We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900
Open access books available

185,000
International authors and editors

200M
Downloads

Our authors are among the

154
Countries delivered to

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Chapter 5

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

Anabela Fernandes-Silva, Manuel Oliveira, Teresa A. Paço and Isabel Ferreira

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

IntechOpen

© 2018 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. CC BY

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

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

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

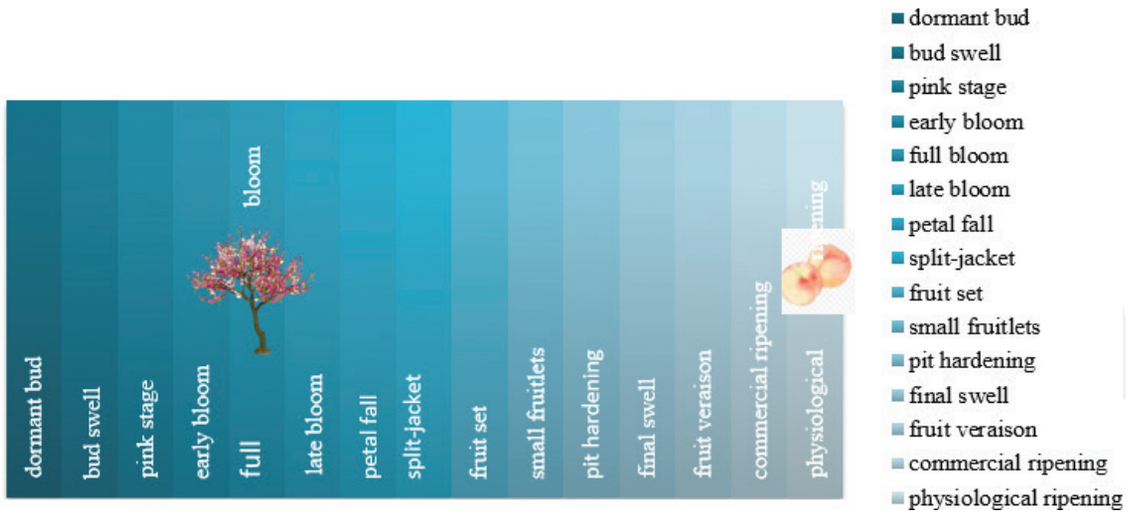


Figure 1. Phenological phases of peach (*Prunus persica*).

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].

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

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

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

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

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

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

Author details

Anabela Fernandes-Silva[1]*, Manuel Oliveira[1], Teresa A. Paço[2] and Isabel Ferreira[2]

*Address all correspondence to: anaaf@utad.pt

1 Centre for the Research and Technology of Agro-Environmental and Biological Sciences, CITAB, University of Trás-os-Montes and Alto Douro, UTAD, Quinta de Prados, Vila Real, Portugal

2 Linking Landscape, Environment, Agriculture and Food (LEAF), Instituto Superior de Agronomia (ISA), Universidade de Lisboa (ULisboa), Lisboa, Portugal

References

[1] Ondrasek G. Water scarcity & water stress in agriculture. In: Ahmad P, Wani MR, editors. Physiological Mechanism and Adaptation Strategies in Plants Under Changing Environments I. Springer New York Dordrecht Heidelberg London; 2014. pp. 75-96

[2] Valipour M. Pressure on renewable water resources by irrigation to 2060. Acta Advances in Agricultural Sciences. 2014;**2**:32-42. http://www.aaasjournal.org

[3] Godfray HCJ, Garnett T. Food security and sustainable intensification. Philosophical Transactions of the Royal Society B. 2014;**369**:20120273. DOI: 10.1098/rstb.2012.0273

[4] Fereres E, Evans RG. Irrigation of fruit trees and vines: An introduction. Irrigation Science. 2006;**24**:55-57. DOI: 10.1007/s00271-005-0019-3

[5] Fereres E, Soriano MA. Deficit irrigation for reducing agricultural water use. Journal of Experimental Botany. 2006;**58**:147-159. DOI: 10.1093/jxb/erl165

[6] Xiloyannis C, Montanaro G, Dichio B. Irrigation in mediterranean fruit tree orchards. In: Lee TS, editor. Irrigation Systems and Practices in Challenging Environments. Rijeka, Croatia: InTech; 2012. pp. 331-341. DOI: 10.5772/31350

[7] Katerji N, Itier B, Ferreira MI, Flura D, Durand B. Etude de quelques critères indicateurs de l'état hydrique d'une culture de tomate en région semi-arid. Agronomie. 1988;**8**: 425-433

[8] Naor A, Yoni Gal Y, Moti Peres M. The inherent variability of water stress indicators in apple, nectarine and pear orchards, and the validity of a leaf-selection procedure for water potential measurements. Irrigation Science. 2006;**24**:129-135. DOI: 10.1007/s00271-005-0016-6

[9] Ferreira MI, Conceição N, Malheiro AC, Silvestre JM, Silva RM. Water stress indicators and stress functions to calculate soil water depletion in deficit irrigated grapevine and kiwi. Acta Horticulturae. 2017;**1150**:119-126. DOI: 10.17660/ActaHortic.2017.1150.17

[10] Behboudian MH, Mills TM. Deficit Irrigation in deciduous orchard. In: Janick J, editor. Horticultural Reviews. 1997;**21**:105-131

[11] Iniesta F, Testi L, Orgaz F, Villalobos FJ. The effects of regulated and continuous deficit irrigation on the water use, growth and yield of olive trees. European Journal of Agronomy. 2009;**30**:258-265. DOI: 10.1016/j.eja.2008.12.004

[12] Fernandes-Silva AA, Ferreira TC, Correia CM, Malheiro AC, Villalobos FJ. Influence of different irrigation regimes on crop yield and water use efficiency of olive. Plant and Soil. 2010;**333**:35-47. DOI: 10.1007/s11104-010-0294-5

[13] Molden DA. Water-productivity framework for understanding and action. In: Kijne JW, Barker R, Molden D, editors. Water Productivity in Agriculture: Limits and Opportunities for Improvement. Colombo, Sri Lanka: International Water Management Institute; 2003. pp. 1-18. DOI: 10.1016/j.agwat.2011.08.022

[14] Pereira LS, Cordery I, Iacovides I. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agricultural Water Management. 2012;**108**:39-51

[15] Monteith JL. Evaporation and Environment. Symposia of the Society for Experimental Biology. 1965;**XIX**:205-234

