	0.95	3.39	0.50	1.78	0.45	1.61
September	16-30	3.01	0.75	2.26	0.50	1.51	0.45	1.35
October	1-15	2.44	0.60	1.46	0.50	1.22	0.45	1.10
October	16-31	1.60	0.55	0.88	0.55	0.88	0.55	0.88

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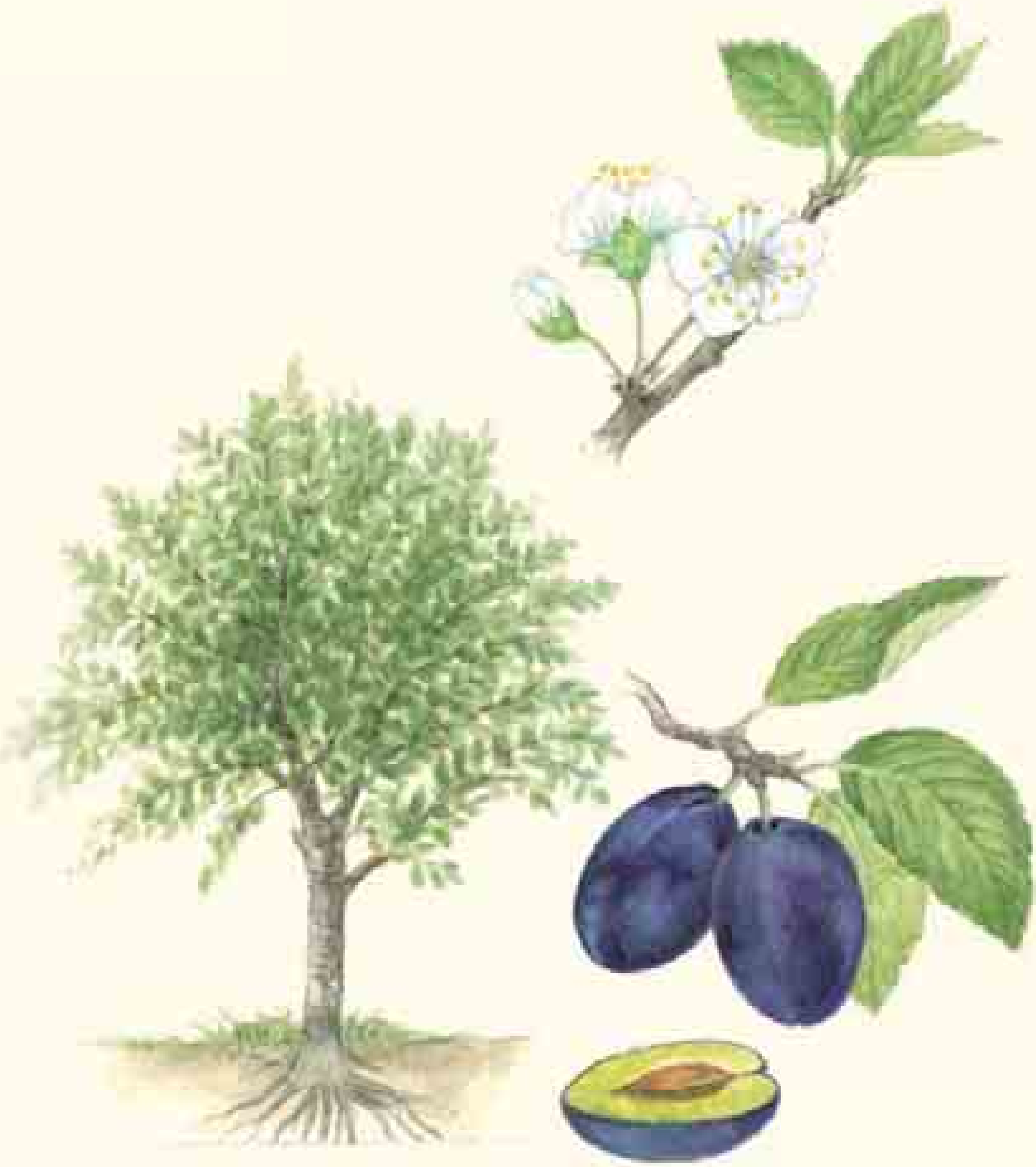

Plum

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Plum

INTRODUCTION AND BACKGROUND

Plum species of commercial importance originated between Eastern Europe and Central Asia. Cultivated plums include two main species, European (*Prunus domestica* L.) or 'prunes' and Japanese plums (*Prunus salicina* L.). Both species are medium-size deciduous stone fruit-trees that differ notably in respect to their climatic requirements. European plums are cultivated in temperate climates to fulfil chilling requirements and to enable proper bud break. They are relatively late flowering, while Japanese plums grow better in temperate-warmer regions, as their chilling requirements are less. Their productive use also differs, as Japanese plums are mainly grown for fresh fruit, while dried fruit (prunes) is mainly obtained from European plum varieties. World acreage was over 2.5 million ha in 2009 with an average yield of 4.3 tonne/ha. China and Serbia are the two main world producers, followed by the United States and Romania (Figure 1). Spain occupies the eighth place with about 191 000 tonne mostly of fresh fruit, but is among the three world highest exporters. France is the main European producer of dried fruit, and Chile is now an important producer and exporter in the Southern Hemisphere (FAO, 2011).

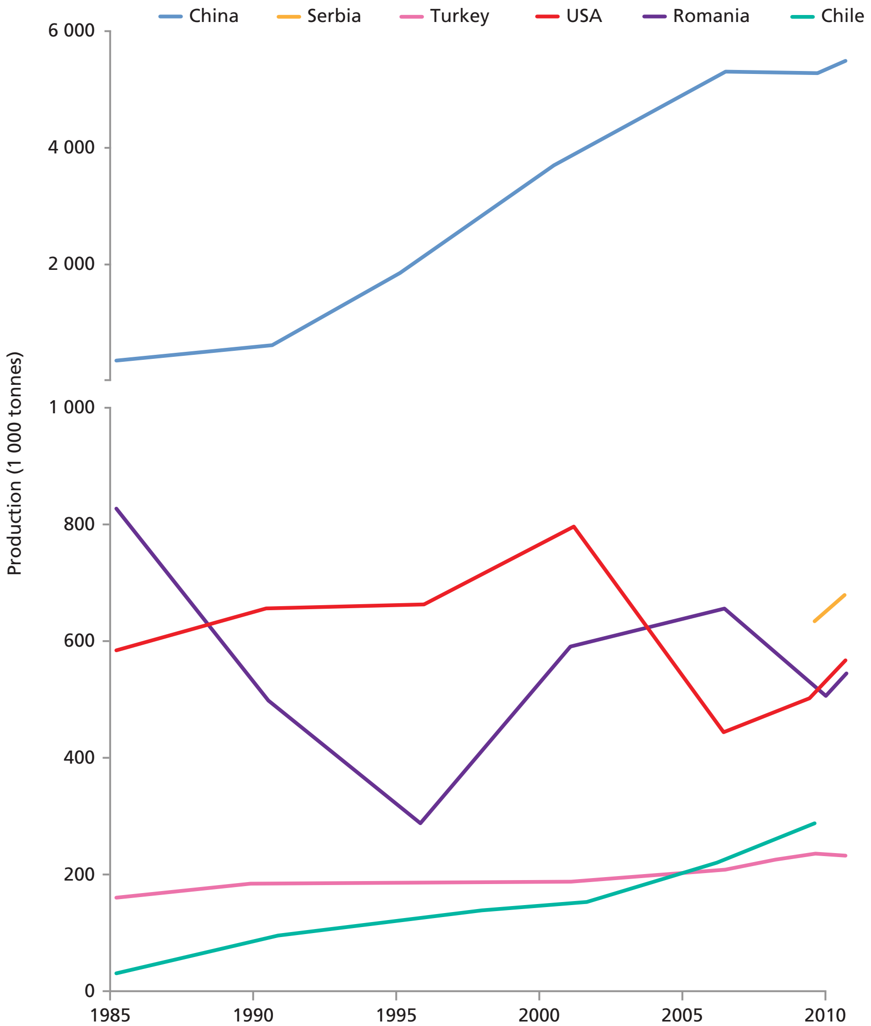
Plum species can adapt to different soil types, although they are sensitive to water-logging, iron chlorosis and salinity. Therefore, the use of rootstocks to cope with these adverse environmental conditions is common. Plum trees generally bear fruit at an early age and the fruiting period lasts 5-35 years. Early varieties can be grown without irrigation in arid climates with rainfall as low as 300 mm/ season, and midseason varieties require at least 400-500 mm/ season. However, productivity and fruit size in these conditions are usually low and, therefore, most plantations are irrigated, especially in arid and semi-arid climates.

The quality features for fresh market include size, colour and a good balance between soluble solids and acidity, while for dry fruit production, soluble solids and size are the two most important quality parameters.

DEVELOPMENTAL STAGES IN RELATION TO YIELD DETERMINATION

Commercial plum tree varieties break dormancy and begin flowering in the Northern Hemisphere between late-February and mid-April, depending on

FIGURE 1 Production trends for plums in the principal countries (FAO, 2011).



the environmental conditions and the cultivar. Bud formation starts with the appearance of the first basal leaves and continues through June on mature trees (Westwood, 1993). Reproductive buds are in a lateral position on terminal shoots or on short shoots called spurs. Flower buds are initiated in the growing season prior to anthesis, and development continues through the dormant season until the following spring just before bud break. The proportion of spur and terminal shoots varies largely with variety and species and so does the proportion of fruit borne on spurs and shoots, which also varies with tree age. Most commercial plum cultivars are not self-pollinating and therefore the use of pollinators is required. Plum trees bloom very profusely and thinning is required, either performed manually, chemically or mechanically to obtain commercial fruit sizes. For example, Black-Gold in Mediterranean conditions may set around 10-40 percent of the flowers produced, but good commercial yields are obtained with only about 5-10 percent of fruit set (Intrigliolo and Castel, 2005). Normally, flowering is completed by late April (Northern Hemisphere) and is followed by rapid fruit expansive growth with concomitant rapid shoot growth.

The fruit with fleshy pericarp is classified as a drupe and is single-seeded. Fruit growth follows the typical double-sigmoid pattern, with rapid exponential growth during the cell division phase (Stage I, ~ 30 days in length), followed by a relatively short period of slow growth during pit hardening and embryo development (lag phase, Stage II). Finally, a second period of rapid cell and fruit enlargement prior to harvest (Stage III), when the fruit can increase in size *ca.* 40-60 percent, although this is linked to accumulated heat units (degree-days) after flowering, in a similar fashion to other *Prunus* species (DeJong and Goudriaan, 1989). Therefore, the length of each stage varies with variety and location. During the postharvest period, some shoot growth and carbohydrate storage for reserves are the primary sinks for carbon assimilation, which continues until leaf fall.

EFFECTS OF WATER DEFICITS

A distinction should be made between plums for fresh fruit production and those for dried fruit production (prunes), as dry matter accumulation is less sensitive to water stress than is the increase in fresh weight, particularly during the last stages of fruit development. In addition, lower fruit hydration rates resulting from water deficits may also offer an advantage for post-harvest fruit processing in the case of prunes for dry fruit production (Lampinen *et al.*, 1995). Thus, prune trees are considered to be moderately resistant to water stress, as indicated by early experiments (Hendrickson and Veihmeyer, 1945) in the deep soils of California's Sacramento Valley, where it took 4 years of no irrigation to detect decreased trunk growth, and 5 years of water deprivation to detect a significant reduction of fruit yields. This is also supported by more recent findings (Goldhamer *et al.*, 1994) where irrigation cutoff, up to 37 days before harvest did not have any negative impact on dry fruit yields of French prune.

Water stress during fruit growth

In Japanese plums for fresh markets, water stress in the final stages of fruit growth significantly decreased fruit size, but accelerate ripening and lead to an increase in fruit sugar concentration (Naor, 2004). Under water stress, average fruit weight and yield were affected by increased tree crop load for Japanese plum (Intrigliolo and Castel, 2005; Naor, 2004) but under minimum stress conditions, the fruit size distribution was unaffected by fruit number per tree, possibly because of low crop yields, which did not introduce significant limitation of assimilates (Naor, 2004). Irrigation of previously water-stressed prune trees 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).

Water stress during postharvest

The practice of reducing or eliminating irrigation after harvest of an early-maturing plum cultivar (*P. salicina*) irrigated with foggers was studied in California (Johnson *et al.*, 1994), where completely cutting off irrigation led to partial defoliation within a few weeks and loss of yield in the subsequent year. Postharvest midday stem-water potential (SWP) reached ~-3.3 MPa with no symptoms of defoliation in Black Amber (Naor, 2004). For trees that were irrigated daily, but at half the rate of the fully irrigated control, no reduction of yield or fruit quality occurred over a 3-year period, possibly because of the contribution of stored soil water. In young orchards, postharvest water restrictions did not affect yield in the short term (Intrigliolo and Castel, 2005). However, after four seasons of deficit irrigation, there was a 10 percent reduction in yield compared with fully irrigated trees because the stressed trees were smaller. Thus, long-term deficit irrigation of young trees causes a reduction in productivity by reducing tree size. Post harvest water stress, despite its moderate detrimental effect in the long term, should be considered for commercial orchards not only in the case of water scarcity, but also as a tool for controlling vegetative growth in areas where vigorous growth may be a problem.

Plant water stress is known to potentially affect flower bud development for the next season, but there are only a few reports on a decrease in next season crop level because of bud damage (Johnson *et al.*, 1994). Water stress during postharvest, as measured by the SWP, was also correlated with the following season's crop yields.

In some cases, there was even an increase in return bloom leading to larger yield in prune trees where a high crop level was the target (Lampinen *et al.*, 1995). In plum trees, water stress did not appear to be associated with the appearance of fruit disorders such as double fruit formation or fruit deep suture, as occurs in other stone fruit-trees such as peach (Johnson and Handley, 2000).

Plant water stress indicators

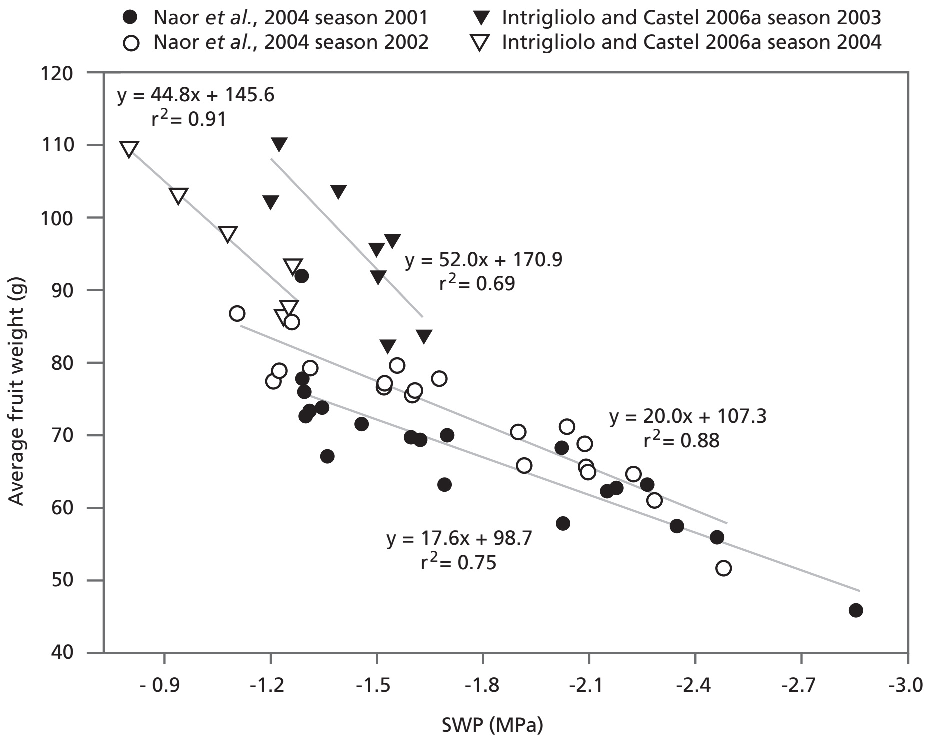
Midday SWP is the most useful indicator of plant water stress in plum trees, since prior to harvest it was highly correlated with tree performance (Naor, 2004; Intrigliolo and Castel, 2005*;* and Intrigliolo and Castel, 2006a). Figure 2 presents the results of two studies on different varieties of Japanese plums: Black-Gold plums (Intrigliolo and Castel, 2006a) and Black Amber plums (Naor, 2004) in the semi-arid climates of Valencia, Spain and Upper Galilee, Israel, respectively. In each location and season, tree-to tree variations of SWP were well correlated with the average fruit weight at harvest. However, there was no unique relationship relating SWP to fruit weight valid for all data across experiments (Figure 2). The differences in the intercept of the lines reported between seasons and locations indicate that fruit weight is not only a function of plant-water status. In addition, the different slopes of the linear relationships between locations suggest that the effect of plant water stress on fruit growth might change according to different environmental or cultural conditions. Overall these results highlight the importance of conducting local experiments when attempting to predict the effect of plant water stress on fruit weight at harvest.

Studies using other water status indicators for plum trees have also shown that daily trunk contraction, continuously measured with stem dendrometers (Intrigliolo and Castel, 2006b), is highly correlated to SWP, but other factors such as tree age and tree crop load also influence the relationship between trunk contraction and SWP (Intrigliolo and Castel, 2006b; and Intrigliolo and Castel, 2007).

WATER REQUIREMENTS

Only a few early studies quantified the consumptive water use of plum orchards. The recommended crop coefficient values for plum trees are included in the stone fruit tree section together with peach trees in the *FAO I&D No. 56* publication (Allen *et al.*, 1998). A specific study

FIGURE 2 Relationships between average fruit weight at harvest and average midday stem-water potential (SWP) during the last phase of fruit growth. Data correspond to the regulated deficit irrigation experiments carried out with Japanese plum cv. Black-Gold and cv. Black-Amber during different seasons.

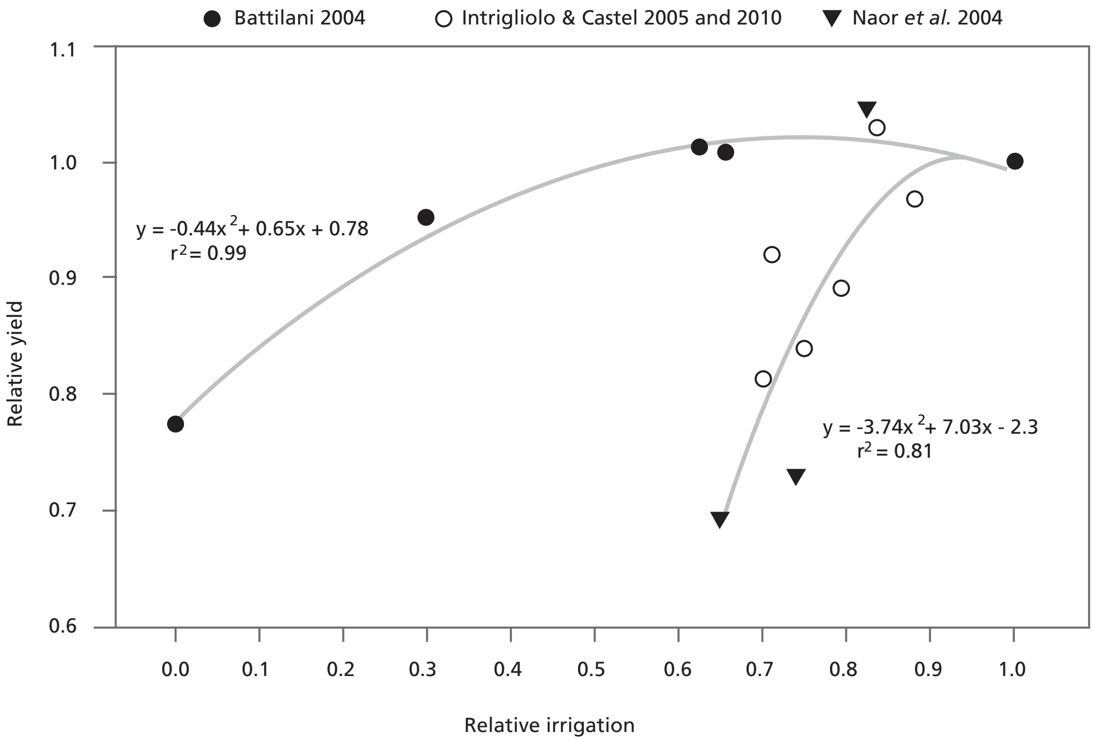


of the water use of plum trees trained to different canopy arrangements (Chootummatat *et al.*, 1990) found that mature trees under a Tatura training system reaching full cover, used 92 percent of class-A pan evaporation in midsummer. Lower water use (82 percent of pan evaporation) was determined for trees trained as vase or palmette systems. As a first approximation, the K_c values for peach (see Peach) should be used for plum orchards.

WATER PRODUCTION FUNCTION

It seems that there are no deficit irrigation trials investigating the relationship between tree water use and yield either for Japanese plums or European prunes. However, from main results reported in the literature it is possible to derive some water productivity functions based on applied water by irrigation. Three studies on different varieties of Japanese plums were included in the analysis: Fortune plums in the humid climate of the Po Valley in Italy (Battilani, 2004), Black-Gold plums (Intrigliolo and Castel, 2006a; Intrigliolo and Castel, 2010) and Black Amber plums (Naor, 2004; Naor *et al.*, 2004) in Valencia, Spain and Upper Galilee, Israel, respectively. In all cases curvilinear functions fit the relationships between relative yield and relative irrigation (Figure 3), but there were differences in the threshold values of relative applied irrigation for no yield reduction. The data from Spain and Israel fell on a single polynomial regression line, which fitted both data set well. In cv. Black-Gold and Black-Amber only 10 percent of reduction in applied water appears to be admissible for no yield penalty,

FIGURE 3 Relationships between relative yield and relative irrigation. Data correspond to regulated deficit irrigation experiments carried out with Japanese plum cvs. Fortune, Black-Gold and Black-Amber. The data from cvs. Black-Gold and Black-Amber were pooled together. All values are calculated relative to the fully-irrigated control plots.



whereas in the study in Italy with the cv. Fortune, it was possible to reduce irrigation by 20-25 percent without any yield reduction. In addition, the response of Black-Gold and Black-Amber plums showed a much sharper decrease in relative yield with irrigation deprivation relative to Fortune plums. The differences in the relationships between applied water and yield are related to the unknown contribution of stored soil water and of in-season precipitation to the crop ET_c under water deficits. The similarity in the response of two different varieties in Spain and Israel probably reflect the limited contribution of soil storage in both studies (hence the sharp decline in relative yield when irrigation decreases). Additionally, the differences between the study in Italy and the other two might be the result of climatic conditions, with higher winter and growing season precipitation in the Po Valley and tree age; mature trees in Italy and younger orchards in the studies in Spain and Israel.

The patterns obtained in the above-mentioned studies are in line with general tree responses to water supply, where yield increases with increasing water application but up to a point where further increases in water application do not produce any increase in yield. Since there are no studies relating yield to ET_c in plum trees, overall data reported in Figure 3 showed that for plum trees deficit irrigation could save around 10-20 percent of applied water with minimum or no yield loss.

SUGGESTED DEFICIT IRRIGATION STRATEGIES

The suggested deficit irrigation strategy may greatly vary depending on the final market product, dried fruit or fresh fruit, and on specific phenological aspects of each variety affecting bloom intensity and fruit set levels and particularly, earliness. The general strategy used to impose the water deficits for French prune was to limit water deficits during early stages of tree and crop development, imposing more severe stress during mid and late season. In this sense, in a clay loam soil in California, allowing a progressive decline in midday SWP to approximately -1.5 MPa by harvest, e.g. irrigating at about 50-60 percent ET_c from spring, resulted in an effective way to reduce irrigation and maintain an economic return over a 3-year period (Lampinen *et al.*, 2001a).

For early season fresh market varieties it can be concluded that water stress after harvest that limits the decline in SWP below -2.0 MPa, despite some possible slight detrimental effect in the long term, should be considered in commercial orchards not only for water scarcity, but also as a tool to control vegetative growth. In young orchards, postharvest deficit irrigation may be combined with closer tree spacing, a feature very common in modern fruit tree plantations where new cultivars and orchards have a short life.

For fresh market varieties water stress, if applied during fruit growth, should be concentrated during pit hardening. The length of this phase depends on the harvest date. Hence, in early and even midseason maturing cultivars there is a risk of extending the water stress into the final fruit growth stage with detrimental effects on fruit size. Recent results (Intrigliolo and Castel, 2010) suggest that some degree of water stress can be applied during the early stage of fruit growth, providing that plant-water stress is mild (SWP > -1.4 MPa) and trees return to optimum water status at least one month before harvest. The convenience of water stress applied during fruit growth would indeed depend upon price market values of different fruit size categories and fruit quality effects of water restrictions. In this sense it should be considered that deficit irrigation during fruit growth advances maturity, increases total soluble solids content and firmness, and may improve fruit colour. The effects of water restrictions on volatile aroma compounds and particularly fibre and other fruit quality components related with human health have not been extensively studied and could be of great importance for plum growers if the consumption of plums is promoted.

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Almond

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Almond

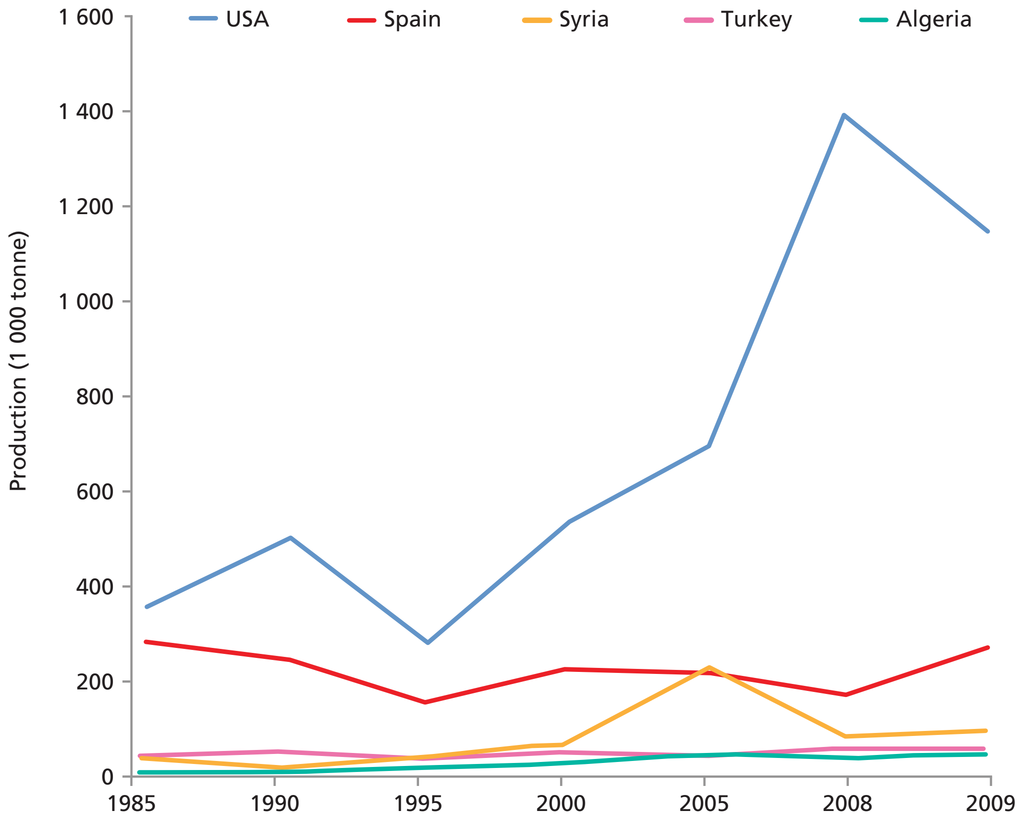
INTRODUCTION AND BACKGROUND

Almonds are grown under both rainfed and irrigated conditions; production in semi-arid zones, such as the western United States and Spain, reflects the drought tolerance of the tree. In many areas of the Mediterranean Basin, almond trees are grown on marginal soils in areas where annual rainfall does not exceed 300 mm, being important for erosion control and to prevent desertification. As a result of the limited water supply and poor soil conditions of the rainfed areas, tree densities are quite low and yields are also low and variable from year-to-year. However, they can be much higher when the water-use requirements of the trees are fully met and, in most areas of the world, this requires irrigation. New irrigated almond plantations have expanded in recent decades in many areas and are highly productive. Nevertheless, almonds are an important crop in very diverse agricultural systems, from very marginal to highly intensive. In 2009, the cultivated area worldwide amounted to 1.8 million ha with an average yield (with shell) of 1.3 tonne/ha (FAO, 2011). Figure 1 shows the recent trends in production of the major producing countries.

Modern almond cultivation presents unique challenges to irrigation in general and regulated deficit irrigation (RDI) in particular. These include dealing with multiple cultivars in each orchard, a long period between flowering and fruit maturity the need to dry the soil prior to harvest in order to mechanically shake nuts from the trees, and a relatively late reproductive bud morphogenesis period. On the other hand, since the fruit is sold dry, many of the problems associated with fresh fruit production, including physical appearance, handling and storage are absent.

The almond flower of most varieties is self-infertile; it cannot pollinate itself. Even for cultivars that are self-compatible, production is enhanced by cross-pollination. Thus, each orchard normally contains at least two different cultivars with overlapping bloom periods to help the process of cross-pollination; the transfer of pollen from the anthers of a flower from one cultivar to the stigma of a flower from another cultivar. This transfer is facilitated by the introduction of honey bees into the orchard during flowering. To maximize pollen exchange, a common arrangement is single, alternating rows of each cultivar. The fact that two or more cultivars exist in a field complicates irrigation management in that the different harvest periods usually result in harvest-related water deprivation for one cultivar, while kernel filling is occurring in the other cultivar. Further, there is some evidence that different cultivars have different stress sensitivities.

FIGURE 1 Production trends for almonds in the principal countries (FAO, 2011).



Quality considerations

Insect damage, shrivel, kernel colour, and broken kernels are quality criteria worldwide. Additionally, marketplace differences result in cultivar-dependent crop values. Some markets also place a premium value on larger nuts; the United States, for example.

DESCRIPTION OF THE STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

Almond trees require very low chilling and thus, vegetative growth and flowering begin very early in the season relative to other deciduous tree species; although plant breeders aim to develop cultivars that bloom late to avoid chilling injuries. This earliness feature relates to the evolution of almonds in mild, subtropical climates with prolonged summer drought. The period from flowering to fruit maturation of almond is relatively long, depending on climate and cultivar; from late January-March to August-September in the Northern. Hemisphere, and the sensitivity of each of the physiological processes during this time to water deficits must be considered to assess the impact of stress on the yield and quality of the fruit at harvest. Not only current season impacts but those of subsequent seasons must be taken into account.

EARLY VEGETATIVE AND REPRODUCTIVE GROWTH

Flowering and initial leaf development occur almost simultaneously from late January in the Northern. Hemisphere for the earliest blooming cultivars until the end of March for the late blooming. Fertilization of the flower is followed by growth of the pollen tube into the ovary, which will evolve into the marketable kernel. The maximum potential fruit production is determined during this early period. It is established by the number of flowers produced (flower set) and the percentage of these that are successfully pollinated (fruit set). Early fruit development is largely the result of cell division. The early stages of fruit growth occur at the same time as most of the leaf expansion and shoot growth. This results in considerable competition for tree resources, principally carbohydrates. Thus, if flowering and fruit set are high, shoot growth may be lower. Since fruit are borne on spurs, this may reduce the number of new reproductive buds produced and, in turn, reduce the crop potential for the following year. In addition to its impact on fruiting positions, this carbohydrate competition can influence fruit set. If carbohydrate reserves from the previous year are low, the current year fruit set may be reduced (Esparza *et al.*, 2001). This effect may enhance alternate bearing in almonds, especially under rainfed conditions.

Stages of fruit growth

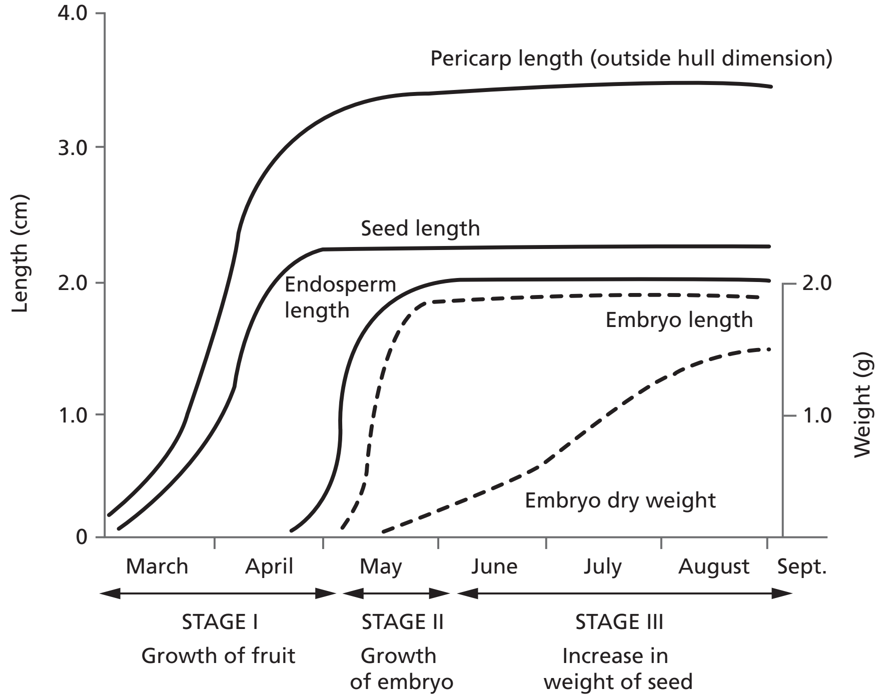
Figure 2 shows the pattern of fruit growth where three stages may be defined:

Stage I is one of rapid growth of the hull, shell, and integuments. The entire fruit remains soft and reaches its maximum size. Cell division is completed in a few weeks; the major part of growth thereafter is expansion. At this point, the kernel is a white structure filled with watery, translucent tissue. The time between fertilization of the flower to the end of fruit development is about two months. The end of Stage I is marked by the attainment of the maximum external dimensions of the hull, shell, and kernel.

Stage II is characterized by shell hardening and kernel expansion. There are two types of almond varieties: hard and soft shelled. Hard shelled, which are many of the Mediterranean varieties, have shelling percentages of 25-35 percent, while soft shelled have 70 percent. They completely harden in Stage II while the soft shelled remain soft. The growth of the embryo involves clear watery tissue becoming translucent, starting at the apical end. This white, opaque embryo rapidly expands during this period. Toward the end of Stage II, kernel dry weight begins to increase.

In Stage III, the major event is the steady dry matter accumulation in the kernel. The morphological differentiation of the hull, shell and kernel are complete. Dry matter accumulation of assimilates continues at a steady rate until maturity, as long as the vascular connections remain intact. Two events signal the approach of maturity: hull split (endocarp dehiscence) and the formation of an abscission layer at the nut-peduncle connection. Complete dehiscence requires an adequate tree-water status because the sides of the hull must be turgid to separate properly. Excessive stress may cause the hulls to adhere to the shells (hull-tights), which complicates processing. Maturity is also characterized by a sharp slowing in the rate of kernel dry matter accumulation. In some areas, commercial harvests occur prior to kernel maturation to avoid insect navel orange worm (NOW) damage.

FIGURE 2 The three stages of almond fruit development and the typical length and weight of the fruit at each stage. Adapted from the UC Almond Production Manual, 1996.



Bud development

The reproductive buds are borne on spurs and are initiated in the spring as the spurs develop. There are three subsequent stages of flower-bud development. The first is induction where the internal physiology of the growing point changes. This occurs in mid-August and the vegetative and reproductive buds are indistinguishable. Second are the morphological-anatomical changes in the internal structure, which are readily observable in September. Third is gradual growth of the reproductive parts during the autumn and winter, i.e. development of the sepals, petals, stamens and ovaries.

RESPONSES TO WATER DEFICITS

As for most crop plants, vegetative growth of almonds is very sensitive to water deficits. Avoidance of water deficits throughout the season in young trees is critical to reach full production in the shortest time period (Fereres *et al.*, 1981). In mature plantations, responses to water deficits depend on the timing of the stress.

In areas that receive substantial winter rainfall, tree processes that occur very early in the season, such as leaf out, flowering, pollination and fruit set, will be under non-limiting soil water levels. However, as the season progresses and evaporative demand increases, shoot, spur, and fruit growth will be subjected to water deficits without irrigation or in-season rainfall. Several reports state almond vegetative growth is very sensitive and directly affected by tree-water deficits.

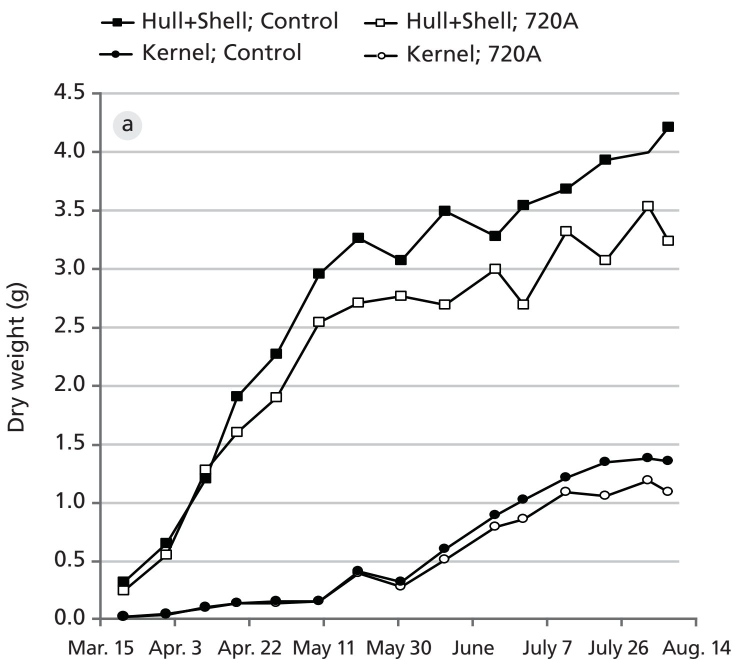
The research results on preharvest impacts of stress on kernel filling are seemingly contradictory and may reflect the importance of stress timing and cultivar differences. A study in Spain (Girona *et al.*, 2005) with cv. Ferragnes, reported that kernel dry weight accumulation was not influenced during the first two seasons of an RDI regime that irrigated at 20 percent of ET_c during late June through the mid-September harvest (minimum predawn leaf water potential of -1.7 MPa in August) but was lower during the final two seasons of the study, which was attributed to the cumulative impacts of stress reducing the reserves of carbohydrates available for kernel filling and to relatively low soil water levels during those years. However, a California study (Goldhamer and Viveros, 2000) with higher evaporative demand (minimum predawn leaf water potential of -3.5 MPa) and earlier stress reported significant reductions in kernel dry matter accumulation with cv. Non Pareil in all experimental years. Dry matter accumulation in the hull and shell after three successive years of preharvest stress, diverged from the fully irrigated in late April, well before there were differences in tree stress, as shown in Figure 3. This was likely because of early season competition for carbohydrates. A study (Romero *et al.,* 2004) with cv. 'Cartagenera' that imposed an RDI regime that resulted in a minimum predawn leaf water potential of -2.5 MPa in late July found no reduction in dry kernel weight at the mid-August harvest.

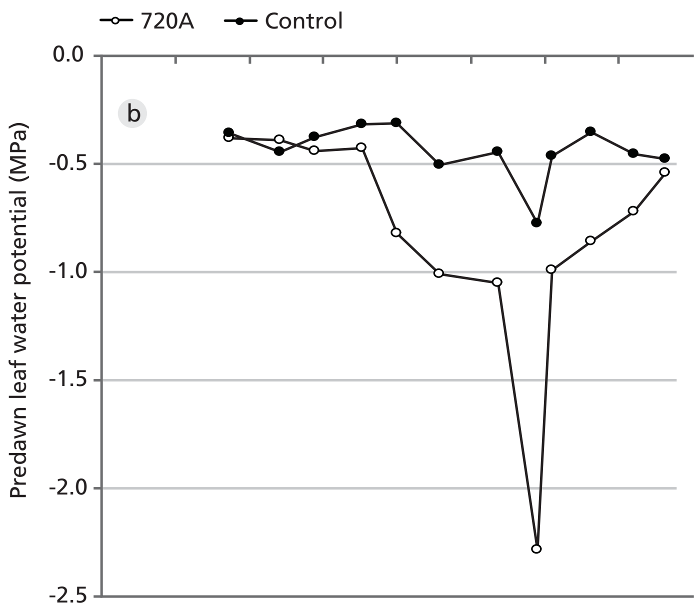
A recent study with cv. Non Pareil in California showed that imposing water deficits primarily from early July through an early September harvest over a four-year period did not reduce kernel weight or nut load (Stewart *et al.*, 2011). These workers attempted to maintain midday stem-water potential between -1.4 and -1.8 MPa during this period. The objective was reduced hull rot, a disease that damages the fruit (Teviotdale *et al.*, 2001), while reducing consumptive use. Other efforts using this same philosophy have achieved positive results and this practice is now being widely adopted by California almond growers with trees afflicted by severe hull rot. However, it should be noted that detailed analysis of the fruit components (hull, shell, and kernel) suggests that the impact of preharvest stress on hull splitting may impact kernel weights. In numerous studies, California researchers found that slight reductions of kernel dry matter accumulation occurred concomitant with the onset of hull split, while at the same time, there were slight increases in the rate of dry matter accumulation in the hulls. The net result was slightly lighter kernels (generally 2-3 percent relative to full irrigation) but no difference in the dry weight of the entire nut. They hypothesized that hull split resulted in some physical disruption in assimilate transport in the pathway leading to the kernel.

It appears that there are two factors involving early season stress timing that can contribute to reduced kernel size: lower cell division and/or expansion, which is enhanced by carbohydrate competition, and the disruption in assimilate transport to the kernels because of accelerated hull split. These stress impacts may well be cultivar-dependent although comparative research studies are lacking.

Of the two primary yield components of almond, fruit load appears to be the most sensitive in terms of water stress impacts on yield. A study in Spain found that fruit loads were reduced in the final two years of a four-year RDI treatment and attributed this to the cumulative impacts of stress on the bearing surface, and thus fruiting positions, of the tree. Another study in California also reported that yield reductions associated with water deprivation in August and September (minimum midday stem-water potential of -2.5 MPa) were the result of a reduced bearing surface resulting from less shoot and spur growth. This study found that yields were reduced only after two years of stress. Other studies have found little impact of preharvest stress on fruit load.

FIGURE 3 Differences in the cultivar Non Pareil trees subjected to preharvest water deficits (720A) and those fully irrigated (Control) in: **(a)** dry matter accumulation in the hulls+shells and kernels with time in the third year of the stress treatments, and **(b)** corresponding predawn leaf water potentials. Adapted from Goldhamer *et al*. (2006).

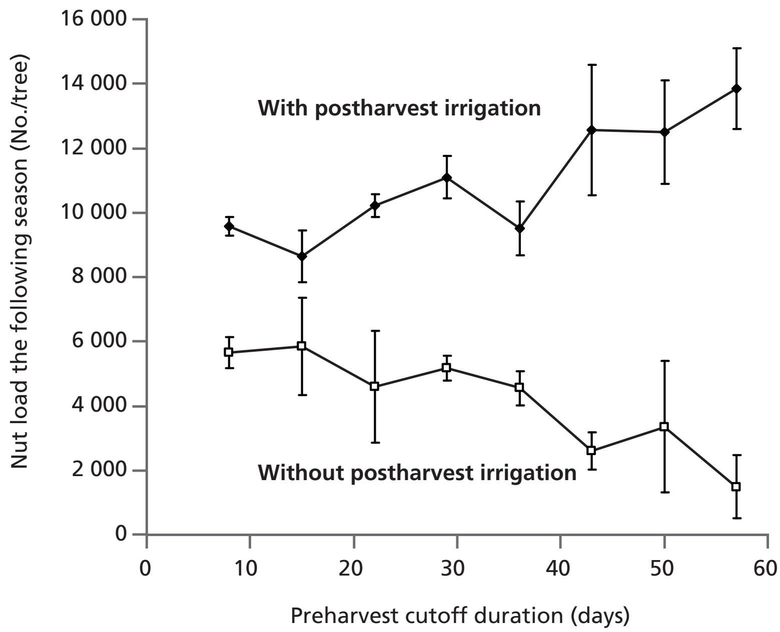




Much less work has been done on the impacts of postharvest stress on almond production, in part, because in many parts of the world, autumn rains eliminate this possibility. However, a dramatic impact of the presence or absence of postharvest irrigation on the following season's fruit load has been detected (Goldhamer and Viveros, 2000) (Figure 4). Even when the trees were near fully irrigated prior to harvest, postharvest water deprivation resulted in 40 percent reduction in fruit load the following season, relative to trees that received postharvest irrigation. It should be emphasized that this was with a mid-August harvest under high evaporative demand; predawn leaf water potential was below -4.0 MPa in mid September. For this same stress level at preharvest, there was near complete defoliation but after the reintroduction of full irrigation postharvest, there was vegetative bud break and new leaf growth, alleviation of the stress, and no reduction in fruit load the following season (Goldhamer and Viveros, 2000).

