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Chapter

Effects of Vine Water Status on Yield Components, Vegetative Response and Must and Wine Composition

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Abstract

Despite *Vitis vinifera* L. is a drought-tolerant species—rainfed traditionally grown in a very diversity of climates—irrigation has more and more become a usual practice aimed to obtain regular yields along seasons and to control must composition. Results on vineyard irrigation are dependent on the timing, length and intensity of the water deficit. From budbreak to flowering, shoot growth is very sensitive to water stress, while reproductive growth is almost unaffected. Severe water deficit during fruit set can reduce yield by affecting ovary cell multiplication and expansion. During maturation water stress induces yield reduction by limiting berry growth; along this phase must composition is also affected. There is a positive, linear relationship between must sugar content and available water; however, no relationship has been found to either total acidity or pH. Biosynthesis of anthocyanins and fruity aromas is enhanced by water deficit. Usually, wines from moderate irrigation treatments scored the highest. There is a general agreement that severe, long water deficits diminish must quality, leaf area, fertility and yield, and it has a negative carryover effect on the next seasons by limiting wood reserves to be used the following seasons.

Keywords: wine grapes, *Vitis vinifera* L., irrigation, water potential, yield, berry size, shoot growth, vigour, soluble solids, pH, total acidity, organic acids, polyphenols, anthocyanins, aroma compounds

1. Introduction

Wine grapes are grown over a very wide diversity of environmental conditions. Originally, wine grapes were confined around the Mediterranean basin, but as humans spread around the world, these plants were able to conquer new habitats. Vineyards now exist in areas with Mediterranean climatic conditions (i.e. with relatively long, dry summers) in Europe, South America and North America but also in Atlantic regions in Europe and North America and in places with a similar climate in New Zealand. In recent decades, *V. vinifera* vineyards have been established in North Beijing and Washington State (USA) where winters are cold and even tropical areas in Thailand. This highlights the plasticity of *V. vinifera* cultivars, which have become adapted to very different climatic conditions, producing reputable wines and table grapes under most of them.

Along history, growers have been forced to choose those cultivars best adapted to the local availability of water, seasonal temperatures, the dry periods they must face, etc., increasing experience allowing the most to be made of each situation. Different training systems and cultivation practices have also been developed, striking a balance between plant, vineyard management and the environment and giving rise to different viticultural landscapes, some now recognized as part of the world heritage. This balance, however, can be altered when priorities change, perhaps driven by the desire to produce more, or because of a change in market conditions. Thus, an area might need to increase yields or open up new areas of sustainable production. Areas naturally suited to raising white wine grape varieties might suddenly need to shift to red, or the variety habitually grown may need to be changed due to customer demand. Under certain circumstances, newly imposed conditions can only be met sustainably by modifying the vineyard agrosystem, perhaps by introducing a different kind of trellising or canopy management or by introducing irrigation.

For a long time, the drought tolerance of grapevines meant irrigation was not contemplated as a viticultural practice. Indeed, it took hard work to overcome the prejudice that grapevines are not well suited to it. By and large, vineyards in growing areas brought into production in the last 50 years have been irrigated. In some traditional areas, however, irrigation was banned until some decades ago. Irrigation results obtained from vineyards under regional regulations (geographical indications), with limitations either to yield or bud load, for example, may complicate the discussions of irrigation as it often happens that irrigated vines cannot express the most of them when we are limiting their optimal performance under those new conditions and when they are harvested at the same date. This turned out that part of the industry felt that the best wines were produced under situations of severe water stress. The aim of irrigating wine grapes is not always to produce higher yields but to ensure the quality required for different products. For example, some grapes are grown with the intention of producing young wines, others are raised to make wines for ageing and yet others for making spirits, etc.; as a result, they require different irrigation regimens and different optimal yields and different harvest time. In recent times, attitudes are changing as irrigation studies have increased and irrigation management becomes ever more technically friendly and controllable, and the consequences of global warming are felt.

In the following paragraphs, a review of the effects of water status on yield, vine growth and must and wine composition is exposed, and results are explained taken into account the phenological stage and the berry growth stage at which excess-optimal-severe available water took place.

2. Effects of plant water status on vine response

2.1 Effects of vine water status on yield components

Different components are taken into account when calculating the yield of a vineyard. The yield per hectare can be expressed as follows:

$$\text{Yield} = \frac{\text{N°vines}}{\text{ha}} \cdot \frac{\text{N°buds}}{\text{vine}} \cdot \frac{\text{N°shoots}}{\text{bud}} \cdot \frac{\text{N°clusters}}{\text{shoot}} \cdot \frac{\text{N°berries}}{\text{cluster}} \cdot \text{berry weight} \quad (1)$$

The vine spacing, training system and pruning level determine the number of potentially productive buds. In most viticultural regions, budburst follows its normal course since soil water is usually available. However, a strong water deficit at the beginning of the season negatively affects budburst since the mobilisation of