[16] Fernandes-Silva AA, Gouveia JB, Vasconcelos P, Ferreira TC, Villalobos FJ. Effect of different irrigation regimes on the quality attributes of monovarietal virgin olive oil from cv. 'Cobrançosa'. Grasas y Aceites. 2013;**64**:41-49. DOI: 10.3989/gya.069712

[17] Machado M, Felizardo C, Fernandes-Silva AA, Nunes FM, Barros A. Polyphenolic compounds, antioxidant activity and L-phenylalanine ammonia-lyase activity during ripening of olive cv. 'Cobrançosa' under different irrigation regimes. Foodservice Research International. 2013;**51**:412-421. DOI: 10.1016/j.foodres.2012.12.056

[18] Ahumada-Orellana LE, Ortega-Farías S, Searles PS, Retamales JB. Yield and water productivity responses to irrigation cut-off strategies after fruit set using stem water potential thresholds in a super-high density olive orchard. Frontiers in Plant Science. 2017;**8**:1-11. DOI: 10.3389/fpls.2017.01280

[19] Fernández JE, Perez-Martin A, Torres-Ruiz JM, Cuevas MV, Rodriguez-Dominguez CM, et al. A regulated deficit irrigation strategy for hedgerow olive orchards with high plant density. Plant and Soil. 2013;**372**:279-295. DOI: 10.1002/jsfa.7828

[20] Fernández JE. Understanding olive adaptation to abiotic stresses as a tool to increase crop performance. Environmental and Experimental Botany. 2014;**103**:158-179. DOI: 10.1016/j.envexpbot.2013.12.003

[21] Connor DJ, Gómez-del-Campo M, Rousseaux MC, Searles PS. Structure, management and productivity of hedgerow olive orchards: A review. Scientia Horticulturae. 2014;**169**:71-93. DOI: 10.1016/j.scienta.2014.02.010

[22] Biasi R, Botti F, Barbera G, Cullotta S. The role of mediterranean fruit tree orchards and vineyards in maintaining the traditional agricultural landscape. Proc. XXVIIIth IHC—IS on the Challenge for a Sustainable Production. Acta Horticulturae. 2012;**940**:79-88. DOI: 10.17660/ActaHortic.2012.940.9

[23] Ruiz-Sanchez MC, Domingo R, Castel JR. Review. Deficit irrigation in fruit trees and vines in Spain. Spanish Journal of Agricultural Research. 2010;**8**(S2):S5-S20. http://www.inia.es/sjar

[24] Fereres E, Goldhamer D. Irrigation of deciduous fruit and nut trees. In: Lascano RJ, Sojya RE, editors. Irrigation of Agricultural Crops. ASA Monograph No. 30. American Society of Agronomy; 1990. pp. 987-1017

[25] Liu F, Shahanzari A, Andersen MA, Jacobsen SE, Jensen CR. Effects of deficit irrigation (DI) and partial root drying (PRD) on gas exchange biomasspartioning, and water use efficiency in potato. Scientia Horticulturae. 2006;**109**:113-117

[26] Katerji N, Mastrorilli M, Rana G. Water use efficiency of crops cultivated in the Mediterranean region: Review and analysis. European Journal of Agronomy. 2008;**28**:493-507. DOI: 10.1016/j.eja.2007.12.003

[27] Garcia-Orellana Y, Ruiz-Sanchez MC, Alarcon JJ, Conejero W, Ortuno MF, Nicolas E, et al. Preliminary assessment of the feasibility of using maximum daily trunk shrinkage for irrigation scheduling in lemon trees. Agricultural Water Management. 2007;**89**:167-171. DOI: 10.1016/j.agwat.2006.12.008

[28] Pérez-López D, Memmi H, Gijón-López MC, Moreno MM, Couceiro JF, Centeno A, et al. Irrigation of pistachios: Strategies to confront water scarcity. In: Tejero IFG, Zuazo VHD, editors. Water Scarcity and Sustainable Agriculture in Semiarid Environment: Tools, Strategies, and Challenges for Woody Crops. Academic Press: Elsevier; 2017. pp. 247-269

[29] Sofo A, Palese AM, Casacchia T, Dichio B, Xiloyannis C. Sustainable fruit production in mediterranean orchards subjected to drought stress. In: Ahmad P, Prasad MNV, editors. Abiotic Stress Responses in Plants Metabolism, Productivity and Sustainability. Springer; 2012. pp. 105-129. DOI: 10.1007/978-1-4614-0634-1-6

[30] Galindo AJ, Collado-Gonzalez J, Grinanc I, Corelld M, Centenof A, Martin-Palomod MJ, et al. Deficit irrigation and emerging fruit crops as a strategy to save water in Mediterranean semiarid agrosystems. Agricultural Water Management. 2018;**202**:311-324. DOI: 10.1016/j.gawt.2017.08.0.15

[31] Chalmers DJ, Mitchell PD, Vanheek L. Control of peach-tree growth and productivity by regulated water-supply, tree density, and summer pruning. Journal of the American Society for Horticultural Science. 1981;**106**:307-312

[32] Mitchell PD, Chalmers DJ. The effect of reduced water-supply on peach-tree growth and yields. Journal of the American Society for Horticultural Science. 1982;**107**:853-856

[33] McCarthy MG, Loveys BR, Dry PR. Regulated deficit irrigation and partial rootzone drying as irrigation management techniques for grapevines. In: FAO, editor. Deficit Irrigation Practices. Water Reports Publication n. 22. Rome: FAO; 2002. pp. 79-87

[34] Domingo R, Ruiz-Sánchez MC, Sánchezblanco MJ, Torrecillas A. Water relations, growth and yield of Fino lemon trees under regulated deficit irrigation. Irrigation Science. 1996;**16**:115-123

[35] Geerts S, Raes D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agricultural Water Management. 2009;**96**:1275-1284

[36] Jones HG. Irrigation scheduling: Advantages and pitfalls of plant-based methods. Journal of Experimental Botany. 2004;**55**:2427-2436

[37] Shackel KA, Ahmadi H, Biasi W, Buchner R, Goldhamer D, Gurusinghe S, et al. Plant water status as an index of irrigation need in deciduous fruit trees. HortTechnology. 1997;**7**:23-29

[38] Marsal J, López G, Girona J. Recent advances in regulated deficit irrigation (RDI) in woody perennials and future perspectives. Acta Horticulturae. 2008;**792**:429-439. DOI: 10.17660/ActaHortic.2008.792.50