The dramatic impact of postharvest water deprivation on fruit load was attributed to stress impacts on reproductive bud development. Early work (Tufts and Morrow, 1925) showed that bud differentiation in almond occurred from late August through early September, and this has been confirmed by more recent work. The timing of bud development showed no clear pattern between cultivars or locations within California, spanning a distance of more than 500 km (Lamp *et al.*, 2001). Thus, bud development can occur both after and before harvest, depending on the cultivar and geographic location. Moreover, bud development is not related to hull split: it occurred three weeks after hull split in Non Pareil but prior to hull split in 'Butte' and 'Carmel.' Stresses that occur during flower development are likely to adversely affect flower quality to the extent that the next season's crop load, and thus yield, would be reduced.

FIGURE 4 Relationships between fruit load in the season following the imposition of different preharvest irrigation cutoff regimes for conditions with and without postharvest irrigation. Vertical lines are plus and minus one standard error. Adapted from Goldhamer and Viveros (2000).



Indicators of tree water status

To precisely schedule irrigation, it may be necessary to monitor a given soil and/or plant parameter and make decisions according to some pre-established criteria. Also, implementing an RDI regime may have to be based on estimates of tree water status, such as the stem-water potential (SWP). The SWP values of well-irrigated almond trees in mid-summer range from -0.5 to -1.0 MPa at midday, depending on the evaporative demand and the time of the year. In one study, there was a 0.2 MPa decrease in the SWP of fully irrigated trees on different days (from -0.7 to -0.9 MPa) when the air temperature increased from 25 to 40 °C. The SWP values decrease as stress increases but in almond, it seldom exceeds -4.0 MPa even under very severe stress (Castel and Fereres, 1982). The tree will shed its leaves before reaching the extreme dehydration levels that would induce lower water potential, as measured in other fruit tree species.

WATER REQUIREMENTS

Most of the almond water use estimates in the literature were developed using soil water balance approaches rather than from more accurate weighing lysimeters. The monthly crop coefficient values (K_c) for clean cultivated, weed free, high evaporative demand conditions published by several authors are shown in Table 1. Because almond ET has often been grouped with peach, apricot, and plum, weighing lysimeter K_c data for peach determined in California are also shown in Table 1 for comparison (Ayars, 2003). Early season crop K_c values for the peach used in their work are relatively low owing primarily to the slow canopy development of this cultivar. Maximum K_c values (July-August) for all the presented data range from 0.95 to 1.08. Recent data from California suggests that almond peak K_c values of an intensive, mature orchard irrigated with microsprinklers may reach as high as 1.17 (Goldhamer, unpublished), which is considerably higher than previously reported. Similar high K_c values have been recently reported in Australia (Stevens *et al.*, 2011). It should be noted that when the early ET data were developed, surface irrigation (border strip) was the primary irrigation method, whereas drip or microsprinklers were used in the more recent studies. The higher K_c values are likely due to the increase in tree densities in recent plantations, larger tree canopies (there is much less annual pruning now than previously), and higher fruit loads. Also, the more frequent wetting of the orchard floor with microirrigation and thus, higher surface evaporation may be another factor for the higher K_c values.

WATER PRODUCTION FUNCTION

Relative yield versus relative applied water data derived from fourteen irrigation studies are presented in Figure 5. It was not possible to estimate ET_c in many of the studies and therefore, the actual production function based on consumptive use could not be drawn. These studies were done over a wide range of evaporative demands, cultivars, and soils with various deficit irrigation regimes; different timing and magnitudes of stress. The correlation coefficients of the linear regressions for these studies ranged from 0.87 to 0.98, indicating a strong functional relationship between yield and applied water. Some of these studies had similar slopes ranging from 0.7 to 0.9, whereas others had a milder slope above 0.3. The lower yield sensitivity of these studies is likely due to a combination of deep soils, relatively low crop loads, and relatively wide tree spacing. Thus, the impact of instantaneous stresses was buffered by the high potential rate of water supply to the trees. It should be noted that these studies generally had consumptive use rates that deprived the trees of up to 30-50 percent of maximum ET_c. Close inspection of

Figure 5 shows that with mild deficit irrigation that would reduce relative ET_c by only 10-15 percent, the impact on production is negligible.

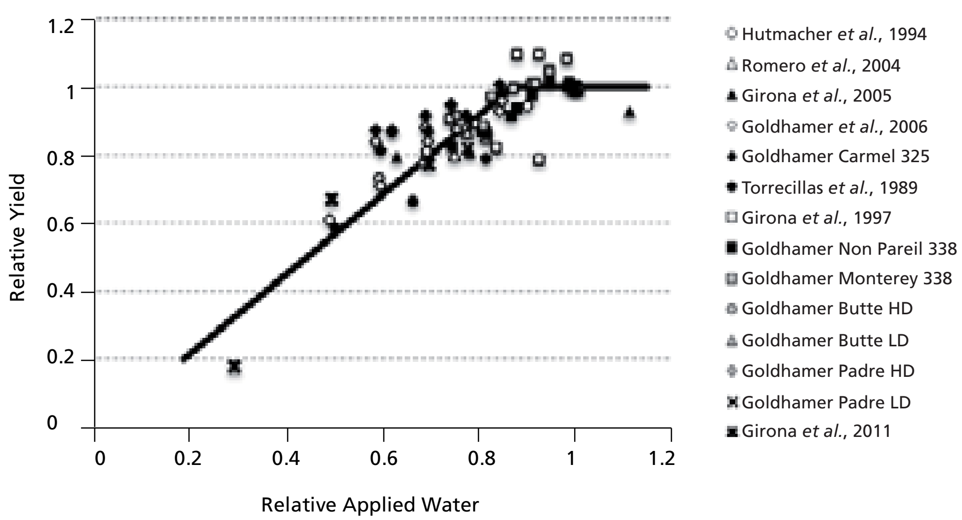
SUGGESTED RDI REGIMES

Growers with limited water supplies must make a decision on when to stress trees. Based on research results, we believe the two most stress sensitive periods are in the Spring when the

TABLE 1 Estimates of the monthly crop coefficient (K_c) values for mature deciduous trees (first column), almond (columns two-five) and peach trees (last column).

	Doorenbos and Pruitt (1977)	Fereres and Puech (1981)	Sanden (2007)	Goldhamer (unpublished)	Girona (2006)	Ayars *et al.* (2003)
March	0.50	0.60	0.59	0.20	0.40	0.28
April	0.75	0.71	0.78	0.67	0.65	0.48
May	0.90	0.84	0.92	0.95	0.80	0.68
June	0.95	0.92	1.01	1.09	0.92	0.88
July	0.95	0.96	1.08	1.15	0.96	1.06
Aug.	0.95	0.96	1.08	1.17	1.05	1.06
Sept.	0.85	0.91	1.02	1.12	0.85(*)	1.06
Oct.	0.80	0.79	0.89	0.85	0.60	0.90
Nov.	0.70		0.69		0.40	

FIGURE 5 Relationships between relative yield and relative applied water for 14 deficit irrigation studies on almond with a wide variety of cultivars, locations, soils, rainfall, stress timing patterns, and evaporative demand.



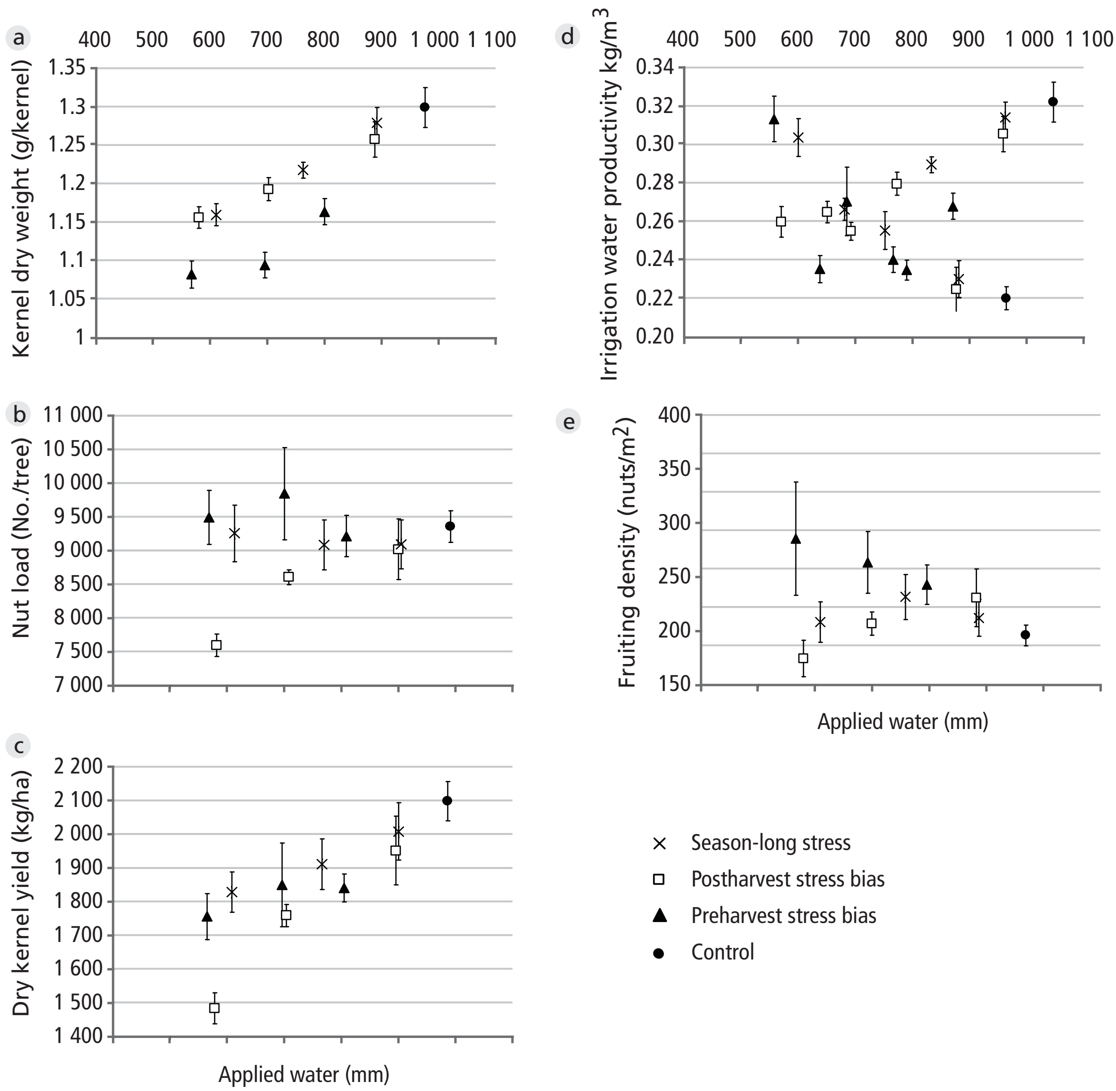
nuts are rapidly expanding and late summer/autumn when bud morphogenesis is occurring. This second stress-sensitive period is usually postharvest for early harvest cultivars but prior to harvest with later maturing cultivars. The results of an experiment (Goldhamer *et al.*, 2006) provide useful information on the relative sensitivity of pre and postharvest stress to aid RDI decision making. It was found that the greater the preharvest water deprivation, the greater was the reduction in kernel dry weight at harvest (Figure 6a). However, minimizing preharvest stress at the expense of postharvest irrigation resulted in significantly lower fruit loads in subsequent seasons (Figure 6b). Yield, the integrator of fruit weight and fruit load, was least affected by minimizing stress after harvest (Figure 6c). These regimes also resulted in the highest irrigation water productivity (Figure 6d).

Water supply constraints may be temporary, as a result of one year drought. Single season drought RDI strategies were tested (Goldhamer and Smith, 1995) where they applied less than 40 percent (400 mm) of potential seasonal ET_c with different timing regimes: irrigating at 100 percent, 75 percent, and 50 percent ET_c until the 400 mm was exhausted, which occurred in early June, mid July, and late August, respectively. They found that full irrigation early in the season limited reductions in fruit size but resulted in dramatic reductions in the following seasons' fruit load (Table 2) (Goldhamer and Smith, 1995). They attributed this to the negative impact of stress on reproductive bud differentiation. The treatment that irrigated at 50 percent ET_c, which applied water longer (through August; two weeks after harvest), did not suffer any significant decrease in fruit load the following season. When they averaged the drought year and the following two fully irrigated recovery years, they found that the 50 percent ET_c treatment had higher yields that the other two RDI regimes; those that applied their available water supply all preharvest. Nevertheless, none of the RDI regimes achieved complete production recovery even after two seasons of full irrigation following the single drought year, suggesting that impacts of reduced shoot and spur growth may have also been a factor (Goldhamer and Smith, 1995).

Suggested RDI regimes for five different levels of available water supply (300, 450, 600, 750, and 900 mm where full ET_c is 1250 mm) expressing irrigation rates as percentages of ET_c are presented in Table 3. To show how these regimes would affect applied water, we used as an example long term values of ET_o from western Fresno County, California and bimonthly crop coefficients (K_c) from Goldhamer (unpublished) for 'Non Pareil' almonds. When the water supply was relatively high, the stress is biased to the preharvest period, saving as much water as possible for the most stress sensitive period; from mid August through the end of September. With a severely restricted water supply, the concern is about tree survival and general health in addition to maximizing stress impacts on time-averaged yields. It must be emphasized that when applying very low amounts of potential seasonal water supply, surface evaporation, and thus, the number of irrigations, should be minimized. Therefore, the duration (amount of applied water) of each irrigation should be maintained as normal but the frequency of irrigation should be changed. For example, if microsprinkler irrigation is normally operated every three days, an RDI strategy that applies 25 percent ET_c would extend the frequency to every 12 days.

Since RDI reduces vegetative growth, it should not be used on young trees where the objective is to grow the canopy to full size, and thus attain maximum yields, as fast as possible. It has been confirmed (Girona *et al.*, 2005) that RDI imposed too early in the life of the orchard can reduce potential yields.

FIGURE 6 Relationships between applied water and a) kernel dry weight, b) fruit load, c) kernel yield, d) irrigation water productivity, and e) fruit density. Vertical lines are plus and minus one standard error. Data are mean values from four experimental years with Non Pareil. Adapted from Goldhamer *et al.* (2006).



Additional considerations

Water stress in almonds has been known to increase spider mite levels (Youngman and Barnes, 1986) and the navel orangeworm (Goldhamer, unpublished data). The latter becomes more of a problem when the onset of hull split is accelerated by preharvest stress and/or the nuts remain longer on the tree before shaking. Hull rot can be dramatically reduced by imposing water deficits during the first two weeks of July (Teviotdale *et al.*, 2001). Their target predawn leaf water potential value was -1.6 MPa.

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TABLE 2 Irrigation management, yield, and nut quality data for a single year drought irrigation study conducted in western Fresno County, California.

Year	Treatment	Water applied through	Water allotment applied ** (mm)	Total kernel yield (lbs/acre)	Individual kernel weight (grams)	Tree nut load (No./tree)	Hull splitting		
							Full hull split	Partial hull split	Hull tight
							(- - - - - % of tree nut load - - - - -)		
Drought	Full irrigation control	Full season	1 024	1 653 a***	1.24 a	7 100 a	98.9 a	0.4 a	0.7 a
Year	100%DY ET_c*	June 19	409	1 362 b	0.97 b	8 160 a	38.2 b	48.1 b	13.7 b
	75%DY ET_c	July 11	411	1 236 b	1.10 bc	6 340 a	85.3 a	11.4 a	3.3 a
	50%DY ET_c	August 28	414	1 448 ab	1.03 bc	7 000 a	99.0 a	0.6 a	0.4 a
Recovery	Full irrigation control	Full season	843	2 730 a	1.04 a	1 2850 a	99.7 a	0.0 a	0.3 a
Year 1	100%DY ET_c*	Full season	836	911 b	1.03 a	4 770 b	99.7 a	0.1 a	0.2 a
	75%DY ET_c	Full season	836	1 493 c	0.99 ab	8250 c	99.9 a	0.0 a	0.1 a
	50%DY ET_c	Full season	846	2 010 d	0.89 b	1 1690 a d	99.6 a	0.0 a	0.4 a
Recovery	Full irrigation control	Full season	838	2 358 a	0.97 a	9 890 a	98.3 a	1.3 a	0.4 a

TABLE 2 (CONTINUED)

Year	Treatment	Water applied through	Water allotment applied ** (mm)	Total kernel yield (lbs/acre)	Individual kernel weight (grams)	Tree nut load (No./tree)	Hull splitting		
							Full hull split	Partial hull split	Hull tight
							(- - - - - % of tree nut load - - - - -)		
Year 2	100%DY ET_c*	Full season	838	2 327 a	1.02 a	9 200 a	98.8 a	0.7 a	0.5 ab
	75%DY ET_c	Full season	838	1 975 b	1.02 a	7 900 b	97.9 a	1.2 a	0.9 b
	50%DY ET_c	Full season	838	1 949 b	1.13 b	7 050 b	98.5 a	1.0 a	0.5 ab
Year 3	Full irrigation control		902	2 247 a	1.08 a	9 948 a	99.0 a	0.5 a	0.5 a
Mean	100%DY ET_c*		693	1 534 b	1.01 a	7 378 b	78.9 b	16.3 b	4.8 b
	75%DY ET_c		696	1 568 b	1.04 a	7 498 b	94.4 a	4.2 a	1.5 a
	50%DY ET_c		**699**	**1 802 c**	**1.02 a**	**8 581 b**	**99.0 a**	**0.5 a**	**0.5 a**

* Irrigation rate until allotment applied; no additional irrigation for the remainder of the season.

** Does not include 100 mm pre-season irrigation applied each year.

*** Numbers for each year followed by a different letter are significantly different at the 5% confidence level using Duncan's New Multiple Range Test.

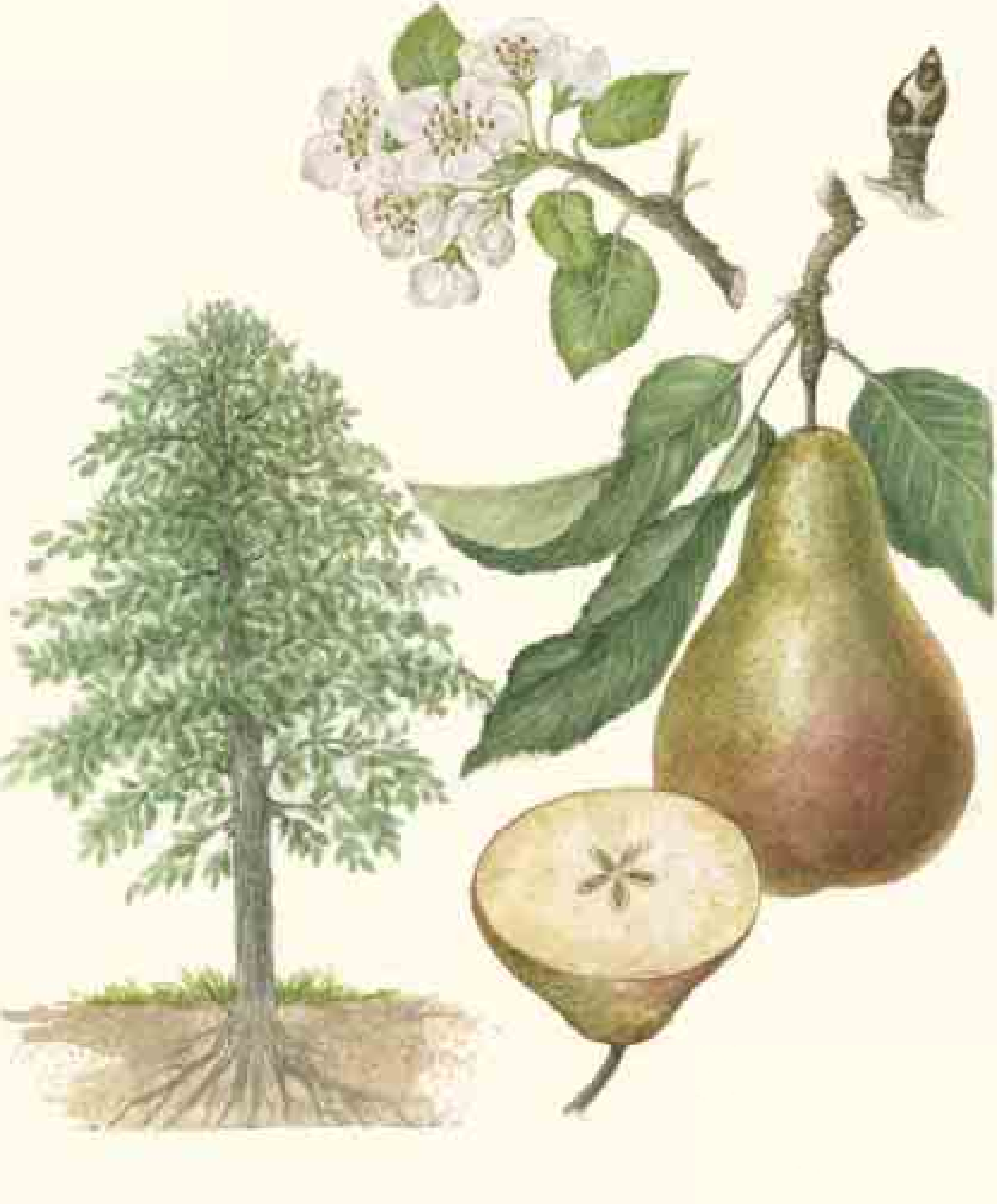
TABLE 3 Suggested RDI strategies for different available water supply scenarios from 900 to 300 mm when potential ETc is 1250 mm.

Date	Potential ET_c in Period (mm)	900 mm available case Irrigation Rate (% ET_c)	900 mm available case Applied Amount (mm)	750 mm available case Irrigation Rate (% ET_c)	750 mm available case Applied Amount (mm)	600 mm available case Irrigation Rate (% ET_c)	600 mm available case Applied Amount (mm)	450 mm available case Irrigation Rate (% ET_c)	450 mm available case Applied Amount (mm)	300 mm available case Irrigation Rate (% ET_c)	300 mm available case Applied Amount (mm)
Mar. 16-31	12	75	9	70	9	60	7	40	5	25	3
April 1-15	35	75	27	70	25	60	21	40	14	25	9
April 16-30	57	75	43	70	40	60	34	40	23	25	14
May 1-15	82	75	61	50	41	30	25	25	20	25	20
May 16-31	106	75	80	50	53	30	32	25	27	25	27
June 1-15	114	75	86	50	57	30	34	25	29	25	29
June 16-30	120	75	90	50	60	30	36	25	30	25	30
July 1-15	121	50	60	25	30	25	30	25	30	20	24
July 16-31	125	100	125	100	125	90	112	75	93	25	31

TABLE 3 (CONTINUED)

	Potential	900 mm Available Case		750 mm Available Case		600 mm Available Case		450 mm Available Case		300 mm Available Case	
	ET_c in	Irri.	Applied	Irri.	Applied	Irri.	Applied	Irri.	Applied	Irri.	Applied
Date	Period	Rate	Amount	Rate	Amount	Rate	Amount	Rate	Amount	Rate	Amount
	(mm)	(% ET_c)	(mm)	(% ET_c)	(mm)	(% ET_c)	(mm)	(% ET_c)	(mm)	(% ET_c)	(mm)
Aug. 1-15	111	100	111	100	111	90	100	60	67	25	28
Aug. 16-31	109	75	82	60	65	50	54	60	65	50	54
Sept. 1-15	90	75	67	60	54	50	45	25	22	25	22
Sept. 16-30	72	75	54	60	43	50	36	25	18	25	18
Oct. 1-15	55	25	14	60	33	50	27	25	14	0	0
Oct. 16-31	32	0	0	0	0	0	0	0	0	0	0
Total	**1242**		**909**		**746**		**595**		**458**		**298**
Irrigations	33*		24		20		16		12		8

* The grower would keep track of cumulative amounts to be applied with RDI scenarios. When they total 37 mm (the amount applied by the microsprinklers in 24 hrs in this example), he irrigates. Thus, there would be one irrigation in the first week of April with full water supply but with 300 mm available case, first irrigation would not be until the first week of May.



Pear

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Pear

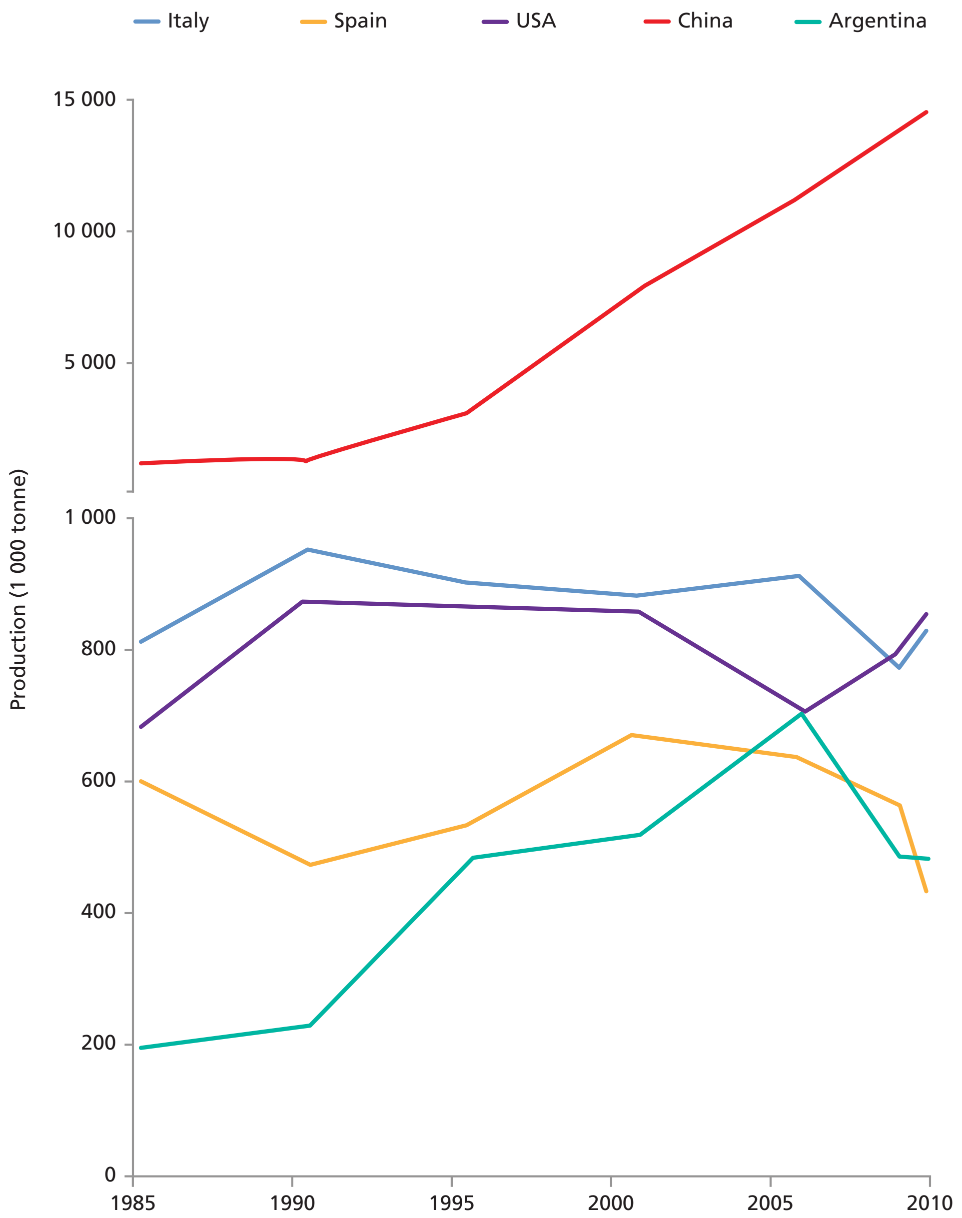
INTRODUCTION AND BACKGROUND

Pears, along with peaches, are the second deciduous fruit tree species in economical importance after apples. The genus *Pyrus* includes about 20 wild species and its primary centre of origin is Europe, and regions in temperate Asia. Two main species are cultivated. European pear (*Pyrus communis* L.) is grown in Europe, United States, South Africa and Oceania, and the Asian pear or Nashi (*Pyrus pyrifolia* Burm.) (syn. *Pyrus serotina*) is traditionally grown in Asia. Other species of the genus have been used as rootstocks such as *Pyrus calleryana* Dcne. Today the most widespread rootstock is clonal quince (*Cydonia oblonga* L.), though its graft compatibility is not good for all cultivars.

The cultivated pear is self-incompatible, and cross-pollination with other cultivars is required for optimum fruit production, with the exception of some varieties such as Bartlett and to some extent Conference. Pears typically bear fruit on spurs in terminal buds. Flower buds are initiated at the end of shoot development during the preceding season, and the formation of these flowers depends on the light received by spurs in the previous season. An open canopy is thus required for full fruitfulness by training branches and pruning to specific shapes.

Other factors that influence flower bud initiation are previous crop load and water stress. Water stress, to a certain extent, can be a positive stimulus for bud initiation, but a high crop load has a negative influence in the next season. For this reason pears often exhibit biennial alternate bearing. Another key issue in pear orchards is growth control to prevent decreased light penetration into the canopy. Water stress, vigour controlling rootstocks, and growth regulators are means available to reduce vigour in pear orchards. Pears are grown in a wide-range of climates, from cool to warm and from humid to arid-areas. In 2009, there were 1.58 million ha of pear orchards globally with an average yield of 14.2 tonne/ha (FAO, 2011). Figure 1 presents the production trends of the major producing countries. The major factors limiting for the expansion of pear production in warm regions are insufficient chilling temperatures during winter and the occurrence of diseases such as fireblight. Pear trees are not a drought resistant species and its commercial production in areas with dry seasons depends entirely on irrigation. As far as irrigation is concerned, pear orchards may benefit from judicial use of deficit irrigation because it can have positive effects by controlling tree vigour during current season and on flowering in the following season.

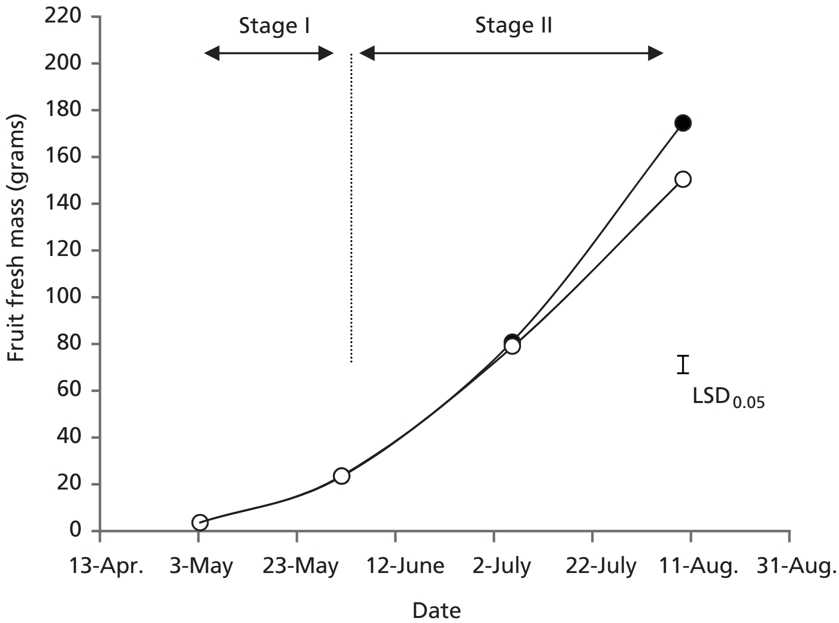
FIGURE 1 Production trends for pears in the principal countries (FAO, 2011).



DESCRIPTION OF THE STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

The reproductive growth of pear trees can be divided into two stages based on the growth rate of the fruit (Figure 2). Stage I of pear fruit development, corresponds to the initial slow growth phase, and Stage II corresponds to the rapid growth phase (Mitchell *et al.*, 1989) which in the cultivar Bartlett the second stage could be differentiated when growth (volume increase) surpasses the rate of 1.5 $cm^3 \cdot day^{-1}$.

FIGURE 2 Reproductive growth of pear trees.



Early vegetative and reproductive growth; growth Stage I

Pear flowers commonly open almost synchronously with leaf appearance. Shoot growth starts after first leaf appearance and occurs concomitantly with the current season reproductive growth. Vigour-conditions will determine the extent and the timing of shoot growth enlargement. In trees grafted on vigour controlling rootstocks such as quince, shoot development occurs in one-to-two flushes during spring (April and May in the Northern Hemisphere). Under more vigorous conditions shoot growth extends into early summer throughout all Stage I. At this time, vegetative growth of the scion is a stronger sink than fruit, and fruit growth is quite slow in terms of dry mass accumulation. Root growth in spring is also relevant and occurs concomitantly with shoot development and ceases near the end of May. Root growth, however, depends on inter-organ competition and availability of carbohydrates. The end of rapid shoot growth is signalled by the appearance of a terminal bud.

Fruit growth starts right after ovary fertilization and this can be measured in the field at about one month after full bloom. Physiological fruit drop, however, lasts longer and can extend until the end of Stage I or onset of Stage II (in midseason cultivars). Stage I corresponds to the fruit main cell-division period, and takes place during the first 7 to 8 weeks after bloom (Bain, 1961). The remainder of fruit development constitutes Stage II when the major increase in cell volume occurs (Bain, 1961). Cell expansion, however, is also active during Stage I, but its effect is masked by the simultaneous occurrence of cell division.

Fruit growth during Stage II

Expansive fruit growth is the main growth event for the tree during Stage II. Stage II corresponds to the period of rapid fruit cell enlargement. Nevertheless, bud development also becomes relevant after cessation of shoot enlargement. Differentiation of buds into flower buds usually occurs at the beginning of Stage II in midseason cultivars (early to mid-June)

(Elkins *et al.*, 2007). The appearance of flower structures takes place during Stage II. However, this process is influenced and modified by climatic conditions and a number of factors that are not yet well understood. Although shoot extension growth is minimal during that time, branch thickening may occur if fruit load is low and water status is optimal.

Postharvest

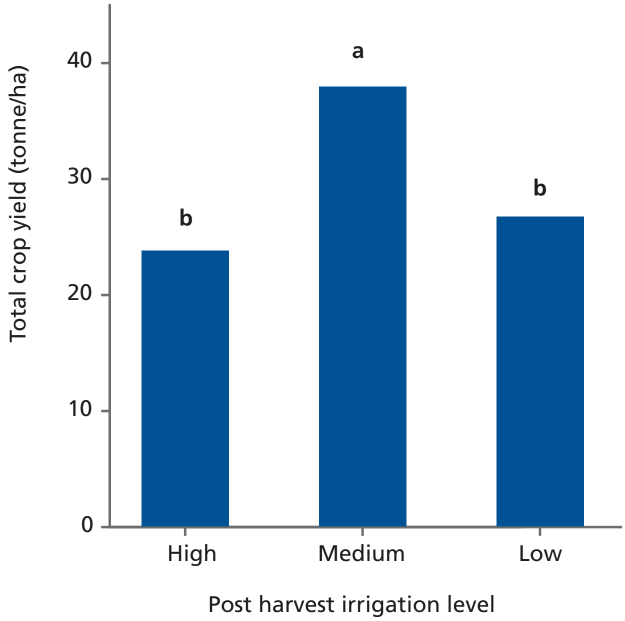
Bud will continue to develop during postharvest and at a slower rate throughout winter. During this period, buds will increase in size by 25 percent, which mainly corresponds with the elongation of the carpels. During the postharvest period, there is a second peak of root growth activity, and this period is also important for reserve accumulation in roots and stems before the start of defoliation. This tends to occur somewhat sooner than in apple and other deciduous species and it is accelerated by low temperatures. Anomalous postharvest flowering can occur in autumn after a period of severe postharvest water stress, if this stress is relieved by irrigation or rainfall a month before leaf die back (Naor *et al.*, 2006).

RESPONSES TO WATER STRESS

Although pear is not considered drought resistant, its organs and tissues can withstand a certain degree of dehydration, which surpasses the capacity of other deciduous fruit trees such as peach, plum or apple. During summer, leaf turgor loss occurs in the cv. 'Barlett' at values of midday stem-water potential (SWP) close to -3.1 MPa (Marsal and Girona, 1997), which is quite low relative to the other deciduous fruit trees. It has also been reported that recovery from water deficits is delayed if SWP reaches values below -3.5 MPa, suggesting this threshold as a limit for the occurrence of vascular embolism (Marsal *et al.*, 2002b). Stomatal conductance and leaf photosynthesis decrease linearly with midday SWP in response to irrigation reductions. For European pear, nearly zero values in both stomatal conductance and leaf photosynthesis have been reported at SWP values of -2.5 MPa (Naor *et al.*, 2000; and Marsal *et al.*, 2002b). Trunk growth ceases at SWP below -2.2 MPa, but shoot extension growth stops sooner, at about -1.7 MPa in the case of moderately low vigour conditions. For more vigorous conditions (i.e. young, defruited trees) extension growth precedes up to -2.0 MPa of SWP. Fruit growth (fresh weight) is somewhat less sensitive to water deficits, stopping at about -2.5 MPa, either during Stage I or Stage II (Marsal *et al.*, 2002b). The SWP values discussed above are indicative of full impairment, but the processes, whether fruit or vegetative growth, are affected by much milder water deficits. For instance, for cv. 'Conference' it was found that to achieve fresh market standards of fruit size for at least 50 percent of harvested fruit, SWP values below -1.1 MPa should be avoided during the Stage II of fruit growing period.

In terms of flowering, moderate water stress during the fruit-growing season (Marsal *et al.*, 2002a) or postharvest (Naor *et al.*, 2006) increases bloom the following season as compared to fully irrigated trees. This behaviour is attributed to the fact that moderate water stress levels hasten development of flower organs (Forshey and Elfving, 1989). However, severe water stress (SWP values below -2.8 MPa) can induce cropping deficiencies next season (Naor *et al.*, 2006). The data in Figure 3 shows that moderate water stress was the best postharvest strategy in terms of subsequent season productivity (Naor *et al.*, 2006). Contrary to European pear, Asian pear seems to have a differential flowering response to water deficit the previous year. In general, water stress reduced return bloom in Asian pears (Caspari *et al.*, 1994).

FIGURE 3 Effects of postharvest irrigation levels on next season crop yield (cumulative of two years). Midday stem-water potential was -2.8 MPa, -2.4 MPa, and -1.5 MPa in the Low, Medium and High irrigation levels, respectively (source: Naor *et al.,* 2006).



In general terms it can be stated that for favourable growing conditions reference midday SWP values for unstressed pear trees oscillate between -0.65 and -0.95 MPa depending on evaporative demand; values below -1.1 MPa are indicative of water stress conditions. On the other hand, it is difficult to diagnose early waterlogging effects from SWP values.

Water stress responses during Stage I

Pear trees are highly responsive to seasonal water stress. Water stress during Stage I decreases shoot growth, fruit growth, final fruit size at harvest, and can increase fruit drop (Marsal *et al.*, 2000; and Naor *et al.*, 2000). Water stress during Stage I can potentially affect fruit cell division, cell enlargement or both processes (Marsal *et al.*, 2000). Only in few cases and under moderate water stress conditions (LWP above -2.5 MPa), final fruit size was not impaired or favoured by the application of early water stress (Behboudian *et al.*, 1994; and Mitchell *et al.*, 1989). These authors argued that such responses were achieved by the occurrence of fruit osmotic adjustment that increased fruit growth after the early water stress. However, other interpretations of these positive effects, such as the different conditions in the timing and duration of the applied water stress, are also possible (Naor *et al.*, 2006). Other factors such as vigour and tree-to tree shading conditions can also be added to this controversy. The early literature from Australia described the application of water deficits to cv. 'Barlett' pear trees in high density orchards (from 2 500 to 5 000 plant/ha) growing on largely vigorous rootstocks (*Pyrus calleriana*). In those experiments, fruit under RDI during Stage I sized larger than Control fruit at harvest, and water stress during Stage I helped reduce vegetative growth that was considered excessive. The growing conditions in these studies were site-specific and do not represent the typical pear-growing conditions around the world where canopy shading is optimized by the introduction of new vigour controlling rootstocks. Experiments carried out in Spain under more common growing conditions including moderate density orchards (1 100-1 600 plant/ha), and using vigour-reducing rootstocks such as clonal quince (BA-29 or M-C) indicated no significant effect on fruit size at harvest in response to RDI Stage I as compared to Control irrigated trees (Marsal *et al.*, 2002a; and Asin *et al.*, 2007). In one case, where trees grew in isolated large containers of 120 litre, deficit irrigation during Stage I actually reduced final fruit size at harvest (Marsal *et al.*, 2000). Furthermore, several attempts in Spain during the nineties to use RDI during Stage I in commercial orchards aimed to increase fruit size above that of fully-irrigated trees, proved unsuccessful.

Water stress responses during Stage II

Water stress during Stage II of fruit development decreased final fruit weight and lower fruit diameter (Behboudian *et al.*, 1994; Marsal *et al.*, 2000; Naor, 2001; Marsal *et al.*, 2002a; and O'Connel and Goodwin, 2007). Water stress at this time mainly reduces fruit cell size (Marsal *et al.*, 2000) and, as a consequence, final fruit size at harvest.

Water stress responses during postharvest

There are few studies available on this topic. One study attempted to use RDI in postharvest for Spadona European pear where the elapsed time for deficit irrigation was three months (from August to the end of October) (Naor *et al.*, 2006). The results of the experiment indicated that water could be saved, provided midday SWP did not surpass the threshold of -2.2 MPa. A positive effect related to moderate postharvest water stress (i.e. SWP >-2.2 MPa) was that, during the following season, return bloom and fruit yield increased significantly compared to fully irrigated and severely stressed trees (Naor *et al.,* 2006).

Similar results regarding increased return bloom have been found by Marsal in Spain for the cultivar Conference. However, in his study fruit set was lower for these trees with higher bloom and this ended up reducing yield but increasing fruit size.

WATER REQUIREMENTS

There are only a few reports available on ET_c information for pear trees. One study used drainage lysimeters of 105 litre capacity and conditions close to hydroponics with the soil surface covered to avoid soil evaporation (Buwalda and Lenz, 1995). The study considered three different cultivars, two training systems and presence or absence of fruit. The effect of both cultivar and training system on tree water consumption was significant; although the differences can be explained by differences in leaf area. However, the presence of fruit increased tree water consumption by 36 percent as compared to de-fruited trees, independently of leaf area (Buwalda and Lenz, 1995). These differences were probably related to increases in stomatal conductance and therefore leaf photosynthesis and transpiration which are frequently observed under higher cropping conditions of pear (Marsal *et al.*, 2008).

The crop coefficients obtained in the lysimeter study (Buwalda and Lenz, 1995) were referred to the Priestley and Taylor ET_o equation, and did not consider a soil evaporation component. Nevertheless, the reported values were quite low, with maximum values of 0.38 for cv. Conference with a leaf area index (LAI) of 2.0. Water use in this study must have been restricted

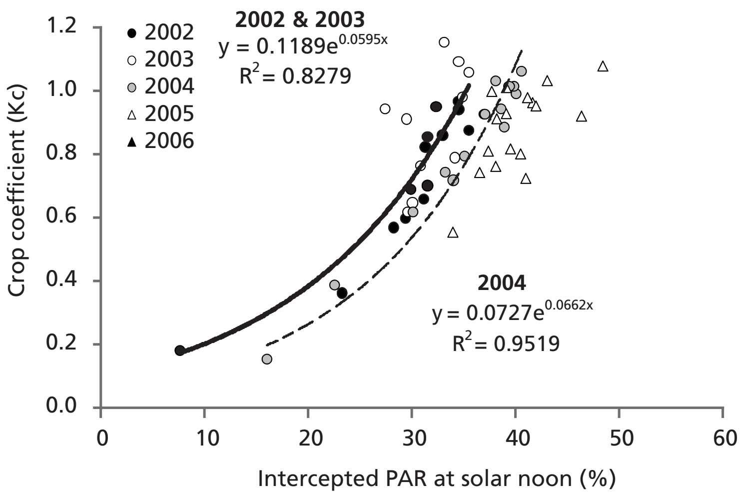
TABLE 1 Crop coefficients relative to grass reference crop (ET_o) for mature pear trees (Conference on quince) grown in a central leader training system and measured using a lysimeter located in an experimental orchard at Lleida, EEL (Spain) by Girona *et al.* (unpublished).

Date	Crop coefficient (K_c)	Ground cover (%)
Apr. 1-15	0.30	23
Apr. 16-30	0.48	30
May 1-15	0.70	36
May 16-31	0.80	39
June 1-15	0.85	40
June 16-30	0.90	40
July 1-15	0.90	40
July 16-31	0.90	40
Aug. 1-15	0.90	40
Aug. 16-31	0.70	40
Sept. 1-15	0.60	40
Sept. 16-30	0.50	40
Oct. 1-15	0.40	40
Oct. 16-31	0.35	36
Nov. 1-15	0.35	25

by the size of the containers because a field study found a midsummer K_c of 0.9 for a pear orchard of the cv. Blanquilla with trees trained to a palmete system (Marsal *et al.*, 2002a). This K_c value is slightly lower than the 0.95-1.0 value that has been traditionally recommended (Allen *et al.*, 1998). A weighing lysimeter study within a pear orchard, measured the ET_c of three pear trees, cv. Conference, trained to a central leader (Girona *et al.*, 2010). Values for crop coefficients (ET_o calculated according to FAO *I&D Paper No. 56* Penman-Monteith equation) in midsummer were around 0.9 with a LAI of 1.4. The seasonal changes in K_c values for Conference trees are presented in Table 1.

