Chapter 5

Deficit Irrigation in Mediterranean Fruit Trees and Grapevines: Water Stress Indicators and Crop Responses

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.80365

Abstract

In regions with Mediterranean climate, water is the major environmental resource that limits growth and production of plants, experiencing a long period of water scarcity during summer. Despite the fact that most plants developed morphological, anatomical, physiological, and biochemical mechanisms that allow to cope with such environments, these harsh summer conditions reduce growth, yield, and fruit quality. Irrigation is implemented to overcome such effects. Conditions of mild water deficit imposed by deficit irrigation strategies, with minimal effects on yield, are particularly suitable for such regions. Efficient irrigation strategies and scheduling techniques require the quantification of crop water requirements but also the identification of pertinent water stress indicators and their threshold. This chapter reviews the scientific information about deficit irrigation recommendations and thresholds concerning water stress indicators on peach trees, olive trees, and grapevines, as case studies.

Keywords: olive, peach, vine, irrigation management

1. Introduction

Mediterranean climate is characterized by hot dry summers, mostly rainy winters, and partially wet autumns and springs. Rainfall occurs mostly throughout the dormant season of fruit trees, hence vegetative and fruit growth and production are dependent on stored soil water and on irrigation during summer. Precise knowledge on when to irrigate and the amount of water to apply are essential to attain sustainable management and environmentally sound water management, since this natural resource is increasingly scarce and expensive. Projected global warming will enhance this problem as climate change scenarios forecast reductions in the total amount of precipitation and changes in its seasonal distribution, up surging the problem of water scarcity for agricultural use [1]. Agricultural water management comprehends different features related to irrigation, for instance, water productivity index (WP), that is, ratio yield/marketable product or yield/net income, to water used by the crop [2]. Optimization of irrigation strategy is necessary to increase WP and minimize yearly fluctuations of crop production. Irrigation is also essential to ensure the productivity increase and therefore meet the rising food needs in a world with an ever larger population, which is expected to augment by 30% in 2050 [3]. Overall, food production from the irrigated agriculture accounts for 40% of the total output, using only 17% of the land area devoted to food production [4]. The agriculture uses correspond to more than two-thirds of the total of freshwater uses [5, 6]. In many parts of the world, irrigation water has been over-exploited and over-used and freshwater shortage is becoming critical mainly in the arid and semiarid areas, such as some of the Mediterranean region. Freshwater allocation between agriculture and other economic sectors is a source of conflict, claiming to a constant need to improve WP of crops. Thus, precise irrigation scheduling, combining plant and/or soil water stress indicators, is one of the tools that can help growers to achieve this goal [7, 8]. The combination of these indicators with modeling has been defended by several authors [9].

In the last decades, extensive research in fruit crops has shown that they respond positively to conditions of mild water deficit imposed by deficit irrigation (DI) strategies [10]. Under this agronomic practice, the amount of water applied is reduced to a value below maximal crop irrigation requirements allowing the development of a mild water deficit with minimal effects on yield [11, 12]. In fact, several studies have demonstrated that DI is particularly suitable for regions where water is scarce, and improving WP is a critical goal [13, 14]. The increase of WP when DI is applied to woody crops is explained by: (i) DI efficiently reduces plant transpiration (T) by stomatal closure in fruit trees and vines as tall, rough canopies are well coupled to the atmosphere [15]; (ii) in most woody crops, net incomes are not linearly linked to biomass accumulation, but to fruit yield and fruit quality [4] and DI normally enhances the quality of fruits and derived products [16–18], eventually increasing the net income of the grower; and (iii) DI increases WP by the control of excessive growth that reduces pruning frequency and intensity. In fact, the control of plant vigor has a particular importance in orchards with high-plant densities, also called super intensive orchards [19, 20], thus DI may increase their productive life through decreasing the competition between trees for solar light [21]. Scheduling DI in commercial orchards usually requires knowledge of the soil water capacity, the actual plant water requirements, plant water relations, and plant stress sensitivity according to their phenological stages.

Fruit orchards and vineyards constitute an integral and significant part of the Mediterranean environment and culture, with a great economic, ecological, and social support in different countries [22]. Therefore, it is easy to understand that the study of the response of fruit trees and vineyards to deficit irrigation is of key importance for the agriculture and the economy of the Mediterranean countries. Based on our own experimental results and also on information from the literature, the aim of the present chapter is to provide criteria to enable the sustainable management of irrigation at farm level in agricultural areas, where water is scarce. Three of the most important productive fruit species of the Mediterranean basin are addressed: peach, olive, and grapevines.

2. Concept and strategies of deficit irrigation

According to Fereres and Soriano [4], the term DI should be defined in terms of the level of water supply in relation to maximum crop evapotranspiration (ETc) and the terms deficit or supplemental irrigation are not interchangeable, because in the latter, a maximum yield is not sought. It is widely known that conditions that limit water use usually decrease crop evapotranspiration (ETc) and crop growth by the limitation of its main component, transpiration (T), and therefore carbon assimilation. Thus, it is of remarkable concern to be aware of the maximum reduction of ETc with the minimum impact on the economic return of production and quality on mature fruit trees, as compared to those obtained when ETc is fully replaced. In young fruit trees, it is not desirable to practice water deficit irrigation once in this stage of development, the main objective is to maximize vegetative growth leading to reach the mature phase as faster as possible to attain full production [23]. The correct application of DI requires precise knowledge on the crop response to water stress at different phenological stages, to identify the periods when fruit trees are less sensitive [24] and in order to define the level of DI to be applied.

This work focuses on the main strategies of DI since they have been studied and applied in olive, peach orchards, and grapevines. They can be depicted as: (i) sustained deficit irrigation (SDI), with a deficit throughout the season; (ii) regulated deficit irrigation (RDI), with periods when the irrigation can be stopped or reduced to a minimum level, based on physiological aspects of the response of plants to water deficit, and (iii) partial rootzone drying (PRD), see Section 2.3 for definition. All these practices aim at maximizing the efficiency of water use and WP [25, 26] with minimum impact on yield, which can be attained if precision tools are used to manage DI [27, 28].

2.1. Sustained deficit irrigation

Sustained deficit irrigation is an irrigation strategy based on the distribution of a reduced water volume, controlled by a water stress indicator or as a percentage of the full water requirements for a crop throughout the whole irrigation season, so that the water deficit is intended to be uniform over the whole crop cycle to avoid the occurrence of severe water stress at any particular moment that might have unfortunate results [29]. At the end of the 1970s, field experiments on irrigation below the ETc demand, but at very frequent intervals, have shown very promising results [30].