[39] Naor A, Stern R, Peres M, Greenblat Y, Gal Y, Flaishman MA. Timing and severity of postharvest water stress affect following-year productivity and fruit quality of field-grown 'Snow Queen' nectarine. Journal of the American Society for Horticultural Science. 2005;**130**:806-812

[40] Dry PR, Loveys BR. Factors influencing grapevine vigour and the potential for control with partial rootzone drying. Australian Journal of Grape and Wine Research. 1998;**4**:140-148. DOI: 10.1111/j.1755-0238.1998.tb00143

[41] Dry PR, Loveys BR, Botting D, During H. Effects of partial rootzone dryingon grapevine vigour, yield, composition of fruit and use of water. In: Stockley CS, Sas AN, Johnstone RS, Lee TH, editors. Proceedings of the 9th Australian Wine Industry Technical Conference. Adelaide, Australia: Winetitles; 1996. pp. 126-131

[42] Dry PR, Loveys BR, McCarthy MG, Stoll M. Strategic irrigation manage-ment in Australian vineyards. Journal International des Sciences de la Vigne et du Vin. 2001;**35**:129-139

[43] Dodd IC, Theobald JC, Bacon MA, Davies WJ. Alternation of wet and drysides during partial rootzone drying irrigation alters root-to-shoot signalling ofabscisic acid. Functional Plant Biology. 2006;**33**:1081-1089

[44] Wilkinson S, Hartung W. Food production: Reducing water consumption by manipulating long-distance chemical signalling in plants. Journal of Experimental Botany. 2009;**60**:1885-1891. DOI: 10.1093/jxb/erp121

[45] Adu MO, Yawson DO, Armah FA, Asare PA, Frimpong KA. Review: Meta-analysis of crop yields of full, deficit, and partial root-zone drying irrigation. Agricultural Water Management. 2018;**197**:79-90. DOI: 10.1016/j.agwat.2017.11.019

[46] Pellegrino A, Lebon E, Simonneau T, Wery J. Towards a simple indicator of water stress in grapevine (*Vitis vinifera* L.) based on the differential sensitivities of vegetative growth components. Australian Journal of Grape and Wine Research. 2005;**11**:306-315. DOI: 10.1111/j.1755-0238.2005.tb00030.x

[47] Ferreira MI, Katerji N. Is stomatal conductance in a tomato crop controlled by soil or atmosphere? Oecologia. 1992;**92**:104-107. DOI: 10.1007/BF00317269

[48] Ferreira MI. Stress coefficients for soil water balance combined with water stress indicators for irrigation scheduling of woody crops. Horticulturae. 2017;**3**:38. DOI: 10.3390/horticulturae3020038

[49] Vishwakarma K, Upadhyay N, Kumar N, Yadav G, Singh J, Mishra RK, et al. Abscisic acid signaling and abiotic stress tolerance in plants: A review on current knowledge and future prospects. Frontiers in Plant Science. 2017;**8**:161. DOI: 10.3389/fpls.2017.00161

[50] McCutchan H, Shackel K. Stem-water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv. French). Journal of the American Society for Horticultural Science. 1992;**117**:607-611

[51] Schultz HR. Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown *Vitis vinífera* L. cultivars during drought. Plant, Cell & Environment. 2003;**26**:1393-1405. DOI: 10.1046/j.1365-3040.2003.01064

[52] Blanco-Cipollone F, Lourenço S, Silvestre J, Conceição N, Moñino MJ, Vivas A, et al. Plant water status indicators for irrigation scheduling associated with iso- and anisohydric behavior: Vine and plum trees. Horticulturae. 2017;**3**:47-64. DOI: 10.3390/horticulturae3030047

[53] Valancogne C, Ameglio T, Ferreira MI, Cohen M, Archer P, Dayau S, et al. Relations between relative transpiration and predawn leaf water potential in different fruit trees species. Acta Horticulturae. 1997;**449**:423-429

[54] Naor A. Irrigation scheduling and evaluation of tree water status in deciduous orchards. In: Horticultural Reviews. Oxford, UK: John Wiley & Sons, Inc.; 2010. pp. 111-165. DOI: 10.1002/9780470767986.ch3

[55] Kozlowski TT. Shrinking and swelling of plant tissues. In: Kozlowski TT, editor. Water Deficit and Plant Growth. New York, NY, USA: Academic Press; 1972. pp. 1-24

[56] Silvestre J, Ferreira MI, Conceição N, Malheiro AC. Can continuous records with plant-based methods be used to estimate water stress intensity in deficit irrigated vineyards? Ciência Técnica Vitivinicola. 2013;**28**:140-146

[57] Fernández JE. Plant-based methods for irrigation scheduling of woody crops. Horticulturae. 2017;**3**:35. DOI: 10.3390/horticulturae3020035

[58] Fernández JE, Cuevas MV. Irrigation scheduling from stem diameter variations: A review. Agricultural and Forest Meteorology. 2010;**150**:135-151. DOI: 10.1016/j.agrformet.2009.11.006

[59] Jackson RD, Idso SB, Reginato RJ, Pinter PJ. Canopy temperature as a drought stress indicator. Water Resources Research. 1981;**13**:651-656. DOI: 10.1029/WR017i004p01133

[60] Jones HG, Vaughan RA. Remote Sensing of Vegetation. Principles, Techniques, and Applications. London: Oxford Press; 2010. 384 p. ISBN: 9780199207794

[61] Alvino A, Marino S. Remote sensing for irrigation of horticultural crops. Horticulturae. 2017;**3**(2):40. DOI: 10.3390/horticulturae3020040

[62] Moriana A, Villalobos FJ, Fereres E. Stomatal and photosynthetic responsesof olive (*Olea europaea* L.) leaves to water deficits. Plant, Cell & Environment. 2002;**25**:395-405

[63] Moriana A, Orgaz F, Pastor M, Fereres E. Yield responses of a mature olive orchard to water deficits. Journal of the American Society for Horticultural Science. 2003;**128**(3):425-431

[64] Pérez-López D, Pérez-Rodríguez JM, Moreno MM, Prieto MH, Ramírez-Santa-Pau M, Gijón MC, et al. Influence of different cultivars-locations on maximum dailyshrinkage indicators: Limits to the reference baseline approach. Agricultural Water Management. 2013;**127**:31-39. DOI: 10.1016/j.agwat.2013.05.016