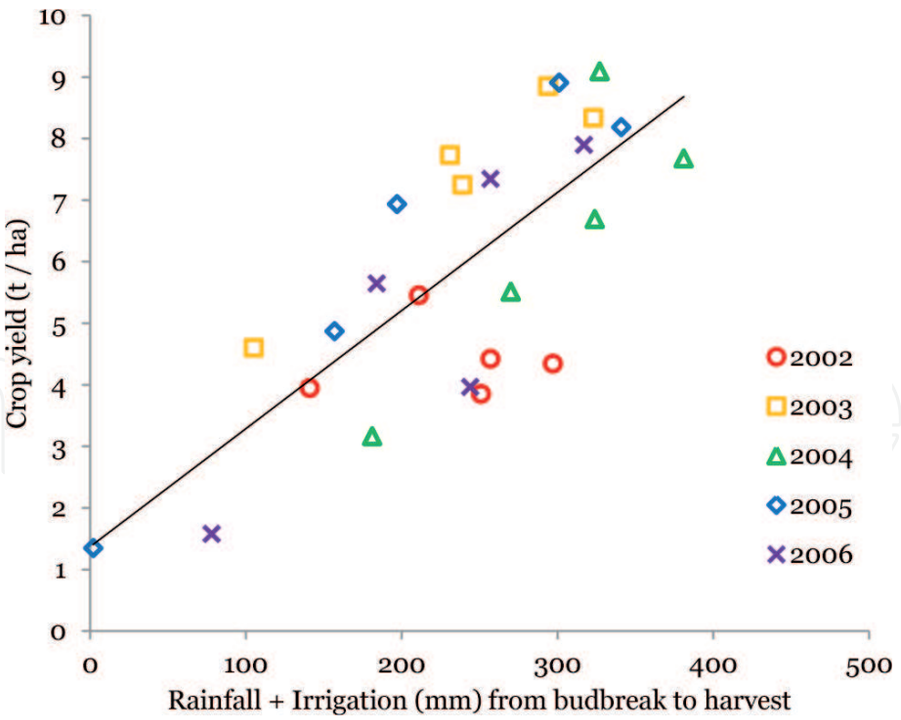


Figure 1.
Relationship between crop yield and water supply (rainfall + irrigation) from budbreak to harvest in a cv. Cabernet sauvignon vineyard in Madrid, Spain. Data correspond to five different irrigation treatments applied during 2002–2006 (adapted from Junquera et al. [6]).

nutrients from the reserve structures is reduced [1]. Once the number of potentially productive shoots is defined, the yield of a vineyard depends on a set of internal and external factors, and the interactions among them, all of which have an impact on the processes of floral induction and differentiation and the growth of the berries. These factors include the genotype of the vine (variety and rootstock), environmental conditions (climate and soil) and cultivation practices [2].

Water deficit is one of the main environmental factors limiting vegetative growth and berry yield [3, 4] (reproductive development is less sensitive to water shortages than vegetative growth [5]). The water status of a vineyard depends on the availability of water (soil water, rainfall and irrigation), atmospheric conditions (relative humidity, vapour pressure deficit, temperature, etc.) and leaf area as well as the ability of the vine to absorb and transport water to its organs.

Some studies have reported a direct relationship between the amount of water available during the growth cycle (rainfall + irrigation) and yield (**Figure 1**) [6, 7]. However, this relationship is not immediately obvious when data from different studies are brought together in the search for correlations. This is largely the consequence of differences in environmental conditions (soil and climate) and vineyard characteristics (genotype, training system, etc.), which generate differences in water use efficiency (kg fresh fruit/m^3 water applied) [8]. However, the meta-analysis conducted by Medrano et al. [8] clearly shows a positive linear relationship between yield and water use efficiency, even when an increase in the latter can only be achieved by reducing the total amount of water used—which generally involves a certain reduction in yield. Indeed, several studies have concluded that irrigation doses equivalent to 60–80% of crop evapotranspiration (ETc) are sufficient to maximise yield [9–11]. Irrigation doses exceeding 100% ETc might lower yield via reductions in fertility, and even in berry weight, perhaps due to competition between berry and vegetative growth [10].

Reproductive growth correlates with water availability, with this relationship dependent on the development stage of the vine. Generally, water deficit reduces yield,

particularly when shortages occur early in the season [12]. However, the complexity and duration of the reproductive cycle of the vine make a more detailed analysis necessary. The reproductive cycle of the vine is completed after a 2-year period: the buds formed in the first season develop and give rise to fruiting shoots in the following season. This process includes numerous phenomena: induction and floral differentiation, flowering, pollination, fertilisation, fruit setting and berry growth [13]. Thus, there is a long period of time over which the yield is liable to alterations due to environmental conditions and/or vineyard management practices.

Intense and persistent water deficits usually reduce bud fertility via falls in the number and size of inflorescences [14]. Induction is particularly sensitive to water stress, with shortages during flowering normally leading to important reductions in bud fertility [15]. Vasconcelos et al. [1] reviewed the different means by which water status can affect floral induction and differentiation, and therefore bud fertility, reporting it to be influenced (1) directly, via the amount of water available to processes determining cell division and expansion, and (2) indirectly, via its effect on photosynthetic activity, nutrition, the microclimate of the renewal zone and hormonal balance. These authors also indicate that the many determining factors and possible interactions among them make it difficult to establish clear correlations between water status and bud fertility. Certainly, the potential for reduced fertility exists via excessive water availability leading to increased vigour and vegetative growth and therefore reduced light interception in the renewal zone [1, 16, 17]. This same excessive vigour and lack of illumination can, however, also favour primary bud necrosis and therefore a lack of primary bud growth at budbreak and reduced fertility [10, 18]. Fertility can thus be reduced by both limited and excessive water availability.

Shortly after budburst, reproductive growth is relatively unaffected by water deficit. In most viticultural regions, water deficit is not normally a problem during inflorescence development; the soil water content is generally sufficient throughout spring, supplied either by rain or irrigation. Moreover, at this point in the reproductive cycle, inflorescences are able to compete for photoassimilates against the vegetative structures of the shoots, with the production of carbohydrates by the former sufficient for self-supply. It is only later, during flowering, when vine requirements for photoassimilates exceed photosynthetic capacity and the sensitivity to water deficit increases [16]. Of course, there may be times when drought conditions occur even during early spring. Excessive water deficit at this time can cause the vine to loose whole inflorescences, reducing the eventual number of future clusters. This is particularly true when such drought conditions are combined with high temperatures and low vigour [13].