It must be emphasized that K_c values in Table 1 are only indicative, and that they may require adjustment to each specific training system and growing conditions. In fact, in the lysimeter study (Girona *et al.*, 2010), K_c showed ample variation over the years (see Figure 4), and there were variations even within the same season after full canopy development. It appears that, at least for the cv. Conference in a semi-arid climate, pear K_c increases under high air vapour pressure deficits (Girona *et al.*, 2010), suggesting that transpiration (Tr) in pears is enhanced relatively more than grass Tr, which is the reference crop for ET_o. This effect makes the use of

FIGURE 4 Relationships between the percentage of photosynthetically active radiation (PAR) intercepted at solar noon and daily crop coefficients (K_c) for individual lysimeter-grown apple and pear trees from bud-break until harvest. The relationships between the percentage of PAR intercepted and daily K_c were fitted to exponential equations. Each K_c value represents the average K_c calculated three days before and after the PAR measurements (*source: Girona et al., 2010*).



a relationship between K_c and the fraction of midday crop intercepted radiation less useful in pear than in peach or apple (see both Sections). Nevertheless, the use of the midday fraction of crop intercepted radiation (or, if midday intercepted radiation data is unavailable, the percent ground cover may be used as a surrogate; see Chapter 4) provides a first approximation for adjusting the K_c values for pear trees.

A water-use study of Asian pear measured the water consumption of trees planted in 12 medium-large drainage lysimeters (9 100 litre) and with a soil surface covered with reflective net (Chalmers *et al.*, 1992). Trees were trained to a Tatura trellis and ET was determined from pan evaporation. This and another study of Asian pears (Caspari *et al.*, 1993; and Caspari *et al.*, 1994), reported their K_c values on a per tree canopy area basis instead of ground area, and thus cannot be compared with the standard K_c values. Nevertheless, the conclusion of the Asian pear studies is that their water requirements are somewhat lower than the values recommended in FAO *I&D Paper No. 56* for this crop.

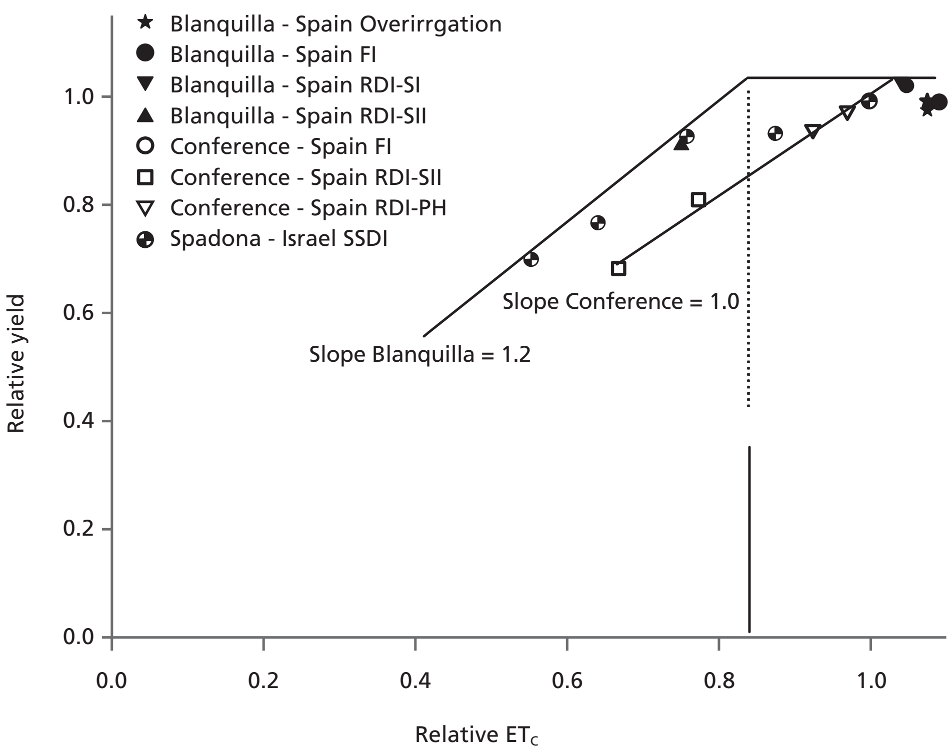
An inherent risk of calculating orchard water requirements is irrigation overestimation. In the case of pears, over-irrigation can have a remarkable negative impact on flowering during subsequent seasons (Marsal *et al.*, 2002a). To avoid this negative impact, accurate determination of crop-water requirements is essential in pear irrigation. One useful strategy could be to apply a mild deficit irrigation programme and monitor the level of stress with soil or plant measurements.

WATER PRODUCTION FUNCTIONS

Water production functions have been derived from four studies: Two of them for the cvs. Blanquilla and Spadona (Spadona and Blanquilla are denominations corresponding to the same cultivar but used in Italy and Spain, respectively); (Naor *et al.*, 2000; and Marsal *et al.*, 2002a), and two other studies on the cv. Conference; the latter dealing with postharvest deficit irrigation (Marsal *et al.*, 2008; and Marsal *et al.*, 2010). In these four studies it has been considered that: i) annual ET_o and effective rainfall were known, ii) ET_c was estimated from soil-water content variation and applied water, and iii) the effects of irrigation on fruit yield were considered for two consecutive years. Figure 5 shows the relation between relative fruit yield and relative ET_c. Relative yield is unaffected by ET_c deficits of 15-20 percent and then declines more or less linearly as ET_c deficits become more severe.

Figure 6 shows the water production function considering relative gross revenue instead of yield as a productive parameter. The relative gross revenue penalizes fruit with cheek diameters of less than 65 mm. The prevailing market conditions are very different between these two cultivars, since Conference pears commonly receive a better price than Blanquilla. Prices may change from country-to-country. For the sake of a fair cultivar comparison and to avoid the specificity of country market effects on gross revenues, the pricing criterion of Conference in Spain was applied to all reported experiments.

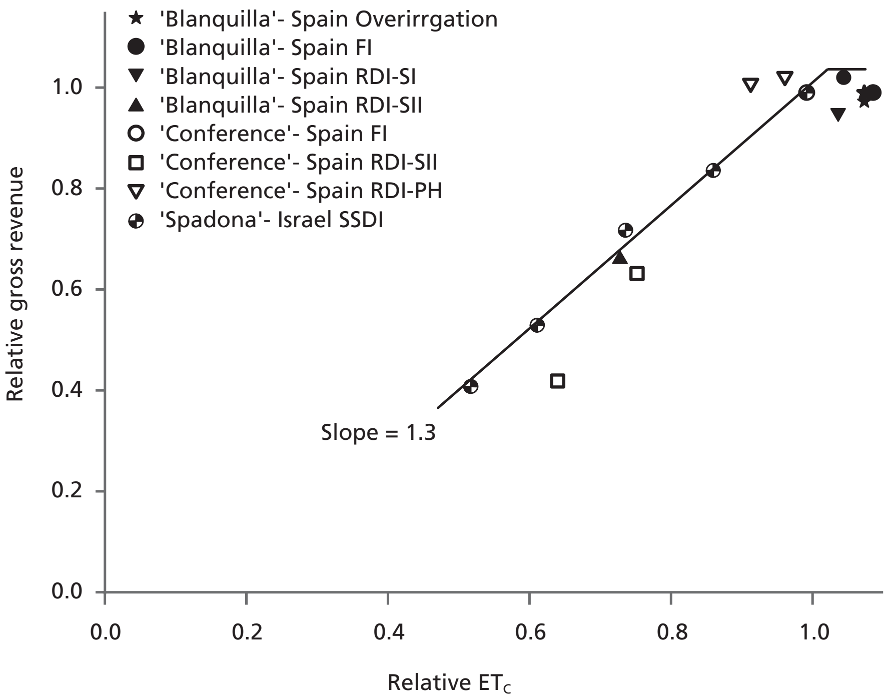
FIGURE 5 Production function developed for RDI strategies that imposed stress during Stages I and II. Data points were obtained from studies of at least two-year duration. Three studies from Spain and one from Israel were used for the relationship (Source: Marsal *et al*., 2002a in Blanquilla; Marsal *et al*., 2008 in Conference; Marsal *et al*., unpublished in Conference; and Naor *et al*., 2000 in Spadona). Linear boundary lines consider separate cultivar fitting through linear regression from the observations defining an upper boundary. FI, RDI-SI, RDI-SII, RDI-PH and SSDI stand for full irrigation, RDI during Stage I of fruit growth, RDI during SII of fruit growth, RDI during postharvest and seasonal sustained deficit irrigation, respectively.



Data in Figure 5 suggest that there are cultivar differences in the response to ET_c deficits, cv. Conference being more sensitive than Blanquilla (or Spadona). A 30 percent reduction in ET_c caused only a 12 percent yield reduction in Blanquilla-Spadona but a 22 percent decrease in Conference. However, cultivar yield sensitivity to ET_c deficits was similar once they showed a response to decreasing relative ET_c; their sensitivity remained similar with a slope for the yield response to ET_c of 1.2 and 1.0 for Blanquilla and Conference, respectively (Figure 5).

An explanation of the differences between cultivars in the yield-response threshold to reduction in ET_c may be related to a complex interaction between three factors: i) the positive effect of moderate water stress on increasing return bloom in the next season, ii) the limited use of fruit thinning as a commercial practice for pear, and iii) the possible fruit-set response to previous season water stress. In other words, changes in return bloom as a consequence of incipient ET_c reductions in the previous season, may produce higher cropping next season, provided fruit set is unaffected. Under these circumstances, increases in crop load leads to the production of smaller fruit, but the smaller fruit size at harvest is often more than compensated by the positive impact of higher fruit number on yield. It is interesting to

FIGURE 6 Relative revenue function developed for RDI strategies that imposed stress during Stages I and II. Data points obtained from studies of at least two year duration. Three studies from Spain and one from Israel were used for the relationship (Source: Marsal *et al*., 2002a in Blanquilla; Marsal *et al*., 2008 in Conference; Marsal *et al*., unpublished in Conference; and Naor *et al*., 2000 in Spadona). Linear boundary lines consider no differences in cultivar response and fitting is performed through linear regression from the observations defining an upper boundary. Note the greater sensitivity to ET deficits in terms of revenue than in yield terms. FI, RDI-SI, RDI-SII, RDI-PH and SSDI stands for full irrigation, RDI during Stage I of fruit growth, RDI during SII of fruit growth, RDI during postharvest and seasonal sustained deficit irrigation, respectively.



notice that this was the case for Blanquilla for RDI-SII in Spain and also for the mild irrigation reductions in the Spadona experiment in Israel (Figure 3). However, this was not found to be so Conference, because RDI-SII, besides increasing blooming return, it also reduced fruit set the next season so that competition between fruit was lowered. Specificity of cultivar yield response to ET deficits could be explained by a different sensitivity of fruit set to current bloom density and past history of water stress. On the other hand, the advantageous yield response observed in Blanquilla was lost when analysed in terms of relative revenue (Figure 6). This was because of the price penalty related to the production of smaller fruit under deficit with high cropping conditions (Figure 6). Therefore Conference and Blanquilla revenue responses were approximated by only one boundary line, which corresponded to the conditions of deficit irrigation applied during the fruit-growing season (Figure 6).

In the case of postharvest deficit irrigation for Conference, it was found that relative revenues rose above the boundary line (Figure 6). Curiously, postharvest water deficit produced yield reductions that were accompanied by reductions in fruit set and associated with increased fruit size. Accordingly, postharvest RDI fruit received a higher price and relative gross revenue was not reduced by the slight ET_c reductions attained in the above-mentioned experiment (Figures 5 and 6). However, under more significant stress during Stage II, which caused a 30 percent reduction in ET_c, the decrease in gross revenue of the cv. Conference reached 60 percent (Figure 6), a response that is substantially more negative than what could be predicted from the yield-ET_c relationship (Figure 5).

SUGGESTED RDI REGIMES

Consistency of results across the different experiments on RDI suggests that this technique may be safely used for pear production. However, the myriad of possible combinations of pear growing conditions (cv. x rootstock x planting density x fruit load x soil type x climate) offer a wide spectrum of possibilities that have not been fully investigated in relation to RDI. Nevertheless, there is no doubt that, in climates having low rainfall during the hot season, reducing irrigation during Stage II should be avoided to guarantee maximum fruit size at harvest (Figure 6). Early water stress should also be avoided in most cases, except for high-density orchards growing under vigorous conditions. The period in which RDI could be applied to save water is postharvest, provided excessive water stress is not achieved. This risk of applying too much water stress during postharvest may depend on each specific situation. Risks increase where growing conditions are suboptimal. Bad weather can affect pollination and fruit set, and fruit drop can occur especially during late spring. Postharvest water stress has been hypothesized to reduce winter reserves in the tree (no data available on pear) and subsequently impair fruit set and yield following season.

The data available on responses to RDI make it difficult to propose a strategy that is applicable to all possible combinations of management practices. Nevertheless, the postharvest period is the safest to apply RDI, but water savings can be short if a late maturing cultivar is used. Therefore, if water shortages have to be more severe, RDI could be applied in combination with other periods. Table 2 presents various RDI strategies for different water allocations that are simulated for specific experimental and environmental conditions (Marsal *et al.*, 2008; and Marsal *et al.*, 2010). Water deficit in Stage I (RDI-SI), only allows a 6 percent reduction of the annual applied water. By using RDI in Stage II (RDI-SII), 33 percent of applied water can be saved, but this causes a reduction in growers' gross revenues (Table 2). A more sensible approach would be to use a combination of deficit irrigation during Stage I and postharvest, in combination with a slight reduction during the first part of Stage II fruit growth (Table 2). The latter strategy would reduce the annual water use by 33 percent (from 600 mm to 400 mm) and probably would have less negative impact on fruit growth than an RDI-SII strategy.

TABLE 2 Suggested RDI strategies for different available water supply scenarios from 600 to 400 mm when potential ET_c is 600 mm. Weather data corresponds to Ebro valley Northeast Spain and K_c corresponds to those presented in Table 1.

Date	Potential ET_c (mm)	Water req. (mm)	RDI-SI (560 mm) Irri. rate (%)	RDI-SI (560 mm) (mm)	RDI-SII (400 mm) Irri. rate (%)	RDI-SII (400 mm) (mm)	RDI-Postharvest (460 mm) Irri. rate (%)	RDI-Postharvest (460 mm) (mm)	RDI-Combined (400 mm) Irri. rate (%)	RDI-Combined (400 mm) (mm)
March 15-30	9	10	100	10	100	10	100	10	100	10
Apr. 1-15	13	14	100	14	100	14	100	14	100	14
Apr. 16-30	15	10	100	10	100	10	100	10	100	10
May 1-15	28	17	40	7	100	17	100	17	40	7
May 16-31	37	28	40	11	100	28	100	28	40	11
June 1-15	56	62	100	62	50	31	100	62	80	49
June 16-30	71	79	100	79	50	39	100	79	80	63
July 1-15	72	74	100	74	50	37	100	74	80	59
July 16-31	77	84	100	84	50	42	100	84	100	84
Aug. 1-15	67	73	100	73	50	37	100	73	100	73
Aug 16-31	65	71	100	71	100	71	10	7	10	7
Sept. 1-15	36	39	100	39	100	39	10	4	10	4
Sept. 16-30	27	30	100	30	100	30	10	3	10	3
Oct. 1-15	16	1	100	1	100	1	10	0	10	0
Oct. 16-31	9	0	100	0	100	0	10	0	10	0
Nov. 1-15	5	0	100	0	100	0	10	0	10	0
Total	**602**	**591**	**-**	**564**	**-**	**405**	**-**	**464**	**-**	**395**

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Peach

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Peach

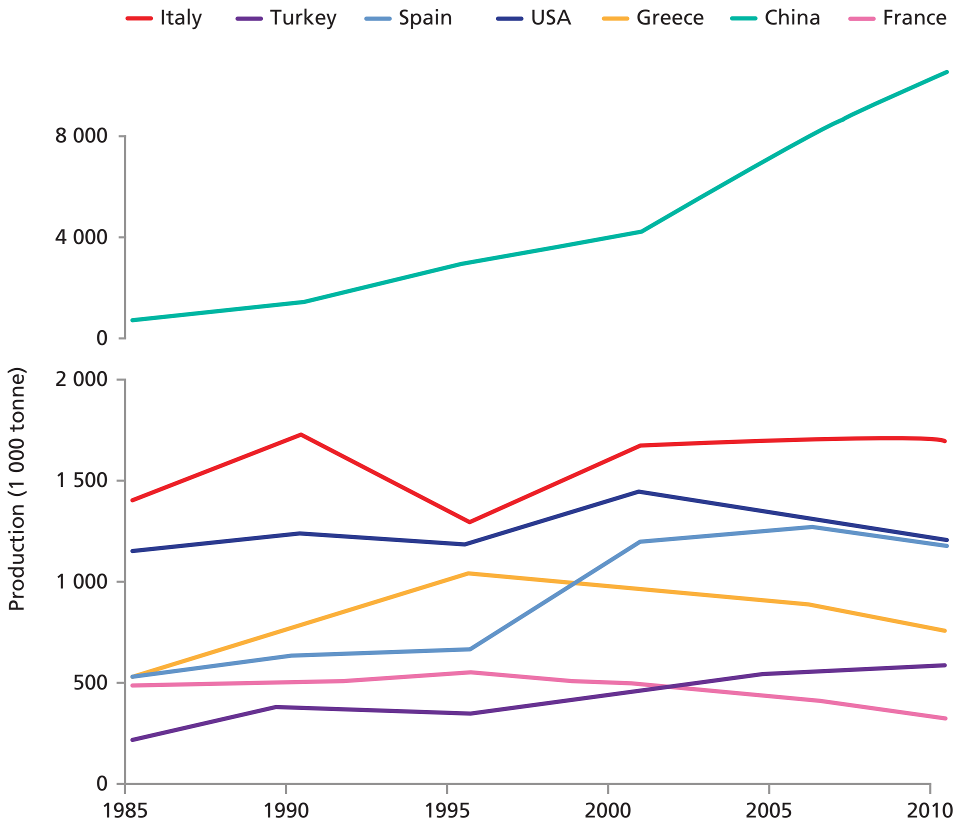
INTRODUCTION AND BACKGROUND

Peach *(Prunus Persica* L.*)*, was originally from China, but in ancient Greece and Rome it was thought to have originated in Persia, is a stone fruit tree that exhibits ample diversity in terms of fruit types: freestone or cling; round or flat shape; hairy or smooth skins; flesh that is either firm or soft and white or yellow. There is also a wide-range of maturity dates for the peach cultivars; from very early where the fruit matures at the end of spring, to very late that reach maturity at the end of summer, as much as four months after the earliest varieties arrive at the market. The tree is vigourous and can reach more than 5 m in height, but peach production is limited worldwide by its relatively narrow range of climatic adaptation. On the one hand, it flowers early and is quite sensitive to frost–particularly at flowering- but on the other, it has chilling requirements that are not met in some of the frost-free areas of the temperate zones and the subtropics.

The evolution of peach production in selected countries in the last ten years is shown in Figure 1. In 2009 there were over 1.5 million ha of peach and nectarine globally with an average yield of 13.0 tonne/ha (FAO, 2011). The main producing country is China, which represents 50 percent of the world peach production. Production in China rose spectacularly over the last decades from 380 000 tonne in 1970 and an average yield of 3.6 tonne/ha to over 10 million tonne in 2009 with an average yield of 14.4 tonne/ha, followed by Italy (FAO, 2011). Other major commercial production areas are located in southern Europe (Spain, Greece, and France), United States (California, Georgia), Chile, and Australia. Highest yields are obtained in United States with almost 20 tonne/ha.

The fruit is usually consumed fresh and, because consumers in many world areas prefer large-size fruit, peach is grown mostly under irrigation even in many subhumid areas. There, the most important role of irrigation is to stabilize production in years of below-normal rainfall, and to guarantee adequate soil moisture during the critical fruit enlarging period, just prior to harvest. In more arid areas where rainfall is only a fraction of ET_c, irrigation is essential for commercial production, as the period of fruit growth can span all summer in the late maturing varieties. Most peach production systems are quite intensive, with orchards planted at high densities (from 400 up to 1 000 tree/ha); the highest densities are normally for peach production used in industry (canning and food processing). A wide-variety of training systems are used, designed to maximize the distribution of solar radiation to all tree parts in order to achieve good fruit colour, and to promote fruiting

FIGURE 1 Production trends for peaches in the principal countries (FAO, 2011).



Fruit quality

There are many factors determining peach fruit quality and some of them have a significant influence in the crop value, particularly, fruit size. Fresh market peaches are valued for their size, and large sizes fetch premium prices in many markets. Fruit size depends on tree fruit numbers and is affected by environmental factors such as water deficits. Colour and lack of visual defects are also important quality aspects; the colour is determined by light exposure during fruit growth that, in turn depends, on tree configuration, degree of vegetative growth and fruit position on the tree. Other quality factors include firmness, concentrations of total soluble solids (*TSS*), soluble sugars, titratable acidity (*TA*), sugar to acid ratio, aroma volatiles, enhanced maturity and better storability (shelf-life). All of these parameters respond to variations in the tree water supply that affect tree water status.

branches throughout the tree canopy. Sometimes, trellises are used with the trees shaped in a horizontal plane, or in a V shape. For the very intensive plantations, low tree vigour is favoured to reduce mutual shading and harvest costs. Some dwarf tree cultivars have been bred in the past, but have had little commercial success.

DESCRIPTION OF THE STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

Vegetative and reproductive growth

As with other stone fruit, peach flowering is immediately followed by vegetative growth in early spring. Peach chilling requirements, usually computed during dormancy as hours above 7 °C, vary widely among varieties, but in some may be substantial. During the canopy development period, fruit set and initial fruit growth take place simultaneously. Figure 2a depicts the patterns of fruit growth for three cultivars differing in maturity and the relative rate of vegetative growth for the late-maturing cultivar. Although early maturing cultivars bloom earlier than the late, initial fruit growth is very similar for the three types. In the early cultivar, such initial growth is directly followed by a fast fruit enlargement phase (Figure 2a) that ends with fruit ripening. In the other cultivars, there is a slowdown in growth rate of the fruit, coinciding with the acceleration of vegetative growth (Figure 2a). Vegetative growth, measured as seasonal shoot length or the increase in trunk diameter, has similar trends for the different cultivars. Extension of primary shoots occurs first followed by the growth of secondary shoots. In the early cultivars there are two peaks of rapid extension growth, the second one taking place after fruit harvest. In the medium and late-maturing cultivars, there is normally only one peak of fast shoot growth, but there may be another one after harvest in some cultivars and environments. At some point in the season, shoot growth slows and the rapid fruit expansion rate period begins (Figure 2b). This last fruit enlargement phase extends until the fruit matures prior to harvest, and the longer this period, the greater is the accumulation of dry matter in the fruit and the larger is the final potential fruit size (Figures 2a and 2b).

Because bud emergence usually occurs with a fully charged soil profile, water deficits affecting the early growth stages of fruit and canopies are uncommon. When they occur, tree leaf area and final fruit size will be reduced, because in the latter case, initial growth is mostly caused at cell division stage that sets the final number of cells that a fruit will have.

FIGURE 2a Evolution of fruit fresh weight for early (A), medium (B) and late (C) maturing peach cultivars. Stages I, II, and III of fruit growth and postharvest (PH) maturing peach cultivars. Stages I, II, and III of fruit growth and postharvest (PH) for a medium cultivar grown in the Northern Hemisphere are shown.

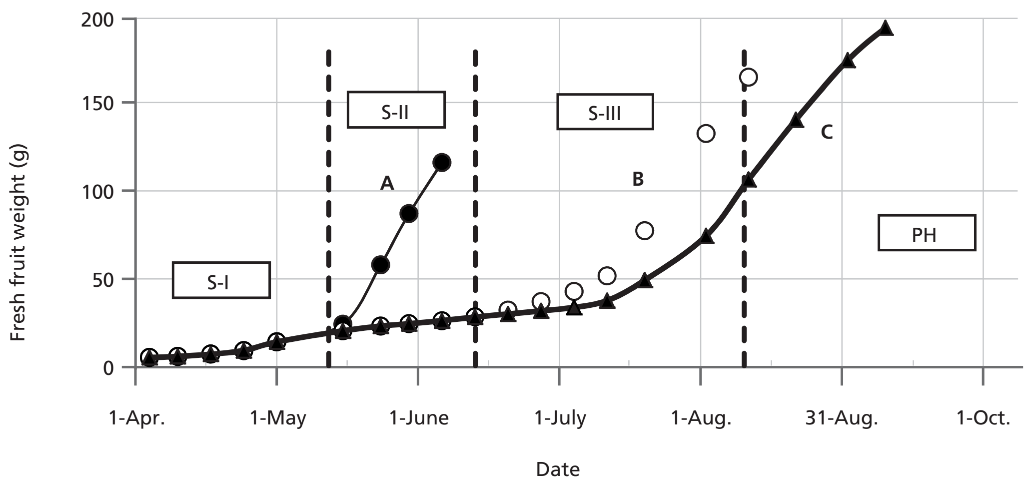
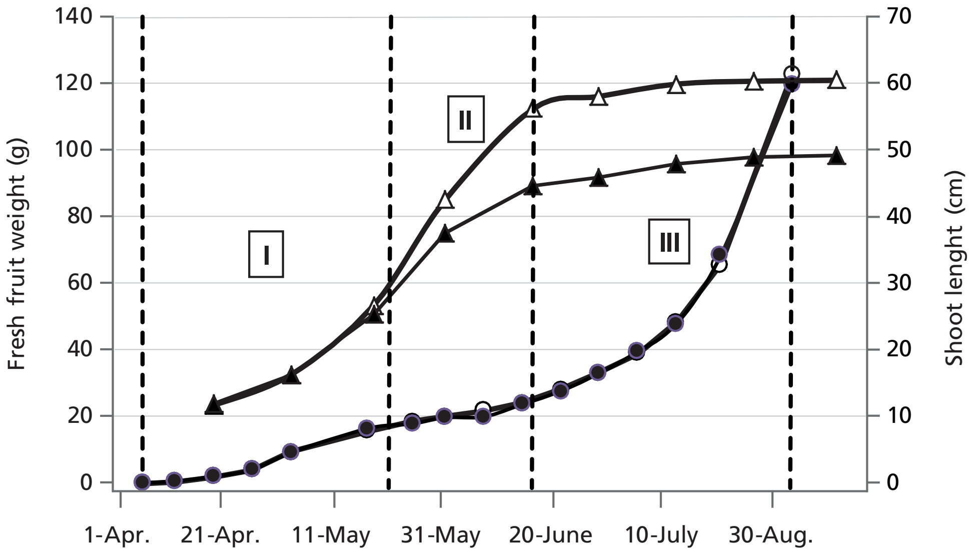


FIGURE 2b Evolution of vegetative (shoot) growth (triangles) and of fruit growth (circles) in peach trees under RDI (closed symbols) and under a fully-irrigated control (open symbols) at Lleida, Spain.



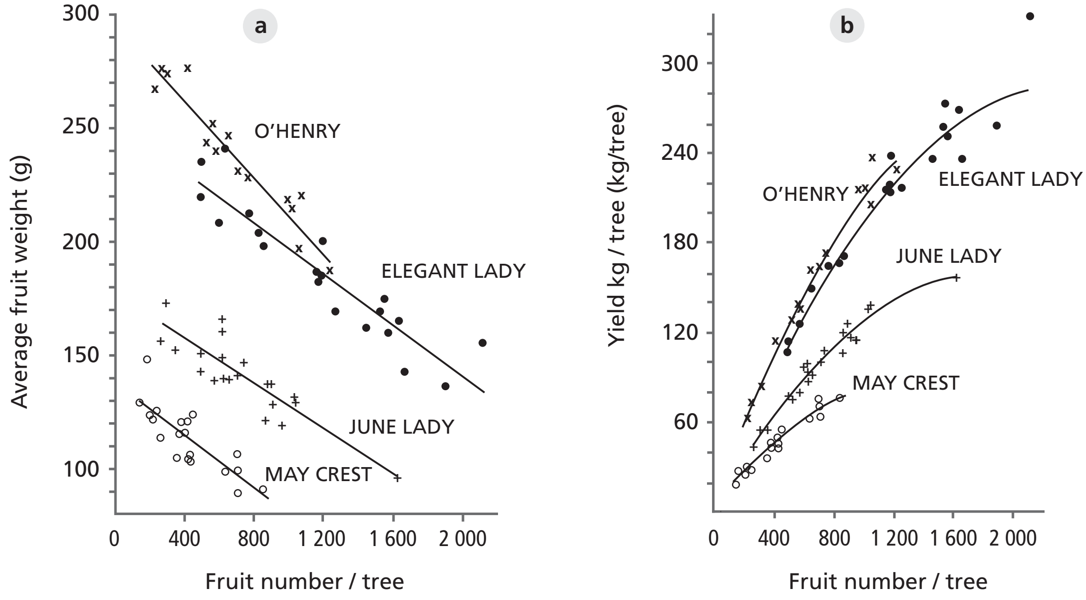
While flower buds are quite resistant to freezing temperatures above -7 to -10 °C during dormancy, flowers and recently formed fruit are very sensitive to mild frosts, with minimum temperatures below -2 to -3 °C. Thus, peaches are very sensitive to spring frosts that can completely wipe out fruit production.

Stages of fruit growth

As discussed above, fruit growth, measured by either increase in fruit volume or in dry weight, follows a double sigmoid curve in peach. From Figure 2 it can be seen that there are three apparent stages of fruit growth, although in early varieties, it is difficult to detect more than two from periodic measurements of fruit volume. The first stage, defined as Stage I, starts soon after pollination and is a period of active cell division that ends around pit hardening, when the fruit has reached about 20 to 25 percent of its final size. Fruit growth slows in the second stage and this coincides with a period of active shoot extension and leaf development (Figure 2b). The duration of this second phase (Stage II) varies; in early varieties, it is hardly detectable, while in very late varieties it can lasts for more than 40 days. Following Stage II, fruit enlargement resumes at a very high rate in what is called Stage III, proceeding more or less in an exponential fashion until harvest (Figure 2b). Dry matter accumulation in the fruit lags behind fruit enlargement, but also follows a double sigmoid pattern, less marked than for the accumulation of fresh weight, and more evident in late varieties but hardly detectable in medium and early varieties. The most relevant difference among cultivars varying in season length, from early to late maturity, is the duration of Stage II (Figure 2a).

Final fruit size is determined primarily by fruit load (number of fruit per tree), but tree size, canopy configuration and pruning, water and nutrient status are also important factors. The relationship between final fruit size and fruit load is cultivar dependent as shown on Figure 3 (Johnson and Handley, 1989) where these relationships are shown for several early

FIGURE 3 (a): Relationship between average fruit weight and number of fruit per tree of four peach cultivars (b): Relationship between yield per tree and number of fruit per tree of four peach cultivars (Johnson and Handley, 1989).



and midseason cultivars. Both final fruit size (Figure 3a) and total yield per tree (Figure 3b) are fruit load dependent. Fruit size increases as fruit load decreases (Figure 3a), while final yield increases with increases in fruit load (Figure 3b) For each cultivar, and depending on market prices, the total number of fruit per tree that are left after thinning should be chosen to optimize profits by obtaining a maximum yield with a minimum fruit load. Final fruit size depends also on the timing of hand thinning. Early hand thinning reduces fruit competition and allows larger fruit.

Bud development

The terminal peach bud at the end of a shoot is always vegetative and produces a leafy shoot. Auxiliary buds develop during the summer at the base of leaves on the current season's shoots and can be either leaf or flower buds. A flower bud produces a single flower that can set one fruit. Each node on a vegetative shoot may have from zero to three buds. The buds that generate vegetative growth are small and pointed while flower buds are larger, rounder, and more hairy. Many of the nodes on the lower two-thirds of a shoot have two or three buds arranged side by side. Most often a leaf bud is flanked by flower buds. The number and distribution of flower buds on a shoot varies with tree vigour, cultivar, and the radiation environment that the shoot experiences. Short shoots generally have the most fruit buds per unit length. Moderately vigorous shoots have a high proportion of nodes with two flower buds. The leaf buds at most nodes develop into lateral shoots that may be fruitful in subsequent years. In the very vigorous current season's shoots, a number of auxiliary buds produce secondary shoots that are not desirable because fruit buds do not develop at many of their nodes. Ideal shoots (between 30 and 50 cm long) have enough growth to produce sufficient fruit buds for the following season but do not have secondary shoots.

The postharvest period is important for peach trees, as it is during this period when next season's flower buds are initiated (usually around August) and when these buds are clearly differentiate from vegetative buds they start to develop floral organs (Handley and Johnson, 2000). Another important feature of the period between harvest and leaf fall is the accumulation of carbohydrate reserves, needed for continuous bud development processes until bloom, and also because fruit set is highly dependent upon carbohydrate availability (Arbeloa and Herrero, 1991). Heat and water stress during post harvest enhances the formation of abnormal fruit (Naor *et al.,* 2005).

RESPONSES TO WATER DEFICITS

Peach water relations have been studied in more detail than most other deciduous fruit tree species. As for most plants, vegetative growth is extremely sensitive to water deficits, and several studies have shown that leaf and young shoot expansive growth are slowed by mild water deficits that are difficult to detect.

Peach trees are mostly grown to produce fresh fruit, where both size and some quality characteristics are important. However, while there is a premium paid for large fruit size in most markets (or a penalty for the small sizes), quality features, other than size, do not generally influence growers' revenue, although many consumers are well aware of the important differences in quality among and within peach and nectarine varieties.

Final fruit size depends directly on the number of cells and the average cell size of the mesocarp. The number of cells is primarily determined during Stage I and several experiments (some in container-grown trees) have demonstrated that this is a very sensitive period for water deficits in terms of final yield and revenue. One field study (Girona *et al.,* 2004) with mild to moderate stress at Stage I demonstrated that fruit dry matter was affected at high fruit loads, but that fresh weight could recover if the water supply during Stages II and III was adequate. Nevertheless, risks of inducing damaging stress levels at Stage I are low because the initial soil profile is usually full, evaporative demand is low and the canopy development process has not been completed (and thus the crop coefficient, K_c, is below the maximum that will be achieved when canopy growth is near completion). Thus, peach transpiration (Tr) is relatively low at this time, which also coincides with seasonal spring rains in many peach growing regions. It is therefore not difficult to avoid water deficits in Stage I, even inadvertently. Nevertheless, in shallow soils and/or very dry environments, or in drought years when the soil profile is dry, it is possible to induce significant levels of water stress that will impact negatively on fruit size and yield (Girona *et al.,* 2004).

As the fruit continue to grow and the pit starts to harden, the rate of vegetative growth accelerates and fruit growth slows at the onset of Stage II. The duration of this phase varies from only a few days in early varieties (and thus is almost impossible to detect) to about 60 days in the very late varieties. Water deficits during Stage II affect primarily lateral shoot expansion and trunk growth while having minimal or no impact on fruit growth. Figure 2b shows the impact of water deficits in shoot extension growth and the negligible influence that it has on fruit growth and final fruit size (Girona *et al.*, 2003). This differential sensitivity between vegetative and fruit growth formed the basis for the successful application of water stress in Stage II in peach first described by Mitchell and Chalmers (*1982*). These authors and several others since that time have found that Stage II is not sensitive to water deficits in terms of negatively impacting yield. It has been shown (Girona *et al.,* 2003) that significant water deficits applied during Stage II may induce some dehydration of the fruit, but that subsequent recovery of fruit growth is usually complete after the water stress is relieved at the onset of Stage III, and that Stage II water deficits have no impact on final yield.

Even though there has been an initial report showing (Chalmers *et al.,* 1981) increased fruit size, relative to fully irrigated controls, when applying RDI in Stage II, no other published papers reported such results, with one exception (Girona *et al.,* 2003) for a single season in a three-year study, where low temperatures at blooming time damaged many fruit and the final fruit load was very low. A comprehensive analysis of the effect of fruit load on the response to RDI at Stage II (Girona *et al.,* 2004), detected larger fruit in the RDI treatment compared with an unstressed control only with low fruit loads, and as the fruit load increased, no effects were detected and in some cases, even a reduction in fruit size was observed. Presumably the RDI in Stage II enhances fruit growth relative to unstressed controls by directing more carbohydrates to fruit growth, but this phenomenon apparently occurs only with low fruit loads (Girona *et al.,* 2004). There have been reports of less fruit drop before harvest under RDI (Girona *et al.,* 2003), and this could explain the few observations where water deficits during Stage II had positive effects on yield, relative to fully-irrigated treatments.

Vigorous fruit expansion takes place during Stage III when the rate of fruit expansion is highest and most sensitive to water deficits. Fruit water content is more sensitive to water deficits than fruit dry weight during this period. A reduction of 25 percent in fruit water content occurred with Stage III water deficits in a medium peach cultivar (Girona *et al.,* 2004). Water deficits that affect fruit dry matter accumulation must be quite severe because, not only must they decrease photosynthesis but they must also counterbalance the tendency of many fruit trees, including peach, where assimilate allocation to fruit has higher priority relative to its distribution to other tree parts (DeJong *et al*., 1987). Leaf photosynthesis and tree transpiration in peach are not affected by water deficits until more than 50 percent of the available water in the root zone is depleted (Girona *et al.*, 2002). When water deficits occur under these conditions, the peak of daily Tr moves from a plateau between noon and 14:00 hours towards the morning hours, and by the time Tr was reduced by 70 percent, the maximum Tr rate occurred at 9:00 am hours (Girona *et al.*, 2002).

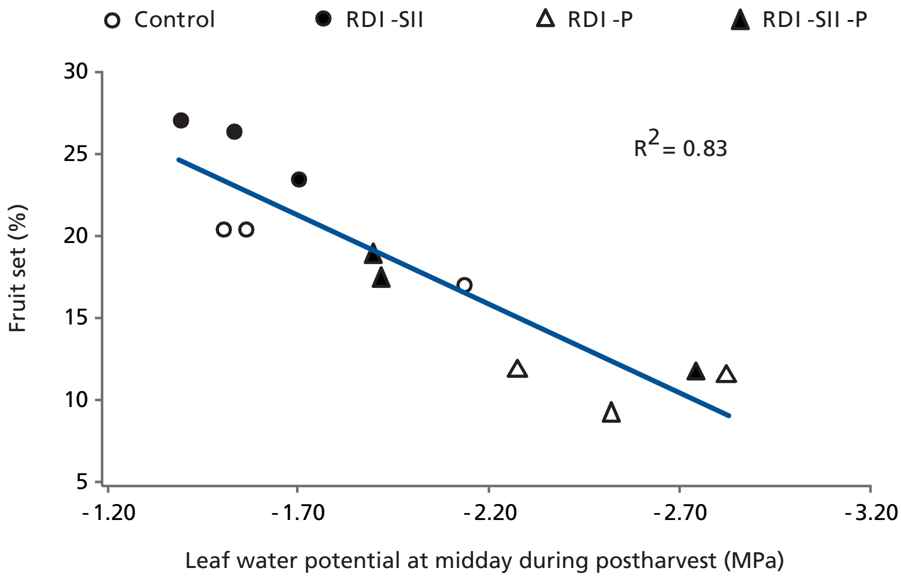
Indicators of peach tree water status are used to quantify the water stress levels. A comparative study among different indicators (Goldhamer *et al.*, 1999) found that indices derived from micrometric measurements of trunk diameter fluctuations were the most sensitive for water stress detection, followed by stem-water potential. Other indicators such as stomatal conductance, leaf photosynthesis, and leaf temperature were less sensitive (Goldhamer *et al.*, 1999).

Water deficits may have a negative impact on fruit appearance in the next season. An increased frequency of fruit doubles and deep sutures have been observed in water-stressed peach trees (Johnson and Phene, 2008). These problems have been overcome by relieving the water stress shortly before and during carpel differentiation (Johnson *et al.,* 1992). With early-season cultivars, this stress-sensitive period is in August and September and suggests avoidance of water deficits during these months (Johnson and Phene, 2008). For a midseason cultivar, the increase in occurrence of double and deep suture fruit is highly correlated with the midday stem-water potential in August of the previous year, i.e. during the initial stages of flower bud development (Naor *et al.,* 2005). The occurrence of double fruit was observed to increase sharply as the midday stem-water potentials fell below -2.0 MPa, suggesting that a midday stem-water potential of -2.0 MPa could serve as threshold for postharvest irrigation scheduling (Naor *et al.,* 2005).

Fruit set can also be influenced by postharvest stress. Both early season (Johnson and Phene, 2008) and midseason (Goodwin and Bruce, 2011) cultivars found that fruit set was moderately sensitive to the degree of water stress during the previous season's postharvest period. In late season-cultivars, fruit set was highly affected by the level of water stress during postharvest, as shown by the strong correlation between the average leaf water potential during the postharvest period and the fruit set (Girona *et al.,* 2004) (Figure 4). The negative impact of water deficits on fruit set in the next year may not be important as thinning is a common practice in peach, but severe impacts on fruit set cannot be corrected by thinning (Goodwin and Bruce, 2011).

Moderate water deficits applied during Stage II improved fruit quality (firmness, colour, improved TSS) without affecting yield (Gelly *et al.*, 2003 *and* Gelly *et al.*, 2004). Moderate water stress in Stage III also improves fruit quality, but a negative impact on fruit size and yield is very likely. The trade-offs between quality and size must be resolved bearing in mind the market where the produce will be sold.

FIGURE 4 Relationship between fruit set 2 months after full bloom in 1996 and seasonal average midday leaf water potential experienced under several irrigation treatments during the previous year at postharvest (Girona *et al.*, 2004).

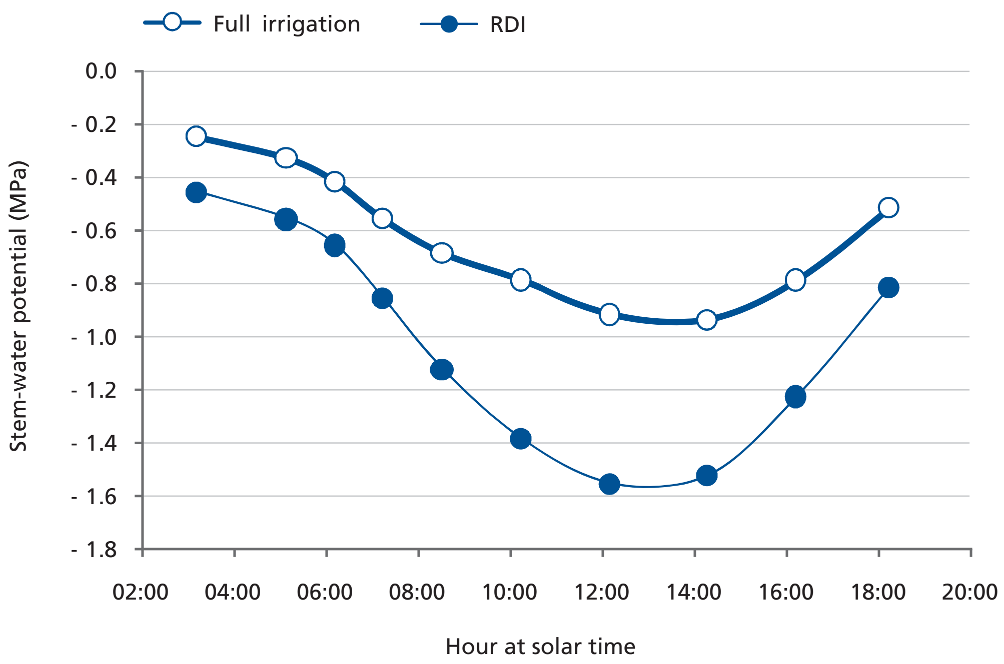


BOX Detecting water stress in peach

Although the established method of detecting tree water stress in peach is the leaf or stem-water potential (Goldhamer *et al.*, 1999), visual indicators may be used to estimate stem-water potential when it is not possible to take actual SWP measurements.

In a normal summer day, typical stem-water potential patterns are shown in the figure below.

FIGURE Diurnal patterns of stem-water potential for fully irrigated (control) and RDI for peach, Lleida, Spain. In both cases, midday stem-water potential values are the lowest and values at predawn (before sunrise) are the least negative, for both well-irrigated and RDI peach trees.



Visually, it is possible to differentiate a leaf that has a water potential of -0.9 MPa from one that has a value of -1.9 MPa. The first is fully expanded and usually oriented towards the sun (Photo D), while the second is partially rolled and droops (Photo A).

For the optimal RDI regime that applies stress on Stage II, it is good practise to arrive at midday SWP values close to -1.5 MPa. At that SWP level, some leaf-rolling symptoms may be observed, but without leaf drop or yellowing, which will indicate excessive water stress. In the morning, growers should observe expanded leaves. A lead rolling symptom of water stress in the morning will indicate excessive stress, while no symptoms at midday will indicate lack of the desired level of stress during Stage II.

PHOTO Peach leaf appearance under three different levels of plant water status.
A: Severe stress (stem-water potential (SWP) = -1.9 MPa); **B**: Very mild stress (SWP = -0.9 MPa); **C**: Moderate stress (SWP = -1.1 MPa); **D**: Well irrigated (-0.8 MPa).

WATER REQUIREMENTS

The water use rates of peach trees are similar to other *Prunus* species, such as nectarines or plums. Table 1 lists the crop coefficients for mature peach trees, and an estimation of the water use at Lleida, Spain. The crop coefficients were obtained from lysimeter studies (Ayars *et al.,* 2003). In one study, the ET_c of a peach tree in a weighing lysimeter was followed for several years since its planting until it reached maturity. This study has provided data on the evolution of K_c for a peach orchard, as the canopy expands (Ayars *et al.,* 2003), and the results are shown in Figure 5. The lysimeter studies have shown that Tr in peach does not decrease much from peak values until soon before leaf fall, unless the water deficits imposed by restricting irrigation in the postharvest period induced stomatal control of Tr and early leaf senescence.