[65] Moriana A, Fereres E. Establishing reference values of trunk diameter fluctuations and stem water potential for irrigation scheduling of olive trees. Acta Horticulturae. 2004;**664**:407-412. DOI: 10.17660/ActaHortic.2004.664.51

[66] Fernández JE, Díaz-Espejo A, Infante JM, Durán P, Palomo MJ, Chamorro V, et al. Water relations and gas exchange in olive trees under regulated deficit irrigation and partial rootzone drying. Plant and Soil. 2006;**284**:273-291. DOI: 10.1007/s11104-006-0045-9

[67] Tognetti R, d'Andria R, Morelli G, Calandrelli D, Fragnito F. Irrigation effects on daily and seasonal variations of trunk sap flow and leaf water relations in olive trees. Plant and Soil. 2004;**263**:249-264

[68] Fernandes-Silva AA, López-Bernal A, Ferreira TC, Villalobos FJ. Leaf water relations and gas exchange response to water deficit of olive (cv. Cobrançosa) in field grown conditions in Portugal. Plant and Soil. 2016;**402**:191-209. DOI: 10.1007/s11104-015-2786-9

[69] Alcaras LMA, Rousseaux MC, Searles PS. Responses of several soil and plant indicators to post-harvest regulated deficit irrigation in olive trees and their potential for irrigation scheduling. Agricultural Water Management. 2016;**171**:10-20. DOI: 10.1016/j.agwat.2016.03.006

[70] Girona J, Gelly M, Mata M, Arbones A, Rufat J, Marsal J. Peach tree response to single and combined deficit irrigation regimes in deep soils. Agricultural Water Management. 2005;**72**:97-108. DOI: 10.1016/j.agwat.2004.09.011

[71] Lopez G, Echeverria G, Bellvert J, Mata M, Behboudian MH, Girona J, et al. Water stress for a short period before harvest in nectarine: Yield, fruit composition, sensory quality, and consumer acceptance of fruit. Scientia Horticulturae. 2016;**211**:1-7. DOI: 10.1016/j.scienta.2016.07.035

[72] Li GY, Huang XF, Wang XW. Water use of drip irrigated peach trees under full irrigation and regulated deficit irrigation. In: Proceedings of the 6th International Micro-irrigation Congress; 22-27 October 2000; Cape Town, South Africa; 2000. pp. 1-6

[73] Paço T, Ferreira MI, Pacheco CA. Scheduling peach orchard irrigation in water stress conditions: Use of relative transpiration and predawn leaf water potential. Fruits. 2013;**68**:147-158. DOI: 10.1051/fruits/2013061

[74] Garcia A, André RG, Ferreira MI, Paço TA. Diurnal and seasonal variations of CWSI and non-water stressed baselines with nectarine trees. Acta Horticulturae. 2000;**537**:415-421. DOI: 10.17660/ActaHortic.2000.537.49

[75] Ferreira MI, Valancogne C, Michaelsen J, Pacheco CA, Ameglio T, Daudet F-A. Evapotranspiration, water stress indicators and soil water balance in a Prunus persica orchard, in central Portugal. Acta Horticulturae. 1997;**449**:379-384. DOI: 10.17660/ActaHortic.1997.449.53

[76] Martorell S, Diaz-Espejo A, Tomàs M, Pou A, El Aou-ouad H, Escalona JM, et al. Differences in water-use-efficiency between two *Vitis vinifera* cultivars (Grenache and Tempranillo) explained by the combined response of stomata to hydraulic and chemical signals during water stress. Agricultural Water Management. 2015;**156**:1-9. DOI: 10.1016/j.agwat.2015.03.011

[77] Bota J, Tomás M, Flexas J, Medrano H, Escalona JM. Differences among grapevine cultivars in their stomatal behavior and water use efficiency under progressive water stress. Agricultural Water Management. 2016;**164**:91-99. DOI: 10.1016/j.agwat.2015.07.016

[78] Girona J, Mata M, del Campo J, Arbonés A, Bartra E, Marsal J. The use of midday leaf water potential for scheduling deficit irrigation in vineyards. Irrigation Science. 2006;**24**:115-127. DOI: 10.1007/s00271-005-0015-7

[79] Malheiro AC, Gonçalves IN, Fernandes-Silva AA, Conceição N, Paço TA, Ferreira MI, et al. Relationships between relative transpiration of grapevines and plant and soil water status in Portugal's Douro Wine Region. Acta Horticulturae. 2011;**992**:261-268. DOI: 10.17660/ActaHortic.2011.922.34

[80] Brillante L, Mathieu O, Lévêque J, Bois B. Ecophysiological modeling of grapevine water stress in Burgundy Terroirs by a machine-learning approach. Frontiers in Plant Science. 2016;**7**:796-816. DOI: 10.3389/fpls.2016.00796

[81] Munitz S, Netzer Y, Schwartz A. Sustained and regulated deficit irrigation of field-grown Merlot grapevines. Australian Journal of Grape and Wine Research. 2017;**23**:87-94. DOI: 10.1111/ajgw.12241

[82] Sousa TA, Oliveira MT, Pereira JM. Physiological indicators of plant water status of irrigated and non-irrigated grapevines grown in a low rainfall area of Portugal. Plant and Soil. 2006;**282**:127-134. DOI: 10.1007/s11104-005-5374-6

[83] Acevedo-Opazo C, Ortega-Farias S, Fuentes S. Effects of grapevine (*Vitis vinifera* L.) water status on water consumption, vegetative growth and grape quality: An irrigation scheduling application to achieve regulated deficit irrigation. Agricultural Water Management. 2010;**97**:956-964. DOI: 10.1016/j.agwat.2010.01.025

[84] Lanari V, Palliotti A, Sabbatini P, Howell GS, Silvestroni O. Optimizing deficit irrigation strategies to manage vine performance and fruit composition of field-grown 'Sangiovese' (*Vitis vinifera* L.) grapevines. Scientia Horticulturae. 2014;**179**:239-247. DOI: 10.1016/j.scienta.2014.09.032

[85] Silvestre J, Ferreira MI, Valancogne C. Evapotranspiration and water relations from a vineyard in Central Portugal during spring-summer periods. Acta Horticulturae. 1999;**493**:213-218. DOI: 10.17660/ActaHortic.1999.493.21