2.2. Regulated deficit irrigation

To our knowledge, the concept of regulated deficit irrigation (RDI) was first presented in the 1980s [31, 32] with the aim of controlling excessive vegetative growth in peach orchards. They founded that water deficit limited shoot growth, when shoots and fruits were competing for photo-assimilates. It is important to bear in mind that fruit tree sensitivity to water deficit is not constant during the whole growing season, and a water deficit during a phenological stage less sensitive might benefit WP, as it increases irrigation water savings, and minimizes negative impacts on yield and crop profits [31, 33, 34]. So, when a RDI strategy is applied, it may be necessary to supply full irrigation during the drought sensitive phenological stages and irrigation may be stopped or restricted during the non-critical periods, less sensitive to drought [31, 35]. The crucial constraints of RDI are: (i) difficulty in keeping plant water status within tight limits of water deficit during noncritical phenological periods; (ii) depending on management, unexpected variation in evaporative demand may result in severe losses of yield and fruit [36]; (iii) need to define precise criteria for the water deficits, in different growth conditions, related to species, weather, soil depth, fruit load, and rootstock [37, 38]; and (iv) lack of precise knowledge in the effect of water deficit during bud development [38, 39].

2.3. Partial root drying system

Partial rootzone drying (PRD) is a strategy of DI that consists in irrigating only one half of the rootzone in each irrigation event, while the other half is allowed to dry. For this, both halves are watered alternately [40]. This technique was first developed in Australia for vineyards and relies on root-to-leaf signaling induced by a rootzone that is in a drying process [41], decreasing stomatal aperture and leaf growth, preventing water loss [42, 43] with a little effect on photosynthesis, hence increasing transpiration efficiency [41]. At the same time, the wet portion of the root system receiving water enables the plant to maintain a favorable plant water status, such that yield is not significantly compromised and quality may even improve [42]. The PRD performance is based on the assumption that photosynthesis and fruit growth are less sensitive to water deficit than transpiration, and besides, water deficit induces the production of chemical signals, like ABA in the root, that can be translocated to leaves [44] inducing stomatal closure. As demonstrated in a recent meta-analysis, the advantages of PRD in relation to RDI are highly controversial and also depend on the soil texture, a success or enhanced yield performance with RDI and PRDI occurring most likely in deep and finely textured soils [45].

3. Water stress indicators and thresholds

3.1. Water status indicators: use in research and in irrigation scheduling practices

The use of water status indicators has been enhanced not only by the increasing importance of DI, but also due to the increased possibilities of automatically recording of some of those variables. This requires the selection of the appropriate variables and their threshold values, for different objectives concerning marketable yields. In the perspective of this contribution, the question is how to select a water status variable and how to transform it in a useful stress indicator for DI scheduling. The requirements of a water stress indicator include the consideration of a consistent answer (similar response in similar circumstances), low cost, and easiness of use, reliability with reasonable low sampling, and possibility to define thresholds that facilitate a decision. Above all these requirements, it is necessary to measure or derive an indicator that depends much more on the water stress affecting yield, then on other variables independent from water stress (such as atmospheric demand).

Stomatal conductance (g_s), which decreases as soil water deficit develops, is a primary mechanism in regulation of plant transpiration; therefore, a potential indicator of water stress [46]. Stomatal opening is not only affected by the soil water status, but also by external factors not related to water stress, such as meteorological conditions at leaf level, mainly vapor pressure deficit (VPD) [47]. Consequently, it makes more sense to use g_s taken in relative, which is the value in a stressed crop divided by the correspondent value in a well-watered one. Such measurements are time consuming, due to the required sampling, consequence of the high scattering in the canopy and instability with clouds or gusts of wind. It is very difficult to automate g_s measurements and the sensors used (porometers) are delicate and expensive. Therefore, its use is limited to research.

Due to the buffer role of the soil, soil water potential and soil water content (θ_s) have the advantage of being almost independent from diurnal atmospheric variations. Soil water potential measurements (with tensiometers) are easy and cheap, they can be, in principle, easily automated, but there are limits concerning the range of soil water status in which tensiometers operate well. The changes in θ_s (volumetric fraction) have the advantage of being a direct component of the soil water balance equation. The relative extractable water (REW) is a very useful concept that relates the actual volume of water available for plants to the total available water capacity, between the so-called field capacity and permanent wilting point (TAW) [48].

Leaf water potential (Ψ_{leaf}) is also related to stomatal closure. Even if, for different reasons, reductions in stomatal opening can occur without changes of Ψ_{leaf} [47, 49], this indicator has been broadly used for irrigation scheduling purposes.

The use of stem water potential at noon (Ψ_{stem}) has the advantage of being less disturbed by environmental conditions than Ψ_{leaf} [50] but it loses its relevance in the case of isohydric behavior, as such plants close stomata so effectively that they avoid important decreases in noon Ψ_{leaf} [51, 52]. In such cases, the difference between irrigated and stressed plants can be higher at predawn than at noon and predawn leaf water potential (Ψ_{pd}), being independent from diurnal oscillations can better represent water status in both cases: isohydric or anisohydric behavior.

The difficulties in finding meaningful correspondence between gas exchange and plant water balances impose limitations on accurate measurement of plant water stress in field conditions. It is largely demonstrated however that, in spite of such limitations, Ψ_{pd} or Ψ_{stem} are variables considered reliable as water status indicators for irrigation scheduling purposes and have been almost unavoidable in research studies [53, 54].

Several variables have been derived from stem diameter variations (SDVs) [55, 56], with the advantage of being cheap and easily continuously recorded. The most used are the organ (stem or fruits) growth rate (OGR), the daily trunk shrinkage (DTS), or the relative DTS

(RDTS), where the relative value of daily amplitude in diameter is divided by the correspondent in well-watered plants, obtaining an indicator practically independent from atmospheric variations, as required. Sometimes, maximum and minimum trunk diameters are used individually (MXTD and MNTD).

The success of SDV-derived variables depends on plants' behavior. Its application seems to be more successful when applied to conditions of anisohydric behavior [57]. Unfortunately, the outputs often are of difficult interpretation [56, 58], sometimes being the use based on visual and qualitative analysis.

Also, as diameter changes, sap flow rate can be continuously and automatically recorded with high resolution across large temporal scale. Sap flow sensors became popular in last decades, and by measuring fluxes, for the same reasons of independence from atmospheric demand, they only can be directly linked to water status indicators, provided relative transpiration (RT) [48] and the absolute values are not used. The inconvenience of requiring well-watered plants as reference limits its use to research.