The reviews by McCarthy [19] and Keller [16] reveal the importance of vine water status during the flowering period. The male organs are more sensitive to this variable than the female organs; deficits near the time of flowering may limit ovary growth, leading to smaller berries, but the effects on pollen formation, germination and pollen tube growth are even more severe. Water deficit, like other stressors, can limit sugar uptake and starch accumulation in developing pollen grains, causing sterility and compromising the course of fertilisation and fruit set, even leading to the loss of whole inflorescences [2]. Severe water stress during fruit set can reduce the success of this stage via reductions in the photosynthetic rate and carbohydrate availability [17].

Once fruit set has taken place, and the final number of berries in the vineyard is determined, the last yield component to play a role in the yield is berry weight. Berry development follows a double sigmoid curve [20] that can be divided into three stages. In Stage I (the beginning of the green phase of berry development), berry growth is caused by cell division and enlargement. Stage II is the shortest stage; growth at this point is markedly reduced. At the end of Stage II, the berry colour starts

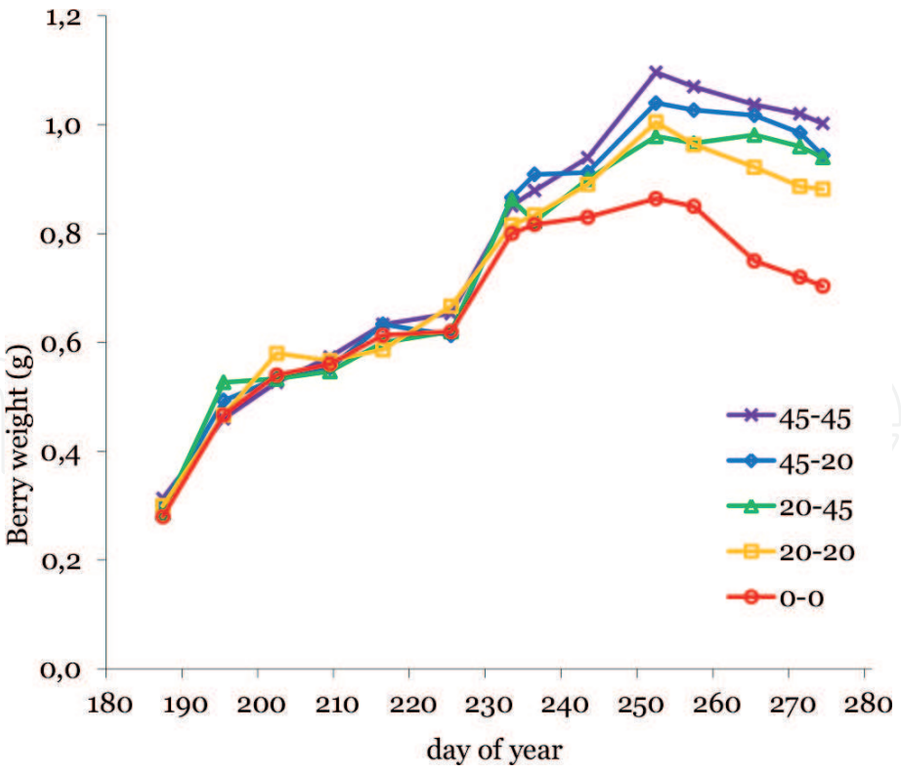


Figure 2.
Change in berry weight for five different irrigation treatments applied during 2004 in a cv. Cabernet sauvignon vineyard in Madrid, Spain. Numbers for each treatment correspond to the %ETc applied by irrigation before and after veraison. Unpublished data.

to change, and metabolic processes that trigger ripening take place. This moment in the cycle is called veraison. In Stage III, the so-called ripening, berry growth is restarted due to cell enlargement. During Stage I, both multiplication and cell growth can be affected by water stress, although multiplication is less sensitive than cell enlargement. Water stress at this time alters the properties of the cell wall, irreversibly restricting the capacity for cell enlargement [21]. Later on in the cycle, only cell expansion is affected by water stress, limiting berry and seed growth. However the effect here is never as significant as in the earlier stages. Berries become increasingly resistant to stress from veraison onward. In fact, the reduction in yield due to water deficit is much more important when this occurs before veraison, as made clear by numerous studies on regulated deficit irrigation (**Figure 2**) [6, 12, 22–25].

In their review, Chaves et al. [4] indicate the effect on photosynthesis to be the main cause of water availability-induced reductions in berry growth after veraison. During ripening, the berries take up water mainly via the phloem; uptake from the xylem is very limited. Occasionally, berry weight losses are observed in late ripening, reducing the final yield (**Figure 3**). Recent studies have shown that, in addition to possible water losses by transpiration (which are less severe at this point than during Stage I), water return via the xylem may occur. This return is dependent on grape variety and is determined by the late-ripening integrity of the cell membranes and the hydraulic conductivity of the xylem [26, 27]. Different grape varieties show either isohydric or anisohydric water regulation behaviours at the leaf and root level; the idea of variety-dependent water regulation strategies at the berry level cannot, therefore, be ruled out [28]. Illand et al. [17] hypothesize weight loss taking place during late ripening whenever berries continue to be vascularly connected to the vine and there is a loss in cell viability (shrinkage in Syrah). This suggests that weight loss would not occur if (a) cell viability is preserved (Thompson Seedless) or (b) the berries become vascularly disconnected from the vine (Chardonnay).



Figure 3.
Shrivelling and weight loss in cv. Graciano grapes during late ripening.