[86] Martinez-De-Toda F, Balda P, Oliveira M. Estimation of vineyard water status (*Vitis vinifera* cv. Tempranillo) from the developmental stage of the shoot tips. Journal International des Sciences de la Vigne et du Vin. 2010;**44**:201-206. DOI: 10.20870/oeno-one.2010.44.4.1476

[87] Rodriguez Lovelle B, Trambouze W, Jacquet O. Evaluation of vegetative growth stage by the "shoot tip method". Le Progrès Agricole et Viticole. 2009;**126**:77-88

[88] Conceição N, Tezza L, Häusler M, Lourenço S, Pacheco AC, Ferreira MI. Three years of monitoring evapotranspiration components and crop and stress coefficients in a deficit irrigated intensive olive orchard. Agricultural Water Management. 2017;**91**:138-152. DOI: 10.1016/j.agwat.2017.05.011

[89] Bellvert J, Marsal J, Girona J, Zarco-Tejada PJ. Seasonal evolution of crop water stress index in grapevine varieties determined with high-resolution remote sensing thermal imagery. Irrigation Science. 2015;**33**:81-93. DOI: 10.1007/s00271-014-0456-y

[90] Grant OM, Ochagavía H, Baluja J, Diago MP, Tardáguila J. Thermal imaging to detect spatial and temporal variation in the water status of grapevine (*Vitis vinifera* L.). The Journal of Horticultural Science and Biotechnology. 2016;**91**:43-54. DOI: 10.1080/14620316.2015.1110991

[91] King BA, Shellie KC. Wine grape cultivar influence on the performance of models that predict the lower threshold canopy temperature of a water stress index. Computers and Electronics in Agriculture. 2018;**145**:122-129. DOI: 10.1016/j.compag.2017.12.025

[92] Selles G, Ferreyra R, Muñoz I, Silva H. Physiological indicators of plant water status as criteria for irrigation scheduling in table grapes cv. Crimson seedless, irrigated by drip. Acta Horticulturae. 2004;**664**:599-605. DOI: 10.17660/ActaHortic.2004.664.75

[93] Oliveira MT, Oliveira AC, Castro CB. Dependence of sap flow and stem diameter fluctuation of grapevines on reference evapotranspiration: An event coincidence analysis. Advances in Plants & Agriculture Research. 2017;**7**:279-287. DOI: 10.15406/apar.2017.07.00279

[94] Ojeda H, Andary C, Kraeva E, Carbonneau A, Deloire A. Influence of pre-and postveraison water deficits on synthesis and concentration of skin phenolic compounds during berry growth of *Vitis vinifera* cv Shiraz. American Journal of Enology and Viticulture. 2002;**53**:261-267. http://www.ajevonline.org/content/53/4/261.1

[95] Gaudin R, Kansou K, Christophe PJ, Pellegrino A, Gary C. A water stress index based on water balance modelling for discrimination of grapevine quality and yield. Journal International des Sciences de la Vigne et du Vin. 2014;**48**:1-10. DOI: 10.20870/oeno-one.2014.48.1.1655

[96] Rallo L, Cuevas J. In: Barranco D, Fernández-Escobar R, Rallo L, editors. Fruiting and Production, Olive Growing Madrid. Spain: Ediciones Mundi-Prensa; 2010. pp. 113-145

[97] Connor DJ, Fereres E. The physiology of adaptation and yield expression in olive. Horticultural Reviews. 2005;**31**:155-229

[98] Beltrán G, Uceda M, Hermoso M, Frias L. Maduracion. In: Barranco D, Fernández-Escobar R, Rallo L, editors. El cultivo de olivo. Madrid, Spain: Ediciones Mundi Prensa; 2008. pp. 163-187

[99] Costagli G, Gucci R, Rapoport H. Growth and development of fruits of olive "Frantoio" under irrigated and rainfed conditions. The Journal of Horticultural Science and Biotechnology. 2003;**78**:119-124

[100] Goldhamer DA. Regulated deficit irrigation for California canning olives. Acta Horticulturae. 1999;**474**:369-372. DOI: 10.17660/ActaHortic.1999.474.76

[101] Caruso G, Rapoport HF, Gucci R. Long-term evaluation of yield components of young olive trees during the onset of fruit production under different irrigation regimes. Irrigation Science. 2013;**31**:37-47. DOI: 10.1007/s00271-011-0286-0

[102] Hernandez-Santana V, Fernandes RDM, Perez-Arcoiza A, Fernández JE, Garcia JM, Diaz-Espejo A. Relationships between fruit growth and oil accumulation with simulated seasonal dynamics of leaf gas exchange in the olive tree. Agricultural and Forest Meteorology. 2018;**256**:458-469. DOI: 10.1016/j.agrformet.2018.03.019

[103] Correa-Tedesco G, Rousseaux MC, Searles PS. Plant growth and yield responses in olive (*Olea europaea*) to different irrigation levels in an arid region of Argentina. Agricultural Water Management. 2010;**97**:1829-1837. DOI: 10.1016/j.agwat.2010.06.020

[104] Conceição N, Tezza L, Lourenço S, Häusler M, Boteta L, Pacheco C, et al. Importance of very fine roots in deep soil layers for the survival of rainfed olive trees. Acta Horticulturae. 2018;**1199**:57-62. DOI: 10.17660/ActaHortic.2018.1199.9

[105] Martín-Vertedor AI, Pérez-Rodríguez JM, Prieto-Losada E, Fereres-Castiel E. Interactive responses to water deficits and crop load in olive (*Olea europaea* L., cv. Morisca). I: Growth and water relations. Agricultural Water Management. 2011;**98**:941-949. DOI: 10.1016/j.agwat.2011.01.002

[106] Martín-Vertedor AI, Pérez-Rodríguez JM, Prieto-Losada E, Fereres-Castiel E. Interactive responses to water deficits and crop load in olive (*Olea europaea* L., cv. Morisca). II: Water use, fruit and oil yield. Agricultural Water Management. 2011;**98**:950-958. DOI: 10.1016/j.agwat.2011.01.003

[107] Lavee S, Hanoch E, Wodner M, Abramowitch E. The effect of predetermined deficit irrigation on the performance of cv. Muhasan olives (*O. europaea* L.) in the eastern coastal plain of Israel. Scienctia Horticulturae. 2007;**112**:156-163. DOI: 10.1016/j.scienta.2006.12.017

[108] Wahbi S, Wakrim R, Aganchich B, Tahi H, Serraj R. Effects of partial rootzone drying (PRD) on adult olive tree (*Olea europaea*) in field conditions under arid climate: I. Physiological and agronomic responses. Agriculture, Ecosystems & Environment. 2005;**106**:289-301. DOI: 10.1016/j.agee.2004.10.015