WATER PRODUCTION FUNCTIONS

A number of experiments have been conducted to quantify the relation between yield and applied irrigation water for peach (Girona *et al.,* 2002). A summary of some of the experiments

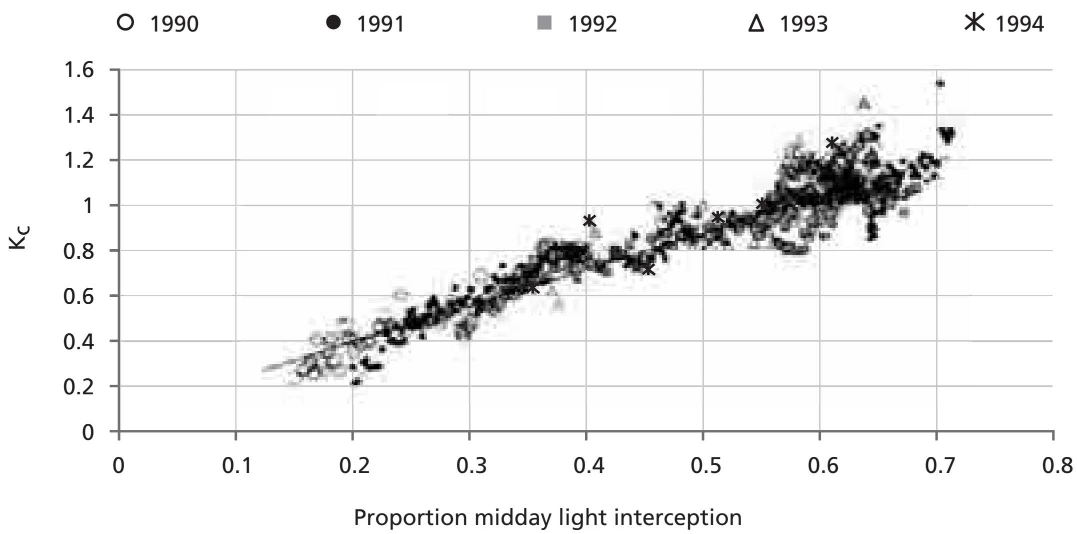
TABLE 1 Crop coefficients relative to grass reference crop (ET_o) for mature peach trees (Phenological stages for midseason cultivar at Lleida, Spain).

Date	Crop Coefficient (K_c)	Growth Stage
Mar. 1-15	0.25	
Mar.16-31	0.30	Bloom
Apr. 1-15	0.45	
Apr. 16-30	0.60	
May 1-15	0.70	
May 16-31	0.80	End of FGS I *
June 1-15	0.90	
June 16-30	0.95	Beginning of FGS III *
July 1-15	1.05	
July 16-31	1.05	
Aug. 1-15	1.05	Harvest
Aug. 16-31	1.00**	
Sept. 1-15	1.00**	
Sept. 16-30	1.00**	
Oct. 1-15	0.75	
Oct. 16-31	0.55	
Nov. 1-15	0.45	

* FGS = Fruit growth stage

** Management reductions in postharvest irrigation may lower these K_c values

FIGURE 5 Relation between the crop coefficient (K_c) for drip-irrigated peach trees measured in a weighing lysimeter in central California and the proportion of light interception by the trees. The linear equation approximation to calculate the K_c is:
$K_c = 0.082 + 1.59$ (PMLI) (Ayars *et al.*, 2003)



concluded that applied water may be reduced by 10- 20 percent below the maximum needs without a negative impact on yield. However, the analyses have very seldom included revenue considerations, relative to the price differential that different sized peach fruit fetches in the market. The response to applied water depends on the water storage capacity of the soil, and thus cannot be generalized. Figure 6 shows the relation between yield and ET_c in relative terms for different irrigations strategies, full irrigation (Control), RDI, and sustained DI (SDI). For the optimal RDI regime, it is possible to reduce the ET_c by 15-20 percent without a detrimental impact on yield. However, when the water deficits were imposed on sensitive stages or throughout the season (SDI), a reduction in ET_c was accompanied by a yield reduction (Figure 6). The differences in the responses to the various DI regimes illustrate the benefits of stress management when planning deficit irrigation programmes.

SUGGESTED RDI REGIMES

Based on the results shown above, it can be concluded that RDI strategies applied during Stage II in peach, especially when a fast recovery at the beginning of Stage III can be achieved, has proved to be very effective in controlling excessive vegetative growth and improving fruit quality without a yield penalty. For early season cultivars, RDI that concentrates the water deficits in the postharvest period is an effective strategy, provided severe water stress is avoided (Tables 2 and 3). Given the impact that different root zone water storage capacities have to the response to RDI, Tables 2 and 3 present different RDI schedules for two types of soils (shallow and deep), also giving indications of the minimum stem-water potential trees can withstand without having a detrimental effect on yield.

FIGURE 6 Relation between relative yield and relative ET_c for peach. The black continuous line represents the production function under no effective RDI irrigation strategies and the dotted black line represents the possible production function under effective RDI (data from Girona *et al*., 2002; Girona *et al*., 2005; Fereres, unpublished; and, Rufat and Villar, unpublished).

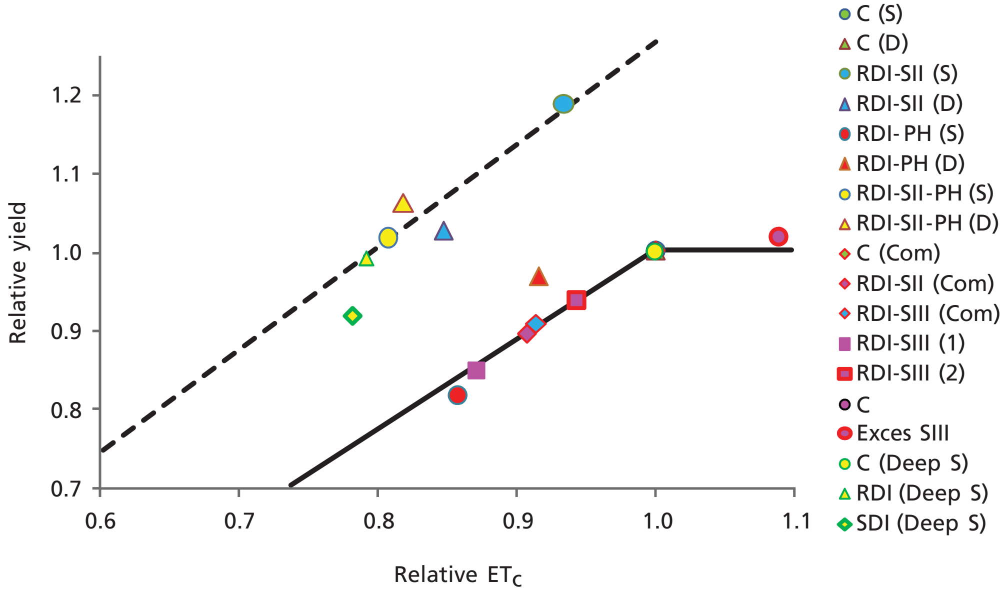


TABLE 2 Suggested limits of midday stem-water potential for late-season cultivars.

Fruit growth stage	Late-season cultivar		
	% of ET_c		Suggested limits of stem-water potential at midday
	Shallow soils (%)	Deep soils (%)	
I	100	100	-0.9 MPa
II	65	35	-1.8 MPa
III	100	100	-1.1 MPa
Ph	80	50	-1.8 MPa

TABLE 3 Suggested limits of midday stem-water potential for early-season cultivars (PH: post-harvest stage).

Fruit growth stage	Early-season cultivar		
	% of ET_c		Suggested limits of stem-water potential at midday
	Shallow soils (%)	Deep soils (%)	
I	100	100	-0.9 MPa
III	100	100	-1.0 MPa
Early Ph	50	35	-1.8 MPa
Late Ph	80	80	-1.2 MPa *

** To prevent next year crop failure*

In applying RDI strategies an important factor is fruit load, and to manage the degree of plant water stress according to the number of fruit per tree. As has been discussed previously, the fruit load *per se* has a strong influence on the final size of the fruit (Naor *et al.*, 1999). If fruit numbers are very high and water is limited, there is a risk that imposing an RDI regime would induce a fruit size reduction. In that case it would be better to reduce fruit load by thinning to achieve the fruit size distribution of the crop that economically provides the highest net profit to the grower. If fruit load is low, RDI may even increase fruit size above that of full irrigation and will decrease vegetative growth and summer pruning costs. With medium fruit loads, optimal RDI that reduce ET_c by 15-20 percent would not have a negative impact on yield in most cases.

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Walnut

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Walnut

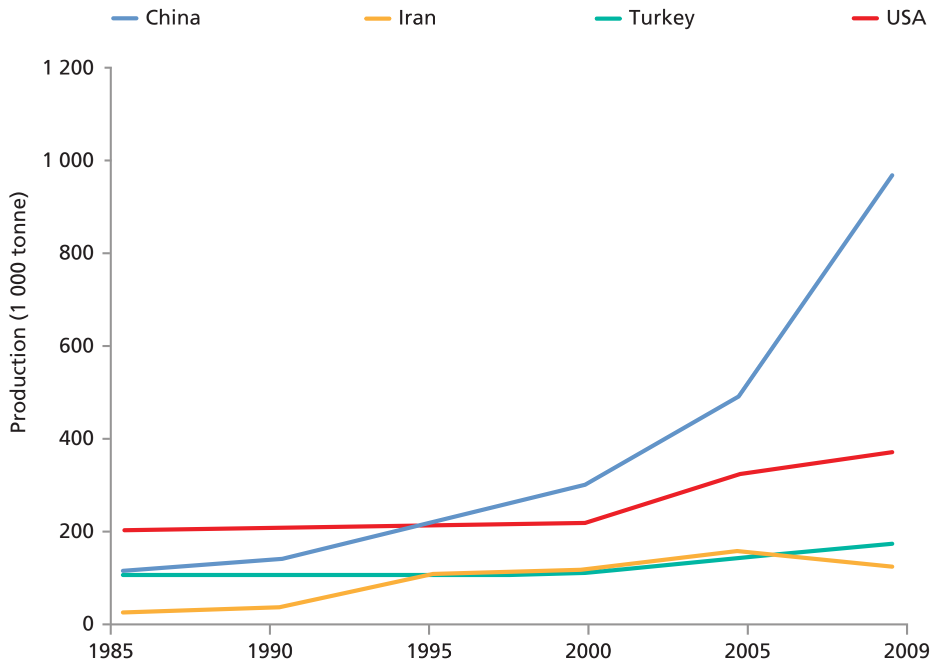
INTRODUCTION AND BACKGROUND

Walnuts *(Juglans regia* L.*)* are large trees that are cultivated in temperate climates for their nuts, rich in oil, and for their wood. Plantations are relatively widely spaced as this species does not tolerate mutual shading well. Common spacing of vigorous varieties varies between 8 x 8 and 10 x 10 m, while the less vigorous cultivars may be planted at 7 x 7 m spacing. Experiments that have increased tree density above the spacing mentioned have resulted in higher yields during the first years of the orchard but this may be at the expense of reduced orchard longevity. In 2009, world acreage was 843 000 ha and average global yield (with shell) was 2.7 tonne/ha (FAO, 2011). Figure 1 presents the production trends of the main producing countries. China and the United States are the two main world producers, followed by Iran, Turkey, and Ukraine. France is the main European producer and Chile is now an important producer in the Southern Hemisphere.

VEGETATIVE AND REPRODUCTIVE DEVELOPMENT

Commercial varieties of walnut trees break dormancy and begin to leaf out in the Northern Hemisphere between mid-March and mid-April, depending on the environmental conditions and the cultivar. This is followed by flowering, both the emergence of pollen-producing male flowers and the female flowers that evolve into the nut after pollination. Normally, flowering is completed by late April and is followed by rapid fruit expansive growth with concomitant rapid shoot growth. Bud formation occurs from leaf out through June on mature trees. By early June, the fruit has reached its full size and this is followed immediately by the internal development of the nut. At this time, shoot growth slows. The internal nut development sequence begins with shell expansion and hardening and dry matter accumulation in the kernel that continues through harvest. The indicator for physiological maturity is the development of 'packing tissue brown' which occurs before hull split. This can be identified by cracking open the nuts and observing the colour of the tissue surrounding the kernel inside the shell. If this tissue is white, the nuts have not reached maturity and there will likely be continued dry matter accumulation in the kernel. A brown colour indicates the nuts have matured and kernel development has ceased. Hull split generally follows closely after walnuts have reached physiological maturity. After splitting, the hulls break down rapidly. During the postharvest period, some shoot growth and carbohydrate storage are the primary sinks of photosynthesis products.

FIGURE 1 Production trends of walnuts in the principal countries (FAO, 2011).



EFFECTS OF WATER DEFICITS

Water stress can decrease nut size and quality (kernel colour and shrivel). Stress-related reductions in shoot growth can reduce fruiting wood for the following season(s). There is some evidence that not only are the number of reproductive buds less because of lower vegetative growth but that some flower buds are not viable, resulting in fewer flowers and ultimately less fruit. Further, the reduction of shoot growth causes higher fruit temperatures as a result of both more sunlight penetration into the canopy and thus, more direct solar radiation on a higher percentage of the fruit, and higher canopy temperatures because of less transpiration, that can darken kernel colour, reducing crop value. This temperature effect is very cultivar dependent.

As walnut fruit load is very dependent on the previous year's shoot growth, the impact of water deficits is much more severe in the season following the imposition of water deficits. The primary impact in the year that stress is imposed is on fruit size and quality while in the following season, the impact is on fruit load, regardless of the irrigation regime used in the following season. One California study found that hedgerow walnuts (cv. Chico) irrigated at 33 and 66 percent ET_c suffered marketable nut yield reductions of 32 and 50 percent, respectively, after three years because of reduced nut size, fruit load, and crop quality (Goldhamer, 1997). Upon returning these trees to full irrigation, tree growth and gas exchange immediately recovered but yields were little changed the first recovery year, even though shoot growth dramatically increased. It wasn't until the second recovery year that harvest yields completely recovered as a result of the fruiting positions created by the first recovery year's shoot growth. Similar stress impacts and recovery results have been obtained from other studies in California (cv. Chandler) (Lampinen *et al.*, 2004). The rapid production recovery from severe water stress was possible because of the absence of stress-induced disease or insect pressures. Trunk diseases such as deep bark canker that often occur in water stressed orchards were not evident in these studies.

WATER USE

Walnut orchards have high water use rates as because of the high leaf, tall tree stature, and near full ground cover when the trees are fully mature. Table 1 provides the crop coefficients for mature walnut orchards obtained from studies in California (Goldhamer, 1997).

TABLE 1 Crop coefficients for mature walnut trees (Goldhamer, 1997).

Date	Crop coefficient (K_c)
Mar. 16-31	0.12
Apr. 1-15	0.53
Apr. 16-30	0.68
May 1-15	0.79
May 16-31	0.86
June 1-15	0.93
June 16-30	1.00
July 1-15	1.14
July 16-31	1.14
Aug. 1-15	1.14
Aug. 16-31	1.14
Sept. 1-15	1.08
Sept. 16-30	0.97
Oct. 1-15	0.88
Oct. 16-31	0.51
Nov. 1-15	0.28

DEFICIT IRRIGATION STRATEGIES

The general strategy followed experimentally for reducing irrigation in walnut orchards has been to limit water deficits during early stages of tree and crop development in favour of imposing them during mid and late season. One study in northern California used midday stem-water potential to impose the 'low' and 'moderate' stress treatments. The target midday stem-water potential values were -0.5 to -0.7 MPa and -1.2 to -1.4 MPa during the bulk of the season for these two regimes with corresponding reductions in applied water of 30 and 50 percent of potential ET_c, respectively (Fulton *et al.*, 2002). It should be noted that the water potential values of fully irrigated walnut trees are much less negative then the two primary nut crops, almond and pistachio. Walnut predawn leaf water potential values for fully irrigated trees range between -0.15 and -0.2 MPa and midday stem-water potential between -0.40 to -0.60 MPa. After three seasons, yields in these stress treatments had declined by 26 and 40 percent, respectively, relative to fully irrigated trees (Lampinen *et al.*, 2004). Full recovery was achieved after two years of full irrigation. A companion study was conducted on deeper soils with older trees with a lower tree density. Yield reductions were appreciably lower at this site, which was attributed to the stress development being relatively slow because of the larger soil moisture reservoir and possibly the larger carbohydrate reserves of the bigger trees.

To simulate a one-year drought with a water supply of 400 mm where potential ET_c was

1 100 mm, a team in California applied 85 percent of ET_c through April to mature cv. Chico trees and then progressively lower percentages of ET_c as the season progressed (25 percent was the minimum from early July through the early September harvest) and no postharvest irrigation (Goldhamer *et al.*, 1989). Fruit yields in the drought year were about 10 percent lower than the fully irrigated control (not statistically significant). However in the following recovery year, when full irrigation was applied to all trees, the drought year trees had about 80 percent lower yields almost entirely the result of a lower fruit load. Yields returned to near full levels during the second recovery year (Goldhamer *et al.*, 1990).

It appears that walnut trees do not respond well to water deficits, regardless of the deficit irrigation strategy, in terms of nut yield. This is probably because of the high sensitivity of shoot growth to water deficits and, in turn, to the heavy dependence of fruit load on the shoot growth of the previous year in walnuts.

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Pistachio

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Pistachio

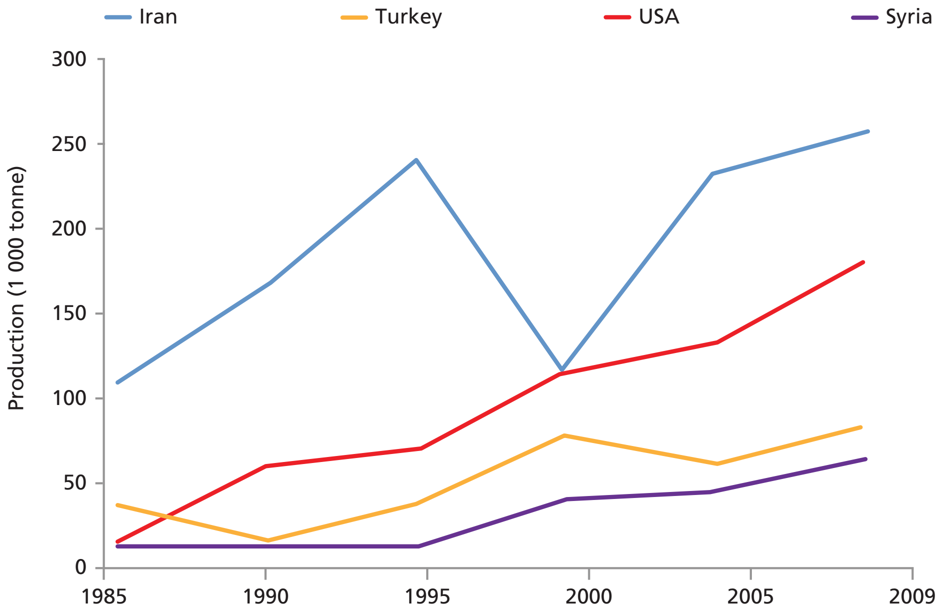
INTRODUCTION AND BACKGROUND

Pistachio *(Pistacia vera* L.*)*, is native to the Near East, primarily Syria and Iran, with large areas planted just recently in the United States. In 2009, there were 586 000 ha globally with an average yield of 1.1 tonne/ha (FAO, 2011). Figure 1 presents the production trends of the main producing countries since 1985. The bulk of Near East production is dryland as the pistachio tree is very drought tolerant. Most of the production in the United States is in California, which is irrigated. There is a huge difference in productivity between dryland and irrigated trees. For example, the average dryland yield in Turkey is only 1.4 kg per tree compared with 16-18 kg per tree under irrigation in California (Tekin *et al.,* 1990). While the value of irrigation for pistachio production is currently unchallenged, there are still some growers in rainfed areas who have the misconception that irrigation is harmful (Kanber *et al.*, 1993). Much of the Near East production is on marginal soils because the tree is perceived to be drought tolerant and good soils are scarce. This is not the case in California where irrigated orchards have been planted on productive valley soils.

The pistachio tree is dioecious; the male flowers are borne on one tree and female flowers on another. The male trees do not produce nuts. However, a certain percentage of the orchard, generally around 4 percent in commercial orchards, must be planted with male trees to ensure adequate pollination.

Among fruit and nut trees, pistachio has one of the highest degrees of alternate bearing. Crop yields can show up to a 90 percent year-to-year reduction. The physiological mechanisms of alternate bearing in pistachio are not well understood. It is likely to involve carbohydrate levels and/or competition with hormonal activity also being a possible factor. Alternate bearing is first manifested during nut filling in early July when the fruit buds (for next year) die and abscise. The heavier the crop, the greater is the bud abscission. The alternate bearing cycle is expressed not only for individual trees but for entire growing regions. It is thought that low production resulting from poor weather in a given year puts the entire region on the same alternate bearing cycle. Excessive alternate bearing in a region can cause a marketing problem for the industry. The current state of the art control of alternate bearing is pruning; heavily prior to an ‘on’ year and minimally going into an ‘off’ alternate bearing year. The fact that pistachio fruit are borne on year-old wood dictate the location and severity of pruning practices designed to mitigate alternate bearing. Moreover, pistachio shoot growth can be characterized as either preformed or neoformed, which is based on when

FIGURE 1 Production trends for pistachios in the principal countries (FAO, 2011).



Quality considerations

Pistachio is distinguished by having more quality components than other nut crops. These include not only the alternate bearing feature that affects nut size but also embryo abortion; nuts that have full size hulls and shells but where the kernels die prematurely or don't fill at all. Also, endocarp dehiscence (shell splitting) is required to produce the highest value nuts. Closed nuts shell at harvest cannot be marketed as snack food, which is the largest market for pistachios. Another type of fruit that is not commercially viable are early splits; nuts that split well before the onset of normal shell splitting. Not only are these nuts worthless but they are prone to fungal disease infection that can lead to the formation of Aflatoxin. Finally, the percentage removal of filled nuts by mechanical shaking also impacts harvest yields.

the tissue was differentiated. Virtually, all the crop is borne on the preformed growth and this has implications for irrigation management.

Although pistachios have been cultivated for centuries in countries of the Near East and West Asia, the industry is relatively young in California compared with the other nut crops grown there. The California pistachio industry is dominated by one variety, Kerman, and large growers and processors have readily embraced advanced practices, including drip or microsprinkler irrigation. In the main producing countries of the Near East, there is a wide-range of varieties and irrigation is being introduced, even though much production is still rainfed. California pistachio growers were very quick to adopt useful research results on water requirements and the impact of water stress on yield and crop quality partly because much of the acreage is located in high water cost and/or low availability areas.

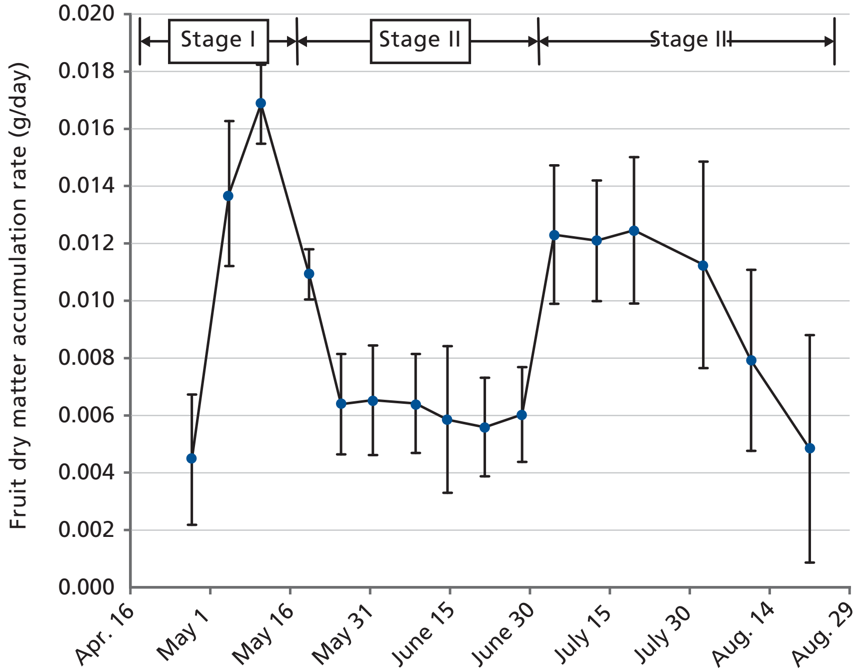
DESCRIPTION OF THE STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

The reproductive growth of pistachio trees can be divided into three stages based upon the development of the nut component parts: the hull+shell and the kernel. The development patterns of the nut components are shown in Figure 2. The hull+shell grows rapidly from late April through mid-May (Northern Hemisphere), after which full size is attained. This period is referred to as Stage I. However, the feniculous (embryo), which will eventually evolve into the kernel, normally does not begin to grow until early July. From mid-May through early July, the nut's primary growth activity is thickening of the shell. This period, characterized by a relatively low rate of dry matter accumulation in the nut, is known as Stage II. Rapid growth of the kernel begins in early July and remains so as harvest is approached. The biofix for this period, which is known as Stage III, is the appearance of a distinct green colour in the feniculous. Research (Spann *et al.*, 2009) has identified the concomitant vegetative growth associated with these stages and their eventual importance as locations for fruiting positions.

Early vegetative and reproductive growth; growth Stage 1

Shoot growth occurs simultaneously with the current season reproductive growth (swelling buds that will form the crop) as well as with embryonic (inflorescence primordia) bud development for the following season's crop from late April through mid May. Lateral inflorescences in the leaf axils are borne on shoots with, generally, a single apical vegetative bud. Buds differentiate in April, May and June, remain quiescent from July to September, and resume differentiation in October.

FIGURE 2 Time course development of dry matter accumulation in pistachio nuts illustrating the three growth stages. Vertical bars are plus and minus one standard error of the mean.



There are two types of shoot growth; the above-mentioned preformed or neoformed. All components of a preformed shoot are differentiated in the dormant bud whereas in neoformed growth, some differentiation of its component parts can occur during the growing season. Most of the buds found on preformed growth are reproductive; there are very few lateral vegetative buds on preformed shoots. Most of the vegetative growth occurs from terminal buds. Preformed shoots tend to be short compared with neoformed shoots which are longer. This longer shoot growth is undesirable because it tends to be weak and hangs down in the orchard rows, making management and harvest difficult. For these reasons, growers typically remove these shoots on mature trees by pruning during the dormant season. However, long shoot growth may be desirable in young, developing trees to ensure the most rapid development of the tree canopy.

Reproductive bud swelling begins in March. By mid-April, there are 100-300 flowers per rachis. Pollination and fruit set occur at this time. There are generally 20-25 developing fruit per rachis and they grow rapidly, with the hull+shell attaining full size by about mid-May. This event also coincides with a hardening of the shell.

Lag phase of reproductive growth: growth Stage II

From mid-May through early July, the primary activity in the nut is thickening and hardening of the shells, a process called lignification. However, dry matter accumulation in the fruit during this growth phase is low relative to the preceding (Stage I) and succeeding (Stage III) periods. There may also be some additional shoot growth in late May. Reproductive buds that will form the following season's fruit continue to differentiate through June. Sometimes there is an additional vegetative flush of growth in late June.

Rapid kernel development: growth Stage III

This phase is characterized by the resumption of a high rate of dry matter accumulation in the nut almost entirely results from the rapid growth of the kernel. Within a matter of a few weeks, the kernel will entirely fill the nut cavity and begin to exert pressure on the shell. Shell splitting is primarily because of this expansion of the kernel (Polito and Pinney, 1999). Shell splitting generally begins in early August. At this time, the hull begins to breakdown, changing from turgid tissue that is tightly bound to the shell with a papery, loosely connected covering that can easily be peeled from the shell. During Stage III, leaves on the same shoot as developing fruit sometimes become yellow and defoliate. This is thought to be the consequence of translocation of resources from the leaves to the fruit.

A certain percentage of the nuts, generally from 10 to 30 percent, do not fill. These are known as 'blanks' or 'aborted' nuts. With the former, there is no evidence of any development of the embryo whereas with the latter, the embryo development is aborted. The term 'blanking' is sometimes used to describe both phenomena. The hulls of these nuts do not breakdown as with the filled nuts. Also they are much more difficult to remove from the tree with mechanical shaking at harvest, resulting in a high percentage remaining on the tree.

Harvest is generally from late August to mid-September. Where it is done mechanically by shaking machines, similar to those used for almonds, which remove the nuts. In addition to the shaker, a companion machine, the receiver, is located on the opposite side of the tree and is used to collect the nuts, which are not allowed to drop to the ground. Drying is accomplished at the processing plant rather than on the ground as for almonds. One primary reason for this is that pistachio nuts need to be dried quickly, otherwise the shell can become stained, making them less attractive to buyers.

Postharvest

From harvest to the onset of defoliation, there is very little outward appearance of tree activity. Following the removal of fruit, reproductive bud differentiation resumes and continues through October. Trees generally defoliate in mid to late November because of leaf senescence, which is accelerated by low temperatures.

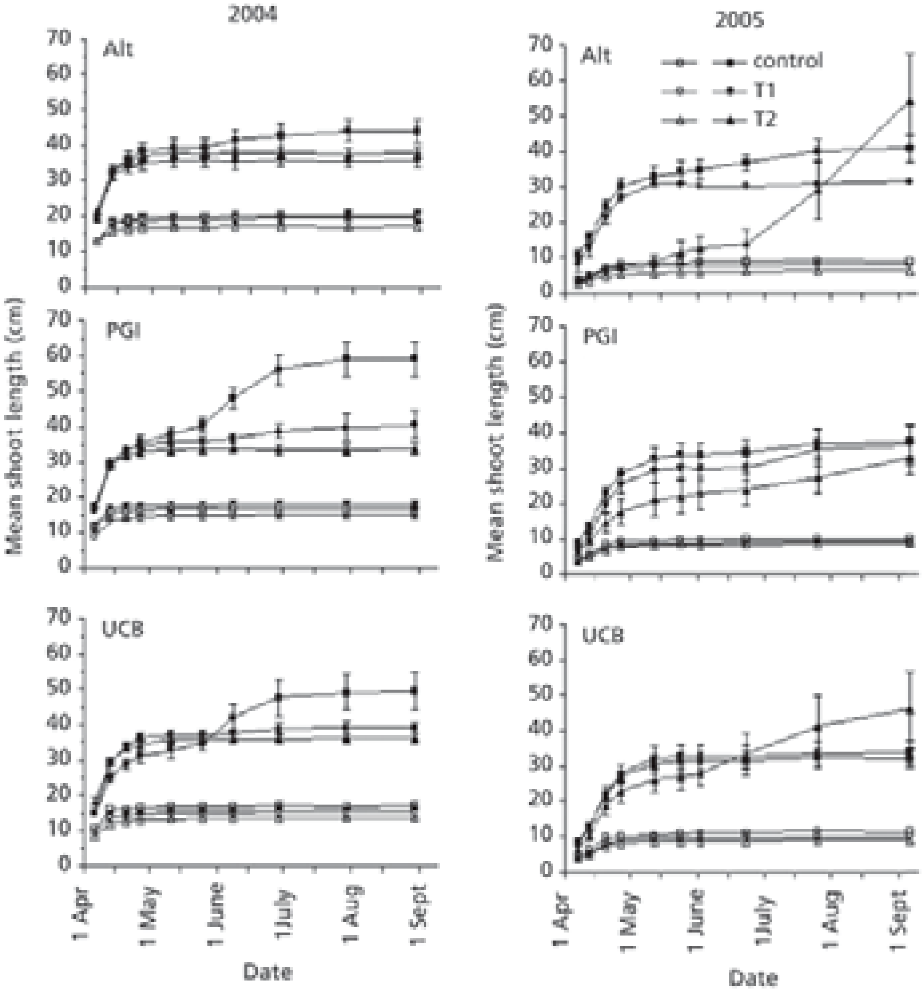
RESPONSES TO WATER DEFICITS

Pistachio has a well-deserved reputation as being drought tolerant. Measurable photosynthetic activity in the leaf has been measured even when leaf water potential (LWP) was in excess of -5 MPa (Behboudian *et al.,* 1986). This was attributed to the fact that pistachio trees had a turgor pressure of about 3 MPa even when the LWP was -6 MPa; a higher value that for even other xerophytes. Pistachio can maintain high turgor even with high soil salinity levels (Walter *et al.,* 1988), and high photosynthesis and stomatal conductance were found in different pistachio species under severe stress (Steduto *et al.,* 2002). Researchers ascribed this primarily to an extensive rooting system rather than xerophytic morphologic characteristics. Unirrigated trees of *P. atlantica* had transpiration rates about three times higher than *P. terebinthus* (Germana, 1997).' This suggests that pistachio trees can transpire at rates far higher than those normally found in mesophytes and that carbon assimilation with limited water supplies can be much higher than in other fruit crops, such as apple, peach, plum, cherry, citrus and almond. Pistachio exhibited a strong photosynthetic response to high N and water supply, although the rates of unirrigated trees were also quite high (Steduto *et al.*, 2002 and Ayd n, 2004). With respect to water, pistachio is somewhat of a paradox; it transpires at an extremely rapid rate, in partly because the fact that its leaves are isolaterals meaning the upper and lower sides are similarly structured with almost identical stomatal density and conductance but, at the same time, it is also extremely drought tolerant.

Effects during Stage I

Spann and others tested RDI regimes that imposed water deficits of about -1.6 MPa midday shaded LWP on mature trees of Kerman on PG1, Atlantica, and UCB rootstocks during Stage I and both Stage I and Stage II. They found that especially for the 'short' shoots, those that are characterized as preformed growth, full elongation occurred by about the third week of April; well before the onset of Stage II. There were generally no reductions in this short shoot length because of these early season water deficits (Figure 3). However, stress during both Stages I and II significantly reduced the growth of the 'long' shoots; the neoformed growth (Figure 3). This did not decrease the number of fruiting positions since they are located mostly on the short shoots. Indeed, they found no differences in fruit load, fruit size and yield between these RDI regimes and the fully irrigated control. This was attributed to the fact that most fruit was borne on the preformed growth and that reducing neoformed growth was actually beneficial in commercial production since it must be pruned. Water and pruning costs are about 30 percent

FIGURE 3 Time course development of shoot length for both short (open symbols) and long (solid symbols) shoots of different cultivars for fully irrigated (Control) and two RDI regimes that imposed stress in Stage I (T1) and both Stage I and Stage II (T2). Vertical bars are plus and minus one standard error of the mean.



of the total for California pistachio growers and thus, the reductions in consumptive use and pruning attributed to the early season stress would likely increase grower profit (Beede *et al.,* 2004). Recent research with the UCB rootstock found some reduction in the total number of growing shoots per tree with both Stage I and Stage II stress that could reduce future yield if it continued for a number of years. This confirmed earlier work (Goldhamer *et al.,* 1987) that stress-related reductions in fruit load were primarily because of the reduction in the initiation of short shoots rather than potential or actual number of nuts per rachis.

Goldhamer and Beede imposed dryland conditions during Stage I with Kerman on Atlantica rootstock. They found that nut size was reduced by 6.1 percent relative to fully irrigated trees but that shell splitting was increased by 14.0 percent. They theorized that the stress impacted shell growth more than kernel growth, resulting in a greater splitting percentage. Since no other yield components were significantly affected, they reported slightly better total kernel yield of marketable product (split nuts) with Stage I stress (Goldhamer and Beede, 2004). More recent research has confirmed that shell splitting can be increased with Stage I stress but at the expense of nut size (Goldhamer *et al.,* 2005). Thus, the decision to use this strategy would depend on whether the grower had a severe problem with the production of closed shell nuts. Closed shell nuts can be as low as 5 percent of the harvested nut load and as high as 60 percent. Further, Stage I stress not only increased shell splitting but it increased the shell opening; the distance between shell halves at the distal end of the nut. This can result in the shell detaching from the kernel during commercial nut processing and the loose kernels can decrease the harvest value.

Effects during Stage II

Goldhamer and Beede evaluated an array of RDI treatments that imposed either dryland, applied water at 25 percent ET_c, or applied water at 50 percent ET_c during Stage II on mature Kerman on Atlantica rootstock under the high evaporative demand conditions of the western San Joaquin Valley in California (Goldhamer and Beede, 2004). These Stage II deficit irrigation treatments were coupled with different postharverst water regimes. They found that none of the Stage II stresses significantly reduced individual nut weight although there was a trend toward lighter nuts when Stage II irrigation was totally eliminated. One of these Stage II dryland treatments, when coupled with irrigation at 25 percent ET_c postharvest, significantly reduced the yield of split nuts. They concluded that Stage II was, indeed, a stress tolerant period, as has been found for other double sigmoid development fruit crops, such as peach, plum, and nectarine, and recommended an RDI regime that irrigated at 50 percent ET_c during Stage II (Goldhamer and Beede, 2004).

A June deficit irrigation schedule of 20 percent less than full irrigation doubled early splits, while a July deficit of 35 percent increased early splits by 30 percent (Sedaghati and Alipour, 2006). Early splits are nuts that split well before the onset of normal shell splitting. These nuts are not commercially viable. Moreover, they are susceptible to fungal diseases that can eventually result in Aflatoxin contamination. Doster and Michailides (1995) recommended that water stress in mid-May be avoided to decrease the incidence of early splits.

Effects during Stage III

Stress imposed during Stage III can have a dramatically negative impact on virtually all the yield components of pistachio. When a dryland treatment was imposed during Stage III, it was found that this reduced individual kernel weight by 10.6 percent, increased the sum of blanking and kernel abortion in the total tree nut load by 22.7 percent, and increased the production of closed shell nuts by 175 percent. Somewhat remarkably, the Stage III dryland treatment had no affect on total tree nut load. However, the yield of split nuts was reduced by 62.6 percent (Goldhamer and Beede, 2004).

Earlier work indicated that withholding irrigation during the first half of Stage III, which reduced consumptive use by 320 mm, had no significant impact on shell splitting but increased the number of filled nuts left in the trees after mechanical shaking by 119 percent. On the other hand, dryland conditions during the last half of Stage III (a 200 mm reduction in consumptive use) both increased the production of closed shell nuts at harvest by 31.6 percent and the number of filled nuts retained on the tree after mechanical shaking by 50 percent. It was concluded that

Stage III was the most stress sensitive period of the season for pistachio (Goldhamer *et al.,* 1991).

Of the numerous pistachio yield components, it is remarkable that tree nut load was unaffected by any of the nine deficit irrigation treatments imposed, including dryland conditions during Stage I, Stage II, Stage III, and postharvest and the various Stage II and postharvest stress combinations (Goldhamer and Beede, 2004). When averaged over the last two years of their four-year study, tree nut load ranged from 10 900 to 12 300 with the fully irrigated trees averaging 11 500 nuts per tree (Goldhamer and Beede, 2004). This suggests that there was enough preformed shoot growth very early in the season, even with Stage I dryland conditions, to produce the number of nodes (fruiting positions) necessary to support a full crop and that stored winter rainfall (200 mm per year) was sufficient to support this growth. This ability of the pistachio tree to produce equal fruit loads under a variety of stress regimes highlights the importance of the preformed shoot growth from mid-April to mid-May; a period when trees would normally rely on stored winter rainfall rather than irrigation. Indeed, the early work of Spiegel-Roy *et al*. (1977) found that 54 to 163 mm of annual precipitation was sufficient for dryland trees to differentiate enough flower buds to obtain appreciable yields.

Effects on alternate bearing

Kanber and others observed that a long duration of water stress aggravated alternate bearing and suggested that irrigation could alter periodicity, presumably by making more carbohydrates available during peak carbon demand periods (Kermani and Salehi, 2006). Goldhamer found that Stage I stress during an 'on' year (shown as 2004 in Figure 4) resulted in more than a three-fold increase in fruit load the following season (the subsequent 'off' year) relative to fully irrigated trees. The mechanisms of why this happened are unknown and it should be emphasized that the early season stress was possible only because winter rainfall was abnormally low. The following season, the winter rainfall eliminated any Stage I stress but the fruit loads of this RDI regime were 25 percent lower than the fully irrigated trees (Figure 4). This pattern continued in the succeeding season when this RDI regime had a fruit load 25 percent higher than those under full irrigation. It appears that regardless of why there are higher yields in a normally 'off' year, the one time higher yields can alter the alternate bearing pattern for the following years.

Crop load also influences the impact of deficit irrigation on the various yield components of pistachio. This was observed when dryland conditions with Kerman on Atlantica rootstock were imposed in both 'off' and 'on' alternate bearing years (Figure 5). All the yield components, with the exception of harvestability, were more negatively impacted in the 'on' year. Harvestability was higher in the 'on' year only because entire rachises, rather than individual nuts, were removed from the tree with the mechanical shaking. Thus, growers can anticipate greater negative impacts of serious droughts during 'on' versus 'off' alternate bearing years. In fact, a possible management strategy, with very limited water supplies under microirrigation, would be to cutoff irrigation to the trees with low fruit loads (those in the 'off' year), making that water available for the trees in the orchard with the high fruit loads.

Indicators of tree water status

The established method to quantify water stress for pistachio is to measure water potential with a pressure chamber. Although the standard method is to measure stem-water potential

FIGURE 4 Total tree nut load for trees subjected to RDI regime that imposed stress in Stage I compared with a fully irrigated control. Note the impact of RDI on the alternate bearing pattern. Vertical bars are plus and minus one standard error.

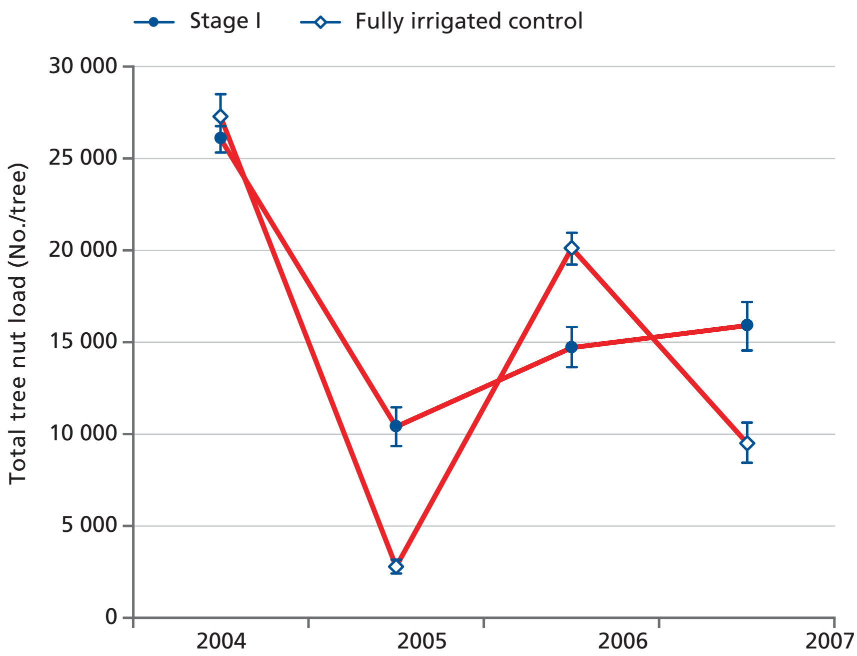
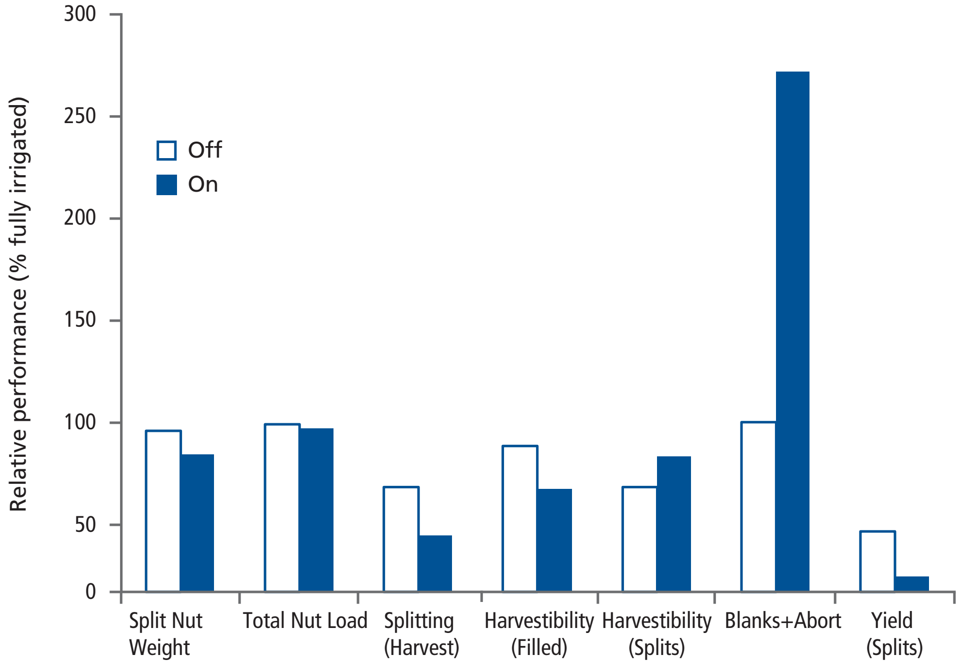


FIGURE 5 The impact of the first year of dryland conditions during both 'on' and 'off' alternate bearing years on the yield and yield components of previously fully irrigated pistachio trees.



(see Chapter 4), as in other species, there is a good correlation between midday shaded LWP (faster to measure) and stem-water potential (Goldhamer *et al.,* 2005).