2.2 Effects of vine water status on vegetative growth

Plant growth is strongly affected by water availability. Freeman and Smart [29] reported increases in root growth under water deficit conditions, while Van Zyl [30] indicated that irrigating vines after 25 or 50% of the total water available had been used up by around the time of flowering led to 190 and 300 actively growing root tips/m^2, respectively. However, this was reduced to 40 root tips/m^2 when the soil was irrigated after 75% of the total water available had been consumed. Prolonged exposure to moderate water deficit thus increases the root-to-shoot ratio [4], but both severe water deficit and irrigation that keep the soil close to saturation for long periods negatively affect root growth.

There is, however, no evidence that vegetative growth in vines is increased under water deficit conditions. Indeed, water deficit negatively affects the vegetative growth of vine trunks, shoots and leaves. However, the limitation of vegetative growth depends on the timing, duration and severity of water deficit. The most active period of vegetative growth takes place between budbreak and veraison [12], with a maximum reached at the beginning of the growth cycle some 60 days after budbreak [6, 31–33]. Growth then progressively decreases until a vegetative stand-still is reached close to the time of veraison.

After budbreak, shoot growth occurs at the expense of reserves stored during previous vegetative cycles [34]. In Mediterranean-type climates, it is uncommon for soil water deficits to be strong enough to inhibit the growth of shoots during this initial growth phase (rain usually falls during this period, and there is still winter rain stored in the soil [35]), although total needs up to veraison are rarely so easily met.

The effect of water deficit on the canopy has been widely studied. Many authors indicate it to reduce shoot growth and canopy development [6, 11, 36–40], a consequence of reduced activity in the shoot terminal meristem [41], reduced leaf area [42] and the senescence and fall of the basal leaves. Physiological changes in the vine, such as reduced leaf photosynthetic activity in response to stomatal closure due to water stress, have been studied in many experiments [4, 22, 43–52].

Post-veraison water stress has little or no effect on shoot growth [22, 53, 54]. Nevertheless, severe water stress during the ripening period can significantly diminish leaf area due to early senescence [55]. During the postharvest period, root growth and nutrient absorption contribute towards the accumulation of reserve carbohydrates. This period is important for the vigour and productivity of the vine

in the following season. The soil water content aimed for at this time should ensure the accumulation of carbohydrates but avoid the regrowth of laterals [56].

Shellie [9] and Greenspan [57] reported a reduction in the main shoot growth from 20 days after budbreak when the midday leaf water potential approached—1.0 MPa in cvs. Merlot, Cabernet Sauvignon and Pinot Gris vines. Munitz et al. [58] observed a reduction in leaf area in cv. Merlot after continuous irrigation at 20, 35 and 50% of the ETc, reaching maximum ψ_{stem} values of −1.2, −1.3 and −1.4 MPa during cluster closure to veraison. However, in cv. Cabernet Sauvignon, Acevedo-Opazo [59] reported no differences neither in shoot length, number of stems, internode length or pruning weight between three treatments in which the midday ψ_{stem} was maintained at between −0.8 and −0.95 MPa, −1.0 and −1.2 MPa and −1.25 and −1.4 MPa, from post-setting to harvest—although in that work ψ_{stem} did reach values of −1.0 MPa close to veraison. Water stress induced at the beginning of the growing season (flowering to cluster closure or earlier) may thus result in a reduction in canopy size. Under field conditions, however, severe water stress might be hard to induce; soils will normally contain some stored water. In another experiment on cv. Cabernet France [36], less shoot growth was observed in an early water deficit treatment compared to control, although the leaf water potential values reached were similar (≈−0.8 MPa). The authors [36] suggested that this level of water deficit was not responsible for the reduced shoot length observed, but to the early limitation of photoassimilates, probably caused by a reduction in the hydraulic conductivity of the wood through prolonged exposure to early water deficit repeated over many seasons [60].

This high sensitivity of shoot growth to water deficit has sometimes been used as an early indicator of the latter (based on allometric measurements). Pellegrino et al. [61] analysed the effects of water deficit on certain components of shoot vegetative growth (the number of leaves to emerge on the first- and second-order laterals, leaf area, internode length of each phytomer on the first-order laterals and the frequency of second-order laterals) in cv. Shiraz. Sensitivity to water deficit was seen to increase as the second-order laterals emerged, i.e. the rate of emergence of second-order laterals decreases in response to water deficit. These authors also established a water deficit indicator (ratio of branching intensity between first- and second-order laterals) that was sensitive to slight water deficit—even more so than the stomatal response. A more recent study showed significant changes in the abundance of proteins involved in translation, energy production, antioxidant defence and steroid metabolism during early growth and indicates these changes to occur before any detectable reduction in shoot elongation, stomatal conductance or photosynthesis [62].

The availability of water in the soil leads to differences in hydraulic conductivity that leave permanent marks on vine plant organs. At the trunk level, high water availability early in the season results in wider xylem vessels (and therefore greater hydraulic conductivity) and greater trunk diameter, ring width and ring area. Also, when vines are subjected to late water deficit, they show more negative water potential values at the end of the season than do vines that receive low-level but relatively constant irrigation [60]. Thus, high water availability during the vegetative growth of *Vitis* increases vessel diameter and hydraulic conductivity, leaving plants more vulnerable to stress during the ripening period [60]. However, at the shoot level, Pagay et al. [63] reported xylem vessels with larger diameters to be more resistant to cavitation, concluding that they have less inter-vessel pitting. This would result in a hydraulic advantage allowing them to better maintain growth and productivity under water stress.