[109] Richard C, Rosecrance RC, William H, Krueger WH, Milliron L, Bloese J, et al. Moderate regulated deficit irrigation can increase olive oil yields and decrease tree growth in super high density 'Arbequina' olive orchards. Scientia Horticulturae. 2015;**190**:75-82. DOI: 10.1016/J.scienta.2015.03.045

[110] Gómez del Campo M. Summer deficit–irrigation strategies in a hedgerow olive orchard cv. 'Arbequina': Effect on fruit characteristics and yield. Irrigation Science. 2013;**31**: 259-269. DOI: 10.1007/s00271-011-0299-8

[111] Padilla-Díaz CM, Rodriguez-Dominguez CM, Hernandez-Santana V, Perez-Martin A, Fernández JE. Scheduling regulated deficit irrigation in a hedgerow olive orchard from leaf turgor pressure related measurements. Agricultural Water Management. 2016;**164**: 28-37. DOI: 10.1016/j.agwat.2015.08.002

[112] Marra FP, Marino G, Marchese A, Caruso T. Effects of different irrigation regimes on a super-high-density olive grove cv. "Arbequina": Vegetative growth, productivity and polyphenol content of the oil. Irrigation Science. 2016;**4**:313-325. DOI: 10.1007/s00271-016-0505-9

[113] Aganchich B, Tahi H, Wahbi S, Elmodaffar C, Serraj R. Growth, water relations and antioxidant defence mechanisms of olive (*Olea europaea* L.) subjected to partial root drying (PRD) and regulated deficit irrigation (RDI). Plant Biosystems. 2007;**141**:252-264. DOI: 10.1080/11263500701401893

[114] Fernandes-Silva AA, Falco V, Correia CM, Villalobos FJ. Sensory analysisand volatile compounds of olive oil (cv. Cobrançosa) from different irrigationregimes. Grasas y Aceites. 2013;**61**:59-67. DOI: 10.3989/gya.069712

[115] Berenguer MJ, Vossen PM, Grattan SR, Connell JH, Polito VS. Tree irrigation levels for optimum chemical and sensory properties of olive oil. Hortscience. 2006;**41**:427-432

[116] Motilva MJ, Tovar MJ, Romero MP, Alegre S, Girona J. Influence of regulated deficit irrigation strategies applied to olive trees (*Arbequina cultivar*) on oil yield and oil composition during the fruit ripening period. Journal of the Science of Food and Agriculture. 2000;**80**:2037-2043. DOI: 10.1002/1097-0010

[117] García JM, Cuevas MV, Fernández JE. Production and oil quality in 'Arbequina' olive (*Olea eurpoaea*, L.) trees under two deficit irrigation strategies. Irrigation Science. 2013;**31**:359-370

[118] Dabbou S, Chehab H, Faten B, Dabbou S, Esposto S, Selvaggini R, et al. Effect of three irrigation regimes on Arbequina olive oil produced under Tunisian growing conditions. Agricultural Water Management. 2010;**97**:763-768. DOI: 10.1016/j.agwat.2010.01.011

[119] Magliulo V, d'Andria R, Lavini A, Morelli G, Patumi M. Yield and quality of two rain-fed olive cultivars following shifting to irrigation. The Journal of Horticultural Science and Biotechnology. 2003;**78**:15-23. DOI: 10.1080/14620316.2003.11511578

[120] Rondanini DP, Castro DN, Searles PS, Rousseaux MC. Contrasting patterns of fatty acid composition and oil accumulation during fruit growth in several olive varieties and locations in a non-Mediterranean region. European Journal of Agronomy. 2014;**52**: 237-246. DOI: 10.1016/j.eja.2013.09.002

[121] Cano-Lamadrid M, Girón IF, Pleite R, Burló F, Corell M, et al. Quality attributes of table olives as affected by regulated deficit irrigation. Food Science and Technology. 2015;**62**:19-26. DOI: 10.1016/j.lwt.2014.12.063

[122] Cano-Lamadrid M, Hernández F, Corell M, Burló F, Legua P, et al. Antioxidant capacity, fatty acids profile, and descriptive sensory analysis of table olives as affected by deficit irrigation. Journal of the Science of Food and Agriculture. 2017;**97**:444-451. DOI: 10.1002/jsfa.7744

[123] Collado J, Moriana A, Giron I, Gil-Izquierdo A. The phytoprostane content in green table olives is influenced by Spanish-style processing and regulated deficit irrigation. Food Science and Technology. 2015;**64**:997-1003. DOI: 10.1016/j.lwt.2015.07.005

[124] Moriana A, Corell M, Giron IF, Conejero W, Morales D, et al. Regulated deficit irrigation based on threshold values of trunk diameter fluctuation indicators in table olive trees. Scientia Horticulturae. 2013;**164**:102-111. DOI: org/10.1016/j.scienta.2013.09.029

[125] Minghetti L, Salvi R, Maria LS, Ajmone-Cat MA, De Nuccio C, Visentin S, et al. Non-enzymatic oxygenated metabolites of α-linolenic acid B1- and L1-phytoprostanes protect immature neurons from oxidant injury and promote differentiation of oligodendrocyte progenitors through PPAR-γ activation. Free Radical Biology and Medicine. 2014;**73**:41-50. DOI: 10.1016/j.freeradbiomed.2014.04.025

[126] Mounzer OH, Conejero W, Nicolás E, Abrisqueta I, García-Orellana YV, Tapia LM, et al. Growth pattern and phenological stages of early-maturing peach trees under a Mediterranean climate. Hortscience. 2008;**43**:1813-1818

[127] Moing A, Rothan C, Svanella L, Just D, Diakou P, Raymond P, et al. Role of phosphoenolpyruvate carboxylase in organic acid accumulation during peach fruit development. Physiologia Plantarum. 2000;**108**:1-10. DOI: 10.1034/j.1399-3054.2000.108001001

[128] Chalmers DJ, Vandenende B. Productivity of peach trees—Factors affecting dry-weight distribution during tree growth. Annals of Botany. 1975;**39**:423-432

[129] Johnson RS, Handley DF, DeJong TM. Long-term response of early maturing peach trees to postharvest water deficits. Journal of American Society for Horticulture Science. 1992;**117**:881-886