As the stomatal conductance is reduced to prevent excessive transpiration, the temperature of leaves and canopy rises. Therefore, the temperature of the canopy in relation to the air is linked to the level of water stress, due to the effect of transpiration evaporative cooling. Several indexes have been proposed and applied in different conditions, space and temporal scales, mainly following the work of Jackson et al. in early 1980s [59], to derive the crop water stress index (CWSI). Measuring canopy temperature is a simple procedure using inexpensive infrared thermometers or any other optical devices that can take many observations rapidly without disturbing the plant. However, canopy temperature is affected by multiple factors, namely VPD, turning it complex to relate with soil water availability.

Overviews and results on remote sensing approaches have been presented [60, 61]. The "advantages and pitfalls" of plant-based methods in the perspective of irrigation scheduling have been discussed by Jones [36]. Fernández [57] recently presented a review of soil or plant water status and other variables used as other water stress indicators for irrigation scheduling. In general, technologies have greatly improved over the years, sensors are more affordable but sampling is still a limitation. In all cases where the relative independence from daily variations in atmospheric demand requires well-watered plants as a reference, this represents a practical disadvantage, limiting its use to the field of research. Unfortunately, these affects many possible indicators and the number of those remaining that are not excessively time consuming, is reduced to a few.

Therefore, the combination of these indicators with models for water balance is advisable [48]. In fact, the most popular variables in irrigation scheduling practices, used at present, either by farmers or enterprises, providing irrigation scheduling services, often include soil moisture quantification, sometimes as a complement to water balance models based on estimated ETc, for example, Ondrasek [1]. This is related to easiness, cost, rapidity to obtain the outputs, simplicity of data treatment/interpretation, and significance. Furthermore, the advantage of directly linking θ_s with the outputs from water balance is crucial. The problems of spatial heterogeneity and the quality of the measurements are often disregarded, meaning that a qualitative use of these outputs is often accepted and considered useful.

Experience and knowledge of varieties, environmental conditions, and technical and financial capabilities of the growers will ultimately determine the most adequate method or combination of methods to use for evaluation of the status of their crops and how to better manage them.

3.2. Olive

In general, plant water potential seems to be a better indicator than the SDV-derived variables, when full irrigation scheduling is applied. Moriana et al. [62] suggested that values of $\Psi_{stem} > -1.65$ MPa in field conditions provide the maximum g_s and when $\Psi_{stem} > -1.8$ MPa, maximum yield was obtained [63]. Pérez-López et al. [64] suggested that a threshold value Ψ_{stem} of −2.0 MPa (moderate water deficit) may be used to DI. Nevertheless, Ψ_{stem} in DI trees was affected by crop load and environmental conditions. Indeed, Moriana and Fereres [65] reported that VPD produced a variation on Ψ_{stem} from −0.8 to around −1.4 MPa in fully irrigated olive trees of different ages and fruit load. A threshold value of $\Psi_{pd} > -0.9$ MPa was often proposed to FI [66–68].

It has been observed that SDVs are affected by seasonal growth patterns, crop load, plant age and size, and other factors, apart from water stress [58]. So, the use of SDV needs expert interpretation, which limits their potential for automating the calculation of irrigation depth (ID). Despite this, they refer that, when combined with aerial or satellite imaging, SDV measurements are useful for scheduling irrigation in large orchards with high crop-water-stress spatial variability.

Alcaras et al. [69] reported that the increase in MXTD showed strong relationships with REW, Ψ_{stem} and g_s. Trunk growth rate (TGR) showed a very early response to water-withholding and it decreased along with Ψ_{stem} until it reached a constant negative growth rate, at Ψ_{stem} of −2.7 MPa. In their study, DTS was much less responsive to irrigation than either MXTD or TGR. They suggest the use of automated soil moisture sensors if reliable soil moisture values can be obtained, and indicate that a continuous recording of trunk diameter has some potential, but further investigation of MXTD and TGR is warranted.

3.3. Peach

For peach, the use of Ψ_{stem} for defining thresholds under DI conditions is referred by Girona et al. [70], who found the value −1.5 MPa, the limit over which the impairing of bloom fertility appears. Naor et al. [39] have observed that the value of −2.0 MPa for SWP was a threshold for the occurrence of double fruits, while Lopez et al. [71] suggest a threshold of −1.05 MPa to obtain fruits with positive effects on consumer acceptance, without significant impacts on fruit composition and yield, as they have observed that a threshold of −1.25 MPa would reduce fruit size and yield, even if advantageous for consumer acceptance.

Other authors, using relative transpiration (RT), have observed that a minimum value of 0.7 has to be observed to avoid yield and quality losses [72].

Using the relationship between (RT) and $\Psi_{pd,}$ it was observed [73] that the Ψ_{pd} threshold corresponding to RT equal to 0.7 is −0.33 MPa. Using CWSI, based on the temperature differences between canopy and air, a threshold of 0.5 was found to trigger irrigation [74]. It was also found that it is possible to identify a threshold in the relationship between g_s and Ψ_p, corresponding to a change in the plant behavior, equal to $\Psi_{pd} = -0.45$ MPa [75].

3.4. Grapevines

A number of indicators related to plant water status of grapevines have been discussed in the literature such as g_s [76, 77], Ψ_p, or Ψ_{stem} [78–81], sap flow and SDV-derived variables. Being very sensitive to transient meteorological conditions, g_s at the time of measurement performed poorly in detecting grapevine water stress in Alto Douro vineyards in Portugal [82]. This can be eventually explained by the fact that either the cultivar displayed an anisohydric behavior [51] or the relative conductance was not used. According to Acevedo-Opazo et al. [83] and Lanari et al. [84], Ψ_{leaf} or Ψ_{stem} are reported to correlate well with both soil water content and net photosynthesis, and they are suitable to perform irrigation scheduling on grapevines under DI. In other studies, a better performance was obtained by using this variable measured at predawn [56, 79, 85]. According to Silvestre (2018, personal communication), there is some experimental evidence that Ψ_{stem} is not a good indicator in vineyards under high VPD.

Measurements of vegetative growth, when applied to grapevines, can offer simplicity, sensitivity to water stress over extended periods [86], as tissue expansion underlying vegetative growth responds to water status, and are interrelated with crop yield and quality. The stage development of shoot tips can be used reliably to estimate vineyard water status and manage irrigation, given that moderate water stress is primarily affected by soil water content [86]. An experiment to evaluate the visual assessment of shoot tip stage as a method to estimate the water status of vineyards and its utility in vineyard management showed that calculation based on the tip stage [87] is fast, nondestructive, and does not require special skills or equipment and it is independent of prevailing weather conditions [86].