Finally, pruning weight is linearly related to the amount of water applied and is less influenced by the timing of the water supply than is leaf area (**Figure 4**) [33, 64]. Reductions in shoot weight are accentuated by long-term water deficit [6]. Thus,

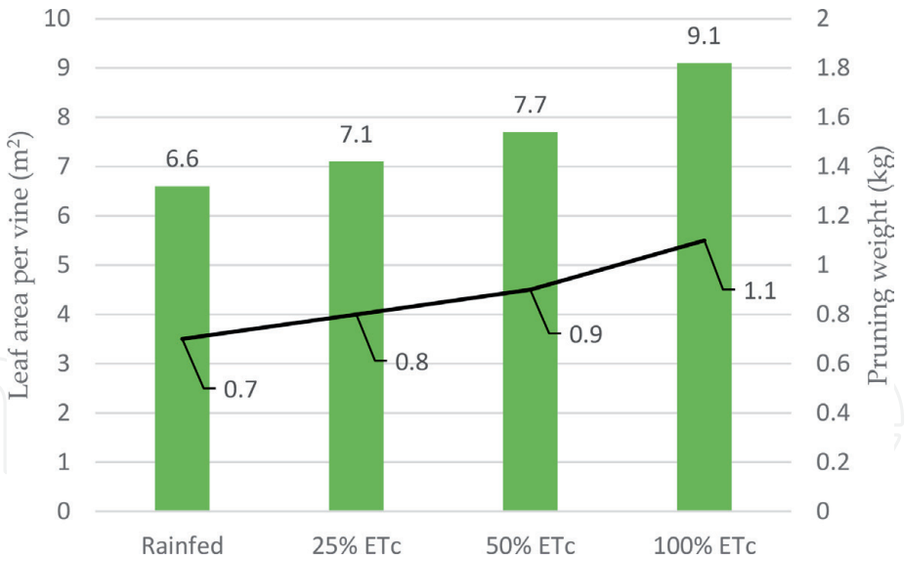


Figure 4.
Leaf area per vine at ripening (green bars) and winter pruning weight (blue line) from rainfed vines and three irrigation treatments applying 25, 50 and 100% of vine evapotranspiration (ETc) in averaged over four seasons in cv. *Tempranillo. After [64].*

water deficit has a cumulative effect, probably due to reduced starch and sucrose accumulation in the perennial organs [65–67]. This is important since the sugars accumulated in the trunk and roots are the first carbohydrates to be used during the following spring's growth.

2.3 Effects of vine water status on must and wine composition

2.3.1 Effects of irrigation on total soluble solids

Total soluble solids (TSS) accumulate in the berry during phase III of berry growth. The increase in sugar content (°Brix) is coupled with a resumption in berry growth, accompanied by a sharp increase in berry weight (**Figure 5**). At the beginning of ripening, sugar accumulation occurs through leaf photosynthesis and through the mobilisation of reserves [68] although this mobilisation soon ceases. Sugar is transported from leaves to the berry via phloem in the form of sucrose. Once in the berry, it is changed into glucose and fructose, the ratio between them remaining close to 1:1 throughout ripening [2]. Since the TSS content is directly related to leaf photosynthetic activity [2, 69], sugar content can be used to indirectly evaluate the plant photosynthesis activity. At the end of ripening, photoassimilates also divert to the fruit and to reserve tissues in the perennial parts of the plant [68].

A linear relationship exists between berry size and TSS (**Figure 6**). Thus, berry size provides a meaningful, inexpensive means of estimating plant activity and tracking ripening. At the end of the ripening period, the increase in berry weight levels off, and the discharge of sugar into the berry ends. When the berries reach maximum TSS due to photosynthesis, ripening is finished. The final °Brix may differ depending on variety, cultivation practices and climate.

The amount of available water influences both the sugar accumulation rate and berry size. Studies have shown that, under water deficit conditions, °Brix increases faster than under high soil water conditions (**Figures 5** and **6**). This means that for the same berry weight, the °Brix reached in rainfed vines (or grown under water deficit conditions) is higher than those reached in well-irrigated vines [33, 71]. However, sugar accumulation expressed on a per-berry basis is higher for irrigated vines. Since irrigated vines produce higher yields than either moderately water

stressed or nonirrigated vines, the sugar concentration of the berries produced under the former conditions increases slower, but finally they can get the same concentration if they remain in the vine (**Figure 6**) [71].

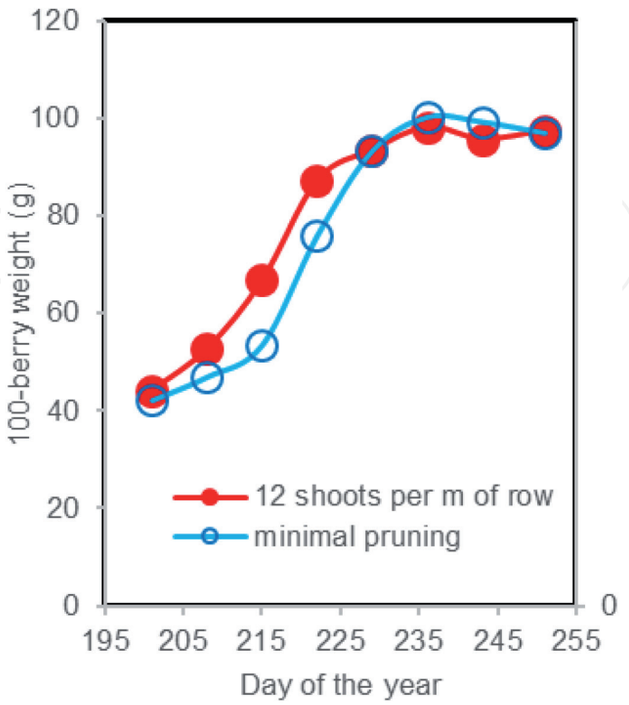


Figure 5.
Seasonal change in 100-berry weight in cv. Merlot in two shoot load treatments. Compact circles represent a shoot load of 12 shoots per metre of row; open circles represent minimal pruning conditions. Unpublished data.