One factor that complicates taking LWP measurement on pistachio leaves is that at the onset of gas injection into the chamber, exudates, presumably from the phloem, appear at the cut end of the petiole. These can interfere with identifying the instant xylem fluids appear. One approach to eliminating this problem is to use a cotton swab to soak up these exudates prior to the appearance of the xylem fluid. Another approach to eliminating this problem uses blotting paper positioned at the cut end of the petiole that absorbs only xylem fluid but excludes the other interfering fluids. A third approach is not to use individual leaves but small, interior shaded spurs that may have one to four leaves. The procedure involves covering the spur with a damp cloth just prior to excision. A few millimiters of bark is removed at the cut end with either a small knife or a thumbnail. The entire spur is placed in the chamber after the cloth is removed and the reading is taken. It is quite easy to identify the appearance of the xylem since there is no interference of phloem exudates and the cross-sectional area of view is larger than the leaf petiole. Goldhamer also found a good correlation between spur water potential and midday shaded LWP. The slope of the relationship was about unity but the intercept indicated that the spur water potential differs from the shaded LWP reading by about -0.7 MPa.

WATER REQUIREMENTS

Relatively few studies have quantified pistachio ET_c. Research in Iran with Ohadi on Badami Zarand rootstock (Kermani and Salehi, 2006), concluded that 600 and 1 200 mm per season should be applied with drip and flood irrigation, respectively, although 910 mm was reported as a 'previously determined' irrigation amount for mature pistachio trees (Kermani and Salehi, 2006). Early studies found that trees irrigated with a K_p (pan evaporation) value of 0.50 produced equally as well as those irrigated with a K_p of 0.75 for Larnaka on P. integerrima rootstock (Monstra *et al.,* 1995). In Southeast Turkey, the K_c values for Antep and Uzun varieties rose from 0.49 in May to 0.80 in August and continued at this magnitude through the first week of September when they declined to 0.32 during October because of leaf senescence (Kanber *et al.*, 1993). However, it was noted that while all irrigation regimes began the season with a nearly full soil water profile, they all ended with it nearly depleted. The researchers suspected that there was insufficient irrigation to meet ET_c for their most heavily irrigated trees (Kanber *et al.*, 1993).

A soil water balance approach with arrays of neutron probe access tubes to a depth of 3 m and ET_o estimates from a nearby weather station was used to calculate bimonthly K_c values for mature Kerman on Atlantica rootstock (Table 1) (Goldhamer *et al.*, 1985). A unique aspect of this approach was to make use of soil hydraulic conductivity data obtained in a separate experiment to eliminate one of the shortcomings of the water balance approach to determine ET_c: deep percolation below the deepest depth monitored.

TABLE 1 Crop coefficients relative to grass reference crop (ET_o) for mature pistachio trees ('Kerman' on *P. atlantica*) measured using on soil water balance approach in western Kings Co., CA (Goldhamer *et al.,* 1985).

Date	Crop Coefficient (K_c)
Apr. 1-15	0.07
Apr. 16-30	0.43
May 1-15	0.68
May 16-31	0.93
June 1-15	1.09
June 16-30	1.17
July 1-15	1.19
July 16-31	1.19
Aug. 1-15	1.19
Aug. 16-31	1.12
Sept. 1-15	0.99
Sept. 16-30	0.87
Oct. 1-15	0.67
Oct. 16-31	0.50
Nov. 1-15	0.35
Nov. 16 -30	0.28

WATER PRODUCTION FUNCTION

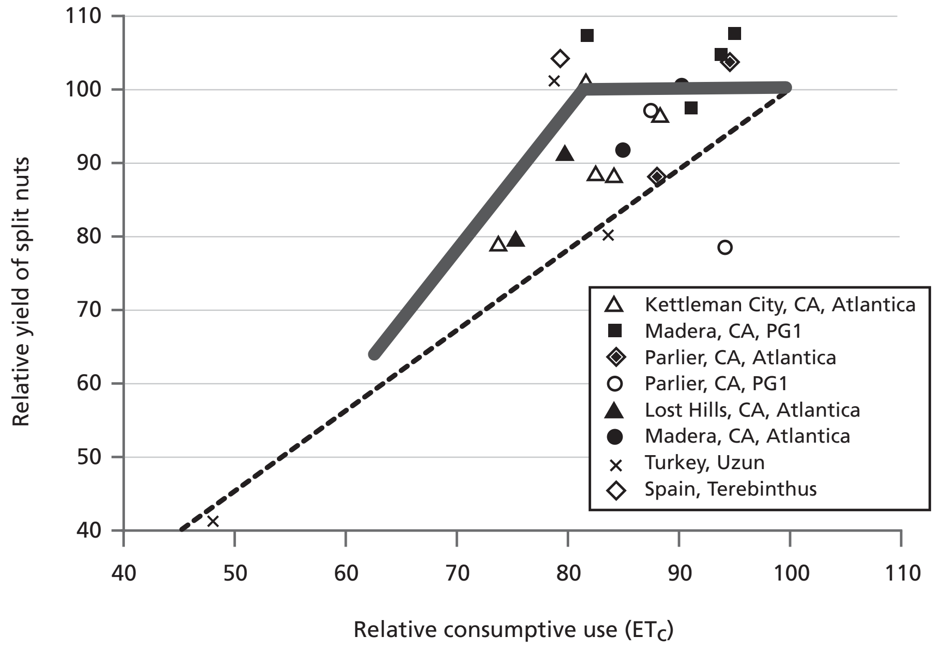
The current recommended optimal RDI regime applies stress during Stage II and postharvest to achieve the same production as fully irrigated trees while reducing the consumptive use of water (Goldhamer and Beede, 2004). These authors tested this approach in numerous field trials (Goldhamer *et al.*, 1984) in the San Joaquin Valley of California. The results of these experiments are summarized in the production function shown in Figure 6. While there is appreciable scatter in the data, it suggests that a plateau in the yield of marketable product is achieved with 10 to 20 percent less consumptive use than potential ET_c. Thus, reducing consumptive use by up to 20 percent can generally be achieved without a negative impact on the yield of marketable product. This occurred with both Altantica and PG1 rootstocks.

It should be emphasized that that a 10 to 20 percent reduction in ET_c would translate into a higher percentage reduction in applied water. For example, if ET_c was 1 100 mm of which 300 mm was effective rainfall, then applied irrigation water would have been 800 mm. A 15 percent reduction in ET_c would reduce consumptive use by 165 mm; that is equivalent to about a 21 percent reduction in applied water. Percentage reductions of applied water would increase as effective rainfall increased.

SUGGESTED RDI REGIMES

Based on the assumption that Stage II and postharvest are the most stress-tolerant periods, Stage I has intermediate tolerance, and Stage III is least tolerant, one can develop an array of drought irrigation strategies based on meeting certain percentages of ET_c during these periods (Table 2). The percentage amounts for each period vary depending on the available water supply. It should be pointed out that these recommendations are based on experimental results of applied water amounts generally above about 750 mm (about 65-70 percent ET_c); tests of RDI regimes below this amount have not been published. Thus, the suggested regimes here for water supplies below 750 mm are our best estimate of what would result in optimal tree performance, again based on the stress sensitivities of each growth stage.

FIGURE 6 Production function developed using RDI strategies that imposed stress during Stages I, II, and postharvest only for at least a four-year duration. Eight studies from USA and Europe met this criterion and are presented. The dashed line shows linear regression from full yield, through zero yield with a 7% ET_c; the level assumed necessary for tree survival.



Since the contribution of soil moisture to ET_c is difficult to determine, especially early in the season, the RDI management strategy of only irrigating at certain percentages of ET_c is problematic. An alternative is to use a plant-based indicator of tree water stress, such as leaf/spur water potential with the pressure chamber. In the studies cited above, midday shaded LWP during Stage I, Stage II, and postharvest did not exceed -1.8 to -2.0 MPa. Recommended values for fully irrigated, mature pistachio trees grown under high evaporative demand conditions should have midday shaded LWP values for Stage I, Stage II, Stage III, and postharvest of -0.7 to -0.8 MPa, -0.8 to -1.0 MPa, -1.0 to -1.1 MPa, and -1.0 to -1.2 MPa, respectively.

One pistachio grower in California has observed that there is little need to irrigate male trees at full ET_c since their only role is to supply pollen very early in the season. He suggests that male tree irrigation can be eliminated or substantially reduced after Stage I with no negative impact on the subsequent season's pollen formation. This can be accomplished relatively easily with microirrigation systems. However, given that male trees usually make up only about 4 percent of all trees, the reduction in irrigation would be small.

Typical microsprinkler application:

Tree spacing	289 ft^2	
Application rate	1.47 ft^3/hr	
Depth application rate per plant	0.01 ft/hr	(0.06 in/hr)
Amount per irrigation	1.47 in/24 hr	(37.2 mm/24 hr)

The grower would keep track of cumulative amounts to be applied with RDI scenarios. When the total is 37 mm, he irrigates. Thus, there would be one irrigation in April 16-30 with full water supply but with 300 mm available case, first irrigation would not be until third week of June.

TABLE 2 Suggested RDI strategies for different available water supply senarios from 900 to 300 mm when ET_c is 1 100 mm.

			Potential	900 mm available case		750 mm available case		600 mm available case		450 mm available case		300 mm available case	
Date	**Growth Stage**		**ET_c in Period (mm)**	**Irrigation Rate (% ET_c)**	**Applied Amount (mm)**	**Irrigation Rate (% ET_c)**	**Applied Amount (mm)**	**Irrigation Rate (% ET_c)**	**Applied Amount (mm)**	**Irrigation Rate (% ET_c)**	**Applied Amount (mm)**	**Irrigation Rate (% ET_c)**	**Applied Amount (mm)**
Apr. 16-30	1	Leafout, flowering; shoot elongation	33	100	33	50	16	50	16	25	8	10	3
May 1-15	1	Fruit set; hull, shell expansion	59	100	59	50	30	50	30	25	15	10	6
May 16-31	2	Shell hardening	91	50	45	25	23	25	23	25	23	10	9
June 1-15	2	Shell hardening	122	50	61	25	31	25	31	10	12	10	12
June 16-30	2	Shell hardening	137	50	68	25	34	25	34	10	14	10	14
July 1-15	3	Rapid kernel growth	128	100	128	100	128	75	96	10	13	10	13
July 16-31	3	Rapid kernel growth	123	100	123	100	123	75	93	75	93	50	62
Aug. 1-15	3	Shell splitting	124	100	124	100	124	75	93	75	93	50	62
Aug. 16-31	3	Hull breakdown	100	100	100	100	100	75	75	75	75	50	50
Sept. 1-15	Harvest		83	100	83	100	83	75	62	75	62	50	42
Sept. 16-30	Posthavest	Bud differentiation	56	100	56	25	14	25	14	25	14	10	6
Oct. 1-15	Posthavest	Bud differentiation	35	100	35	25	9	25	9	25	9	10	4
Oct. 16-31	Postharvest	Bud differentiation	19	100	19	25	5	25	5	25	5	10	2
Nov. 1-15	Postharvest	Defoliation	10	100	10	25	2	25	2	25	2	10	1
Total			**1 121**		**946**		**722**		**583**		**438**		**284**
Irrigations per season			30		25		19		16		12		8

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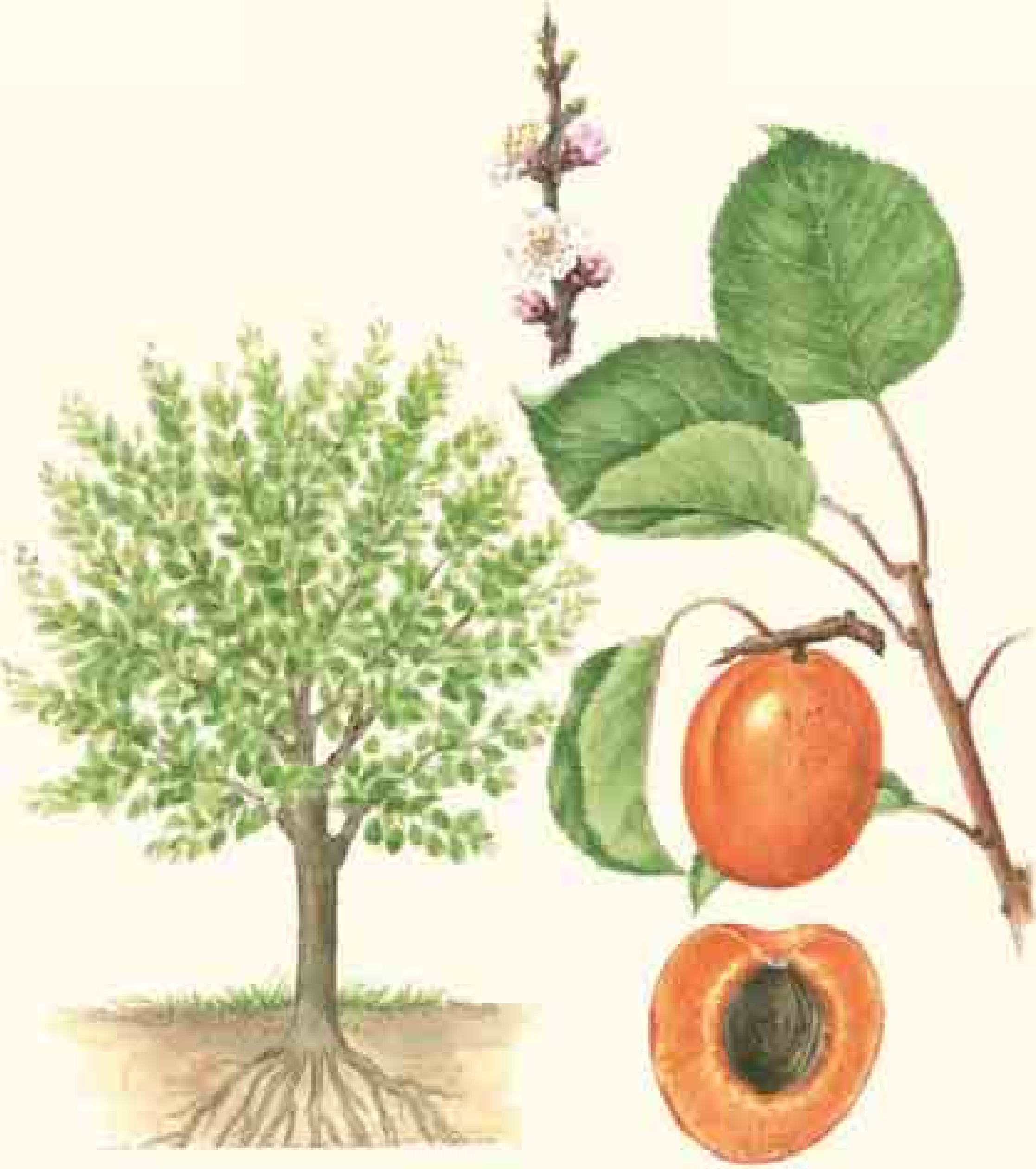

Apricot

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Apricot

INTRODUCTION AND BACKGROUND

Throughout the world, 90 percent of commercially grown apricots are derived from the *Prunus armeniaca* (L.) specie, a few cultivars are from *P. mume* or *P. sibirica*, or more recently, originate from apricot × plum (and *vice versa*) hybrids. Apricots are small-to-medium sized trees with spreading canopies (usually kept under 3.5 m), cultivated for fresh or processed fruit (dried, jam, juice), and for their oil extracted from the kernel. Apricot grows well in temperate regions; however, it is also able to tolerate very low temperatures during winter. Particularly, *P. sibirica* can tolerate air temperatures of about -35 °C, and soil temperatures down to -13 °C at the 40 cm depth did not damage its roots (Kramarenko, 2010). Total global production in 2009 was 3.73 million tonne on 504 000 ha (FAO, 2011). Figure 1 presents the evolution of production since 1985. Turkey is the main producer, followed by Iran; Italy is the first producer in the European Union. Most cultivars mature between the end of April and end of June (Northern Hemisphere). Over the last five years, new cultivars with a much later maturity date (August-September) have been bred and introduced in some areas.

Normal plantation density is about 400-500 tree/ha, using some training systems (e.g. transverse Y) density could reach 1 200–1 500 tree/ha. In this case careful canopy management (e.g. summer pruning) is required to minimize excessive shading that reduces water-use efficiency at the leaf level (Figure 2), the size, sugar content and colour of the fruit, bud induction and flower quality for next year yield and the level of carbohydrate stored in the buds, flowers and shoots (Nuzzo *et al.*, 1999 and Xiloyannis *et al.*, 2000).

STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

Floral bud induction begins in late spring or summer. The chilling requirements for flowering (No.of hours < 7 °C), range from 300 to 1 200, depending on the cultivar. The minimum bloom temperature (namely the GDH heat units required after rest (Ruiz *et al.*, 2007)) is relatively low, causing apricots to bloom (and leaf out) early in most locations, thus apricot flowers and new shoots tend to suffer frost injury in early spring. Apricot trees break dormancy and begin to bloom in the Northern Hemisphere by mid-February, depending on the environmental conditions and cultivar. Usually, flowering

FIGURE 1 Production trends for apricots in the principal countries (FAO, 2011).

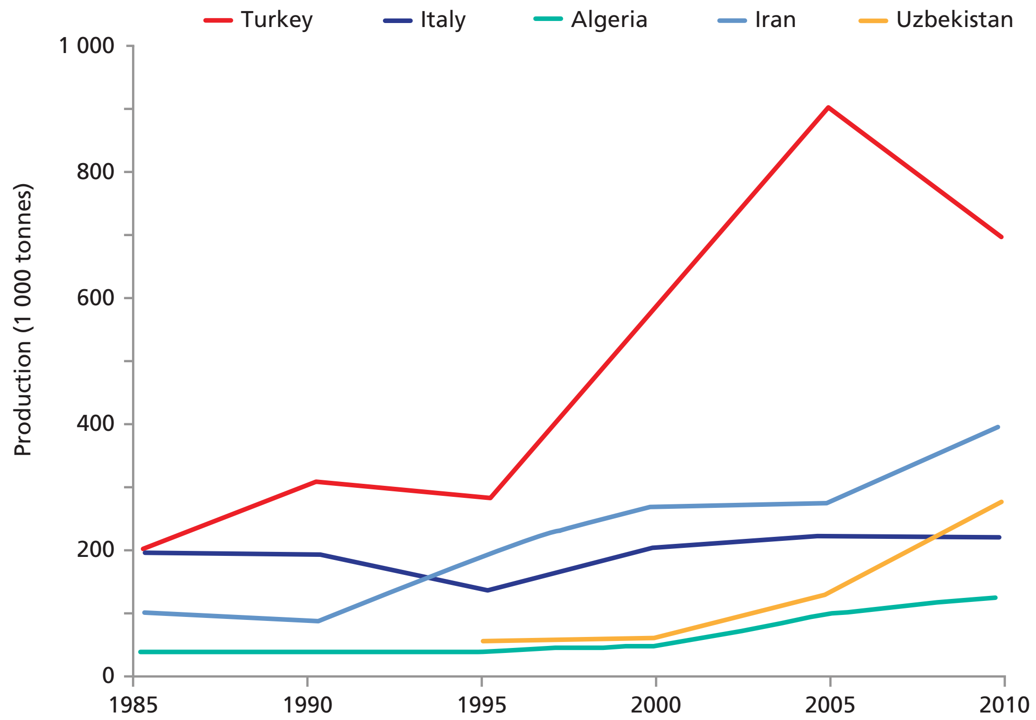
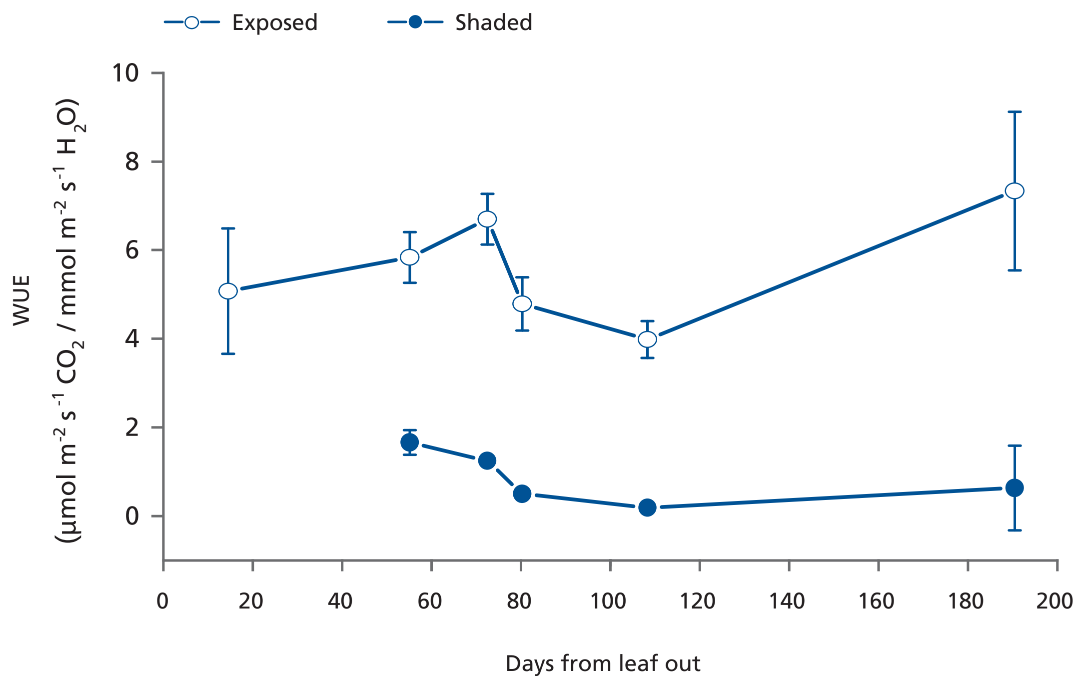


FIGURE 2 Seasonal variation of the daily mean water-use efficiency (WUE) (±SE) measured in exposed and shaded (< 350 μmol m^{-2} s^{-1} PAR) leaves in apricot trees trained to transverse-Y (cv. Tyrinthos, 1 111 plant/ha) (source: Xiloyannis *et al.*, 2000).

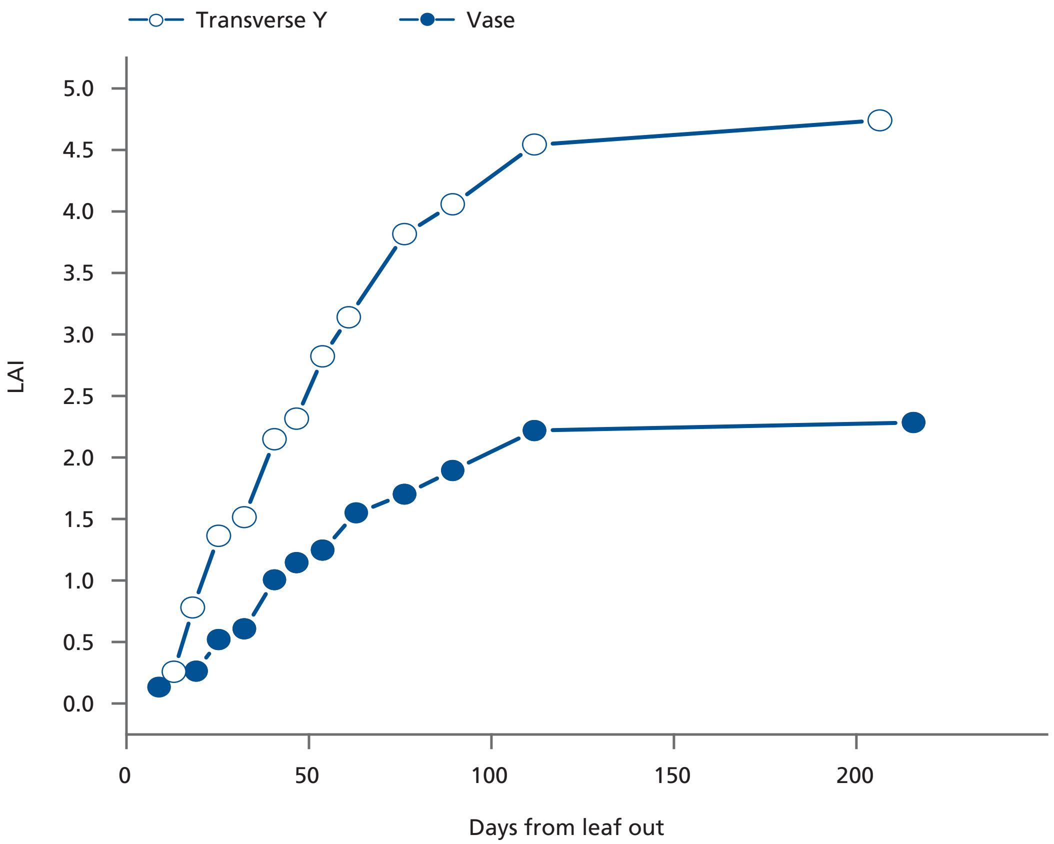


is completed within 20 days; thereafter fruit grows rapidly and attains its maximum size by mid-May (Northern Hemisphere). At this time, about 90 percent of total fruit dry matter has been gained (in early cultivars). In temperate regions, harvest starts by the end of May and lasts until the end of July; Northern Hemisphere).

Leaf emergence takes place at the end of February followed by fast shoot growth rates. About 80 percent of full leaf area is completed by the end of May. Thereafter, about 95 percent of final leaf area is achieved by the end of June (Figure 3). Values of leaf area index (LAI) range from about 2 in orchards with normal plantation density (~400 plant/ha) up to 4.5 in orchards planted in high density systems (~1 100 plant/ha) (Figure 3).

In Mediterranean climates, vegetative shoot growth of apricot trees continues (especially in young orchards) for several months after fruit have been picked, until October. During this postharvest period, carbohydrates and mineral elements stored in the different plant organs are of primary importance. Thus, it is important to provide sufficient mineral nutrition and water supply from irrigation to protect the trees from abiotic stress, during the postharvest period. In this way leaf photosynthetic activity is maintained and extended until natural leaf senescence, and in turn, storage of reserves in shoots, buds, branches and main roots is maximized.

FIGURE 3 Seasonal LAI evolution in apricot orchards (cv. Tyrinthos) trained to Vase (400 plant/ha) and Transverse Y (1 111 plant/ha) (redrawn from Dichio *et al.*, 1999).



RESPONSES TO WATER DEFICITS

In areas of winter and spring rainfall, water stress conditions rarely occur before harvest in early cultivars, particularly when soils are deep and with high water-holding capacity. The effects of reduced soil water availability, as well as the level of stress experienced by plants, depend on the intensity and duration of the water deficit, and on the plant phenological stage. Generally in June, July and August (months with high evaporative demand) the effects of water deficit are more evident.

Apricots, like most stone fruit trees, are sensitive to water shortages during the entire fruit development period. The early stages of fruit growth are of great significance not only for fruit size but also for the accumulation of some phloem-immobile nutrients (e.g. calcium, Ca). About 85 percent of fruit Ca content at harvest is gained within the early four weeks of development (Montanaro *et al.*, 2010). Hence optimal soil water supply during these weeks is essential to avoid reduction of water (and nutrients) uptake.

Water deficits during the later stages of fruit growth lead to smaller fruit at harvest. However, it has been reported that for the cv. Búlida, recovery from water stress (-1.0 MPa predawn leaf water potential (LWP)) during Stage II of fruit growth, induced a compensatory fruit growth rate during the final stages, which allowed the fruit to reach a similar diameter as fruit from fully irrigated plants (Torrecillas *et al.*, 2000). In the same experiment, water deficits applied during Stages I and II that imposed mild to moderate stress from mid-March to mid-May (predawn LWP of -1.1 MPa) caused a yield decline of about 15 percent in the last three years of a four-year experiment. Surprisingly, this difference was not statistically significant from the yield of a fully irrigated control (predawn LWP of -0.4 MPa) (Torrecillas *et al.*, 2000).

For mature trees water deficits (-1.0 MPa predawn LWP) negatively affected trunk growth during the drought period (Perez-Pastor *et al.*, 2009). However, upon recovery of optimal soil water condition trunk circumference may easily recover (Torrecillas *et al.*, 2000).

Water stress (-1.5 to -2.2 MPa of predawn LWP) occurring during the early postharvest period (~30 days after harvest), could have detrimental effects on the potential yield of the following year, particularly for early cultivars. This is because water deficits at this time negatively affect bud induction and the floral differentiation process, which happen in the early postharvest period.

WATER REQUIREMENTS

The water requirements for irrigation depend primarily on the annual water deficit of the environment, than on cultivar and yield target. For example, the amount of irrigation water needed to produce 1 kg of fruit in southern Italy, where the seasonal water deficit (ET_o-rainfall) is around 850 mm/year, is about 160 litre (~30 tonne/ha yield). For the same cultivar, this value decreases to about 40 litre/kg in northern Italy (44°08′ N; 12°44′ E) where the seasonal water deficit is only around 160 mm/year.

There have been very few measurements of the consumptive use (ET_c) of apricot trees. Crop coefficients (K_c) for apricot orchards are similar to those of other stone fruit such as plum or peach. However, because fruit is harvested quite early, limited post harvest irrigation is common, which affects the reported K_c values, sometimes much lower than the values that may be observed in orchards where the water supply is not limiting transpiration after harvest. Table 1 provides adjusted K_c values for mature drip-irrigated apricot orchards based on an experiment in southeastern Spain (37°52′ N; 1°25′ W) (Abrisqueta *et al.*, 2001).

TABLE 1 Crop coefficients for mature apricot trees (soil was not tilled, trees were drip irrigated).

Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
0.4	0.7	0.8	1.0	1.0	0.85	0.7	0.5

WATER PRODUCTION FUNCTION

Based on results from published experiments relating yield to different irrigation regimes for apricots (Torrecillas *et al.*, 2000 and Perez-Pastor *et al.*, 2009) and from our own experience, an SDI programme has been outlined in Table 2 and an RDI strategy in Figure 5. This programme reduces the seasonal applied water by 20 percent relative to a fully irrigated orchard, will decrease irrigation water use without impacting negatively on yield.

TABLE 2 Recommended crop coefficients for a SDI strategy. Data obtained in Southern Italy (40 N; 16°38′ E; C. Xiloyannis, unpublished).

Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
0.4	0.5	0.6	0.7	0.85	0.5	0.5	0.5

SUGGESTED RDI REGIMES

As described above, apricot trees have some positive characteristics that help them face water restrictions and these can be used in RDI strategies. Moreover, shoot and fruit growth are separated (Figure 4) in late cultivars. As for peach, this is highly relevant when adopting deficit irrigation strategies devoted to the control of vegetation without affecting fruit growth. However, the opportunity to reduce water application in Stage II is limited for apricots, in particular in early cultivars where the duration of Stage II is quite limited.

A regulated deficit irrigation strategy should avoid water deficits during the critical period of high sensitivity to water stress (i.e. the whole fruit growth and the early postharvest period, around 30 days after harvest). After this period, based on the amount of water available in the soil volume explored by roots, irrigation could start being reduced just after harvest. In this way, the trees deplete water from the deep soil layers and gradually adjust their water status without affecting bud induction and differentiation processes. It is recommended that in the early 30-day period after harvest, the predawn Ψ_{leaf} should not be below -0.7 MPa. After this period, a reduction of about 50 percent of the ET_c is a practicable deficit irrigation strategy (Figure 5). To avoid excessive tree water stress it is desirable to monitor tree water status (minimum predawn Ψ_{leaf} should not be below a threshold of -1.30 MPa, which corresponds

FIGURE 4 Apricot (cv. Búlida) shoot length and fruit diameter as % of their final value (Torrecillas *et al.* 2000).

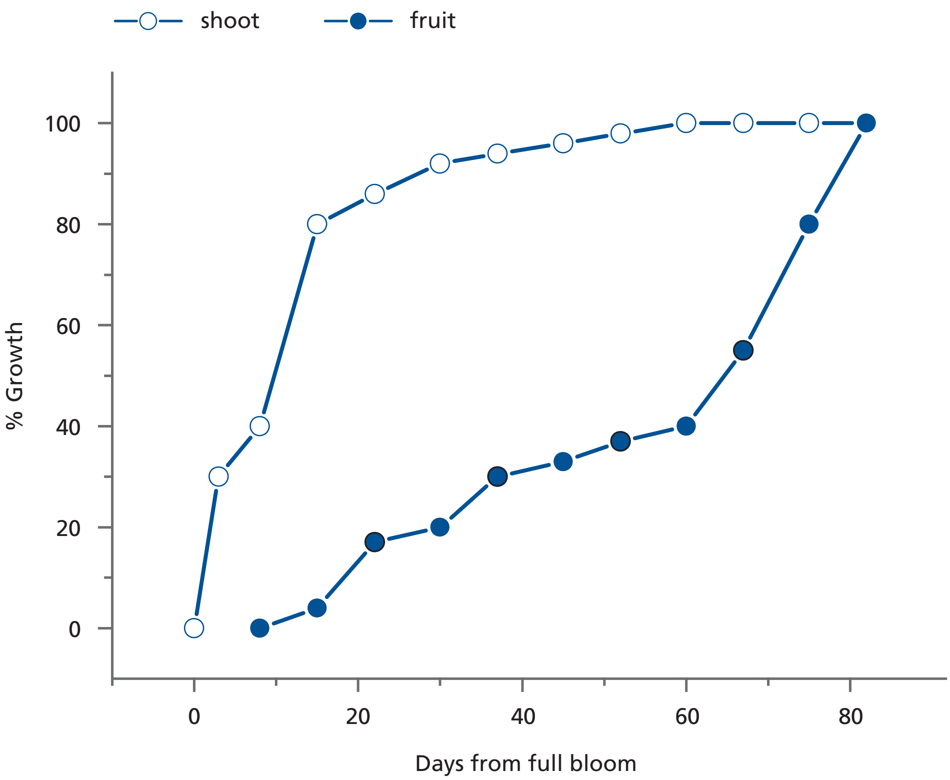
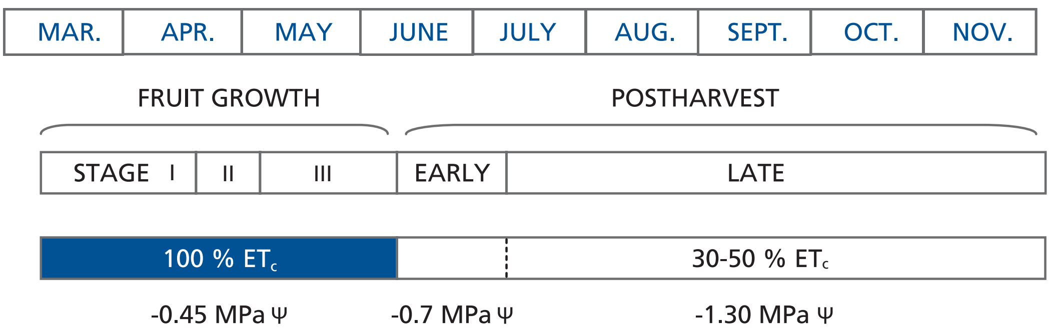


FIGURE 5 Schematic representation of the recommended RDI strategy during the season. A reduction down to 30-50 percent ET_c (depending on soil water holding capacity) should be evaluated according to the water availability in the soil explored by roots. Ψ indicates the minimum predawn leaf water potential below which there is risk of yield reduction. The developmental pattern is that of an early ripening cultivar.



to a midday value varying between -2.5 to 3.0 MPa). The percentage of ET_c reduction should be carefully evaluated according to the available water in the root zones, which is affected by soil hydraulic characteristics and rootstocks. Table 2 presents recommended K_c values for an SDI strategy tested in Southern Italy. This strategy was tested for three years in a drip irrigated apricot orchard (cv. S.Castrese, Palmette 740 plant/ha) grown in an area with 980 mm ET_o from April to September. About 5 600 m^3/ha were supplied during the whole season. Long-term application of the SDI strategy should be evaluated locally and season-by-season. The sustainability of the orchard under the RDI/SDI regime in the long run depends on how effectively winter rainfall refills the soil volume explored by roots.

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Avocado

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Avocado

INTRODUCTION AND BACKGROUND

Avocado *(Persea americana* Mill*)* is a tree that has been known for centuries in areas of Central and South America, but only recently has become a commercial crop. In 2009, there were over 430 000 ha of commercial plantings with a world average yield of 8.8 tonne/ha, with Mexico (100 000 ha), Chile and the United States as the main producing countries. Other countries with significant exports are South Africa, Spain, and Israel (FAO, 2011). Figure 1 presents the production trends of the main producing countries. Avocado fruit yields are comparatively low relative to those of other fruit trees because of the high energy requirements of producing fruit, because of both its large seed size and its composition, rich in oil (Wolstenholme, 1986). Average yields of the variety Hass, one of the most popular commercial cultivars, are around 12 tonne/ha, but may reach 25 tonne/ha in very good years, with the fruit containing up to 20 percent oil. There are three avocado races: Mexican, Guatemalan and West Indies, with different sensitivity in their responses to the environment. Avocadoes have evolved in volcanic soils that have very low bulk density, acid pH, and very high pore volume. It is therefore not surprising that this species is extremely sensitive to waterlogging and does not do well in heavy soils with aeration problems. Planting on berms or ridges is customary when feasible to improve drainage around the areas close to the trunk base. For this reason, sandy rather than heavy soils are preferred for planting avocados. Avocados are also very sensitive to low temperatures, and even light frosts (temperatures below -1 to -2 °C) may cause significant damage. Among the three races, the Mexican is most tolerant to cold temperatures, as it originated in the cool highlands of Mexico.

GROWTH AND DEVELOPMENT IN RELATION TO YIELD DETERMINATION.

Vegetative growth occurs in two flushes; a strong one in spring and a weaker one in the autumn. Flowering occurs in spring (between early October and mid-November in the Southern Hemisphere) and is followed by fruit set. Heavy fruit drop takes place during the first 3-4 weeks after fruit set, at the end of spring, leading to a first adjustment in fruit number, which is further adjusted with an additional fruit drop period, which takes place around the end of summer, when fruit size is between 10-40 percent of mature size. Figure 2 depicts the developmental stages of the cultivar Hass in Central Chile showing also two root growth periods occurring in early summer and at the beginning of fall.

FIGURE 1 Production trends for avocado in the principal countries (FAO, 2011).

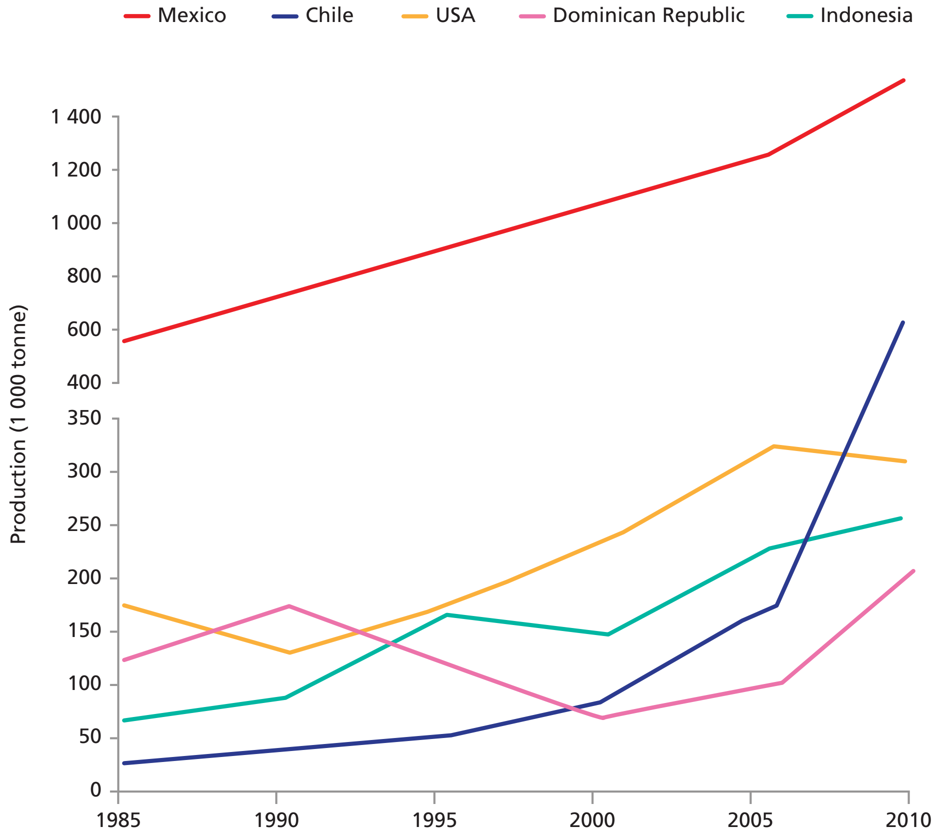
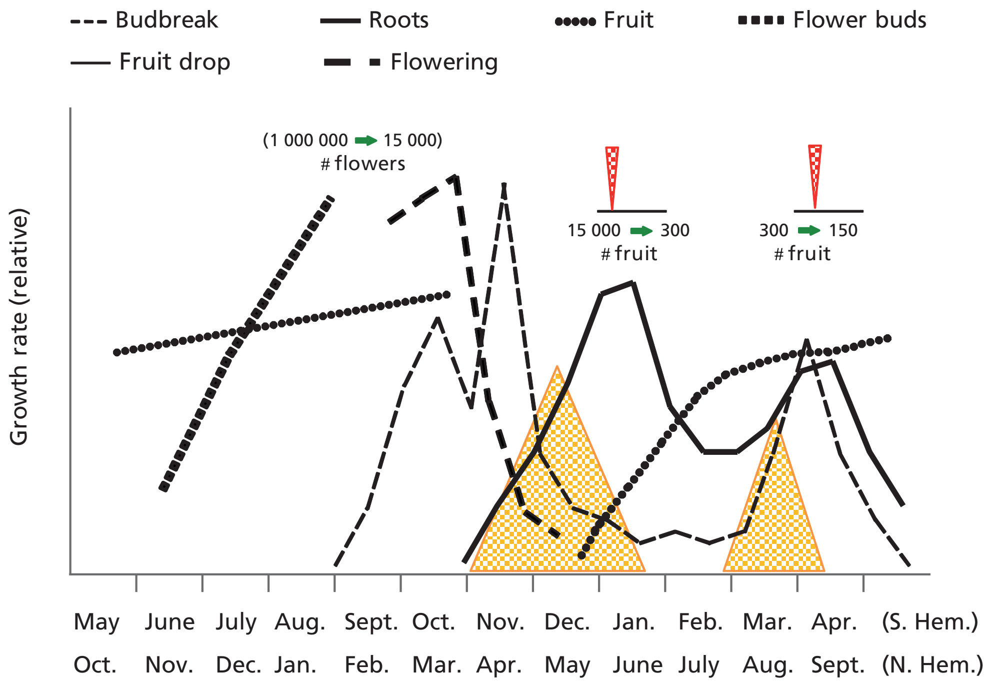


FIGURE 2 Developmental patterns of avocado (cv. Hass) as observed in the Central Valley of Chile.

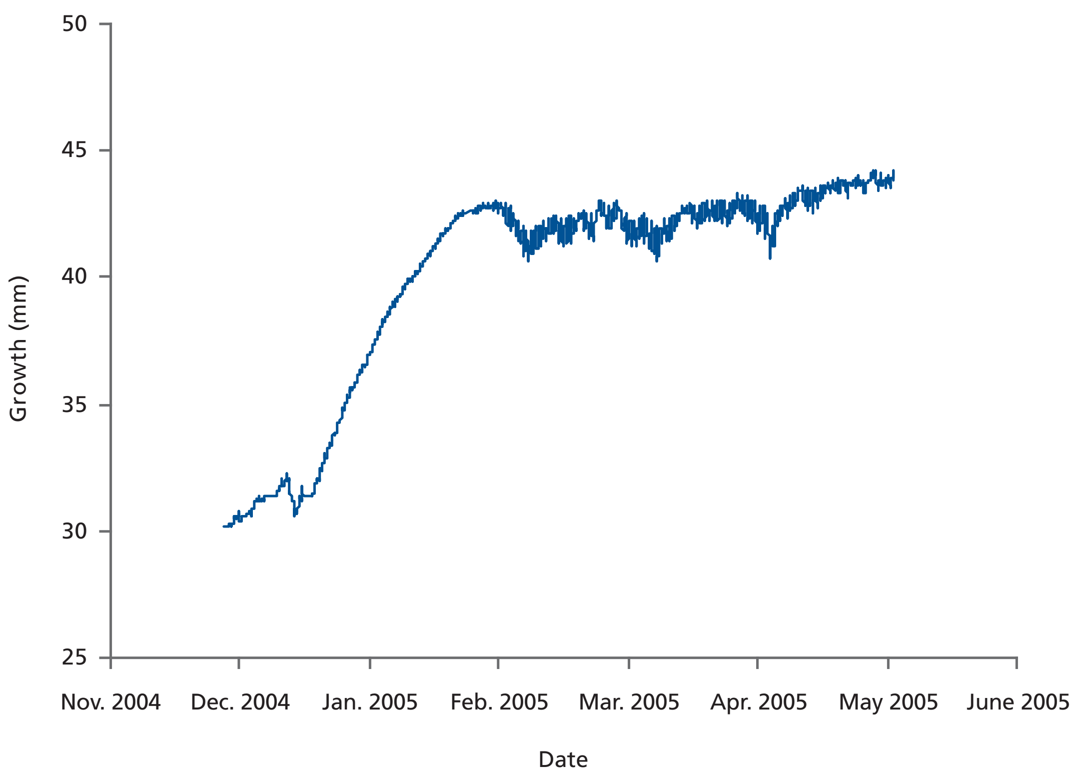


The most critical developmental period for avocado take place between late spring and early summer. At this time, there is vigorous shoot and root growth, the fruit are set and their final size is defined. Environmental stress could negatively affect fruit set, final fruit numbers and fruit size. It may induce some fruit internal defects as well. During that period, evaporative demand is relatively low and variable, and thus it is possible this inadequate irrigation practices cause water deficit or excess. Even though fruit expansion rates are quite high during a short time period, as shown in Figure 3, fruit growth and development takes a long time, from spring to fall. Fruit shape is also affected by temperature; it becomes more elongated with lower average temperatures.