Brillante et al. [80] observed that canopy temperature was an important predictor in determining the water stress experienced by grapevine, especially at midday. These positive results are not always observed: due to excessive wind and turbulence in SW of Portugal, the significant differences in DI treatments could not be identified using proximal radiative canopy temperature [88]. Bellvert et al. [89] emphasized the influence of VPD in using airborne thermal imagery in vineyards. Canopy temperature and derived parameters such as the empirical CWSI [59] have also been used in vineyards by Grant et al. [90] and King and Shellie [91] to monitor plant water stress.

Sap flow performed satisfactorily in detecting grapevine water stress in Alto Douro [82], and in a study developed by Selles et al. [92], diameter changes proved more sensitive than water potentials. Again, many different results were obtained in South Portugal, where differences in DI could not be distinguished using SDV, but were quite clear regarding sap flow records for different treatments [56]. If a single indicator based on sap flow or SDV did not reflect the grapevine response, according to Oliveira et al. [93], their combination could provide more detailed information.

In general, threshold values for DI in vineyard based on water potential have been abundantly suggested, but in the case of vine production, the quality issues are crucial; therefore, information is quite complex and scattered. Classical recommendations often include the use of leaf water potential [94]; a new water stress index based on a water balance model was proposed and tested by Gaudin et al. [95] as a tool for classifying water stress experienced by grapevines in vineyards.

4. Responses to deficit irrigation regarding agronomic aspects and quality

4.1. Olive

4.1.1. Vegetative growth and production cycle

Shoots growth and fruits development are cyclical and both are repeated on an annual basis, but only vegetative growth is completed in the same year, while olives production needs two consecutive seasons [96]. In the first one, the formation of the buds and their floral induction take place. In the following year, flower development occurs as well as flowering, fruit set, growth, and oil accumulation. In Mediterranean climate conditions of northern hemisphere, shoot growth takes place from March until the middle of July, although a second flow of growth can occur in late August, when olive trees are fully irrigated, or at the beginning of autumn rainfall [97]. Water deficit reduces shoots growth and has a negative effect on the potential production of the following year. Flowering occurs at the end of spring, and it is very sensitive to water deficit [63], or at high temperatures. Fruit set is very sensitive to water deficit and fruit growth has a double sigmoid behavior [96, 98] with three main stages, as follows. Phase I is the fast-growing, when both the cell division and expansion contribute to the size increase, the endocarp being the main tissue in development, reaching 80% of the volume of the olives [98] with full expansion about 8 weeks after full bloom [99]. The occurrence of water deficit in this stage results in a small endocarp and extreme water stress can compromise the viability of the fruit. Phase II, of slow-growth, is less sensitive to water deficit [100], when the endocarp progressively hardens and both the embryo and the endocarp reach their final size [98]. During phase III, of fast growing, parenchyma cells of the mesocarp experience a large increase in size, entirely due to cell expansion, and the oil biosynthesis begins [98]; so water availability for the fruit determines its size and the accumulation of oil. Thus, water deficit may produce small fruits and the mesocarp/endocarp ratio is reduced due to decreased weight of the mesocarp.

4.1.2. Olive response to water deficit

Many studies had showed that high soil water availability increments yield components such as fruit number, fruit fresh weight, fruit volume, pulp:stone ratio, and oil content; therefore, increasing fruit and oil yields [12, 63] and that water scarcity can have a negative effect, depending on its level. In addition, irrigation regime can influence the relationship between vegetative and reproductive growth [101].

Hernandez-Santana [102] observed that olive trees prioritize fruit growth and oil content accumulation over vegetative growth, suggesting a higher sink strength for reproductive growth than vegetative growth. In the initial years of orchard establishment, when rapid vegetative growth is desirable in order to quickly obtain optimum tree size and canopy, as well as to begin fruit production as soon as possible, it is critical not to depress vegetative activity. For this reason, in commercial orchards, DI is commonly implemented only once, trees are fully grown to avoid negative effects on the formation of tree structure during the training period [102]. DI at early stages of tree development may result useful not only for water saving but also for controlling vigor in super high-density (SHD) orchards, in particular in regions where local conditions lead to excessive vegetative growth, such as in northern Argentina [103]. The choice and success of DI strategy is conditioned by tree density and rootzone size. It seems that SDI is more interesting when trees explore large volumes of soil, as in low-density orchards that maximize the availability of stored soil water per tree, compared to higher densities [97, 104]. Moreover, the success of SDI as compared to FI depends on the crop load of olive. About this issue, Martín-Vertedor et al. [105, 106] conducted a long term studied in "Morisca" orchard (417 trees ha^{-1}), in the Southwest of Spain. They observed that SDI (75% ETc) reduced yield in "on" years. Nevertheless, they reported that this DI could be advisable during "off" years, when a lower water use is observed, and trees are less sensitive to water deficit with low-crop load. There is still uncertainty about which DI strategies are better, regarding SDI or RDI [58, 101].

Lavee et al. [107] suggested that the most efficient schedule for RDI irrigation was to withhold water till the end of endocarp hardening and then to apply full irrigation from that stage till 2 weeks prior to harvest.

The literature provides results, for low-density orchards (300–600 trees ha^{-1}) under FI [63], SDI [12], RDI [11], and PRD [108] and for SHD olive orchards >1500 trees ha^{-1} [109].

Often, DI strongly reduces vegetative growth, but only slightly reduces the final fruit volume. Water stress caused a higher reduction in fresh fruit yield than oil yield due to a higher oil concentration in DI irrigated trees "in Picual" (Spain), without differences between SDI and RDI [11]. Moreover, Iniesta et al. [11] observed that WP for oil production has tripled for a 25% decrease in total water applied. They conclude that both irrigation strategies may be used with moderate reductions (about 15%) in oil yield. Similarly, Fernandes-Silva et al. [12] ("Cobrançosa," Portugal) reported that for a SDI at 30% ETc, WP for oil is higher or very close to FI, depending on the year, and is more than double the one obtained in rainfed conditions; oil yield is reduced only 35% as compared to FI, while saving 60% of water applied. Nevertheless, oil concentration on a dry matter basis (DM) in SDI was 7–19% higher as compared to FI, hence oil yield reduction was lower than yield of fruit (DM). The higher oil yield observed in FI is mainly due to higher number of fruits, although under SDI, fruits have slight higher values of mesocarp (>3–5%) as compared to FI olives, mainly attributed to a higher crop load in FI olive trees. Fernandes-Silva et al. [12] founded a good relationship between the oil amount per mesocarp dry mass (g) ($y = 0.83 \times -0.17$, $r^2 = 0.97$). This may be useful in supporting the decision of the most suitable time for harvest to optimize oil productivity.