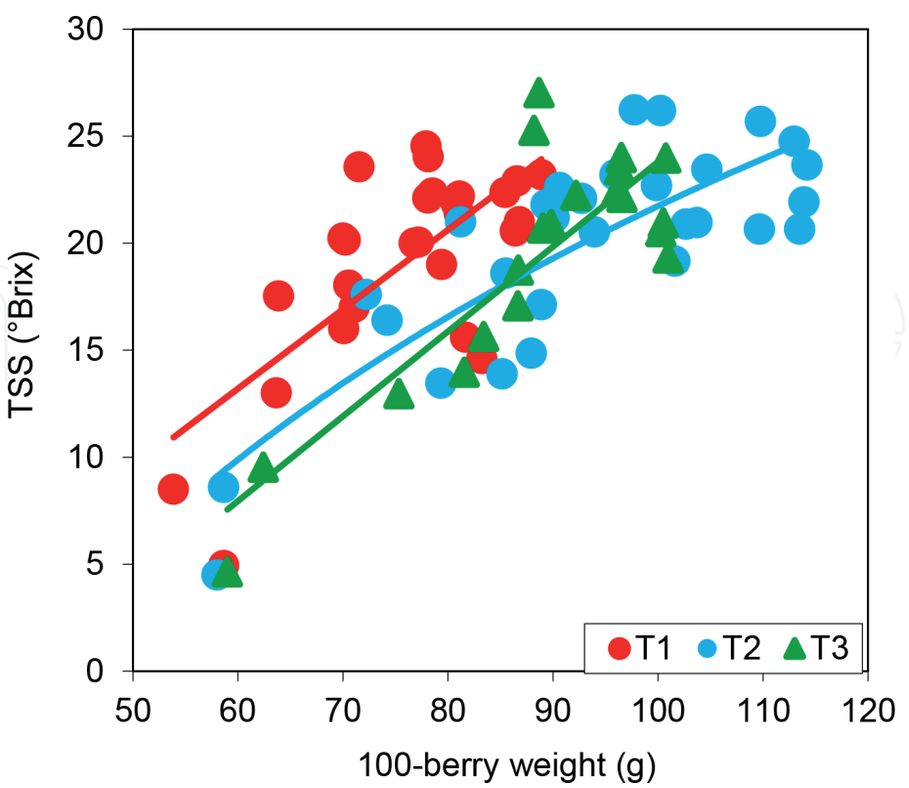


Figure 6.
Change in the relationship between berry size and TSS under three irrigation regimens in cv. Cabernet sauvignon in Madrid (Spain). T1: rainfed (Y = 0.37x − 9.0R_2 = 0.50), T2: irrigated 0.4·ETo (Y = 23.2Ln(x) − 85.12R2 = 0.68**), T3: irrigated 0.2·ETo (Y = 0.40x − 15.82R2 = 0.71**) [70].*

Berries increase in weight according to the availability of soil water. In trials involving different irrigation treatments, seasonal berry weight trends run in accordance with the supply of water [33, 72]. However, other authors report that berry sugar concentration may not differ between irrigation treatments since the smaller photosynthetic rate reached during ripening may be compensated for by a smaller berry weight [6, 71, 73]. Under moderate water stress, berry weight is reduced, but ripening quality in terms of sugar content is unaffected [9, 21, 74–76]. When water deficit is very mild, neither berry size nor sugar content is affected [77].

Although berry sugar concentration may not be affected by an increase in water deficit, other must components—such as anthocyanins [6]—may be. When water deficit has been long and intense, photosynthetic rates become low, and leaf abscission can occur at mid ripening, collapsing the ripening process [6, 69, 72]. Thus, final sugar content depends on water deficit intensity and deficit timing; several authors [8, 9, 59, 69, 70, 72, 78] have examined the thresholds between moderate deficit and severe water stress; on the whole, a midday stem water potential (Ψ_s) of −1.2/−1.3 MPa is required to maintain the yield and must quality within the required range. A midday Ψ_s of ≤1.4 MPa has clearly detrimental effects on photosynthesis, quality and yield. Some authors report that over optimal irrigation can have a detrimental effect on sugar content and lead to delayed ripening, increased acidity, reduced berry colour intensity and a smaller yield [35, 79–81], but in some of these experiments, however, midday Ψ_s was kept at above −0.9 MPa [80].

2.3.2 Effects of irrigation on pH and titratable acidity

Must titratable acidity and pH are important quality variables in winemaking. They both affect wine perception in the mouth (including smoothness, freshness and stringency). pH also influences the colour of the anthocyanins (red-blue at pH 3.0, orange near pH 4.0 and transparent at around pH 7.0), conditions microbial stability and when low acts as a shield against oxidation in musts and wines.

Organic acids accumulate in the berries during pre-*veraison*, increasing in concentration from fruit set to the end of phase II of berry growth [2]. At the end of this phase, the berries contain many different acids, but tartaric and malic acids together account for 70–90% of the total acid content.