RESPONSES TO WATER DEFICITS

Avocado trees are quite sensitive to water deficits; it has been determined that their inflorescences are more sensitive to water deficits than the surrounding leaves. The sensitivity of fruit set to water deficits is also quite high, and fruit drop may occur at any time between fruit set and about 50 percent of final size, if water stress is induced by lack of irrigation. Fruit size is affected by water deficits during its growth period that lasts about four months after fruit set. Water stress during fruit development in the later stages of fruit growth negatively affects the quality of mature fruit. When trees are frequently irrigated calcium concentration in the fruit increases and this seems to prevent several fruit physiological disorders.

FIGURE 3 Expansive growth of an avocado fruit of the cv. Hass, monitored continuously in central Chile.



Stem-water potential (SWP) values at midday of well-watered trees on a typical summer day oscillate between 0.5 MPa and -0.6 MPa. These values should be the reference threshold levels of SWP. Mild water deficits induce midday SWP values between -0.6 and -1.0 MPa. More severe water deficits are indicated by SWP levels below -1.0 MPa reaching down to -2.0 to -3.0 MPa. Stomatal conductance values are somewhat above those of citrus leaves but below the values observed in deciduous orchards. Average leaf conductance values around 0.3 cm/s have been measured for well-watered trees (Ferreyra *et al.*, 2007). Excess water in poorly drained soils does affect avocado tree water relations and, therefore, its overall performance. Low oxygen levels in the soil reduce leaf expansion rates as well as root growth and, if prolonged, may cause root necrosis and leaf abscission. Several studies measuring the oxygen diffusion rate have shown that avocado roots are extremely sensitive to anaerobic conditions. While most species vegetate well in soils, where just 10 percent of the pore volume is air filled, avocado roots seem to require a minimum of about 30 percent pore volume air filled for optimum performance (Ferreyra and Selles, 2007). In addition to the aeration problem, there is a pathogen, *Phytophthora cinamomi*, which thrives in waterlogged soils and can kill avocado trees upon infection (Stolzy *et al.*, 1967).

Avocado trees are also quite sensitive to salinity, the Mexican race being the most sensitive and the West Indian, the least. While sodium is excluded by the roots up to some level, chloride moves freely along with the transpirational stream and causes tip burn and leaf abscission.

WATER REQUIREMENTS

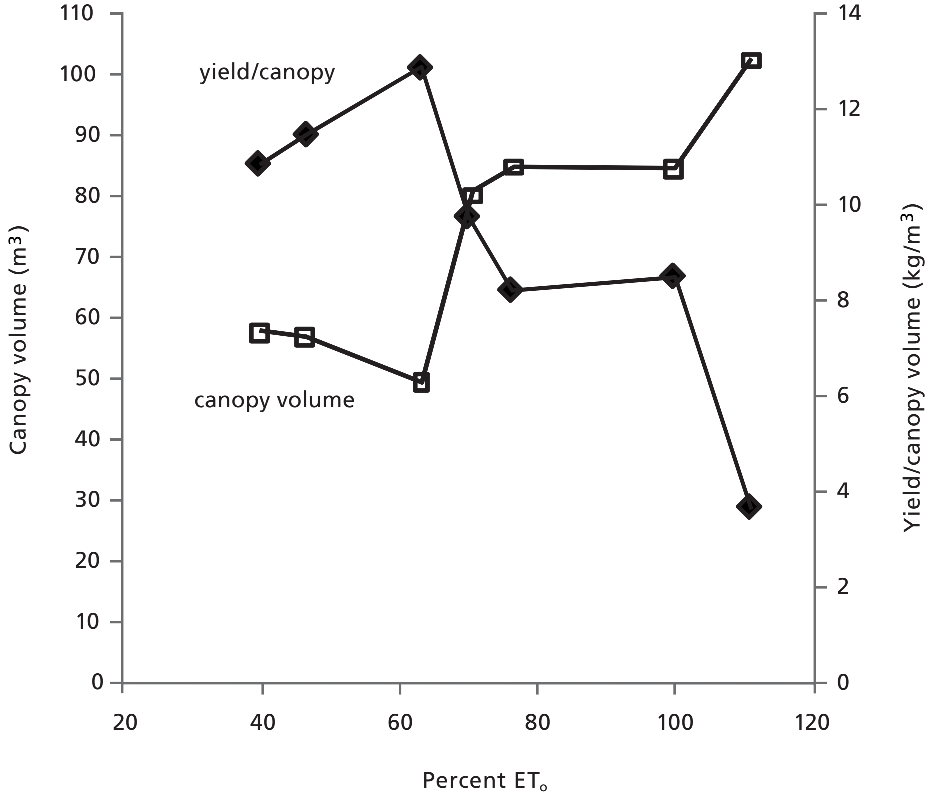
Avocado is an evergreen tree that follows the evaporative demand of the environment. Studies in Chile and in California indicate that an average crop coefficient (K_c) between 0.7 and 0.72 throughout the year adequately represents the ET_c of avocado. One additional study in California has suggested a somewhat lower K_c of 0.64. However, there are trade-offs between irrigation amounts, canopy size and production efficiency (Faber *et al.*, 1995) Figure 4 shows that the canopy size increases and yield per unit canopy volume drops as the fraction of ET_c increases from 60 to 115 percent of the requirements. Canopy size is therefore the determining factor of actual ET_c , but yields were maximized in the study when a K_c of 0.64 was used throughout the year (Faber *et al.*, 1995).

Part of the avocado water requirements are met by rainfall; in central Chile, annual gross irrigation needs vary between 800-900 mm, while in the drier areas of Southern California it may reach values of over 1 000 mm. To determine the actual irrigation needs in an area, there would be a need to carry out a water budget that takes into account the effective rainfall and the actual ET_c.

IRRIGATION SCHEDULING AND DEFICIT IRRIGATION

The extreme sensitivity to water deficits and water excess indicate that irrigation scheduling in avocado must focus on maintaining adequate aeration at the same time that tree water deficits are avoided (Lahav and Kalmar, 1983). In this situation, irrigation frequency is an important issue; in coarse-textured, well-drained soils, daily applications using drip or micro-sprinklers are appropriate. However, in heavier-textured soils that could suffer anaerobic

FIGURE 4 Effects of the level of applied water expressed as a fraction of reference ET (ET_o) on canopy volume and on the yield canopy volume ratio.



conditions, irrigating every 2-3 days is more desirable. Experiments in Chile have shown that allowing 50 to 60 percent soil water depletion between irrigation applications (every 5-6 days) did not affect yield and fruit size as compared to more frequent applications (Ferreyra, *et al.*, 2006). Irrigation frequencies that deplete about 25-30 percent of the tree-water reservoir are adequate for most soils as a compromise to maintain both adequate water and oxygen supply to the avocado root system. Under drip irrigation, it is important to be able to leach the excess salts out of the potential root zone, and to wet enough soil volume particularly in shallow, coarse-textured soils. Fruit oil content is an important quality feature that is negatively affected by inadequate irrigation.

All experimental evidence so far indicates that RDI is not a recommendable practice for irrigation of avocadoes, because of the high sensitivity of commercial yields to water deficits during most of the irrigation season. On the other hand, excess irrigation is highly detrimental, given the sensitivity to water logging and the high risks of fungal disease infection. Best irrigation practices for avocado should be based on supplying ET_c at optimal intervals that both prevent tree water deficits and supply adequate oxygen to the root system.

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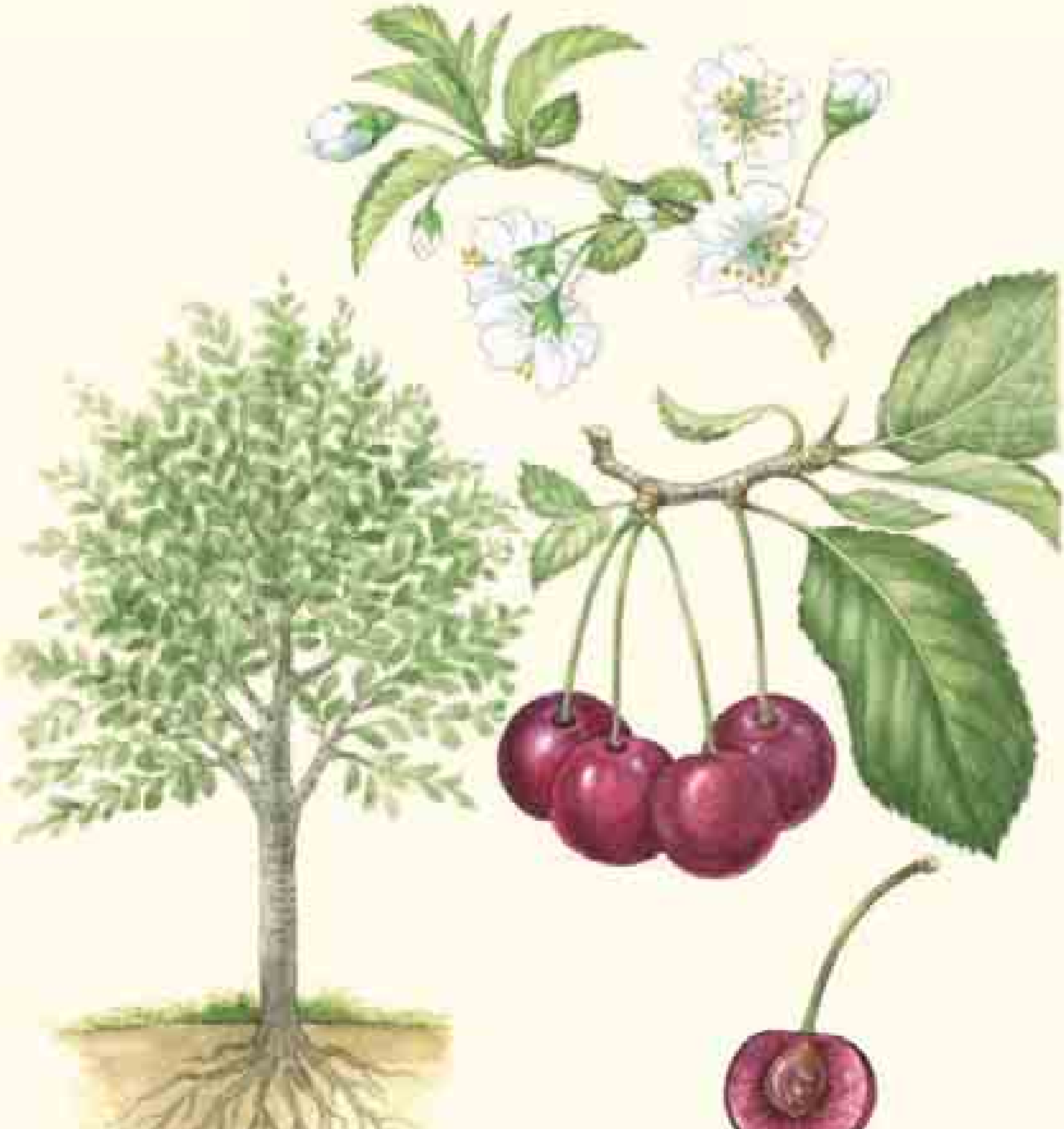

Sweet Cherry

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Sweet cherry

INTRODUCTION AND BACKGROUND

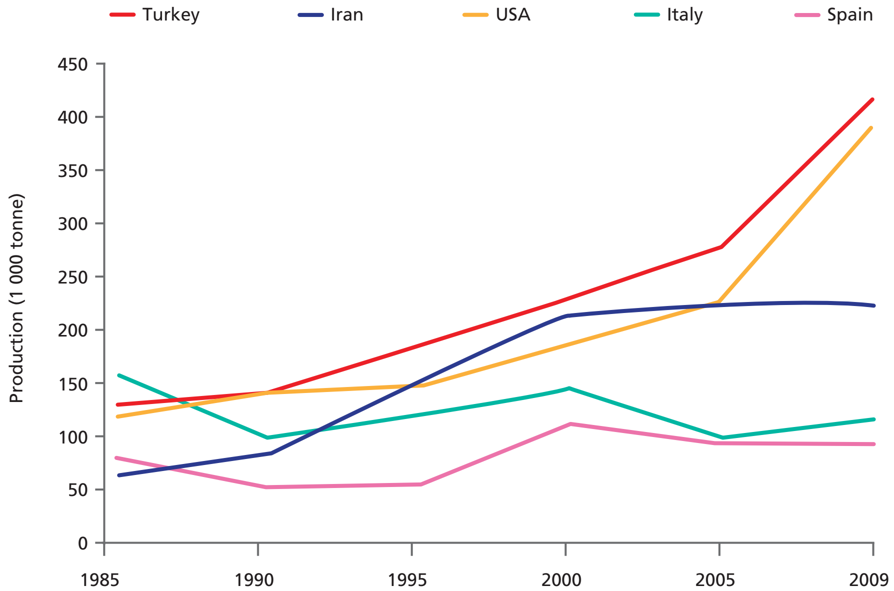
Sweet cherry *(Prunus avium* L.*)*, contribute modestly to the global economy of deciduous fruit tree species. However cherry production can be crucial at local level in regions specialized for cherry growing, while for other areas it can become a good alternative whenever the market for the main fruit trees, such as apple, peach, and pears slows down. In 2009, there were 381 000 ha with an average world yield of 5.8 tonne/ha (FAO, 2011). Figure 1 presents the production trends for the principal countries.

Foliage development of cherries follows a pattern similar to that described in the peach chapter. Cherry flowers develop in clusters from individual buds. Each bud bears two-to-five flowers. These buds can be borne laterally in individual buds or can be grouped in short spurs on two-year old twigs. Although cherry flowers are monopistil, in very hot summers many form two pistils that result in double fruit. It has been argued that water stress could have a role in helping the formation of undesired double fruit, as it occurs in peaches, but there is little evidence for this in sweet cherries (Beppu and Kataoka, 1999). In addition, air temperatures also affect fruit shape, becoming more irregular at high air temperatures. Canopies can be cooled by using overhead sprinkler irrigation. The majority of commercial sweet cherry cultivars are self-sterile and thus they require the use of pollinizers. Cherry trees are very vigorous and annual shoot extension rates can surpass 1 m when they are young. Cherry trees have an upright growth habit and may need the use of adequate rootstocks to help controlling vigour and induce early appearance of reproductive buds. Vigour control is commonly managed with growth regulators.

STAGES OF DEVELOPMENT

Cherry flower buds, initiate just before the end of the shoot enlargement phase, and will continue to form and develop throughout postharvest (Flore, 1994). Next spring cherry flowers will open before leaf appearance. The reproductive growth can be divided into approximately three growth stages; similar to the case of early maturing peach fruit. Stage I comprises the first month after full bloom and it is characterized by a rapid increase of fruit volume which is mainly produced by cell division (Figure 2). The extent of the activity in cell division will have a major contribution to fruit final size. Stage II corresponds to the pit hardening phase and it can coincide with a slowing of the fruit growth rate (Figure 2). Finally, Stage III takes place around 20 days

FIGURE 1 Production trends for sweet cherries in the principal countries (FAO, 2011).

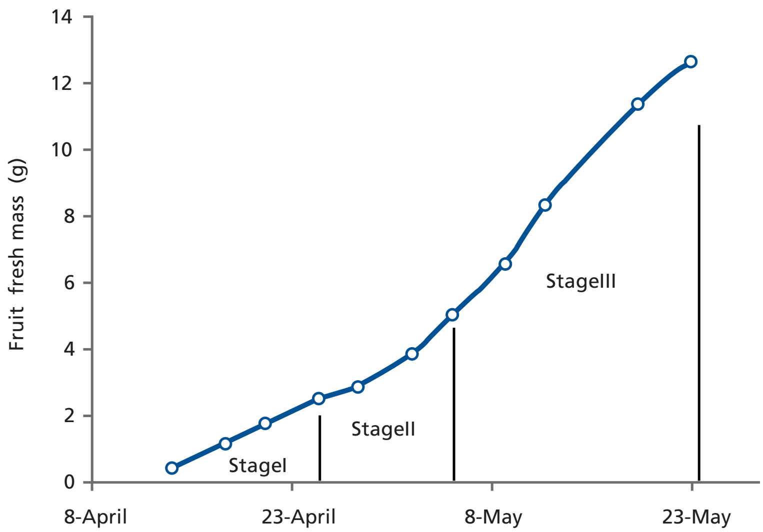


before maturation and leads to a rapid increase in fruit size (Figure 2). This is a phase of rapid expansive growth. All three stages may take place in less than three months depending on the cultivar used and the temperature regime (growing degree days) of the site.

RESPONSES TO WATER DEFICITS

The timing of water stress is important for cherry. Stages I and III are short and very sensitive to water stress. Stage II can be even shorter and usually overlaps with Stages I and III; for this reason

FIGURE 2 Daily patterns of mean individual Summit cherry fresh mass grown in fully irrigated trees. Fruit growth stages are signalled in-between vertical lines.



water stress should not be imposed on any of the fruit growth stages. However, irrigation can be reduced under certain conditions i.e. deep soils and low evaporimetric demand, without inducing plant water stress. The postharvest phase is the period for accumulation of reserves. Fruit set in the following spring will be affected by the level of carbohydrate reserves, which have been accumulated during the previous growing season, and more so if flower buds developed earlier than vegetative buds as for cherries. Sweet cherry trees do not grow well without irrigation in areas having dry and warm seasons (Proebsting *et al.*, 1981). Providing accurate information on how to irrigate cherry trees requires a good assessment of plant water status. The standard method of assessing plant water status in cherry orchards is to measure midday stem-water potential (SWP). Air vapour pressure deficit (VPD) has a definite impact on the measures of SWP in cherry trees and VPD reference lines need to be developed to account for this effect. In cherry, Ψstem values below -1.0 MPa during midseason are likely to be indicative of water stress conditions (Marsal, 2009 and Marsal, 2010). Therefore, the level of water stress in a tree having a SWP lower than -1.0 MPa would depend on the prevailing VPD conditions. For instance, early season (from late April until the end of May, Northern Hemisphere), with typically low VPD (< 1.5 kPa) and a canopy still under development, a non-water stressed cherry tree would have a Ψstem less than -0.7 MPa (Marsal, 2009 and Marsal, 2010). The level of SWP is related to tree transpiration because, as water stress increases leaf conductance to water vapour decreases. The response of leaf conductance to SWP for cherry trees follows a standard exponential function (Figure 3); however the response of tree transpiration to midday SWP has not yet been described. Incipient leaf wilting in cherry trees can be observed in the field at a SWP of -1.8 MPa. At this value, stomata are mostly closed and vegetative growth hastened (Figure 3 – midseason conditions). However, leaf wilting can be more clearly observed at SWP values below -2.2 MPa.

FIGURE 3 Relationship between midday stem-water potential and midday leaf conductance in two different times of its seasonal development (at harvest and at postharvest early September) in 'Summit' sweet cherry, obtained in different irrigation treatments.

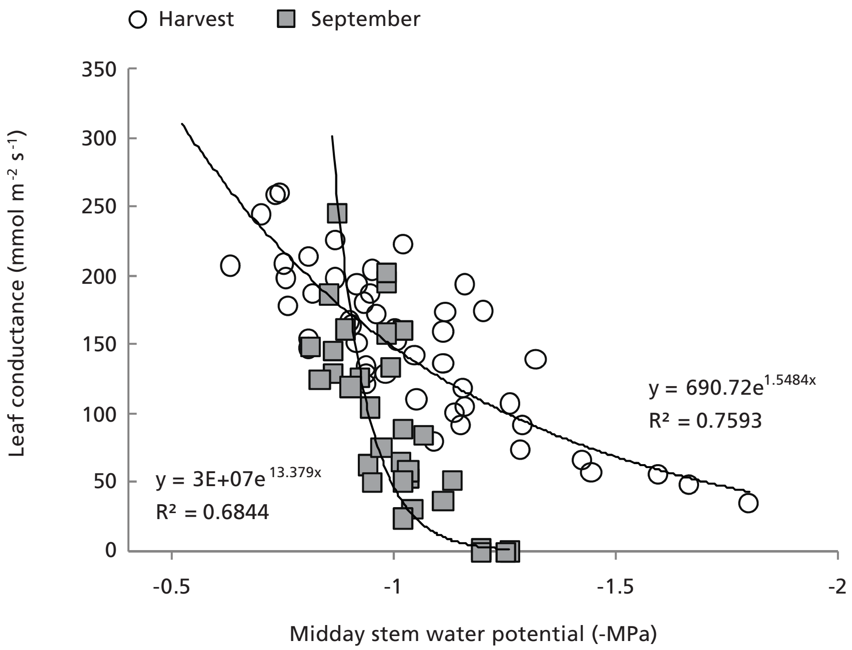


FIGURE 4 Daily patterns of sunlit leaf net assimilation rate measured after harvest with IRGA in Summit sweet cherry trees. Trees were fully irrigated throughout the season.

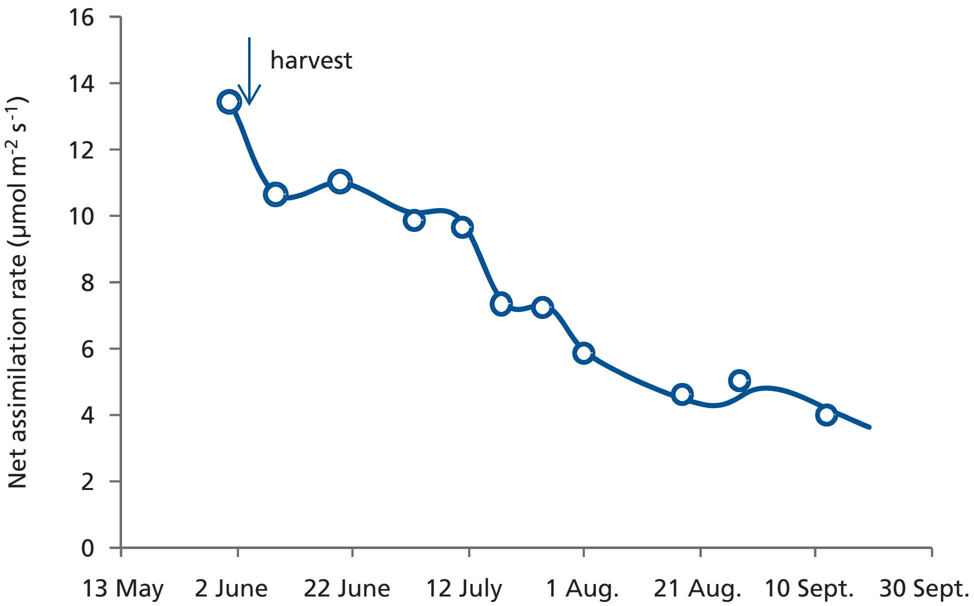
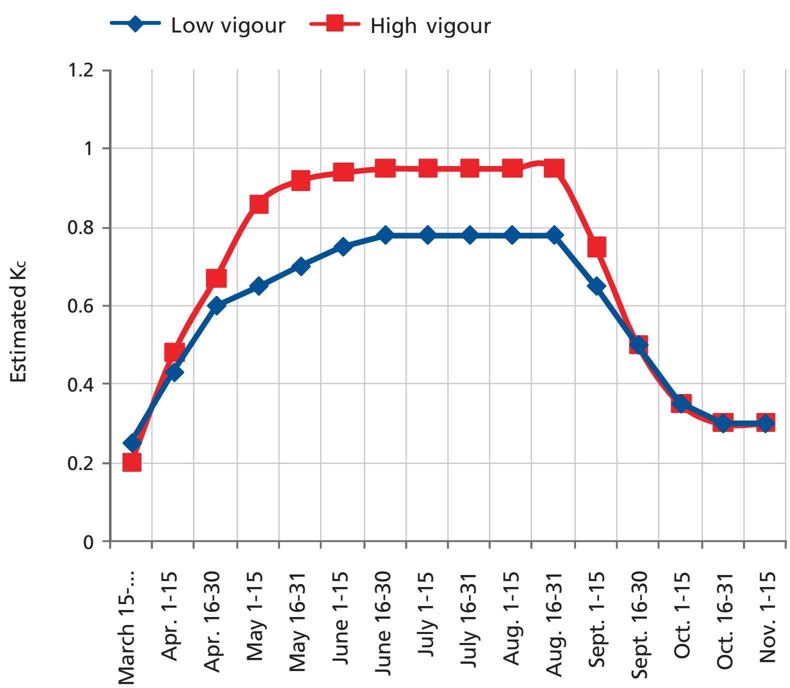


FIGURE 5 Estimated crop coefficients for mature sweet cherry trees grown in a vase training system under two different growing conditions (high vigour in squares and low vigour in rhomboids). The midday intercepted radiation for the high vigour and low vigour orchards during midseason was 0.54 and 0.45, respectively.



Under certain growing conditions, stomata remain slightly closed at the end of the postharvest season, even when the trees are not water stressed (Figure 3 – September conditions). This has been found in cherry orchards growing under warm Mediterranean conditions. Since the cherry market in these regions sets pressure for the use of early ripening cultivars, the postharvest period may last more than four months. During this period, little growth is being accomplished because tree growth is checked by the application of growth regulators. After harvest, leaf net photosynthetic rates tend to decrease with time (Figure 4). Reductions in photosynthesis usually come with reductions in stomata aperture and consequently, the transpiration also declines with time. This is referred in the physiology literature as photosynthetic down-regulation.

WATER USE

Although some preliminary work on modelling cherry tree transpiration has been done recently (Antunez, 2006), specific reports on measurements of cherry ET_c or K_c values are lacking in the literature. Cherry irrigation requirements could be approximated by using the information developed for peach trees (see Peach Section) where the K_c is related to tree intercepted radiation at midday. An example of the seasonal evolution of K_c is provided in Figure 5 where cherry tree intercepted radiation was measured every two weeks until mid-August. A steady decrease in K_c is assumed after mid-August. This K_c decline is due to a leaf die-back process, but also to the previously referred effect of the down-regulation of photosynthesis, which may already apparent by late July (Figure 5). Two different tree vigour conditions are considered in Figure 5, and the effects on crop intercepted radiation and estimated K_c is evident. Low vigour conditions had noticeable lower K_c, resulting in a 18 percent reduction in annual water requirements for the conditions in the Ebro basin, Spain (Marsal, 2010). This emphasizes the need to adjust the K_c values to the specific orchard conditions.

SUGGESTED RDI REGIMES

The application of RDI is currently widespread in some regions along with the use of growth regulators. However RDI before harvest is rarely used because besides reducing fruit growth and fruit final size (Werenfels, 1967), it can also increase cracking if stress is relieved during ripening (Sekse, 1995). RDI is more commonly applied after harvest. The reason for the grower acceptance of using postharvest RDI is because it decreases tree internal shading and controls excessive vigour. However, deficit irrigation is often applied after harvest in the absence of research-based recommendations. For instance, in certain areas irrigation is commonly reduced until visual leaf wilting without being aware of possible carryover effects during the following season. From the few research reports published it can be inferred that, under certain conditions, postharvest water deficits can negatively affect cherry quality the following season, with excessive water stress exacerbating this problem. A study on postharvest RDI in New Star sweet cherry grown in the semi-arid climate of Catalonia, Spain found a significant linear relationship between reduction in cherry firmness and soluble solids with the average midday stem-water potential experienced the previous postharvest season (Marsal, 2009). Another issue related to the use of postharvest RDI is the possibility of applying excessive water stress and negatively influencing fruit set and crop load in the next season, as it has been reported for peach and almond. In a recent study on Summit cherry, a postharvest RDI treatment, receiving 50 percent of the water given to a Control treatment, reduced fruit set and crop load in the following season (Marsal, 2010). However, the realization of possible yield reductions in the next season after a RDI postharvest treatment will depend on whether cherry thinning is being used to maintain fruit size (Marsal, 2010). Nevertheless, if water stress during postharvest is maintained above -1.5 MPa in midday stem-water potential, large savings of up to 40 percent of the water used in a fully irrigated control during postharvest can be achieved without noticeable negative impact on fruit yield and quality. The avoidance of water stress, more severe than a certain level (i.e. -1.5 MPa), implies that irrigation reduction must be adjusted with time and a fixed irrigation rate should only be maintained for a certain period to avoid surpassing such tree water status threshold. For this reason significant irrigation reductions during postharvest have to be applied cautiously. Irrigation could also be reduced during postharvest at lower rates (i.e. 80 percent full irrigation). The use of 80 percent full irrigation during postharvest produced water savings up to 15 percent of annual applied water with no detrimental effects on fruit yield and quality (Table 1) (Marsal, 2009 and Marsal, 2010) although the research indicated that cherry quality and yield responses to RDI are cultivar dependent. Therefore more research is needed before reliable assessments can be made for each specific growing condition.

TABLE 1 Suggested Postharvest RDI strategies for different available water supply scenarios from 690 to 430 mm. Weather data corresponds to the Ebro valley (Northeast Spain) and K_c corresponds to those presented in Figure 2 for high vigour growing conditions.

	Potential ET_c	Water req.	RDI-Postharvest (580 mm)		RDI-Postharvest (430 mm)	
	(mm)	(mm)	Irrigation rate (%)	(mm)	Irrigation rate (%)	(mm)
March 15-30	9	10	100	10	100	10
Apr. 1-15	24	26	100	26	100	26
Apr. 16-30	34	31	100	31	100	31
May 1-15	50	42	100	42	100	42
May 16-31	49	40	100	40	100	40
June 1-15	66	72	80	58	50	36
June 16-30	80	88	80	70	50	44
July 1-15	76	78	80	62	50	39
July 16-31	81	89	80	71	50	44
Aug. 1-15	70	77	80	62	50	39
Aug. 16-31	68	75	80	60	65	49
Sept. 1-15	38	42	80	34	50	21
Sept. 16-30	23	25	80	20	50	12
Oct. 1-15	11	0	80	0	50	0
Oct. 16-31	7	0	80	0	50	0
Nov. 1-15	5	0	80	0	50	0
Total	**690**	**696**		**587**		**434**

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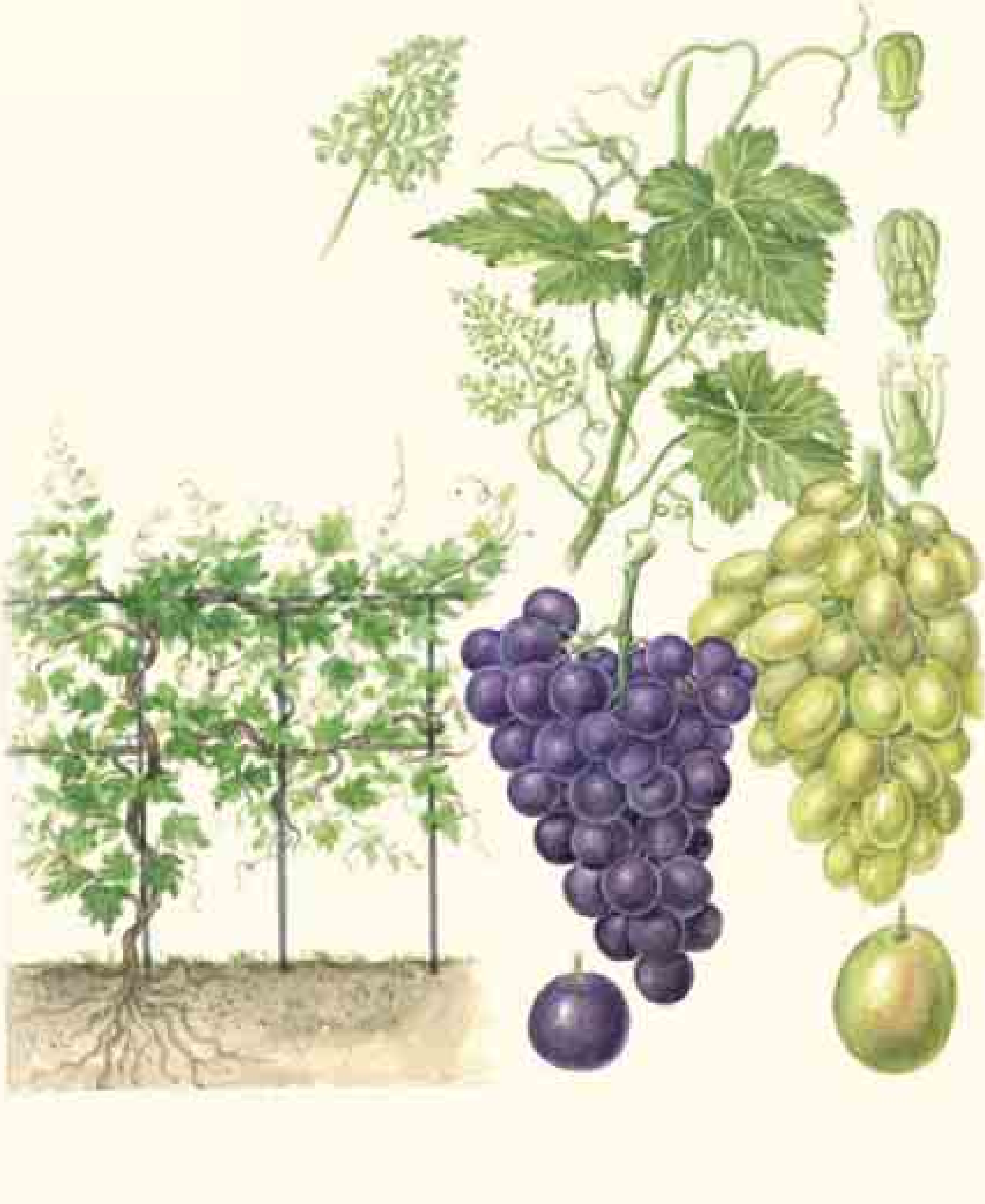

Grapevine

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Grapevine

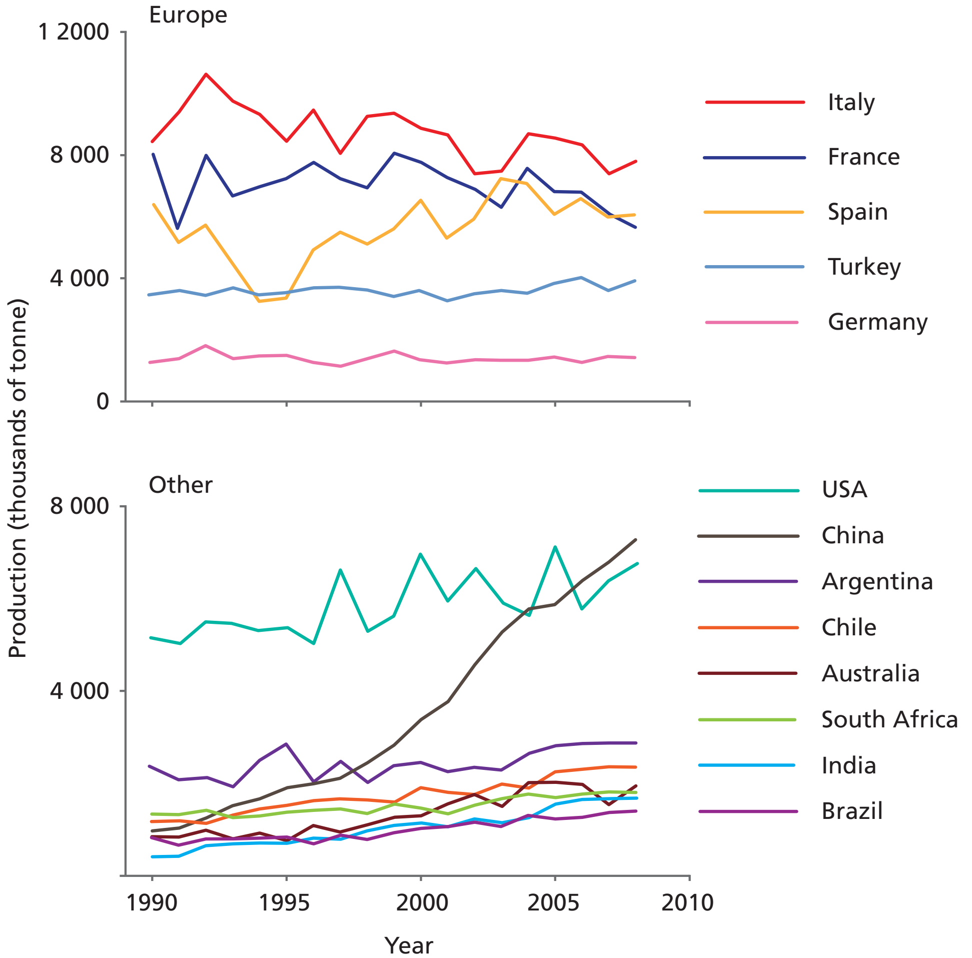
INTRODUCTION AND BACKGROUND

Grapevine is a long-lived deciduous crop traditionally grown in a latitudinal range between 30º and 50º. The geographical range of wine grapes includes the traditional European countries Italy, France and Spain that account for most of world production, and other countries where the industry has achieved different degrees of maturity (Figure 1). The crop is expanding into new areas in countries with an incipient industry; in 2000, Denmark was accepted as a commercial wine producing nation within the European Union and the Association of Danish Winegrowers had 1 400 members in 2009 (Bentzen and Smith, 2009). Tonietto and Carbonneau (2004) characterized worldwide macroclimates for viticulture using three indices: soil water balance over the growing cycle, solar radiation and temperature conditions, and night temperature during maturation relative to variety requirements, vintage and wine quality.

Profitability of the wine industry is related to both production volume and value per unit volume. The relative contribution of these two factors ranges from enterprises specializing in a high-volume approach to those targeting low-volume, high-value product. Trade-offs between high yield and berry traits related to wine quality are not universal but are common and may constrain the dual maximization of volume and value per unit volume of production. The trade-off between yield and quality underlies regulations in some European countries where no irrigation is allowed for quality wine production. Accepting that wines attracting higher prices are often from vines producing low to moderate yields, the critical question from an irrigation viewpoint is how to manage irrigation to capture the benefit of high yield while achieving a level of quality that maximizes economic returns.

Thus, whereas the core of the grapevine crop remains in the temperate latitudinal band, there is an increasing diversity of environments that, together with diverse production objectives and potential trade-offs dictate contrasting water-management practices in the vineyard. Additionally, the grape and wine industries operate in a global context of competing agricultural and non-agricultural uses of scarce resources – chiefly land, water, and energy – increasing environmental concerns, and shifts in climates and markets.

FIGURE 1 Grape production between 1990 and 2008 (FAO, 2011).



STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

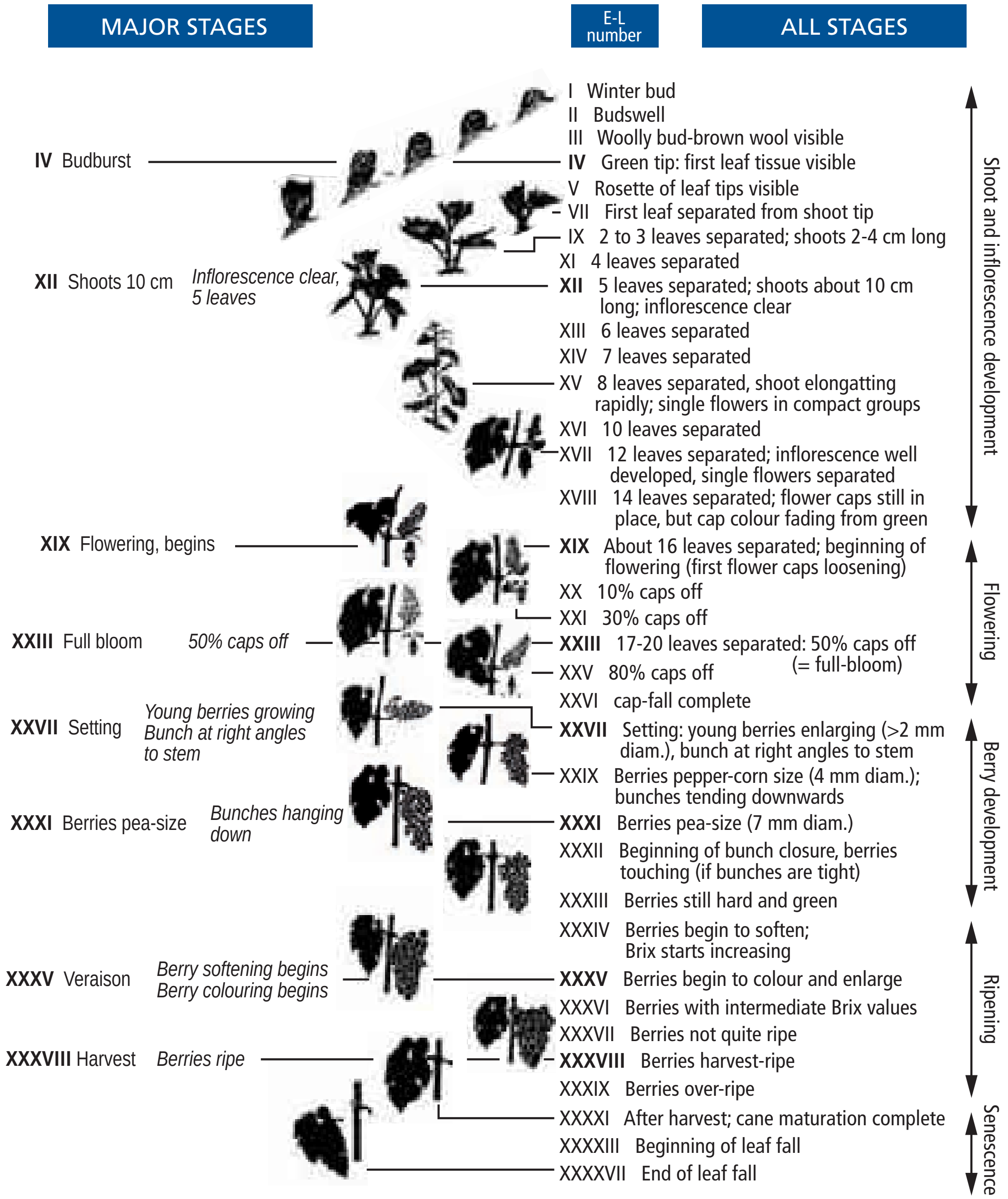
Overview

The annual cycle of grapevine in temperate and cool environments includes a dormancy phase and a phase of active vegetative and reproductive development and growth. In tropical environments, vine physiological activity is continuous during the year. Figure 2 shows a scale accounting for phenological stages in temperate environments and Table 1 illustrates the range of key vegetative and reproductive components of grapevines in vineyards with contrasting yield targets.

After an overwintering period, when vegetative and reproductive buds remain dormant, visible leaf tissue marks the beginning of budburst (Stage IV in Figure 2). Early shoot growth depends on plant reserves and is initially slow; it then accelerates in late spring. Parallel to root and vegetative shoot growth, two important reproductive processes take place: (a) inflorescence primordia initiated in the previous season resume growth, branching, branch elongation and flower formation, and (b) a new set of reproductive buds is induced and starts differentiation that will be completed in the following season (Dunn, 2005). Bunch number is generally the largest source of seasonal and site-related variation in grapevine yield (Tables 1 and 3).

Current season inflorescences become visible several weeks after budburst. Flower cap fall and stamen release marks the full bloom stage (Stage 23 in Figure 2). Berries per bunch, the second yield component, depend on number of flowers and berry set, which may be particularly affected in some particular combinations of sites, seasons and cultivars, e.g. Chardonnay in cool conditions. As in most flowering plants, however, only a fraction of flowers set fruit, typically for grapevine this is 20-50 percent.

FIGURE 2 Major stages in the modified Eichhorn and Lorenz (E-L) phenological scale (from Coombe 1995).



Modified from Eich horn and Lorenz 1977 by B.G. Coombe

TABLE 1 Key vegetative and reproductive components in low and high-yielding vineyards (*Pearce and Coombe,* 2005).

Component	Low	High
Yield (kg m^{-2})	0.20	5.0
Equivalent volume of table wine (litre m^{-2})	0.12	3.0
Pruning weight (kg m^{-2})	0.03	1.0
Leaf area index (m^2 m^{-2})	0.50	5.0
Number of nodes (m^{-2})	3	30
Number of shoots (m^{-2})	2.5	25
Number of bunches (m^{-2})	5	50

Berry growth has a characteristic double-sigmoidal pattern; it is dominated by cell division in the first two weeks after flowering and by cell expansion afterwards. The first sigmoidal trajectory reaches a plateau in synchrony with full seed size in seeded varieties. After an intervening lag-phase, the onset of the second sigmoidal phase is characterized by berry softening, accumulation of sugars, decline in acid concentration and accumulation of pigments in the skin of coloured varieties. This stage is called veraison (Stage 35 in Figure 2) and is very responsive to environmental factors. For example in physically constrained berries, the threshold cell turgor pressure ≈ 0.1 MPa associated with veraison under the experimental conditions of Matthews *et al.* (2009) was delayed by two weeks in relation to controls, and a similar delay was recorded for the onset of sugar accumulation. The second sigmoidal stage ends in a plateau corresponding to variety- and environment-specific maximum berry size. Varieties like Shiraz, which often exhibit substantial berry dehydration late in the season are characterized by a decline in fresh weight rather than a plateau at the end of the second phase (Sadras and McCarthy, 2007). This decline is also observed when harvest is delayed to enhance berry traits associated with wine quality at the expense of fruit weight and yield. Harvest maturity (Stage 38 in Figure 2) is defined by winemaking criteria for fruit composition; it is often specified in terms of sugar concentration or sugar: acid ratio in cooler climates, but colour and flavour criteria complement these simple definitions. Environmental variables including temperature, radiation and water availability during berry growth and ripening can have substantial impact on berry composition and hence on wine attributes. This viticulturally important aspect of berry biology is beyond the scope of this section, but readers are referred to reviews by Coombe and Iland (2005), Conde *et al*. (2007), and Dai *et al.* (2010). We focus on the effects of water deficits on berry and wine attributes in a further on in this section.