Irrigation is particularly an important component in SHD orchards as the trees are expected to have more reduced volume of the rootzone. There is not a consensus on the best irrigation approach for SHD olive orchards. A reduction in water applied up to 16% in July did not affect oil production [110], while a reduction of 72% (30 RDI) resulted in 26% less oil yield and a best balance between water saving, tree vigor, and oil production was achieved [19].

Fernández et al. [19] and Padilla-Díaz et al. [111] applied RDI in a SHD olive orchard using a strategy of 45% of the total irrigation requirements (IN) in total distribution, according to the vegetative phase: period 1–100% IN, before and during bloom; period 2–80% IN, during the maximum rate of pit hardening (6–10 weeks after bloom) that coincide with the phase of flower induction; period 3–100% IN at the end of pit hardening until the last week of September, and 20% IN during fruit maturity. During the end of June and till the last week of August IA was 20% of IN.

Marra et al. [112] conducted a study in west of Sicily (Italy) in a SHD orchard (cv "Arbequina"), where five irrigation treatments were tested: 100% of IN, three SDI treatments with 75, 50, and 25% of IN, and a nonirrigated "rainfed" control. They found that oil yield increased with higher irrigation amounts up to a certain level (50 SDI) and a further increase in irrigation level improved crop load on the one hand, but decreased vegetative growth and increased the severity of biennial bearing. They conclude [112] that irrigation scheduling in the new SHD orchards should be planned on a 2-year basis and corrected annually based on crop load.

With regard to PRD, Wahbi et al. [108] analyzed the effect of applying PRD (50% of ETc) to "Picholine marocaine" olive trees in Marrocos in field grown conditions. They reported a yield reduction of 15–20%, achieved with 50% ETc, and that WP increased by 70% in PRD treatments. However, the lack of comparison between PRD and RDI did not clarify whether the effects observed were specifically triggered by PRD or if they were simply associated with general water deficits. Later, Aganchich et al. [113] addressed this question by comparing the effects of PRD and RDI in the same cultivars grown in spots. They reported that plant vegetative growth was substantially reduced under both PRD and RDI, more pronounced in PRD, compared with FI, as expressed by lower values of shoot length, leaf number, and total leaf area. In many cases, PRD treatment has been compared to a FI treatment, so doubt remains on whether the observed benefits correspond to the switching of irrigation or just to PRD being a DI treatment. In addition, not always a PRD treatment has been found advantageous as compared to a RDI treatment [66]. Taking into account that an irrigation system suitable for the PRD approach is more expensive and difficult to manage, the literature suggests that there are no agronomical advantages on PRD as compared to RDI [66]. It is of great importance to bear in mind that results depend mainly on cultivar, orchard characteristics, environmental conditions and agronomic practices, and to the large variability in rainfall, climate, and soil types between the various growing regions. Consequently, caution must be taken when applying the findings reported by different authors to a particular orchard.

4.1.3. Effect on fruits and olive oils quality

The concept of quality in fruit products is wide, complex, and dynamic. In the case of olive trees, two main products are obtained from olive fruits: virgin olive oil (the juice of the fruit) and table olives; both are staple foods of the Mediterranean diet. The quality attributes that are considered for each product largely differ from one another.

High irrigation rates are associated with a decrease mainly in minor compounds of virgin olive oil (VOO) as they are total polyphenols (TP), orto-diphenols (OD), tocopherols (TC) volatile compounds (VC) [16, 114] that have an important role in nutritional value, biological proprieties, and organoleptic characteristics of VOO. There is a controversy about the effect of irrigation in overall quality of VOO. In the literature, there are researchers who argue that FI lowers the quality of olive oil [115]. If this may be true for Cvs poor in TP, such as "Arbequina," FI may compromise the conditions necessary for virgin extra category and in other hand, decrease its self-live time. Nonetheless, in Cvs very rich in PT (>1000 mg/kg), such as "Cornicabra," VOO is very bitter and pungent, and therefore with poor acceptability by the consumer, FI may help to overcome this problem.

Motilva et al. [116] observed that RDI strategies applied to "Arbequina" induced a significant increase in polyphenol concentration and oil stability. Fernandes-Silva et al. [16] found a strong relation ($r^2 = 0.715$; $p = 0.033$) with TP and between water stress integral (WSI). Similarly, Pearson's correlation coefficients between oxidative stability (OS) and TP was high and significant (p = 0.026), but no significant correlation was found between OS and TC (p = 0.322). Moreover, Gómez del Campo [110] and García [117] observed that the application of RDI in summer produced a significantly higher OS, which coincided with a significantly higher content of TP derivatives. These compounds are of great interest because they influence the quality and the palatability of VOO and increase their self-life time by slowing the formation of polyunsaturated fatty acid hydroperoxides.

Irrigation regimes either equivalent to 30 or 100% of ETc, applied to olive trees, "Cobrançosa" affects significantly the activity of L-phenylalanine ammonia lyase (PAL, EC 4.3.1.5), that is considered as the key enzyme in phenolic biosynthesis, the TP and amount of individual polyphenols [17]. Higher PAL activity, TP and individual polyphenol contents were observed for the rainfed conditions in the first picking date, and decreased with maturation of the olive fruits. Also, this effect was observed for the two irrigation regimes applied. The difference in the PAL activity, TP and individual polyphenol content between the three water regimes, decreases as olives become more mature.

Olive oil fatty acid composition is often not affected by RDI strategies [118], although other studies indicate that irrigation strategies cause small variations in the oleic and palmitic acids [16, 116]. Magliulo et al. [119] reported that olive oil fatty acid composition from two different cultivars ("Frantoio"; "Leccino") was more affected by varietal factors and climatic conditions of the year than by water regimes. Curiously, when cv "Arbequina," is cultivated in warm arid valleys of North Western Argentina, produced a lower content of 18:1 acid in relation to the Mediterranean region [120] and a decrease with increasing temperature during oil accumulation of 2% per °C was found.

DI can also influence the sensory attributes of olive oil. In cultivars such as "Arbequina," which normally has low-phenolic concentrations, DI is beneficial due to the greater polyphenol concentrations. More phenolics contribute to better balanced oils with a more sophisticated pungent and bitter flavor [114].