[130] Girona J, Mata M, Goldhamer DA, Johnson RS, DeJong TM. Patterns of soil and tree water status and leaf functioning during regulated deficit irrigation scheduling in peach. Journal of American Society for Horticulture Science. 1993;**118**:580-586

[131] De la Rosa JM, Conesa MR, Domingo R, Aguayo E, Falagan N, Perez-Pastor A. Combined effects of deficit irrigation and crop level on early nectarine trees. Agricultural Water Management. 2016;**170**:120-132. DOI: 10.1016/j.agwat.2016.01.012

[132] Massai R, Remorini D, Ferreira M, Paço TA. Sap flow in peach trees during water stress and recovery in two environmental conditions. Acta Horticulturae. 2000;**537**:351-358. DOI: 10.17660/ActaHortic.2000.537.41

[133] Marsal J, Casadesus J, Lopez G, Mata M, Bellvert J, Girona J. Sustainability of regulated deficit irrigation in a mid-maturing peach cultivar. Irrigation Science. 2016;**34**:201-208. DOI: 10.1007/s00271-016-0498-4

[134] Pascual M, Villar JM, Rufat J. Water use efficiency in peach trees over a four-years experiment on the effects of irrigation and nitrogen application. Agricultural Water Management. 2016;**164**:253-266. DOI: 10.1016/j.agwat.2015.10.021

[135] Zhou HM, Zhang FC, Kjelgren R, Wu LF, Gong DZ, Zhao N, et al. Peach yield and fruit quality is maintained under mild deficit irrigation in semi-arid China. Journal of Integrative Agriculture. 2017;**16**:1173-1183. DOI: 10.1016/S2095-3119(16)61571

[136] Zhang HH, Wang D, Gartung JL. Influence of irrigation scheduling using thermometry on peach tree water status and yield under different irrigation systems. Agronomy. 2017;**7**:1-15. DOI: 10.3390/agronomy7010012

[137] Vera J, Abrisqueta I, Abrisqueta JM, Ruiz-Sanchez MC. Effect of deficit irrigation on early-maturing peach tree performance. Irrigation Science. 2013;**31**:747-757. DOI: 10.1007/s00271-012-0358-9

[138] Pérez-Sarmiento F, Miras-Avalos JM, Alcobendas R, Alarcon JJ, Mounzer O, Nicolas E. Effects of regulated deficit irrigation on physiology, yield and fruit quality in apricot trees under Mediterranean conditions. Spanish Journal of Agricultural Research. 2016;**14**. DOI: 10.5424/sjar/2016144-9943

[139] Lorenz DH, Eichhorn KW, Bleiholder H, Klose R, Meier U, Weber E. Growth stages of the grapevine: Phenological growth stages of the grapevine (*Vitis vinifera* L. ssp. vinifera)—Codes and descriptions according to the extended BBCH scale. Australian Journal of Grape and Wine Research. 1995;**1**:100-103. DOI: 10.1111/j.1755-0238.1995.tb00085.x

[140] Cortázar-Atauri GI, Brisson N, Gaudillere JP. Performance of several models for predicting budburst date of grapevine (*Vitis vinifera* L.). International Journal of Biometeorology. 2009;**53**:317-326. DOI: 10.1007/s00484-009-0217-4

[141] Martínez-Lüscher J, Kizildeniz T, Vučetić V, Dai Z, Luedeling E, van Leeuwen C, et al. Sensitivity of grapevine phenology to water availability, temperature and CO_2 concentration. Frontiers in Environmental Science. 2016;**4**:1-14. DOI: 10.3389/fenvs.2016.00048

[142] Shellie K, Kovaleski AP, Londo JP. Water deficit severity during berry development alters timing of dormancy transitions in wine grape cultivar Malbec. Scientia Horticulturae. 2018;**232**:226-230. DOI: 10.1016/j.scienta.2018.01.014

[143] Webb LB, Whetton PH, Bhend J, Darbyshire R, Briggs PR, Barlow EWR. Earlier wine-grape ripening driven by climatic warming and drying and management practices. Nature Climate Change. 2012;**2**:259-264. DOI: 10.1038/nclimate1417

[144] Tomasi D, Jones GV, Giust M, Lovat L, Gaiotti F. Grapevine phenology and climate change: Relationships and trends in the Veneto region of Italy for 1964-2009. American Journal of Enology and Viticulture. 2011;**62**:329-339. DOI: 10.5344/ajev.2011.10108

[145] Bonada M, Sadras VO. Review: Critical appraisal of methods to investigate the effect of temperature on grapevine berry composition. Australian Journal of Grape and Wine Research. 2015;**21**:1-17. DOI: 10.1111/ajgw.12102

[146] Lovisolo C, Hartung W, Schubert A. Whole-plant hydraulic conductance and root-to-shoot flow of abscisic acid are independently affected by water stress in grapevines. Functional Plant Biology. 2002;**29**:1349-1356. DOI: 10.1071/FP02079

[147] Patakas A, Noitsakis B. Mechanisms involved in diurnal changes of osmotic potential in grapevines under drought conditions. Journal of Plant Physiology. 1999;**154**:767-774. DOI: 10.1016/S0176-1617(99)80256-9

[148] Jones GV, White MA, Cooper OR, Storchmann K. Climate change and global wine quality. Climatic Change. 2005;**73**:319-343. DOI: 10.1007/s10584-005-4704-2

[149] Jones GV, Alves F. Impacts of climate change on wine production: A global overview and regional assessment in the Douro Valley of Portugal. International Journal of Global Warming. 2012;**4**:383-406. DOI: 10.1504/IJGW.2012.049448

[150] Duchêne E, Huard F, Dumas V, Schneider C, Merdinoglu D. The challenge of adapting grapevine varieties to climate change. Climate Research. 2010;**41**:193-204. DOI: 10.3354/cr00850

[151] Oliveira M. Viticulture in warmer climates: Mitigating environmental stress in Douro Region, Portugal. In: Jordão AM, Cosme F, editors. Grapes and Wines—Advances in Production, Processing, Analysis and Valorization. Rijeka, Croatia: InTech; 2018. pp. 59-75. DOI: 10.5772/intechopen.71155

[152] Oliveira MT, de Freitas V, Sousa TA. Water use efficiency and must quality of irrigated grapevines of north-eastern Portugal. Archives of Agronomy and Soil Science. 2011;**58**:871-886. DOI: 10.1080/03650340.2011.551875