Varietal differences in development

The developmental plan outlined in the previous section applies to all grape varieties. However, the actual timing of each critical stage and the resultant season length are genetically controlled and modulated by the environment, chiefly temperature. Some phenological stages may also be responsive to management practices, e.g. timing of pruning may shift the timing of budburst, and manipulation of canopy-to-fruit ratio by defoliation or bunch removal may delay or advance ripening in some conditions.

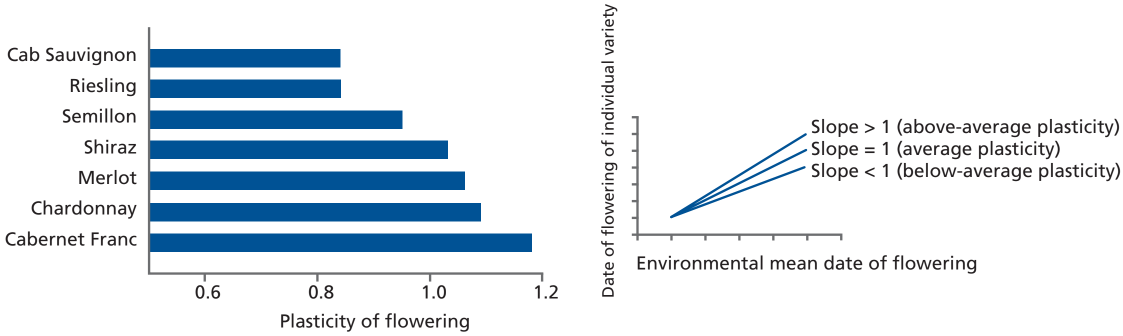
There are two distinct aspects related to the variety-dependent phenological pattern. One is the average time to reach a certain stage; for example Gladstones (1992) classified varieties in eight maturity groups (Table 2). The other aspect is the plasticity of phenological development, defined as the degree of response in phenology to environmental conditions. Cabernet franc and Riesling, for example, have comparable maturity requirements ~ 1 200-1 250 °Cd (Table 2), but under South Australian conditions Cabernet franc is phenologically more plastic than Riesling (Figure 3), as its flowering date varies more in different environments than that of

TABLE 2 Maturity groups and biologically effective thermal time* from October 1st (Southern hemisphere) or April 1st (Northern Hemisphere) to ripeness of grapevines according to Gladstones (1992).

Maturity group (°Cd to maturity)	Red wine	White or rosé wine
1 (1 050)		Madeleine, Madeleine-Sylvaner
2 (1 100)	Blue Portuguese	Chasselas, Müller-Thurgau, Siegerrebe, Bacchus, Pinot Gris, Muscat Ottonel, Red Veltliner, Pinot Noir, Meunier
3 (1 150)	Pinot Noir, Meunier, Gamay, Dolcetto, Bastardo, Tinta Carvalla, Tinta Amarella	Traminer, Sylvaner, Scheurebe, Elbling, Morio-Muskat, Kerner, Green Veltliner, Cardonnay, Aligoté, Melon, Sauvignon Blanc, Frontignac, Pedro Ximenes, Verdelho, Sultana
4 (1 200)	Malbec, Durif, Zinfandel, Schiava, Tempranillo, Tinta Madeira, Pinotage	Sémillon, Muscadelle, Riesling, Welschriesling, Furmint, Leanyka, Harslevelu, Sercial, Malvasia Bianca, Cabernet Franc
5 (1 250)	Merlot, Cabernet Franc, Shiraz, Cinsaut, Barbera, Sangiovese, Touriga,	Chenin Blanc, Folle Blanche, Crouchen, Roussanne, Marsanne, Viognier, Taminga, Cabernet Sauvignon
6 (1 300)	Cabernet Sauvignon, Ruby Cabernet, Mondeuse, Tannat, Kadarka, Corvina, Nebbiolo, Ramisco, Alvarelhão, Mourisco Tinto, Valdiguié	Colombard, Palomino, Dona Branca, Rabigato, Grenache
7 (1 350)	Aramon, Petit Verdot, Mataro, Carignan, Grenache, Freisa, Negrara, Grignolino, Souzão, Graciano, Monastrell	Muscat Gordo Blanco, Trebbiano, Montils
8 (1 400)	Tarrango, Terret Noir	Clairette, Grenache Blanc, Doradillo, Biancone

** calculated using a base temperature of 10 °C, and a cutoff in the monthly average temperature at 19 °C.*

FIGURE 3 Plasticity of flowering of grapevine varieties in southeastern Australia. Plasticity is calculated as the slopes of the lines relating date of flowering of each variety and the environmental mean date of flowering (inset). Adapted from Sadras *et al.* (2009).



Riesling. The actual timing of occurrence of critical phenological stages, total season length and phenological plasticity are critical traits in the quest to match varieties and environments including the fine-tuning of irrigation management.

Grapevine development and warming trends

Phenology is temperature driven; therefore warming trends recorded since the middle of the twentieth century are reflected in grapevine phenological shifts of great significance for vine management and winemaking (Duchene *et al.*, 2010). Several studies have assessed the rates of change associated with phenological variables in both the northern and Southern Hemisphere (Wolfe *et al.*, 2005 and Duchene and Schneider, 2005). Not surprisingly, vines develop faster in warmer conditions but the actual rates need consideration. Two important aspects of these responses are the differential sensitivity of particular phenological phases, and the potential decoupling of berry attributes. For example faster sugar accumulation that is not fully compensated by early harvest means higher sugar content in berries and higher alcohol potential, as suggested for Riesling in Alsace and for Cabernet Sauvignon and Shiraz in Australia (Petrie and Sadras, 2008 and Duchene and Schneider, 2005).

RESPONSE TO WATER DEFICITS

Overview: rainfall patterns and development of water deficit

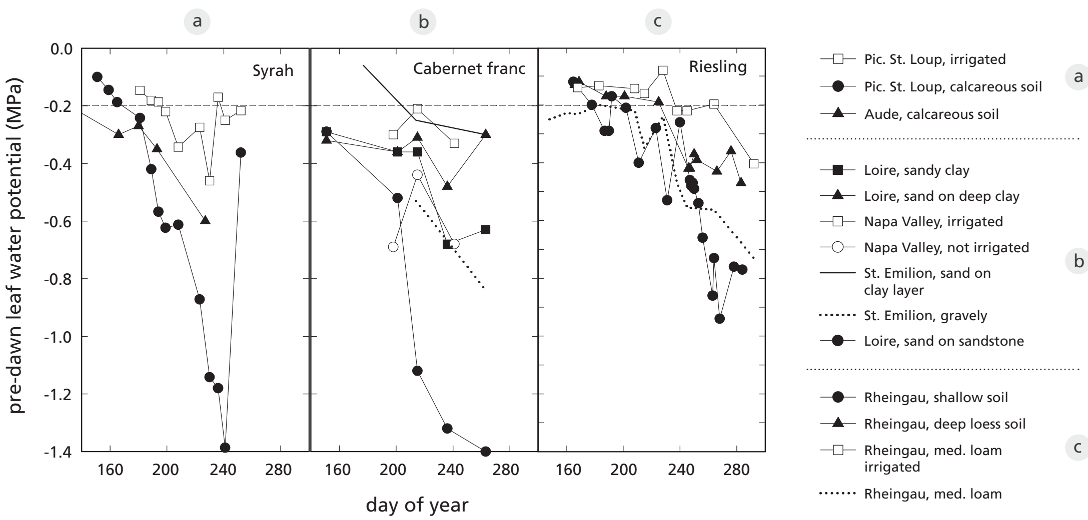
Rainfall pattern and soil-water storage capacity are major drivers of the temporal pattern of water supply and water deficit in rainfed systems, as illustrated by comparison of winter- and summer-rainfall viticultural regions. Aschmann (1973) highlighted the concentration of rainfall in the winter half-year as the most distinctive element of the Mediterranean climate, and proposed 65 percent of annual rainfall in this period as a boundary in his definition. Grapevines are grown in Mediterranean-type climates in southern Europe, California, and parts of South Africa, Chile and Australia. Winter rainfall often ensures soil water storage that allows for early growth, whereas a pattern of terminal drought is typical of rainfed vines in Mediterranean environments. Temporary water deficits are common in temperate, summer rainfall regions of western and central Europe where vineyards are established in shallow soils or soils with low water-holding capacity. In these environments, rainfall pulses and limited buffering capacity of soils drive marked wet-dry cycles. The frequency, duration and severity of the dry spells in these cycles are largely unpredictable. Owing to drying trends and reliability of quality wine supply required by globalized markets, supplemental irrigation is likely to increase even in these areas that have been traditionally rainfed.

Figure 4 compares the plant water status of rainfed vines from contrasting climates and soils within a given region; examples from irrigated vines are also included. It is clear that irrigation stabilizes predawn leaf water potential at a level rarely found naturally over the growing season in these areas, including the very cool climate regions of the Loire Valley in France and the Rheingau in Germany. Figure 4 also shows that the differences in water status between vineyards within each of the regions could be larger than the differences in general water status between different climate zones. It is also clear that variation in water status during a particular season increases from warm and dry climates to summer rainfall because of the irregularity of the frequency and intensity of summer precipitation in the latter.

Growth and yield

Crop responses to water deficit depend on the intensity, duration and timing of stress. Intra-specific variation has been reported for major traits related to the development, water and carbon economy of grapevine including phenology, susceptibility to embolism, stomatal density and stomatal conductance in response to both soil water content and vapour pressure deficit, biomass per unit transpiration, dry mater partitioning, and rootstock response to water deficit, salinity and soil-borne diseases.

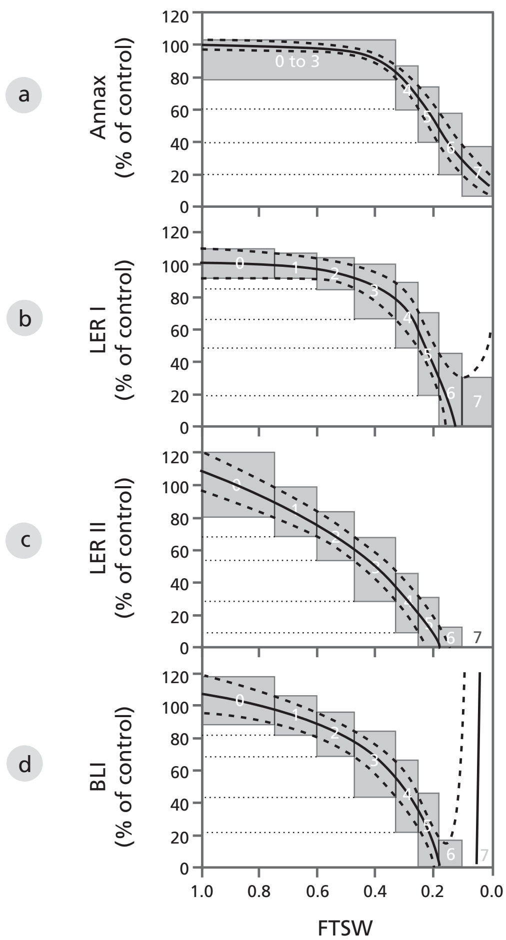
FIGURE 4 Seasonal courses of predawn leaf water potential from different vineyard sites in contrasting environments. Left panel is Syrah from two warm, dry areas in southern France: Pic St. Loup area north of Montpellier (Schultz, 2003) and Aude region (Winkel and Rambal, 1993). Central panel is Cabernet franc from vineyards with three contrasting soils in the cool, summery rainfall Loire Valley of France (Morlat *et al.*,1992), the warm, summer rainfall St. Emilion region of France (van Leeuwen and Seguin, 1994), and the warm, dry Napa Valley of California for an irrigated treatment and a water deficit treatment after veraison (Schultz and Matthews unpublished). Right panel is White Riesling from the cool, summer rainfall Rheingau region in Germany collected in 1999 (open symbol and dotted line) and 2002 (closed symbols); adapted from Gruber and Schultz (Gruber and Schultz, 2005). All treatments were rainfed, unless otherwise indicated.



In common with most crops, tissue expansion in grapevine is more sensitive to water deficit than stomatal regulation and gas exchange (Figure 5a-d). The effects of intensity and duration of water stress have been integrated in stress indices based, for example, on soil water status (Figure 5a-d), plant-water status or canopy temperature (Figure 6). Box 2 summarizes techniques used to monitor water status of vines, and below analyses yield response to water deficit from the perspective of production functions.

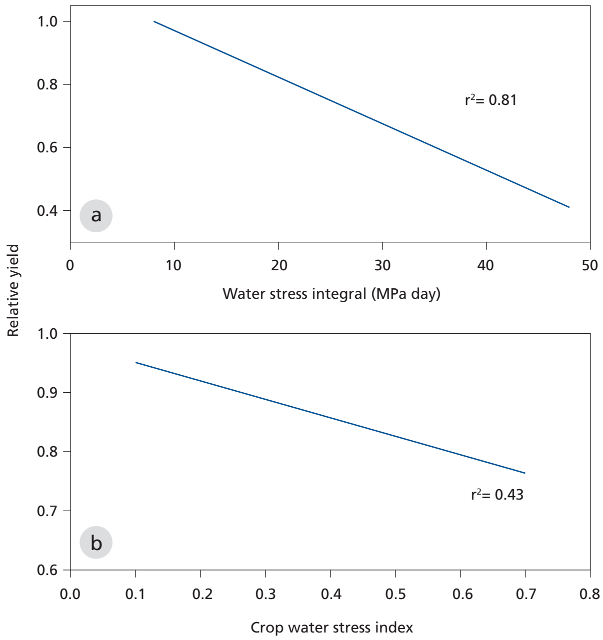
Owing to the developmental programme of the plant and the definition of yield over two consecutive seasons, we need to consider the effects of water deficits in the previous season on the growth and yield in the current season. All possible responses have been reported, namely effects

FIGURE 5 Scheme for water management derived for Shiraz, Grenache and Mourvèdre in southern France. Relationships between fraction of transpirable soil water (FTSW) and the rate of (a) light-saturated net photosynthesis; leaf emergence rate in (b) first-, or (c) second-order lateral branches, and (d) final length of first-order lateral branches. Rates measured in water-deficit treatments are normalized with respect to well-watered controls. The boxes (0 to 7) represent eight classes with characteristic impairment of plant function by drying soil; for instance in (a) light saturated photosynthesis is above 80 percent of controls in classes 0 to 3, and is reduced to 60, 40, 20 and 7 percent of controls as soil dries from classes 4 to 7. The table shows recommended level of water stress (FTSW class) for quality red wine production at different phenological stages. Adapted from Pellegrino *et al.* (2006).



Phenophase (E-L stage)	FTSW class for quality red wine production
Budburst to flowering (4 to 23)	0 to 1
Flowering to bunch closure (23 to 32)	2
Bunch closure to veraison (32 to 35)	3
Veraison to harvest (35 to 38)	5 to 6

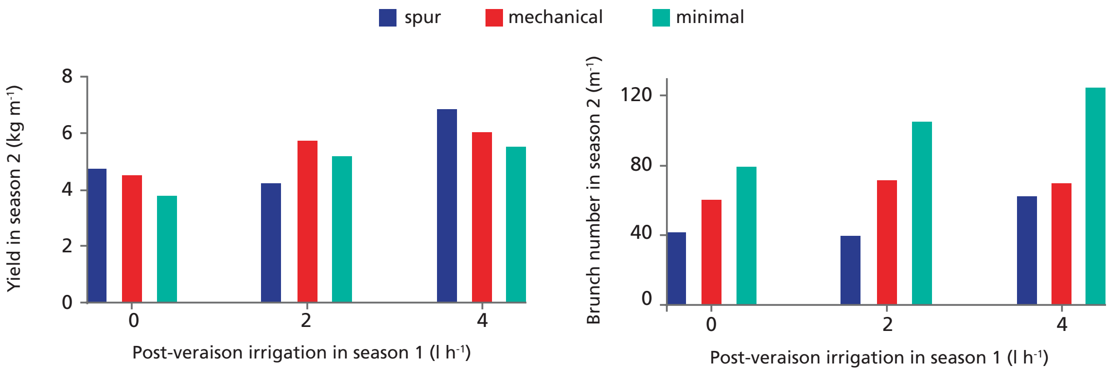
FIGURE 6 Yield reduction with increasing water deficit quantified using (a) the integral of stem-water potential and (b) the difference between canopy and air temperature corrected by vapour pressure deficit. Sources: (a) Salón *et al.* (2005), (b) Grimes and Williams (1990).



of water deficit in season 1 had negative, neutral or positive effect on reproductive outcome in season 2 (Williams and Matthews, 1990). This diversity of responses is partially the result of differences in varietal sensitivity, timing, intensity and duration of water deficit, interactions with other factors, and in same cases to poorly designed experiments. In a well-designed factorial experiment looking at the combined effects of pruning and post-veraison irrigation on Shiraz, Petrie *et al.* (2004) measured statistically significant reductions in shoot number, bunch number and yield in season 2 in response to reduction in irrigation rate in season 1 (Figure 7). In an equally well designed experiment with Tempranillo, Intrigliolo and Castel (2010) found no carry over effect of irrigation regime on bud fertility. Nevertheless, grape growers do have some capacity to regulate yield components by pruning and bunch thinning (Table 1, Figure 8).

Many studies measured the effect of in-season water supply on yield and its components, as illustrated in Table 3 for three contrasting production systems. The combination of cultivar, environment and management resulted in yield of fully irrigated vines from 10 kg/vine for Bobal in Requena and Chardonnay in Niagara to 20 kg per vine for Shiraz in Riverland. Comparison of rainfed and fully irrigated crops shows a large (up to twofold) benefit of irrigation in the drier environments (Riverland, Requena) in comparison to yield gains of only 10-25 percent in the cooler, humid environment (Niagara). Bunch number shows large variation among production systems, but is relatively stable in response to in-season water supply, as expected from the reproductive cycle of vines. In-season water deficit therefore reduces yield by reducing bunch weight, and the relative importance of its components, namely berry number and size, depends on the timing of water deficits. Water deficit around anthesis and berry set has the potential to reduce berry number and size, whereas water deficit at later stages only reduces berry size. The post-veraison period is particularly critical because of the trade-off between maintenance

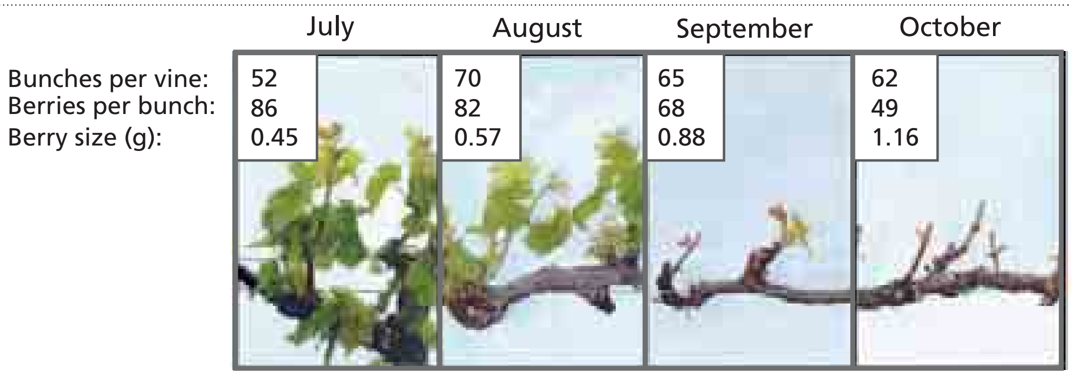
FIGURE 7 Reduction in irrigation rate post-veraison in season 1 reduced yield and bunch number of Shiraz in season 2 irrespective of pruning system. Yield and bunch number are expressed as per metre of canopy. Source: Petrie *et al.* (2004).



irrigation: $P < 0.05$
pruning: n.s.
interaction: n.s.

irrigation: $P < 0.05$
pruning: $P < 0.01$
interaction: n.s.

FIGURE 8 Shoot development recorded on mid-October (photographs) and yield components at harvest (numbers) in Merlot vines pruned at monthly intervals between mid-July to mid-October. Source: Friend and Trought (2007) for experiments in Marlborough (41 °S, 174 °E), New Zealand.



of water supply to ensure berry growth and the requirements of berry composition, which may benefit from controlled water deficit.

Fewer studies characterized the long-term effect of water deficit on grapevine yield. For Riesling on a steep slope vineyard in Germany, the combination of in-season and across-season temporary water deficits reduced long-term production from an average 7.6 tonne/ha in vines with small amounts of supplementary irrigation (29 litre/m^2 per season) to 5.0 tonne/ha for rainfed vines (Table 4).

Availability of water after harvest has at least two effects. First, it may influence canopy activity, build up of reserves and hence the performance of the crop in the following growing cycle. Second, irrigation between harvest and leaf fall may alter phenology under some conditions; for instance reduced irrigation after harvest may advance budburst in the following season (Williams *et al., 1991*), potentially increasing frost risk in some environments.

TABLE 3 Yield and yield components of Shiraz in Riverland (Australia), Bobal in Utiel Requena (Spain) and Chardonnay in Niagara-on-the-Lake (Canada) in response to irrigation regime. Values are ranges over three seasons. Sources: Riverland, McCarthy (1997); Utiel Requena, Salón *et al.* (2005); Niagara, Reynolds *et al.* (2005).

Irrigation regime		Yield (kg/vine)	Bunches per vine	Bunch weight (g)	Berries per bunch	Berry weight (g)
Riverland						
Fully irrigated	(between budburst and harvest)	13.4-19.5	166-182	81-108	67-81	1.2-1.5
Post-anthesis deficit	(irrigation withheld for 1 month after anthesis)	9.8-18.3	156-190	63-104	57-81	1.1-1.5
Pre-veraison deficit	(irrigation withheld for 1 month before veraison)	11.4-20.1	168-210	68-97	62-75	1.1-1.3
Post-veraison deficit	(irrigation withheld for 1 month after veraison)	11.2-18.2	160-193	71-98	63-77	1.1-1.3
Pre-harvest deficit	(irrigation withheld for 1 month before harvest)	12.4-20.1	154-197	81-106	67-78	1.2-1.5
Anthesis-veraison deficit	(irrigation withheld between anthesis and veraison)	9.6-19.9	164-204	58-99	59-77	1.0-1.4
Veraison-harvest deficit	(irrigation whithheld between veraison and harvest)	11.2-17.3	154-176	73-99	62-76	1.2-1.4
Rainfed	(no irrigation)	4.7-13.8	153-200	29-80	42-73	0.7-1.3
Utiel Requena						
Fully irrigated	(between anthesis and harvest)	6.4-9.5	11-14	613-711	107-263	2.7-3.0
Post-veraison mild deficit	(50% of control irrigation from veraison)	6.7-8.0	11-14	549-738	193-271	2.7-2.9
Post-veraison severe deficit	(irrigation withheld from veraison)	6.8-8.6	10-14	488-727	202-253	2.4-3.0
Rainfed	(no irrigation)	3.5-4.2	9-13	346-476	169-248	1.8-2.1
Niagara						
Fully irrigated		3.2-9.2	39-84	83-110	56-66	1.4-1.7
Post-set deficit	(irrigation withheld after fruit set)	3.2-8.4	39-88	81-106	58-67	1.4-1.6
Post-lag phase deficit	(irrigation withheld after lag phase)	2.7-8.7	35-84	76-103	54-65	1.4-1.6
Post-veraison deficit	(irrigation withheld after veraison)	2.6-10.0	33-78	79-128	60-83	1.3-1.7
Rainfed	(no irrigation)	2.9-7.8	36-84	81-102	60-66	1.4-1.6

TABLE 4 Yield, fruit sugar concentration and sugar yield of irrigated and rainfed Riesling on a steep slope vineyard close to Geisenheim (50 °N), Germany. Values are mean ± standard deviation for eight consecutive years since 2002. Combination of an irrigation threshold of -0.3 MPa predawn water potential and weekly irrigation decision interval resulted in 7.4 ± 3.4 irrigation events per season, and applied water 29.3 ± 12.2 litre/m^2 (Gruber and Schultz, unpublished).

Response variable	Irrigated	Rainfed
Yield (tonne/ha)	7.6 ± 3.22	5.0 ± 2.16
sugar conc. (g/litre)	212 ± 19.5	204 ± 29.7
sugar yield (kg/ha)	1 182 ± 460.1	728 ± 280.1

Berry and wine attributes

Wine quality is an elusive concept and attempts to quantify it are bound to be controversial (Box 1). Quantitative assessments of berry and wine attributes in response to water deficit are, however, essential for irrigation scheduling. Indeed, regulation of grapevine water relations is an important tool for quality management in irrigated viticulture. There is a significant body of literature dealing with the effects of water relations on the composition of red grapes, especially on phenolic compounds; information regarding the effects of plant water status on the composition of white varieties is scarce.

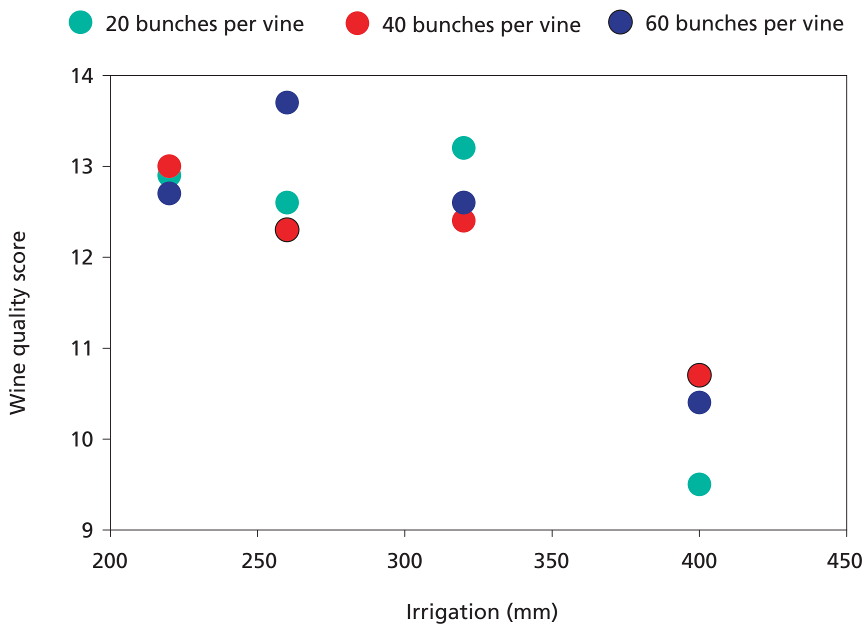
Red varieties

Figure 9 illustrates a typical, although not universal, relationship between wine quality and irrigation for red varieties. The negative association between water supply and wine quality is partially mediated by an apparent trade-off between yield and quality attributes of berries (Figure 10, Figure 11). The negative associations between rate of accumulation of sugar and anthocyanins and yield components in Figure 10b probably reflect a high fruit-to-canopy ratio, rather than high yield per se. If this hypothesis is correct, manipulation of this ratio by irrigation,

BOX 1 Wine quality

The elusiveness of 'wine quality' stems from the complexity of wine attributes compounded by the complexity and variability of human smell and taste sensitivity. Temporal and regional variation in wine quality has been assessed with price and vintage ratings (Cicchetti and Cicchetti, 2009 and Almenberg and Dreber, 2009). The drawbacks of each of these approaches are many, including marketing factors influencing price beyond specific quality parameters, and vintage scores derived from expert, albeit subjective evaluations (Sadras *et al.*, 2007). Views on vintage scores range from "…controversial, potentially misleading and essentially impossible to get consistently correct…" (Fuller and Walsh, 1999) to the proposal of ratings that "…express the likelihood of what might reasonably be expected from a wine of a given year…" (Stevenson, 2005). Individual attributes of berries and wine such as colour or content of many critical compounds, on the other hand, can be measured with accuracy. The challenge to this approach is however, the integration of individual measurements into a complete measure of quality. There is no doubt that wine quality is a controversial concept, and there is no doubt either that, however imperfect, quantification of key berry and wine attributes is essential to irrigation management.

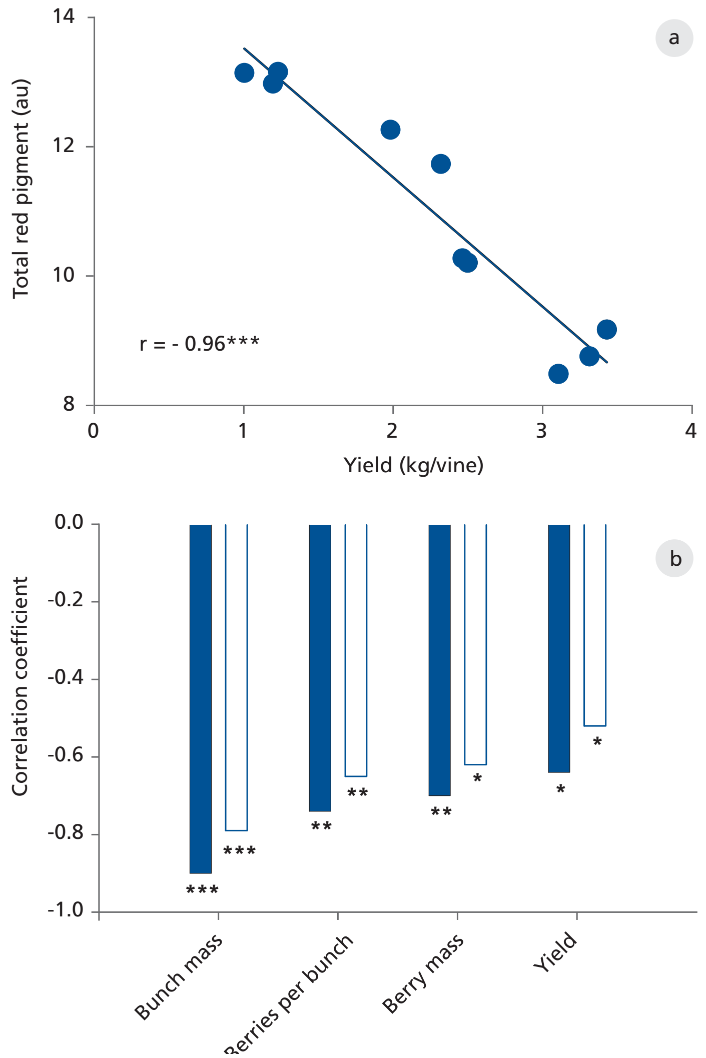
FIGURE 9 Wine quality score as a function of total irrigation for Cabernet Sauvignon in Adulam, Israel. Source: Bravdo *et al.* (1985).



pruning, thinning, and canopy management maybe important to achieve both high yield and high quality.

Water deficit generally increases the concentration of phenolic compounds, but has a differential effect on individual groups of phenols depending on timing and severity of the stress. Tannin biosynthesis can be negatively affected by severe stress after anthesis (Ojeda, 2002), but later deficits often increase tannin concentration (Roby *et al.,* 2004). In most cases, anthocyanin concentration responds positively to water shortage after veraison but less frequently to pre-veraison deficits (Matthews and Anderson, 1988); although the expression of genes involved in anthocyanin biosynthesis can be increased by water stress pre-veraison (Castellarin *et al.,* 2007). Aside from phenolic compounds, aroma attributes may also be affected (Chapman *et al.,* 2005). Differences in the response of varieties are likely but not well documented (see: Suggested RDI regimes below for examples). In addition to the effects on amount and proportion of key compounds, water deficit can cause more subtle but relevant effects. For example, water deficit after veraison has been shown to increase the structural complexity (degree of polymerisation) and to reduce the extractability of phenolic compounds in berries of several red varieties (Ojeda *et al.,* 2002; Sivilotti *et al., 2005*). The effects of water deficit on berry attributes are partially related to reductions in berry size, although size-independent effects have also been reported. Allometric analysis is required (i) to separate size-dependent effects of water deficit on a particular component, e.g. sugar, and (ii) to compare the relative responsiveness of different berry components to water deficit (Sadras *et al.,* 2007 and Sadras and McCarthy, 2007). For example, allometric analysis revealed that water deficit accelerated the rate of accumulation of anthocyanins with respect to sugar of Cabernet Sauvignon in a warm environment (Figure 12). Water management is therefore important to ensure a certain coupling of key berry components during ripening; this will eventually affect wine balance.

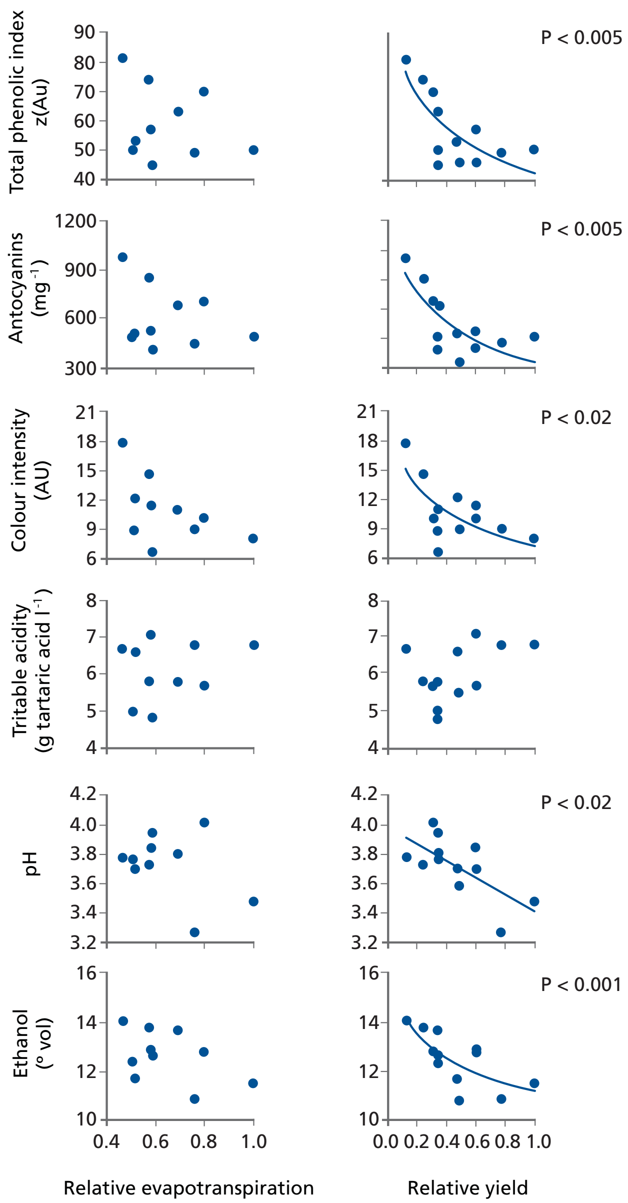
FIGURE 10 Negative associations between berry traits related to wine quality and yield. (a) Total red pigments in berry skins of Pinot Noir grown in a cool climate. (b) Correlation coefficients of the regressions between the rate of anthocyanins or soluble solid accumulation in berries and yield related variables in Cabernet Sauvignon grown in a warm environment. Sources of variation were (a) source: sink manipulation through bunch thinning and pruning, and (b) season, water supply and fruit load. Asterisks indicate $P < 0.05$ (*), $P < 0.01$ (**) and $P < 0.0001$ (***). Adapted from (a) Dunn *et al*. (2005) and (b) Sadras *et al*. (2007).



White varieties

Compared to red varieties, white varieties are generally more sensitive to stress periods and can show negative compositional changes (Christoph *et al.,* 1998 and Peyrot des Gachons *et al.,* 2005). Phenolic compounds are judged less desirable in white grapes, since sensory attributes such as astringency or bitterness, associated with both flavonoid, i.e. flavan-3-ols and proanthocyanidins (Singleton and Noble, 1976 and Brossaud *et al.,* 2001) and nonflavonoid phenols, i.e. hydroxycinnamic acids or their esters (Arnold *et al.*, 1980 and Hufnagel and Hofmann, 2008) are incompatible with the current type of white wine popular

FIGURE 11 Wine attributes of Tempranillo in Requena, Spain, as a function of relative evapotranspiration and relative yield. Fitted models are shown when significant ($P < 0.05$).
Source*:* Intrigliolo and Castel (2008).

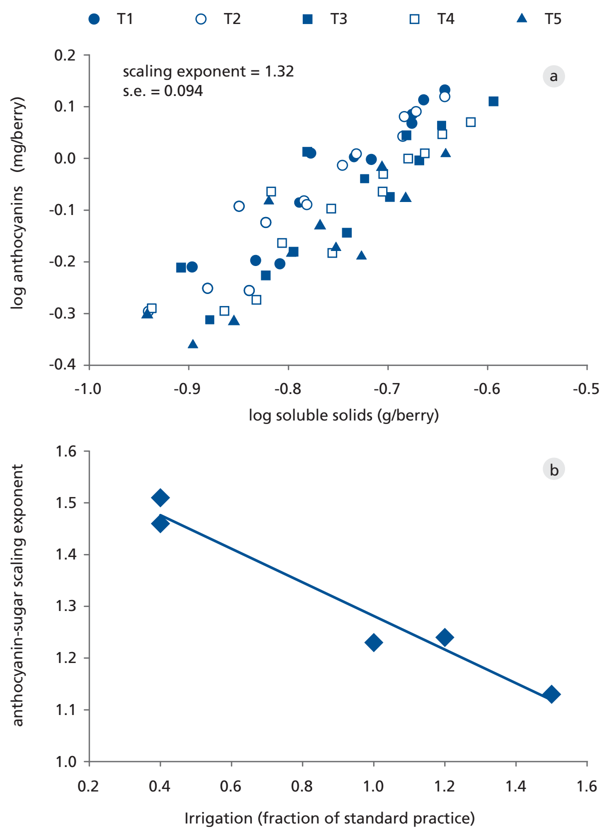


with the consumer. Flavonoids undergo oxidative polymerisation, thus lowering their flavour threshold during wine ageing (Schneider, 1995) and can negatively affect the volatility of flavour compounds (Aronson and Ebeler, 2004). Depending on the variety, water stress and associated reduction in nitrogen uptake, have been implicated in alterations of flavour-quality of various white varieties such as Chasselas, Silvaner, Sauvignon blanc and Riesling (Peyrot des Gachons *et al.*, 2005 and Linsenmeier, 2008). In one example, the development of negatively judged wine attributes after only a short period of bottle ageing was retarded by irrigation (Table 5). However, there has been at least one report showing an increase in glycosidically bound monoterpenes contributing to the flavour profile of White Riesling under water deficit

TABLE 5 Sensory evaluation of experimental wines from White Riesling either receiving supplemental irrigation or only natural precipitation from the 2003 vintage in the Rheingau region, Germany. Bottled wines (screw cap) of both treatments were in part 'artificially aged' by warm-storing these bottles at 25 °C for three months. Wine attributes were rated on a scale from 0-5 (higher values indicated more intense perception of the respective attribute) by 115 judges on 7 September, 2004. Source: Schultz and Gruber (2005).

Attribute	Irrigated		Non-irrigated	
	not aged	artificially aged	not aged	artificially aged
Positive aroma attributes	3.45	2.37	2.85	1.93
Negative aroma attributes	2.10	2.61	2.43	3.79
Acidity	2.35	2.95	2.43	2.95
Bitterness	2.40	2.63	2.70	2.87

FIGURE 12 (a) Allometric relationship between amount of sugars and amount of anthocyanins during the linear phase of accumulation in Cabernet Sauvignon berries under five treatments (irrigation and fruit load) during three seasons. The scaling exponent (i.e. slope of the regression in a log-log scale) is greater than 1, thus indicating that the relative rate of accumulation of anthocyanins was greater than the relative rate of accumulation of sugar across treatments. (b) Relationship between the sugar-anthocyanin scaling exponent and irrigation; the standard treatment received 160 mm in 2003-2004, 210 mm in 2004-2005, and 220 mm in 2005-2006. Source: Sadras *et al.* (2007).



(McCarthy and Coombe, 1999), but even in that particular trial, sensory attributes changed differentially over time.

WATER REQUIREMENTS

Crop evapotranspiration increases with vine age from establishment until the canopy and root system reach their full capacity to capture radiation and water (Figure 13). For established vines, seasonal ET_c in semi-arid to arid environments, e.g. central California (United States), and Riverina (Australia) ranges from approximately 500 to 800 mm (Williams and Matthews, 1990). Figure 14 shows the seasonal dynamics of K_c as affected by crop age and environment (temperate vs tropical). The seasonal dynamics of crop coefficients comprises two phases with increasing K_c from onset of active growth to peak canopy size, and decreasing K_c during leaf senescence. Assuming linearity, the average rate of increase of K_c was 0.005 d^{-1} for young vines, 0.007 d^{-1} for older vines in Washington, and 0.013 d^{-1} in the tropical São Francisco region. In the declining stage, the rate of change in K_c was 0.006, 0.011, and 0.042 d^{-1}, respectively. In addition to differences in rate of change in K_c, non-zero K_c at the onset of the irrigation season in tropical environments reflects the lack of dormancy and continuous physiological activity during the year in tropical environments.

More refined crop coefficients could be obtained on the grounds of a direct, often non-linear association with canopy light interception or related variables such as leaf area index. Owing to large variation in canopy structure with pruning and training systems, however, the relationship

FIGURE 13 Change in crop evapotranspiration (ET_c) with vine age in Washington, USA. ET_c was measured in large drainage lysimeters. Seasonal (1 April to 31 October) reference evapotranspiration (ET_o) derived from Penman (alfalfa reference) is also shown; the dotted line is the average. Adapted from Evans *et al.* (1993).

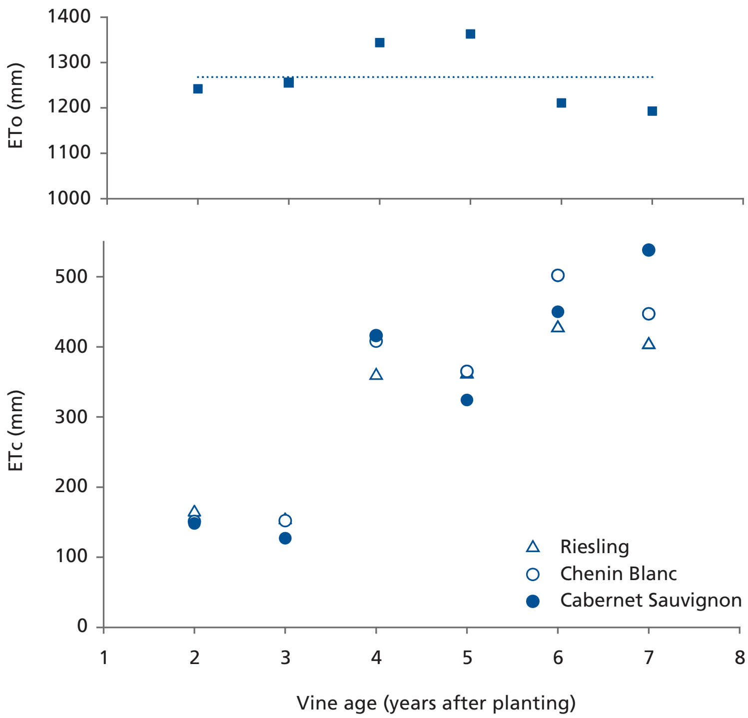
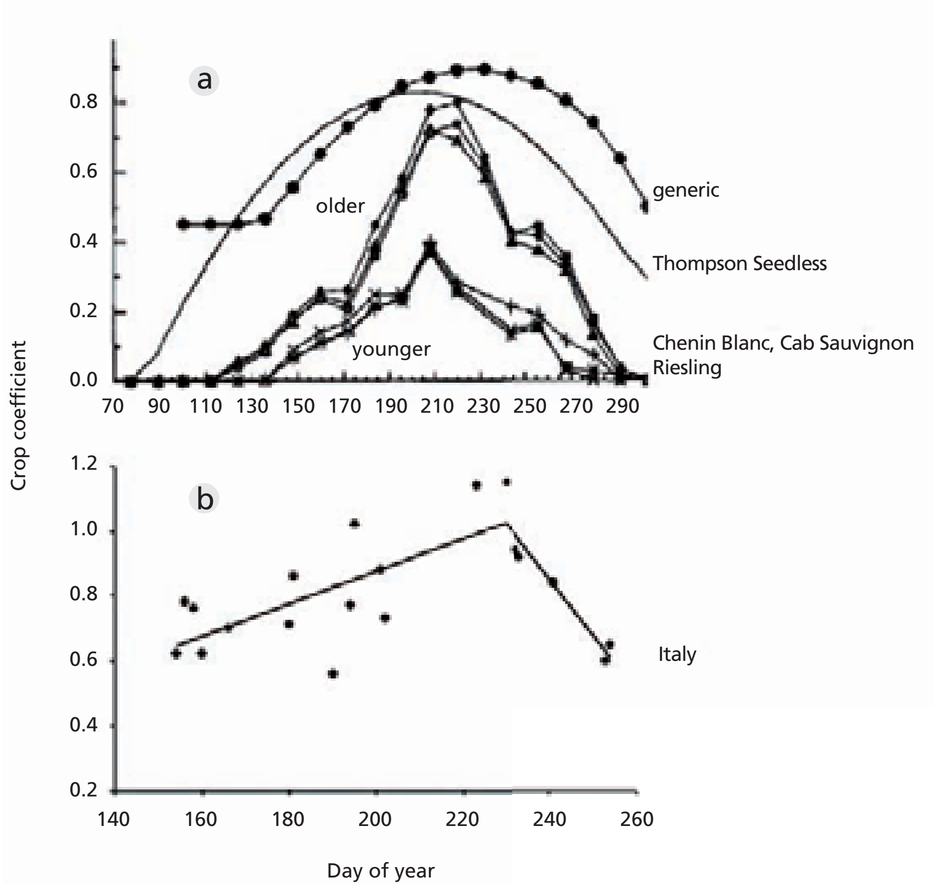


FIGURE 14 Seasonal dynamics of crop coefficients for vines in (a) central Washington (46 ºN, USA) and (b) São Francisco (9 ºS, Brazil). Sources: (a) Evans *et al.* (1993) and (b) Teixeira (1999).