With regard to the quality attributes of tables' olive, they are also affected by DI strategies. Cano-Lamadrid et al. [121] and Cano-Lamadrid et al. [122] evaluated the quality of table

http://dx.doi.org/10.5772/intechopen.80365

olives ("Manzanilla"), after processing that were previously submitted to three irrigation treatments: FI; RDI_1 with moderate stress during pit hardening (soft water stress) and RDI_2 with low stress at the end of flowering stage, and moderate during pit hardening. They observed that FI olives had the highest weight and size, and were rounded. Color coordinates L* and b* had the highest values in RDI_2 olives. Aldehydes and monounsaturated fatty acids predominated in FI olive fruits, while terpenes and polyunsaturated fatty acids predominated in T1 fruits, and saturated fatty acids were abundant in RDI_2 olives. Sensory evaluation indicated that global acceptance was higher for RDI_1 olives, with high satisfaction degree among consumers due to fresh olive flavor, crunchiness, and global satisfaction. They argue that both RDIs are effective and can be a good alternative irrigation practice for this cultivar. However, these authors evaluated table olives quality after processing, an evaluation after harvest, that is, before olives processing may be more interesting.

Water deficit effect could increase of PhytoPs content, chemical compounds analogs to prostaglandin, which belong to a novel family of plant effectors, may be related to the enhancement of reactive oxygen species (ROS) production under drought stress, which induce the formation of an array of lipid peroxidation products [123]. The phase II of fruit growth can be noncritical considering fruit yield or fruit size [124] but is clearly critical for PhytoPs formation. Thus, olive table trees under RDI can be considered as complementary actions to enhance the PhytoP content and hence their potential beneficial effects on human health as they play a role in regulation of immune function [125].

4.2. Peach

4.2.1. Vegetative and productive cycle

RDI is based on restraining irrigation during certain periods of the vegetative cycle of the crop, therefore implying the knowledge of the several phases and sometimes its differences between genotypes, since the length of some phases (fruit development period and ripening) varies for early-maturing or late varieties [126]. The phenological stages of peach *Prunus persica* L. Batsch) can be depicted as shown in **Figure 1**. During the fruit growth period, three phases are classically considered: phases I and III, where rapid growth occurs and a phase II characterized by a plateau [127] having the growth curve, a double sigmoid pattern [128].

4.2.2. Peach response to water stress

Several studies over the last decades have addressed the use of deficit irrigation, namely RDI, in peach. Ref. [31] have applied the method to peach during the phase of final swell and observed a significant production and fruit growth increase, if irrigation restrictions were applied while excessive vegetative vigor could be suppressed to favor fruit growth. Mitchell and Chalmers [32] have used RDI during the phase of fast vegetative growth, obtaining similar yield and fruit growth to a nonrestricted situation, while saving ca. 30% of irrigation water and controlling the vegetative growth. For the post-harvest phase, [129] observed that irrigation reduction decreased pruning requirements and increased flowering in the next season. For the same phase, and also during fruit development, [130] saved 40% of irrigation water with light implications in production and fruit size. More recently, the benefits of applying

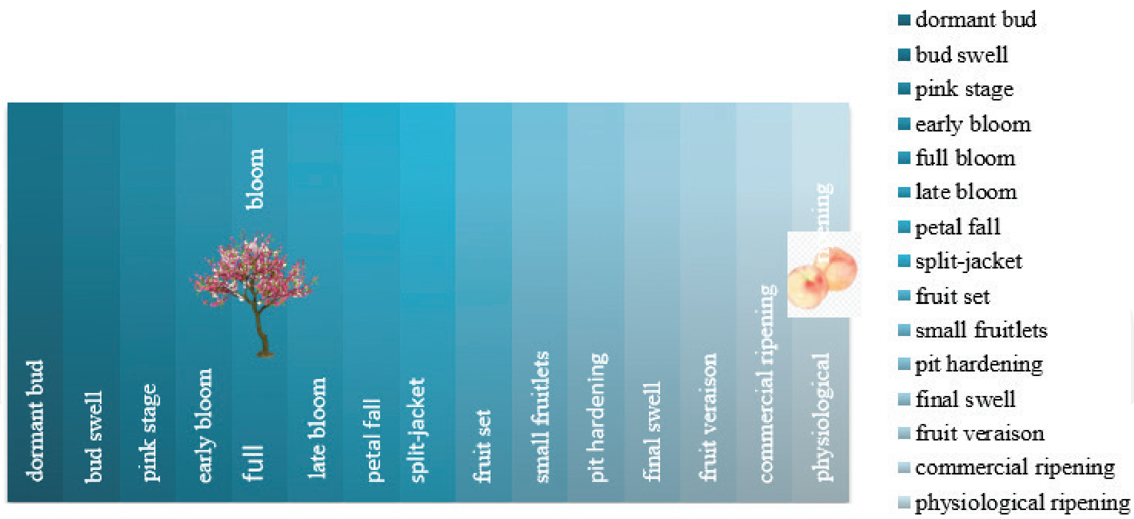

Figure 1. Phenological phases of peach (*Prunus persica*).

RDI during stage II of fruit development have also been stated [89], including beneficial reduction of tree vigor and improvement of fruit quality [71]. De la Rosa et al. [131] applied RDI after harvest, concluding that it was beneficial to control vegetative growth. Results from [70] also confirm the positive effects of RDI to control vegetative growth without a significant effect in fruit production. However, these authors recommend caution in long-term (over 3 years) application of RDI, since it gradually reduces canopy, what can affect fruit yield. The same effect was observed by [132, 133], and these last authors even advise the discontinuing of RDI after 3 years. A prevalent long-term plant adaptive response over an immediate causal effect of RDI in a single season is therefore foreseen. **Table 1** presents an overview of the most common practices for RDI in peach referred in literature. RDI has been mostly applied in the phase of late fruit development or after harvesting, and in general, the most reported effects refer to a decrease in vegetative vigor, production and fruit size, but an increase in fruit quality and water use efficiency.

Thus, for peach, considering the available information on the use of RDI, production is not significantly affected as long as applied in an adequate phase and bearing in mind, the variety relative precocity. Other advantages can be pointed out such as an easier management of the crop (if the vegetative vigor is restrained) and an increased efficiency in the use of water resources. Precaution is advised concerning long-term cumulative effects in production, as sometimes a negative influence has been observed.

PRD strategies for peach have showed contradictory results as sometimes a positive effect has been observed in yield, in comparison with other conventional DI practices [43], but other studies advocate no agronomic advantages in such technique, especially if the increased installation costs are considered [137].

4.2.3. Effect on fruits quality

Studies addressing the effect of deficit irrigation on peach fruit quality either refer to an improvement of it [71] or no effect [134, 136].