[153] Keller M, Romero P, Gohil H, Russell RP, Riley WR, Casassa F, et al. Deficit irrigation alters grapevine growth, physiology, and fruit microclimate. American Journal of Enolology and Viticulture. 2016;**67**:426-435. DOI: 10.5344/ajev.2016.16032

[154] Bonada M, Sadras V, Moran M, Fuentes S. Elevated temperature and water stress accelerate mesocarp cell death and shrivelling, and decouple sensory traits in Shiraz berries. Irrigation Science. 2013;**31**:1317-1321. DOI: 10.1007/s00271-013-0407-z

[155] Esteban MA, Villanueva MJ, Lissarrague JR. Effect of irrigation on changes in berry composition of Tempranillo during maturation. Sugars, organique acids and mineral elements. American Journal of Enology and Viticulture. 1999;**50**:418-433. http://www.ajevonline.org/content/50/4/418

[156] Chaves MM, Santos TP, Souza CR, Ortuño MF, Rodrigues ML, Lopes CM, et al. Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. Annals of Applied Biology. 2007;**150**:237-252. DOI: 10.1111/j.1744-7348.2006.00123

[157] Etienne A, Genard M, Lobit P, Mbeguie-A-Mbeguie D, Bugaud C. What controls fleshy fruit acidity? A review of malate and citrate accumulation in fruit cells. Journal of Experimental Botany. 2013;**64**:1451-1469. DOI: 10.1093/jxb/ert035

[158] Cohen SD, Tarara JM, Gambetta GA, Matthews MA, Kennedy JA. Impact of diurnal temperature variation on grape berry development, proanthocyanidin accumulation, and the expression of flavonoid pathway genes. Journal of Experimental Botany. 2012;**63**:2655-2665. DOI: 10.1093/jxb/err449

[159] Bonada M, Jeffery DW, Petrie PR, Moran MA, Sadras VO. Impact of elevated temperature and water deficit on the chemical and sensory profiles of Barossa Shiraz grapes and wines. Australian Journal of Grape and Wine Research. 2015;**21**:240-253. DOI: 10.1111/ajgw.12142

[160] Sadras VO, Stevens R, Pech J, Taylor E, Nicholas P, McCarthy M. Quantifying phenotipic plasticity of berry traits using an allometrictype approach: A case study on anthocyanins and sugars in berries of Cabernet Sauvignon. Australian Journal of Grape and Wine Research. 2007;**13**:72-80. DOI: 10.1111/j.1755-0238.2007.tb00237

[161] Sadras VO, Moran MA. Elevated temperature decouples anthocyanins and sugars in berries of Shiraz and Cabernet Franc. Australian Journal of Grape and Wine Research. 2012;**18**:115-122. DOI: 10.1111/j.1755-0238.2012.00180

[162] Giese G, Velasco-Cruz C, Roberts L, Heitman J, Wolf TK. Complete vineyard floor cover crops favorably limit grapevine vegetative growth. Scientia Horticulturae. 2014;**170**:256-266. DOI: 10.1016/j.scienta.2014.03.011

[163] Smart RE, Robinson M. Sunlight into Wine: A Handbook for Wine Grape Canopy Management. Adelaide, Australia: Winetitles, Pty. Ltd; 1991. 88 p

[164] Basile B, Marsal J, Mata M, Vallverdu X, Bellvert J, Girona J. Phenological sensitivity of Cabernet Sauvignon to water stress: Vine physiology and berry composition. American Journal of Enolology and Viticulture. 2011;**62**:452-461. DOI: 10.5344/ajev.2011.11003

[165] Intrigliolo DS, Perez D, Risco D, Yeves A, Castel JR. Yield components and grape composition responses to seasonal water deficits in Tempranillo grapevines. Irrigation Science. 2012;**30**:339-349. DOI: 10.1007/s002

[166] Resco P, Iglesias A, Bardají I, Sotés V. Exploring adaptation choices for grapevine regions in Spain. Regional Environmental Change. 2016;**16**:979-993. DOI: 10.1007/s10113-015-0811-4

[167] Kang S, Zhang J. Controlled alternate partial root-zone irrigation: Its physiological consequences and impact on water use efficiency. Journal of Experimental Botany. 2004;**55**:2437-2446. DOI: 10.1093/jxb/erh249

[168] Tarara JM, Peña JEP. Moderate water stress from regulated deficit irrigation decreases transpiration similarly to net carbon exchange in grapevine canopies. Journal of the American Society for Horticultural Science. 2015;**140**:413-426. http://journal.ashspublications.org/content/140/5/413.full.pdf+html

[169] Oliveira MT, Sousa TA. Organic acids and sugars in musts of irrigated grapevines in Northeast Portugal. Journal of Wine Research. 2010;**20**(1):1-13. DOI: 10.1080/09571260902978485

[170] Romero P, García JG, Fernández-Fernández JI, Muñoz RG, Saavedra FA, Martínez-Cutillas A. Improving berry and wine quality attributes and vineyard economic efficiency by long-term deficit irrigation practices under semiarid conditions. Scientia Horticulturae. 2016;**203**:69-85. DOI: 10.1016/j.scienta.2016.03.013

[171] Koundouras S, Marinos V, Gkoulioti A, Kotseridis Y, Van Leeuwen C. Influence of vineyard location and vine water status on fruit maturation of non-irrigated cv Agiorgitiko (*Vitis vinifera* L.). Effects on wine phenolic and aroma components. Journal of Agriculture and Food Chemistry. 2006;**54**:5077-5086. DOI: 10.1021/jf0605446

[172] Koundouras S, Van Leeuwen C, Seguin G, Glories Y. Influence of water status on vine vegetative growth, berry ripening and wine characteristics in Mediterranean zone (example of Nemea, Greece, variety Saint-George, 1997). International Journal of Wine Research. 1999;**33**:149-160. DOI: 10.20870/oeno-one.1999.33.4.1020

[173] Peterlunger E, Sivilotti P, Bonetto C, Paladin M. Water stress induces changes in polyphenol concentration in Merlot grape and wines. Rivista di Viticoltura e di Enologia. 2002;**1**:51-66

[174] Niculcea M, Martinez-Lapuente L, Guadalupe Z, Sánchez-Diaz M, Ayesteran B, Aantolín MC. Characterization of phenolic composition of Vitis vinifera L. 'Tempranillo' and 'Graciano' subjected to deficit irrigation during berry development. Vitis. 2015;**54**:9-16

IntechOpen

IntechOpen