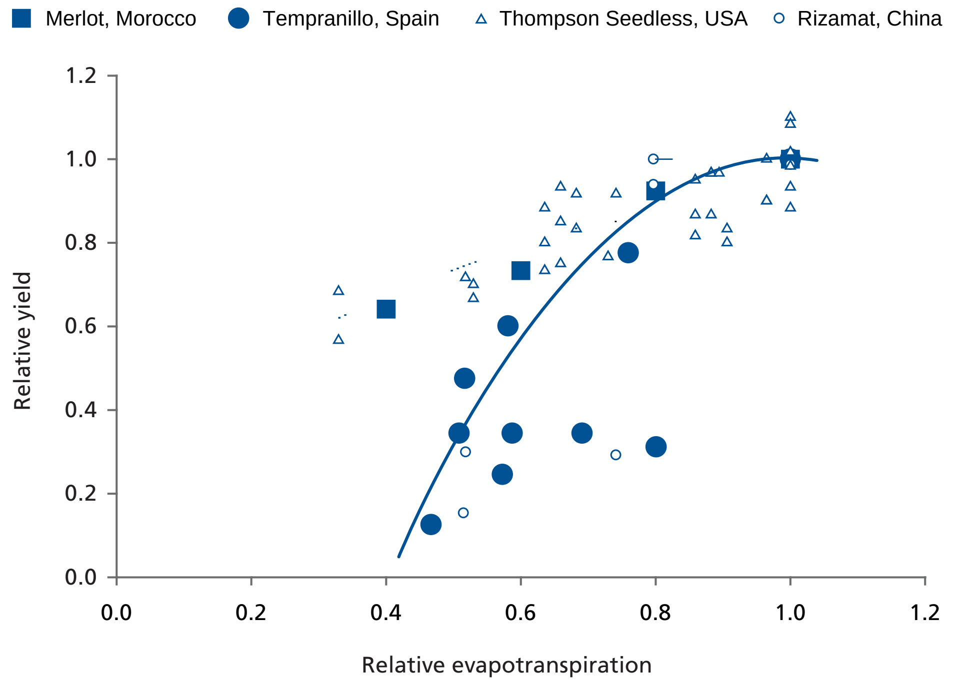


between crop coefficient and leaf area index is not unique. The relationship between crop coefficient and leaf area index may also show hysteresis, i.e. the relationship is different for increasing or decreasing K_c (Netzer *et al.*, 2009). To deal with these problems, Williams and Ayars (2005) proposed an approach to characterize crop coefficients on the basis of canopy light interception, and demonstrated the robustness of a practical grid-method to measure the amount of shade cast on the ground by table grapes.

WATER PRODUCTION FUNCTIONS

The diversity of production systems targeting different combinations of fruit volume and quality contribute to the large scatter in the relationship between yield and water use. Furthermore, scarcity of data means the actual shape of the function remains speculative in particular for relative ET_c below 0.4 (Figure 15). In common with other tree crops yield is maintained until relative ET_c approximates 0.8, and a consistent almost linear decline is observed in the range of relative ET_c from 0.8 to 0.4. The data for Tempranillo wine grapes suggest a more sensitive response to relative ET deficits in contrast with the response of table grapes (Figure 15). This is probably because of a limitation in the maximum ET_c imposed by pruning and other cultural techniques in the case of wine grapes, while such limitation is not normally imposed in table

FIGURE 15 Relative yield as a function of relative evapotranspiration in wine grapes (closed symbols). The solid and dashed lines attempt to capture the upper limit for wine grapes. Table grapes (open symbols) and the function fitted for Thompson Seedless (dotted line) are shown for comparison. Sources: Messaoudi and El-Fellah (2004), Intrigliolo and Castel (2008), Du *et al.* (2006) and Grimes and Williams (1990).



grapes. The variations in the scarce data in wine grapes of Figure 15 suggest that the production function is probably variety and cropping system dependent.

Qualitatively, the relationship between gross revenue and ET_c in wine grapes is expected to feature an optimum resulting from the mismatch between the ET_c required to maximize yield and the ET_c required to maximize quality and value per unit volume (Box 19 in Chapter 4). The actual parameters of this function, however, are likely to be specific for local production systems with their own water and grape prices.

SUGGESTED RDI REGIMES

For wine grapes, where the quality objective is critical to profit, the recommended irrigation regime must account for many more factors than in most other crops. To achieve the triple aim of high yield, quality and irrigation water productivity, irrigation of red grape varieties in temperate environments needs to ensure vegetative growth and early reproductive growth in spring, and allow for progressive water deficit to develop towards maturity. For white grapes, water management should seek to avoid both severe water deficit and excess water supply. Management of irrigation after harvest accounts for the need to build up carbohydrate reserves in vines. Owing to the many factors involved, we selected five case studies to illustrate this general pattern, and the variations particular to the target production system. These examples also highlight the application of different monitoring methods (Box 2).

Box 2 Crop and soil measurements to schedule grapevine irrigation

Plant, crop and soil indices of water status have been tested in vines grown in diverse environments. The table below presents some examples, and: Suggested RDI regimes outlines the application of some of these methods in irrigation scheduling. Measurement of leaf water potential is time consuming and requires considerable expertise, but seems more consistent than faster measurements including trunk diameter and stomatal conductance.

Under the conditions of the study of Girona *et al.* (2006), midday leaf water potential outperformed soil water balance as a trigger for irrigation, i.e. leaf water potential captured spatial variability better, and crops managed using this plant-based index had less variability in yield and berry composition, that could potentially improve the homogeneity of grape juice. Thermal, visible and hyperspectral imagery are attracting increasing attention (*Moller et al., 2007; Rodriguez-Perez et al., 2007*). These technologies, coupled with GIS, allow for effective account of spatial variation at relevant scales from region to fields. There is a large variation in cost and expertise required for the implementation of these approaches, form relatively cheap, easy-to-use hand-held infra-red thermometers to tractor-mounted, air-borne or satellite imagery across wide spectral ranges. Soil water status can be assessed indirectly through predawn leaf water potential, and directly through measurements with a range of instruments including neutron probes, time domain reflectometry and pressure transducer tensiometers (Chapter 4). A water balance model is often a practical alternative to direct measurements of soil water status (Pellegrino *et al.,* 2006).

Suitable indices for irrigation management need to combine flexibility, and a reasonable accuracy-to-acquisition cost ratio in terms of time, resources and skills. In addition to trade-offs between accuracy and cost, there are also trade-offs between the multiple effects of irrigation on yield, quality, reserves and diseases (Pellegrino *et al.*, 2006). Pellegrino *et al.* (2006) developed an elegant method that combines a soil water model and simple, empirical response function that allow for the changes in crop responsiveness to water deficit through the growing season (Section 5.1).

Box 2 (CONTINUED)

Principle	Crop and region	Features	Source
Hyperspectral remote sensing	Pinot Noir California (38 °N)	Reflection and transmission measures, 350-2 500 nm. Alternatives of top-of-canopy, i.e. mounted on vehicle (0.7 m), airborne or satellite imaging. Block scale; spatial resolution. Generally consistent with measures of leaf water status (leaf water potential and water content). Variable results with canopy shape, sun or sensor perspective.	72
Thermal and visible imagery	Merlot Israel (33 °N)	Thermal imager (7.5-13 μm); digital colour images. Mounted on truck-crane (15 m). Crop water index closely associated with stomatal conductance.	73
Thermal imagery	Castelão, Aragoněs SE Portugal	Thermal imager (8-12 μm) with 0.1 °C resolution. Wet and dry references. Crop water stress index related to stomatal conductance.	74
Trunk diameter	Tempranillo Spain (39 °N)	Trunk diameter measured with linear variable differential transformers; logged at 30 second intervals. Maximum daily trunk shrinkage and trunk growth rate were highly variable and had no resolution after veraison.	76
Water potential, stomatal conductance	Tempranillo Spain (39 °N)	Predawn and mid day leaf water potential; morning and midday stem-water potential measured with pressure chamber. Midday stomatal conductance measured with diffusion porometer. Predawn and morning water potentials best indicators. Large influence of canopy size.	77
Water potential	Cabernet Sauvignon Spain (40 °N)	Explored relationship between timing of measurement of leaf water potential (predawn, midmorning and noon) and net CO_2 assimilation rate, vegetative growth rate, yield components and must composition.	78
Water potential	Pinot Noir Spain (42 °N)	Midday leaf water potential measured with pressure chamber. Compared to water balance method, midday leaf water potential was better to capture spatial variation.	43
Sap flow	Malagouzia Greece (41 °N)	Sap flow measured with the Granier method, which allows for continuous measurement and logging compared to heath-pulse system. Requires fully irrigated reference. Reasonable correlations with vapour pressure deficit and midday leaf water potential.	79
Vegetative growth	Shiraz Controlled environment	Length and leaf number of lateral branches was sensitive to medium-mild water deficits. These indicators were more sensitive to soil water deficit than predawn leaf water potential stomatal conductance.	80
Modelled soil water balance linked to plant response functions	Several varieties Southern France (43 °N)	Modelled soil water budget is linked to photosynthesis and tissue-expansion related responses to the fraction of transpirable soil water (FTSW). Allowance is made for variable stress during the crop cycle.	41

Shiraz, Grenache and Mourvèdre in southern France

Figure 5 outlines a scheme for water management derived for Shiraz, Grenache and Mourvèdre in vineyards of southern France (43 °N) with contrasting soil types (Pellegrino *et al.*, 2006). This scheme is based on eight classes of water deficit and aims at quality wine production. It highlights the need for good water supply, i.e. fraction of transpirable soil water (FTSW) above 0.6, early in the season. This allows for the establishment of a balanced canopy and fruit load, and proper development of inflorescence buds that would largely determine next season's yield. A mild water deficit from flowering to veraison, (FTSW between 0.6 and 0.4) leads to a drier finish to account for disease and berry composition at harvest. High water supply, particularly during ripening, may lead to a combination of undesirable indirect (e.g. disease) and direct effects on berry composition and wine quality. The goal of this RDI regime is to achieve a dry finish that often leads to higher concentration of colour and flavour compounds in berries.

Cabernet Sauvignon in California, United States

Prichard (2009) derived an RDI regime based on extensive experimentation with mature Cabernet Sauvignon at Lodi (38 °N). The regime aims at the best yield/quality relationship and is conceptually similar to the general pattern outlined above, namely ensure good water supply at the beginning of the growing season, and progressively reduce water supply towards ripening. After harvest, full watering is recommended to encourage root growth and accumulation of plant reserves in an environment notably warmer and with greater evaporative demand than in the previous case study.

Pinot Noir and Tempranillo in Lleida, Spain

Girona *et al.* (2006) used mid-day leaf water potential to schedule irrigation of 12-year-old Pinot Noir vines at Raïmat (42 °N) during three consecutive seasons. They used the same general principle of ensuring water supply early in the season and allowing for a deficit at late reproductive stages using the thresholds summarized in Table 6. The RDI in this study reduced yield by 14-43 percent, increased irrigation water productivity by 28-46 percent and improved concentration of anthocyanins and polyphenols in berries by 10-19 percent (Table 6).

Working with Tempranillo in the same environment, Girona *et al.* (2009) measured the effect of timing of water deficit on must attributes including soluble solids content, polyphenol, and anthocyanin concentration. They found negative impact of water deficit between fruit set and veraison and positive effects of mild water deficit after veraison. They proposed that irrigation management should aim to avoid severe water deficits for Tempranillo before veraison and that RDI should target the window between veraison and harvest.

Sauvignon Blanc in Marlborough, New Zealand

Irrigation in this cool climate needs to account for the high evaporative demand in mid-summer (ET_o > 7 mm/d) and the risk of excess irrigation with negative effects in terms of both wine quality and environmental deterioration associated with leaching of nutrients and pesticides. Greven *et al.* (2005) established an RDI study on 5 ha of 9-year old Sauvignon Blanc. They combined measurements of vine water use, assessments of vegetative and berry growth, and modelling to calculate transpiration. Before veraison, vines were irrigated when predawn leaf water potential was below –0.2 MPa and the threshold was –0.4 MPa between veraison and harvest. Preliminary

TABLE 6 Comparison of three irrigation regimes based on thresholds for midday leaf water potential and their effects on yield, irrigation water productivity (IWP, yield per unit irrigation), and anthocyanins and polyphenols in berries of Pinot Noir. Source: Girona *et al.* (2006).

Treatment	Threshold SWP (MPa)			Irrigation[a]	Yield[b]	IWP [c]	Anthocyanins[d]	Polyphenols[e]
	Vegetative	Initial berry growth	Post-veraison					
Control	-0.73	-0.88	-0.93	1	1	1	1	1
Control-deficit	-0.73	-0.86	-1.12	0.67	0.85	1.28	1.12	1.10
Deficit-deficit	-0.86	-1.13	-1.20	0.39	0.57	1.46	1.19	1.17

a fraction of control; control ~ 378 mm
b fraction of control; control ~ 10.8 kg/vine
c fraction of control; control ~ 54 kg/ha per mm
d fraction of control; control ~ 556 mg/kg
e fraction of control; control ~ 13.0 mg/kg

conclusions for this particular production system are that yield and juice attributes were unaffected by reductions in seasonal irrigation up to 40 percent from fully irrigated vines receiving 360-690 mm.

Riesling in the Rheingau area, Germany

The region is characterized by vineyards on slopes, some of them very steep with shallow soils (depth < 0.8-1 m). Midsummer reference evapotranspiration is between 3 and 6 mm d^{-1} and annual precipitation is 534 mm. Due to the strong variability in cloud cover, temperature and vapour pressure deficit (also in the absence of precipitation), leaf or stem-water potential are not stable enough to schedule irrigation. The irrigation threshold used is a predawn water potential of -0.3 to -0.4 MPa throughout berry development, with the exception of the first berry growth phase, where no irrigation is applied. Very small amounts of water are given at each irrigation event (on average 4 litre/m^2) to minimize the risk of excess water when precipitation occurs shortly after an irrigation. Over a period of 8 years, vines were irrigated 7.4 times per year on average with a total of 29.3 mm per year (Table 4), which represents about 5.5 percent of annual precipitation. Despite these small amounts, yield of the irrigated vines was about 50 percent higher at similar sugar concentrations (Table 4).

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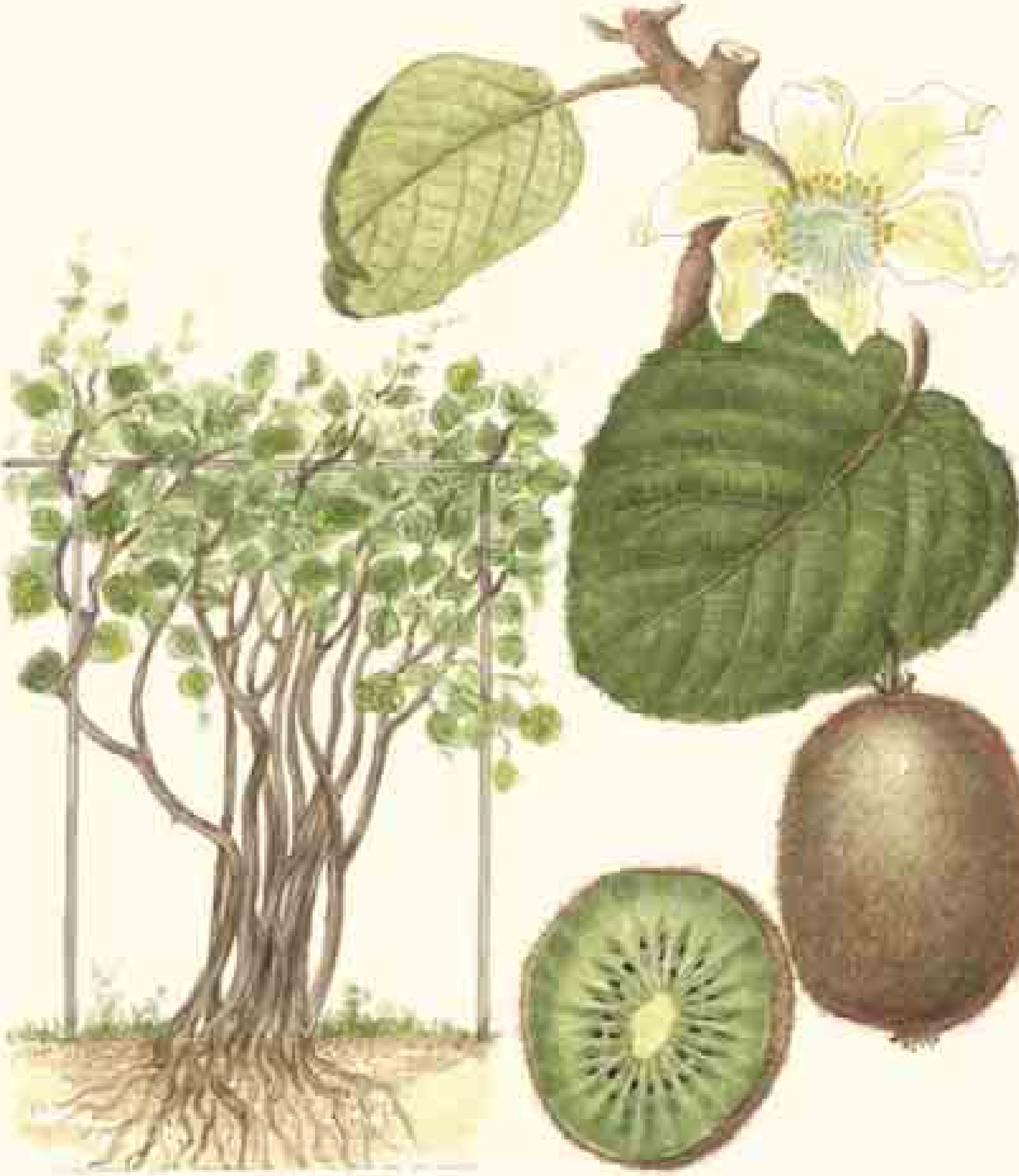

Kiwifruit

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Kiwifruit

INTRODUCTION AND BACKGROUND

Globally, the green kiwifruit (*Actinidia deliciosa* [A.Chev.] C.F. Liang and A.R. Ferguson), represents about 95 percent of the commercial kiwifruit, all produced with just one variety, Hayward. Other species, such as *Actinidia arguta* (known as baby kiwi) is grown for a niche market and is also recognized for ornamental purposes. Only recently, some yellow fleshed varieties that originated in in New Zealand and Italy (*Actinidia chinensis* Planch.) have appeared on the international markets.

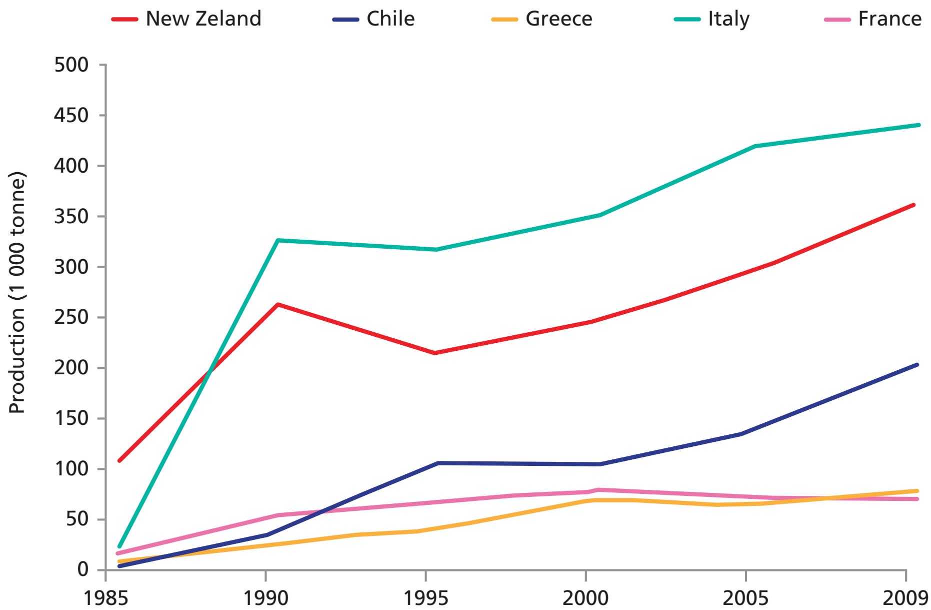
The main training systems adopted for the kiwifruit are the T-bar and the Pergola, with plantation densities ranging from 400-600 (Pergola) up to 720 plant/ha (T-bar). Canopy management should focus on determining the appropriate bud load (150 000 - 200 000 bud/ha) in winter and on maximizing the carbon budget during the growing season by reducing the amount of shaded leaves by summer pruning (Xiloyannis *et al.*, 1999). This in turn enhances light availability within the canopy improving fruit growth and some fruit quality traits (e.g. calcium content, Montanaro *et al.*, 2006).

As for pistachio, kiwifruit needs male plants to produce pollen for the female. The standard male to female plant ratio adopted is 1:6. Distribution of male plants is important to ensure pollination and adequate fruit size and yield. The use of bee hives or artificial pollen distribution during bloom is recommended.

Total global production in 2008 was 1.31 tonne, on 82 547 ha production area (FAO, 2011). Italy is the first producing country in the world (36 percent) followed by New Zealand (28 percent) and Chile (13 percent). However, these statistics do not include China, whose production has been estimated at 403 000 tonne of fruit in 2004 (about 65 000 ha producing area). Figure 1 presents the production trends of the main countries since 1985.

In addition to the green cultivar Hayward, a recent review describes the new cultivars of *A. deliciosa* and *A. chinensis* (yellow fleshed), which have been recently selected and released (Testolin and Ferguson, 2009).

FIGURE 1 Production trends for kiwifruit in the principal countries (FAO, 2011).



Quality considerations

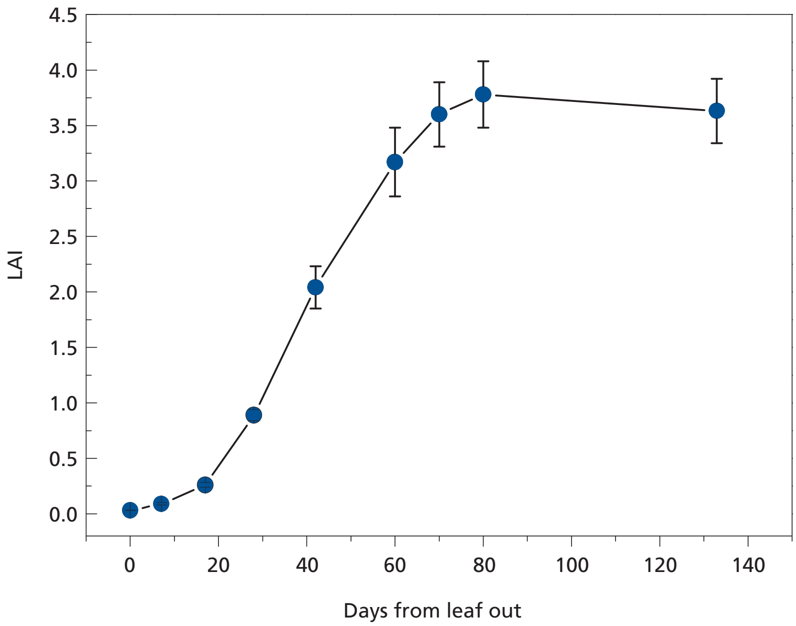
Particular attention should be paid to kiwifruit calcium (Ca) nutrition because of its involvement in determining tissue mechanical strength and tolerance to biotic and abiotic stresses. Cessation of Ca import into fruit has been linked to a number of morpho-anatomical changes of fruit properties related to reductions in fruit water loss, as transpiration from the fruit is the only mechanism responsible for Ca import. Therefore, it is desirable that canopy and irrigation management ensure adequate light distribution and windspeed within the canopy to enhance fruit transpiration and Ca accumulation. (Montanaro *et al.*, 2006; Xiloyannis *et al.*, 2008).

STAGES OF DEVELOPMENT IN RELATION TO YIELD DETERMINATION

Bud development starts in spring and is largely completed by midsummer. Some buds are vegetative in that they give rise to vegetative shoots, while others are mixed, generating both leaves and flowers that develop from the same bud. The induction of the reproductive development of the bud occurs during late-summer to autumn followed by inflorescence differentiation, which will be completed by the next spring.

The chilling requirement to break dormancy is about 700-800 Richardson units for the Hayward cultivar (Linsley-Noakes, 1989), while for the yellow-fleshed cultivars chilling requirements are lower (500-600 units). The growing-degree-hours for bud break range from about 9 000 to 16 000 (Wall *et al.*, 2008). The buds break in spring which takes 10-15 days, thereafter shoots elongate quickly reaching 20-30 cm after 3 weeks. Leaves expand very rapidly during the early 30 days of growth, and the full leaf area is reached within three months (Figure 2). Values of LAI

FIGURE 2 Seasonal pattern of the leaf area index (LAI) in a *A. deliciosa* (Hayward) mature orchard in Italy (Pergola, 625 plants/ha). The day 0 is the April 10th (Xiloyannis *et al.*, 1999).



are around 2.5-3 in orchards trained to T-bar (~400 vine/ha), and up to 4-5 in orchards trained to the pergola system (~700 vine/ha). Different vigour rootstocks could greatly affect the LAI (Figure 3) particularly during the early years after planting. The evolution of LAI during the first years of planting is shown in Figure 4. Because the fraction of shaded leaves may represent up to 60 percent of LAI in pergola trained vines (Figure 5), it is important to control growth by summer pruning so that the proportion of leaves with high water use efficiency increases (Figure 6) and some fruit quality traits (e.g. calcium content) related to light availability are enhanced (Montanaro *et al.*, 2006).

After fruit set, the development of a fruit entails an initial rapid growth (predominant cell division stage) which spans about 50 days and is followed by the cell enlargement stage that slows down late in the season. The pattern of fruit growth, described as changes in fruit length or surface area, is shown in Figure 7.

RESPONSES TO WATER DEFICITS

Kiwifruit is quite sensitive to water deficit; vines do not survive stress levels associated with predawn leaf water potential values (LWP) below -1.5 MPa. Even mild water deficits determine rapid stomatal closure and increase in leaf temperature, which results initially in leaf tip burn and later leads to necrosis of the entire lamina. Restriction of water supply over the summer easily reduces fruit size at harvest. Mild water stress (about -0.5 MPa predawn LWP) occurring during the early growth of fruit (cell division stage) or later during fruit growth, causes a reduction in fruit size (Figure 8). However, in the case of deep soils with high water-holding capacity, an initial irrigation deficit may be tolerated without affecting fruit size (Reid *et al.*, 1996) as long as the soil

FIGURE 3 Evolution of the LAI in *A. chinensis* (cv. Hort16A) scion grafted on two Actinidia rootstocks in the Southern Hemisphere (Clearwater *et al.*, 2004).

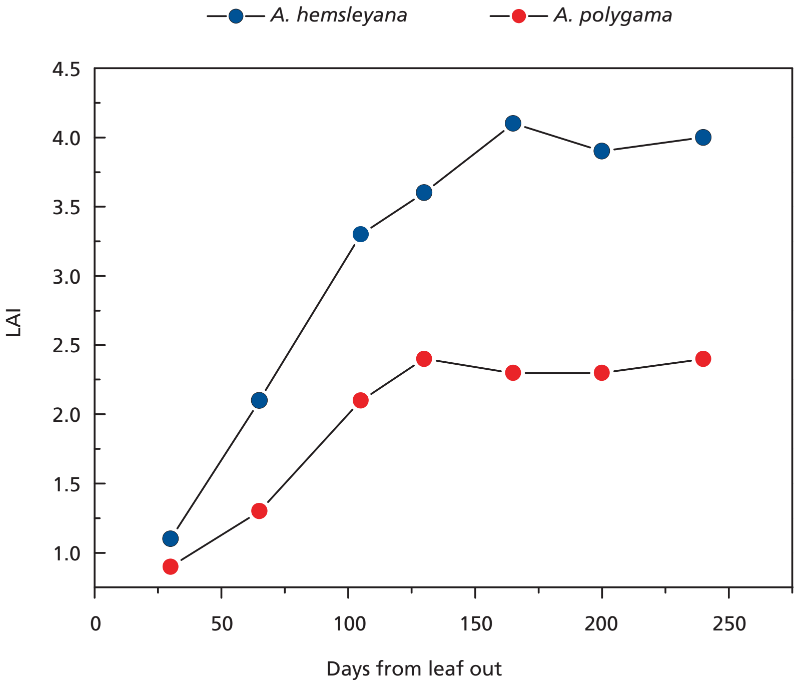


FIGURE 4 Variation of LAI in kiwifruit vines (cv. Hayward) trained to T-bar during the early 4 years after planting. Vines were planted at distances of 4.5 m between rows and 3 m along the row. The yield at the third year was 7 tonne/ha. (Xiloyannis *et al.*, 1999).

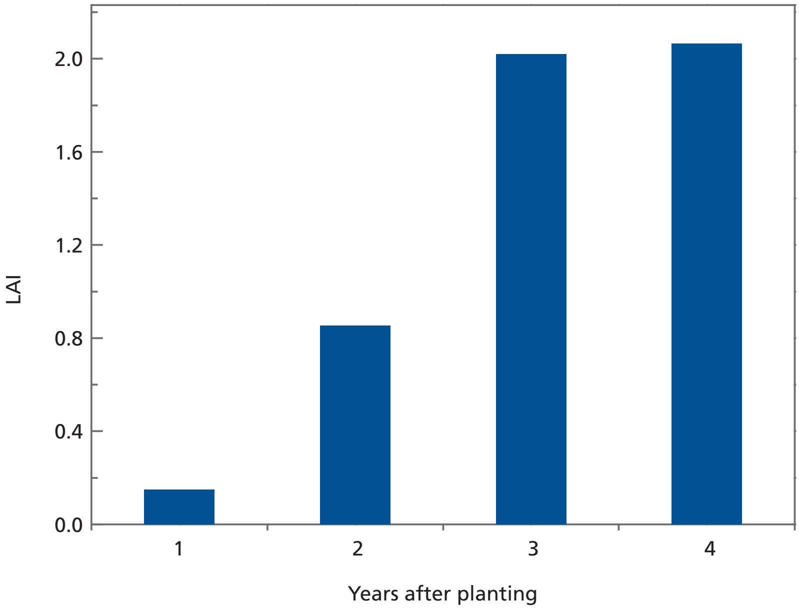


FIGURE 5 Fraction of the exposed and shaded (< 350 µmol m^{-2} s^{-1} PAR) LAI in a Pergola-trained Hayward kiwifruit.

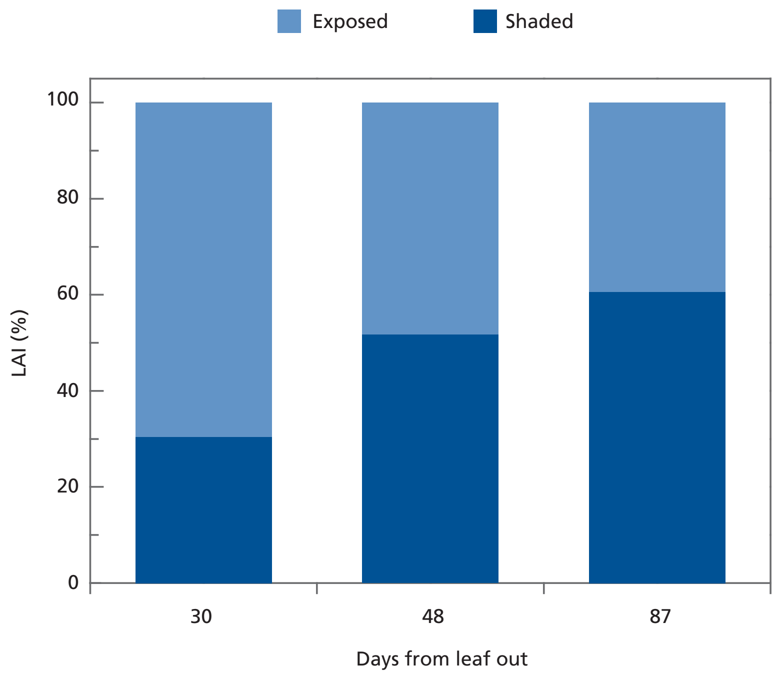


FIGURE 6 Daily mean water use efficiency (WUE) in exposed (•) and shaded (o) leaves during the season. DOY = Day of Year (Xiloyannis *et al.*, 1999).

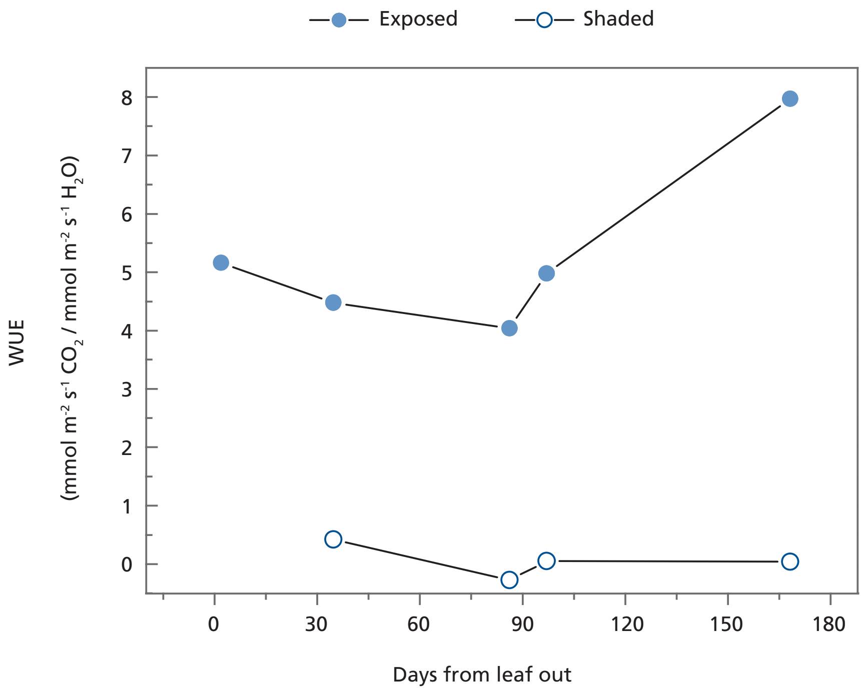


FIGURE 7 Schematic representation of the seasonal evolution of fruit length (continuous line) and of the fruit surface area (dotted line) in a mature kiwifruit orchard (cv. Hayward).

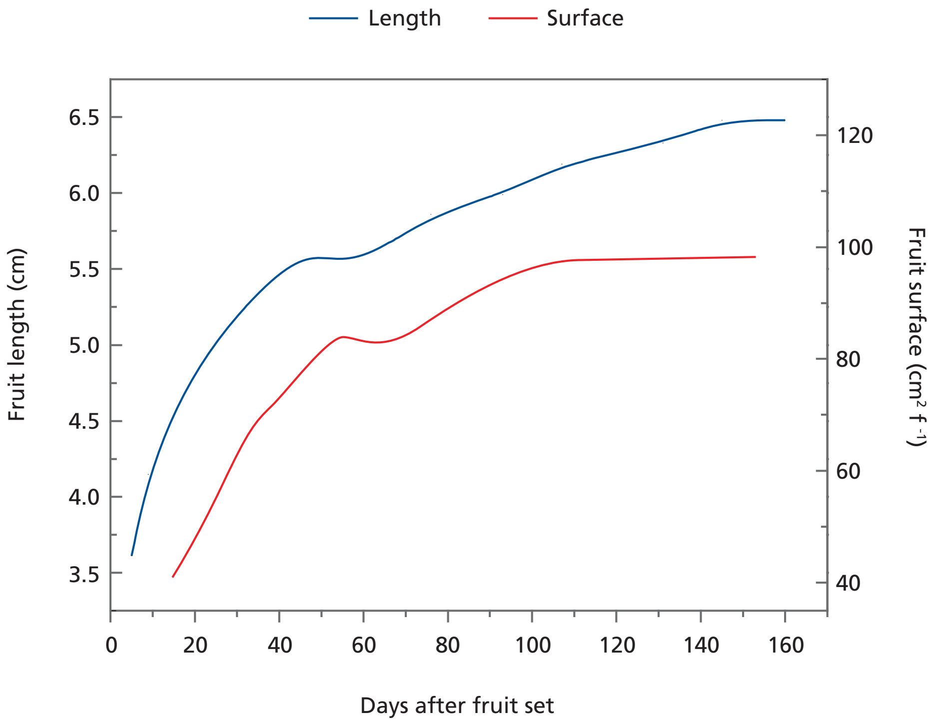


FIGURE 8 Effects on kiwifruit volume of water stress period (21 days) imposed in early (green line) or late summer (red line) compared to well-irrigated vines (blue line).
The grey strips represent the period of water deficit (Redrawn from Miller *et al.*, 1998).

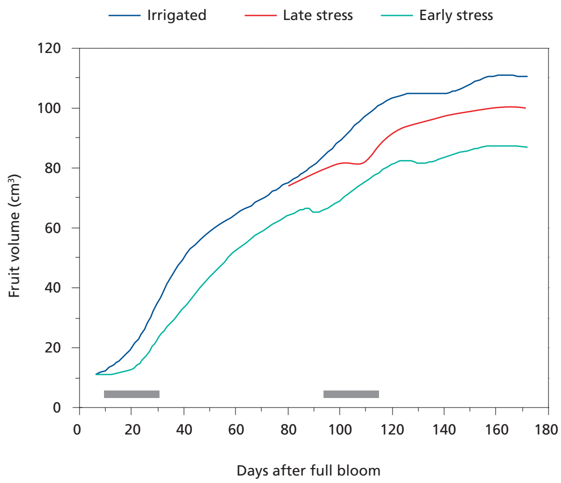


FIGURE 9 Soil volume explored by roots and the relative available water in an ownrooted kiwifruit orchard (740 plant/ha) during the early 4-years after planting. The yield at the third year was 7 tonne/ha. (Field capacity: 22.3 percent DW; wilting point: 11 percent DW) (Adapted from Xiloyannis *et al*., 1993).

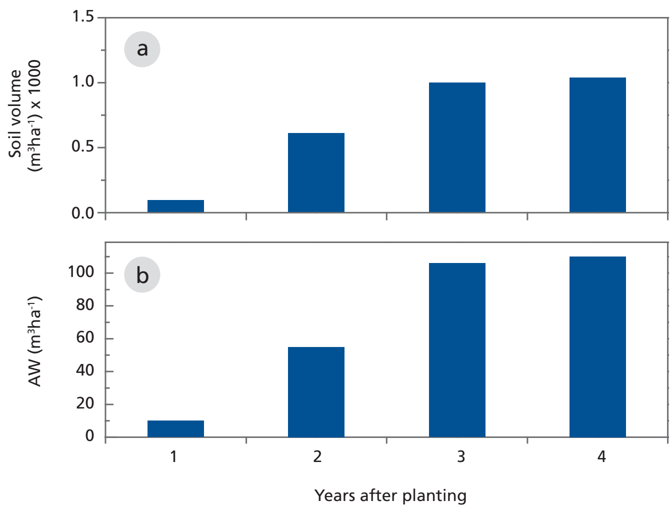
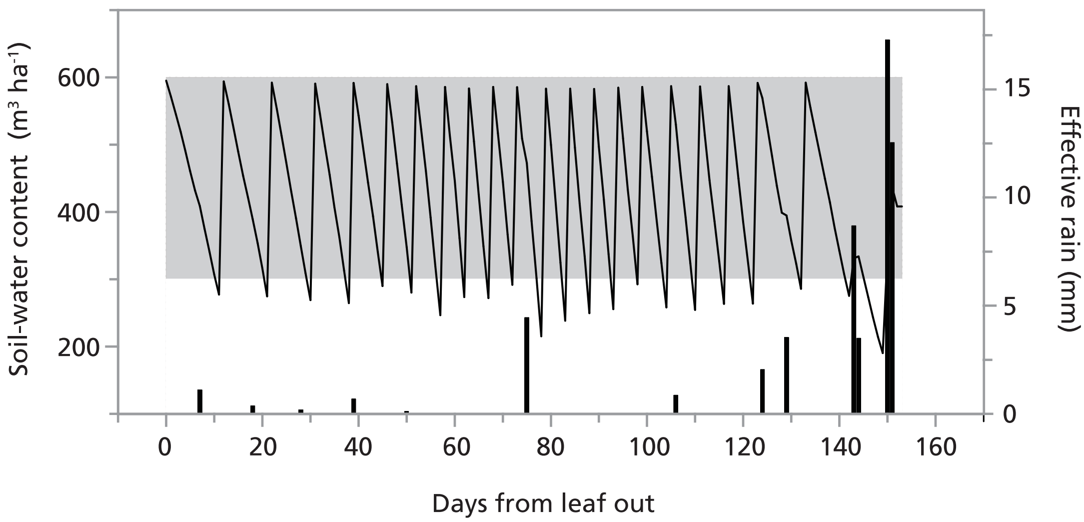


FIGURE 10 Variation of the volumetric soil-water content in a 0-70 cm soil layer. Irrigation has been scheduled when soil water content was below the lower threshold of the readily available water (RAW) (seasonal irrigation volume = 10 012 m^3/ha; ET_o from April to September = 993.7 mm). The grey strip represents the RAW. Bars are the effective rainfall. DOY = day of year. (Soil was not tilled, vines were irrigated by microjet wetting the whole soil surface) (from Montanaro *et al*., in preparation).



water content is high enough to avoid mild water stress. Further, the evaporative demand and vine water consumption are low at this time.

Achieving a specific fruit dry matter (DM) target has been identified by the industry as a key component in the ongoing sustainability of kiwifruit production. Moreover, the minimum DM content for marketable fruit has been established in some countries (e.g. 15 percent DM is the minimum threshold for European markets (EC, 2004). The accumulation of DM in the fruit depends on maintaining high canopy photosynthesis, which is related to the training system, the light distribution inside the canopy and the level of orchard management (irrigation, fertilization, protection from biotic stress). Photosynthetic rates recover within about 10 days upon re-watering in severely (-1.0 MPa predawn LWP) stressed vines (Montanaro *et al.*, 2007) but apparently the loss in dry matter accumulation during a stressed period is never recovered.

Kiwifruit is quite sensitive to water stress throughout the whole growing season, hence soil water content should not decline below 70 percent of the water available in the root zone (Miller *et al.,* 1998). Knowledge of the effective soil volume explored by roots is of great significance when designing and managing irrigation of both mature and young orchards (Figure 8). Because of the peculiar kiwifruit root system, which has low dominance of root apex and a high number of lateral roots (Figure 9 and Photo 1), the kiwifruit has an overall high rooting density in the explored soil volume (~ 0.9 cm per cm^3) (Miller *et al.*, 1998) in comparison to other fruit tree species, but the lack of dominance of a tap root slows down and limits the exploration of the subsoil by kiwi roots. This pattern of root exploration may be partly responsible for the high sensitivity of kiwi to water deficits.

PHOTO 1 Root system of a self-rooted kiwifruit vine uprooted at the end of the fourth year after planting.

WATER REQUIREMENTS AND IRRIGATION MANAGEMENT RECOMMENDATION

On a midsummer day, a Mediterranean kiwifruit orchard consumes ~ 60-70 m^3 of water per ha, and seasonally, around 300-350 litre of water per kg of fruit are supplied (for a yield of 35 tonne/ha). Because of its high water demand and the sensitivity to dry environments, kiwifruit grown in areas of high evaporative demand must be irrigated by microsprinklers in order to maximize the soil surface area that is wetted. Volumetric soil water content should remain close to field capacity at all times (never reaching values below 30 percent of the root zone water storage capacity), hence the need for frequent irrigation applications. The recommended crop coefficients for kiwi are reported in Table 1, and Figure 10 shows an example of the seasonal variation of soil water content in a Hayward kiwifruit orchard (southern Italy 40°08′ N; 16°38′ E).

TABLE 1 Crop coefficients for a mature microjet irrigated kiwifruit (Hayward) orchard grown in the Northern Hemisphere (N 40° 23′ E 16° 45′). (seasonal irrigation volume = 10 012 m^3/ha). Note that the whole soil surface area was wetted and the soil was not tilled.

Apr.	May	June	July	Aug.	Sept.	Oct.
0.5	0.7	0.9	1.1	1.1	0.80	0.80

In conclusion, because of the sensitivity of kiwifruit to water deficits, RDI is not feasible in this species, and full water supply to meet the crop water requirements must be ensured for sustainable kiwifruit production.

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