During ripening, the berry acid content decreases by (1) dilution as sap flows inwards from the phloem, (2) by malate being used as a carbon source in respiration and (3) by gluconeogenesis in the berry, although this is responsible for only a small amount. Citric acid transforms into malic acid which might then follow any of its degradation routes. During ripening, the total acid content of the berry decreases, and the pH increases (**Figure 7**). At the end of ripening, the berry acid content and pH depend on the balance between the acid content at pre-*veraison*, leaf photosynthetic activity during pre- and post-*veraison*, the vine microclimate during pre- and post-*veraison*, final berry size and the berry cation (Ca^{2+} and K^{+}) content, which transforms free acids into their corresponding salts. Variety and rootstock influence cation uptake, thus affecting the final pH too.

In trials, the effects of irrigation on total acidity and pH have been inconsistent. Irrigation has been reported to increase, reduce or not affect either variable. Esteban et al. [71] in a trial comparing nonirrigated and irrigated vines of cv. Tempranillo grafted onto 110 Richter rootstocks found that the grape must of the irrigated vines had lower pH and higher titratable acidity. In contrast, after a 5-year study of different irrigation regimens on cv. Cabernet Sauvignon/SO4, Junquera et al. [6] reported a positive relationship between water availability and total acidity but indicated that must pH was unaffected by irrigation. Differently again, after a 5-year of study involving cv. Tempranillo/161-49C, Intrigliolo and Castel [33] concluded that the

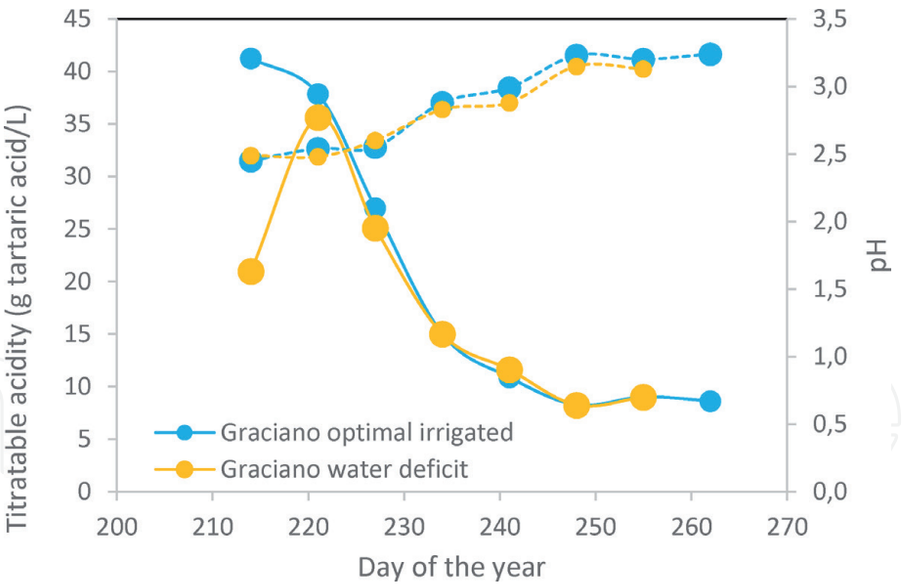


Figure 7.
Seasonal change in titratable acidity (compact lines) and pH (dashed lines) in cv. Graciano/41B under optimum water availability (compact circles) and water deficit conditions (empty circles).

only detrimental effect of irrigation was an increase in pH compared to no irrigation, with total acidity increasing. In another trial involving cv. Tempranillo in pots, [72] titratable acidity increased with increasing water stress regardless of the stage at which water stress was induced. Working in a very warm region with the white cultivar Doña Blanca, Uriarte et al. [73] reported higher tartaric acid and lower malic contents in the must of water deficit vines, regardless when water deficit was induced. However, after a 3-year trial on cv. Monastrell/1103 Pa [81], neither titratable acidity nor the malic or tartaric acid contents were altered by any irrigation treatment. They did indicate pH and K^+ to be significantly reduced in the highest irrigation treatment, but these differences were negligible from an oenological point of view; adding to the confusion, the tartaric and malic acid contents were inconsistent from 1 year to the next.

The results of other authors have further compounded the problem. For instance, neither Acevedo-Opazo [59], who ran a 3-year trial on cv. Cabernet Sauvignon in Chile, nor Munitz et al. [32], in their 4-year trial in Israel involving cv. Merlot, could found any differences in total acidity or pH between irrigation treatments. However, in a trial involving cv. Tempranillo/110R under a wide range of irrigation doses between budbreak and *veraison* and between *veraison* and harvest, Santesteban et al. [24] obtained higher titratable acidity values in the higher irrigation treatments before *veraison* (average predawn leaf water potential ~ −0.35 MPa). Regarding organic acid results, differences were significant 2 years out of 4 for the tartaric and malic acid contents which make us to state that irrigation effects on must acidity are still inconclusive.

These apparently very contradictory results do have some explanation, however, when examined taking into account vine physiology and factors that regulate the synthesis, accumulation and breakdown of these components [24, 69, 81, 82]: when water deficit is imposed from early in the season up to *veraison*, it negatively affects vigour, berry size and photosynthetic rate. If the photosynthetic rate is low, the acid and phenol contents accumulated in the berry during phase I are reduced [71, 83, 84]. On the contrary, optimal vine water status during this phase enhances photosynthetic activity, vigour and the acid and phenol content in the berries.

Esteban et al. [71] and other works obtained a tight positive, linear relationship between pH and K^+ in grape must. Potassium is meanly accumulated in berry

during maturation [85]; grapevines suffering water deficit during maturation have lower berry potassium concentration due to reduced mobility in soil and impaired root uptake [85]. This could explain the reduced pH in lower irrigated vines with respect to irrigated ones resulted in some trials [33]. Therefore, final pH and titratable acidity will depend on the timing and intensity of vine water deficit.