RDI	Phase															RDI effects					
Reference	**Dormant bud**	**Bud swell**	**Pink stage**	**Early bloom**	**Full bloom**	**Late bloom**	**Petal fall**	**Split-jacket**	**Fruit set**	**Small fruitlets**	**Pit hardening**	**Final swell**	**Fruit veraison**	**Commercial ripening**	**Physiological ripening**	**Tree vigor**	**Production**	**Fruit size**	**Fruit quality**	**WUE**	**Irrigation water/ restrictions**
Mitchell and Chalmers [32]						■	■	■	■							<	=	=			<30%
Johnson et al. [129]															■	<					Several
Girona et al. [130]									■	■	■	■	■	■	■						<40%
Bellvert et al. [89]											■	■	■	■	■	<			>		50% ETc
Lopez et al. [71]													■	■			</=	</=	>		15% ETc
De la Rosa et al. [131]															■	<					60% FI
Girona et al. [70]													■	■	■	<	=				35% ETc
Naor et al. [39]															■		<		<		SWP −2.0 MPa
Marsal et al. [133]													■	■			<	<			80% ETc
Marsal et al. [133]													■	■	■			<			SWP >−1.5 MPa
Marsal et al. [133]													■	■	■			<			SWP >−1.8, −2.02 MPa
Pascual et al. [134]											■	■				<		<	=		30% ETc
Pascual et al. [134]													■	■	■	<		<			70% ETc
Zhou et al. [135]												■	■	■		<	=	>	>	>	75% ETc SDI
Zhang et al. [136]															■		<	=/<	=		25% ETc
Abrisqueta et al. (2010)	■	■	■	■	■	■	■	■	■	■	■	■				<	<	<		>	25% ETc

SWP, midday stem water potential; ET_c, crop evapotranspiration (not stressed); FI, full irrigation.

Table 1. Deficit irrigation practices applied to peach—application phases and effects referred in literature.

Pérez-Sarmiento et al. [138] applying several RDI strategies to apricot have found improvements in some qualitative characteristics of the fruits, such as the level of soluble solids, sugar/acid ratio, and fruit color, without negative effects in yield. Along with these characteristics, fruit firmness was also improved in a study conducted by Zhou et al. [135] when applying an SDI strategy with a light water stress. Therefore, from these studies, it can be concluded that the use of deficit irrigation in peach doesnot seem to induce negative effects in the fruit quality parameters referred above. Nevertheless, several authors refer the occurrence of double fruits or fruit cracking, if severe water stress is imposed. For example, Naor et al. [39] refer this occurrence for values of stem water potential lower than −2.0 MPa. This suggests that, in what concerns fruit quality, there is an identifiable limit to the application of deficit irrigation, as discussed in Section 4.

Most of the studies addressing water use efficiency (WUE) in peach under deficit irrigation report an increase in comparison to full irrigation practices, although with lower yields for moderate or severe water stress [135].

4.3. Grapevines

4.3.1. Vegetative growth and production cycle

Grapevines (*Vitis vinifera* L.) develop over a number of periodic events, phenological stages, mentioned in the literature as budbreak, flowering and veraison [139]. Budbreak signals the beginning of the vine seasonal growth and physiological activity after a period of dormancy during the coldest months of the year but its starting date is neither influenced by winter temperature or precipitation [140, 141]. However, a recent report [142] mentions that water-stressed grapevines delay the onset of bud dormancy, reduce the cold exposure required for releasing buds from dormancy, and hasten budbreak. Flowering initiates the reproductive cycle and is followed by the fruit setting. At veraison, the ripening process is initiated when important must, and later wine, quality attributes develop. The time needed to reach berry maturity is related to temperature and precipitation and it is shortened as the temperature rises and precipitation decreases [141]. Grapevine phenology is strongly influenced by weather and climate [143] and the duration of each stage is largely determined by temperature [144]. Moreover, ambient temperature conditions the plant physiology, imparts the berry composition, and ultimately, the wine quality [145].

The climates with best potentials for quality wines are those with mild and wet winters, warm springs, and hot and dry summers. These climatic characteristics are common for the so-called Mediterranean climate well-known for its dry summer, and grapevines are well adapted to water scarcity because of its extensive, deep roots, and mechanisms of drought resistance such as tight control of stomatal aperture [146] and osmotic adjustment [147].

The cultivation of grapevines, fruit in Europe is mainly used for winemaking, is a climate-sensitive agricultural system and it expected a rise in average temperatures worldwide by 2050, some regions might be over the optimum range of temperature for the growing season [148]. Precipitation in many viticultural areas is expected to decrease substantially in the period between budbreaking and veraison [149] resulting in more intense water stress during a critical stage for grapevines. Given the actual trend in climatic change, the grapevines will advance their phenological stages, shorten the growing season with maturation occurring under hotter and drier conditions [150], a phenomenon already observed in the viticultural region of Alto Douro, Portugal [151].

4.3.2. Grapevines response to water stress

The wine grower has to manage irrigation for the benefit of yield and quality that maximizes the returns as the growers profits are a combination of both yield and quality, and a very low yield, no matter what quality might not be profitable [152].

It is well documented that irrigated grapevines increased significantly their yield per plant over rainfed plants. The increased yield is due to larger berries that diluted color, aroma, and soluble solids, and correspond to a lower quality of the must and hence the wine.

Imposing very high levels of water stress must be avoided because it results in declining vine capacity and productivity, eventually becoming economically unsustainable [153].

In viticultural regions where water stress can cause damages to the production objectives, DI strategy is a management tool that can ensure a balance between vegetative and reproductive development while maintaining yields and improving fruit composition [42] but the irrigation timing and amount must be adjusted to the local environment (*terroir*) and to wine typicity to avoid potential negative impacts [154]. Too small quantity of irrigation water can be an expensive procedure with no beneficial effect while too much water might induce an excessive vegetative growth, increase berry size, and reduce the concentration of important metabolites for quality wines [155].

Nevertheless, simultaneous events of high temperatures, drought and elevated evapotranspiration have detrimental effects on yield and berry composition as the plant carbon assimilation is much reduced due to lower photosynthetic activity compounded by loss of leaf area [156]. It is well documented that water stress decreases leaf stomatal conductance, leaf water potential, vegetative growth, leaf to fruit ratio, berry size and their fresh and dry weights, and yield [46, 141].

Water stress and temperature have a complex relationship. Higher temperatures can enhance both sugar accumulation and organic acid decay, but acidity is more affected than sugar levels, then, for the same sugar level, grapes grown under warmer conditions have lower acidity [157]. This decoupling has been reported for other metabolites, such as anthocyanins [141], proanthocyanidins [158], and aromas [159]. The decoupling of anthocyanins and sugars, in favor of anthocyanins, was observed in Cabernet Sauvignon under increasing water stress [160]. During the ripening period, if elevated temperature and drought occur simultaneously, the effects on the decoupling of anthocyanins and sugars can be felt only slightly due to the contrasting responses to these two factors, and in fact, restricted water supply during berry development can partially restore anthocyanin/sugar ratios disrupted by high temperature [161]. In "Red Tempranillo," elevated temperature and drought reduced total polyphenol index, malic acid and increased color density, but did not modify anthocyanin concentration [119].

Grapevines exhibit a vigorous vegetative growth between budbreak and veraison [162] and as consequence, the plant has its highest demand for water during this period. If there is an ample availability of soil water that might be supplemented with occasional rains, the plant grows a dense, shaded canopy at expense of reproductive berries with negative impacts on fruit and wine quality potential, foster pests and diseases, and the grower has to resort to expensive canopy management such as shoot and leaf thinning, hedging, and shoot repositioning to correct the canopy architecture and manipulate the plant yield [163]. Attending the effects of these contrasting conditions, a degree of water stress is considered beneficial for the production of quality grapes [164, 165].

The use of irrigation in these increasingly stressful environments is a mitigating solution to maintain quality in wine production, minimize the most serious risks of drought damage, and in extreme cases, guarantee plant survival [151, 166].

Under RDI, plant water status is maintained within limits of deficit during certain phases of the seasonal development, normally when fruit growth is least sensitive to water reductions [167]; then, RDI at early stage of grapevine development looks more promising than in later stages. RDI has become widely adopted in the production of wine grapes in arid and semiarid areas [168] and several works have shown that it brings better results than simple DI or FI.

The demand for vineyard irrigation is on the rise as climate becomes more stressful but water is scarcer and the competition among stakeholders becomes acute, factors that require an improvement in the efficiency of water use.

In Alto Douro region, the highest water use efficiency (WUE) was reached in rainfed grapevines at expense of yields that were economically unsustainable because the benefits of irrigation were disproportional to the amount of water necessary to bring them about [152, 169]. To strike a balance between yields, berry quality and WUE, it is advisable to impose a moderate stress before veraison but after fruit setting. Pre-veraison RDI compared to SDI reduces vine water use and increases the canopy WUE, decreases the berry polyphenolic but might lower the financial return due to lower yields [170].

4.3.3. Effect on berries quality

There is no consensus among the various authors regarding the accumulation and concentration of important metabolites because it depends on skin to pulp ratio in berries [171] as smaller berries favor their concentration in the must. The soluble solids that determine the alcohol content in wine, was found to be more concentrated in grapevines subjected to SDI than in rainfed or abundantly irrigated plants [172], while others found a lower concentration under very restricted DI [153] or did not find any significant difference in their concentration [173]. These contradictory results might be related to the accuracy of vine water status monitoring necessary to regulate and manage the physiological changes imposed to the vines by DI [83]. In other words, DI might be beneficial if an accurate control of water deficits is exerted [94].

Studies have shown that changes in grapevine water status, at selected and critical phenological stages, are as important as the amount of water applied on influencing vegetative growth, yield, and fruit metabolism [40]. Experiments with DI of "Tinta Roriz" (Tempranillo) carried in Alto Douro (Portugal) [152, 166] showed that RDI was effective to increase the yields and also induced higher concentration of organic acids in the musts but insufficient to reach the desirable level of 6–7 mg L^{-1} equivalent of tartaric acid. Total soluble solids and the concentration of glucose and fructose decreased as the rate of irrigation increased, mainly if water was applied after veraison. Irrigation had no influence on pH, anthocyanidins and flavonols of the must when compared with rainfed grapevines, but the effect was negative upon the polyphenol index, the total anthocyanins, and the color intensity. The adverse effects of irrigation were mitigated when vines were deficit irrigated between flowering and veraison followed by no irrigation till harvest. Some of these results were corroborated by other authors [81, 174]. The experiment also showed that rainfed vines produced musts with attributes very desirable for high-end wines but the yield was too low (as little as 300 g per plant) to guarantee a satisfactory economic return. RDI can result in substantial improvements on fruit quality through decreasing yield and berry size [94] and has a positive effect over synthesis and concentration of phenolic compounds, soluble solids, and anthocyanins.

5. Conclusions

The recommended irrigation strategy should be the one that maintains better tree water status throughout the season, depending on the soil water content at the beginning and the availability of water. These factors change between years, so deficit irrigation studies should be carried out for longer time than 2 or 3 years to produce a better knowledge of water stress effects.

For the above reasons, and based on the successful use of RDI in fruit trees and grapevines reviewed herein, the adoption of RDI strategies in water-limited areas should be encouraged.

So, it is of great importance to bear in mind that results depend mainly on cultivar, orchard characteristics, environmental conditions, and agronomic practices and to the large variability in rainfall, climate, and soil types between the various growing regions; thus caution must be taken when applying the findings reported by different authors to a particular orchard.

Acknowledgements

This work is supported by: European Investment Funds by FEDER/COMPETE/POCI—Operational Competitiveness and Internationalization Programme, under Project POCI-01-0145-FEDER-006958 and National Funds by FCT—Portuguese Foundation for Science and Technology, under the project UID/AGR/04033/2013" and by fellowship (FCT/SFRH/BD/18441/2004) awarded to Fernandes-Silva, AA. This work was also developed under the activities of project: Water Saving in Agriculture: technological developments for the sustainable management of limited water resources in the Mediterranean area WASA, [ERANETMED/0006/2014] which aims at developing tools for deficit irrigation scheduling in woody crops.

Conflicts of interest

The author declares no conflict of interest.

Abbreviations

g_s	Stomatal conductance
ID	Irrigation depth
DTS	Daily trunk shrinkage
CWSI	Crop water stress index
Ks	Stress coefficient
IN	Irrigation needs
Kc	Crop coefficient
IA	Irrigation applied
Ψ_{leaf}	Leaf water potential, in general
OGR	Organ growth rate
Ψ_{pd}	Leaf water potential measured at predawn
PWP	Permanent wilting point
Ψ_{stem}	Stem water potential measured near solar noon
SDV	Stem diameter variations
θ_s	Volumetric soil water content
SWD	Soil water depletion
AW	Available water
TAW	Total available water
DI	Deficit irrigation
VPD	Vapor pressure deficit
WP	Water productivity

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