The effect of water deficit on must composition during ripening depends on the plant's previous water status. Mild water stress (midday Ψ_{stem} = −1.2/−1.3 MPa) after no previous water stress favours an optimal photosynthetic rate and sugar accumulation by the berries while avoiding excess berry growth. Thus, acids and phenols are not diluted and reach an optimal concentration at the end of ripening. Severe water deficit after *veraison* slows sugar accumulation severely and can collapse ripening. At this point, water stress favours leaf abscission, and the berries remain unripe with a high acid content, with a low sugar content and with an unripe colour and immature seeds. Early leaf fall renders the clusters more exposed to direct sunlight, affecting the breakdown of malate and the synthesis of anthocyanins. Either overirrigation or excess of available soil water after *veraison* may cause the berry acids to be diluted due to excess berry growth [16]. If there is a high soil water content, laterals develop and compete with the berries for sugars from leaf photosynthesis. Ripening is then delayed, something that could be sought more often in warm growing areas.

2.3.3 Effects of vine irrigation on berry phenolic maturity and aroma compounds

Volatile and phenolic compounds are grapevine secondary metabolites critical to grape quality and wine sensory attributes. Viticultural practices can influence the concentration of these compounds and their precursors in grapes via plant stress responses. Deficit irrigation (moderate water restriction), for example, is an important vineyard management strategy used to alter grape composition and therefore improve the final organoleptic quality of wine [85]. Water deficit in the vineyard reduces vegetative growth, alters the canopy microclimate and increases the amount of intercepted light in the cluster zone [9, 33, 86]. This renders the fruit more susceptible to heat stress, especially when there are high levels of ambient solar radiation. However, increased exposure of the fruit to sunlight has been associated with improvements in must and wine quality [87]. Indeed, several authors have reported it to be associated with increases in the volatile compound contents of grapes and wines, especially monoterpenes and carotenoids [88, 89]. Light and temperature also influence norisoprenoid concentrations, which correlate directly with the concentrations of carotenoids in grapes under moderate water stress [90, 91].

Both light intensity and temperature also affect phenolic compound composition and berry colour. Sunlight favours the accumulation of polyphenols in the berries, mainly anthocyanins [92, 93], but increased temperatures from excessive exposure to sunlight may lead to reduced berry colour, especially in warm-climate regions [94–96].

Berry size is widely acknowledged to affect berry quality. Vine water deficits generally lead to smaller berries being produced and changes in fruit and wine composition [74]. Depending on the moment of induction of water stress and its severity, the proportion of skin surface area to mesocarp volume changes [74, 97] as does the rate of biosynthesis and degradation of volatile [98] and phenolic compounds [97]. Several authors have reported the effect of vine water status on grape and wine volatile compounds [98–106], while Chapman et al. [99] showed that water deficit influences berry composition and improves wine sensorial quality, increasing fruity aromas and reducing vegetation aromas.

Bindon et al. [101] report that deficit irrigation increases the concentration of some C13-norisoprenoids, such as β-damascenone and β-ionone, in cv. Cabernet Sauvignon berries at harvest. Other studies also report a positive effect of deficit irrigation on

grape and wine volatile compounds in cv. Cabernet Sauvignon berries [100, 105]. Water deficit also affects cv. Merlot grape maturity and composition. Deficit irrigation reduces the concentration of negative compounds and increases the concentration of positive compounds [102]. Certainly, Qian et al. [98] observed that cv. Merlot wine produced from deficit-irrigated vines has increased vitispirane, β-damascenone, guaiacol, 4-methylguaiacol, 4-ethylguaiacol and 4-vinylguaiacol concentrations compared to wines produced from well-watered vines. Deficit irrigation had no effect on the concentrations of other measured volatile compounds such as esters and terpenes. Similarly, Talaverano et al. [103] suggest that low water supply has a negative effect on the aromatic potential (mainly related to ethyl esters) of wines at a similar ripening stage. However, this effect could be countered by harvesting at a later date. Recent work reported by Vilanova et al. [105] shows that volatile composition in cv. Verdejo wines is modified by the water regimen, with concentrations increasing under the most severe deficit irrigation regime.

In a study examining the effect of irrigation on the sensory profile of wines from Galicia, those made with grapes of the white cultivars Albariño and Godello were judged to be better when the vines were rainfed rather than irrigated. Wines made from cv. Treixadura grapes, however, were judged better when the vines were irrigated [107]. Balint and Reynolds [108] studied the effect of different irrigation strategies on cv. Cabernet Sauvignon aroma descriptors and reported regulated deficit irrigation (RDI) to improve wine quality over both full irrigation and no irrigation treatments. The 25-RDI (25% ETc) treatment especially returned higher scores for most of the positive sensory characteristics of cv. Cabernet wines. The former authors reported that soil and plant water status could be used to predict the flavour profile of these wines, reflecting the relationship of these variables with sensory descriptors. It was concluded that 100% water replacement was not recommendable at any phenological stage. However, 50 and 25% water replacement had overall positive effects on fruit composition and wine varietal typicity.

Water deficit can enhance the accumulation of anthocyanins by stimulating anthocyanin hydroxylation [4, 97]. Castellarin et al. [109] showed that water deficits accelerate anthocyanin accumulation and increase the expression of many genes responsible for the biosynthesis of anthocyanins. Moreover, the concentrations of different individual phenolic compounds are reported to change in response to plant water status, with those of flavonol and proanthocyanidin less affected than those of anthocyanins [97]. Ojeda et al. [110] report that severe water deficit before *veraison* reduces cv. Syrah anthocyanin synthesis. Similar results were reported by Romero et al. [69], with severe water stress associated with total grape phenolic compound concentration in cv. Monastrell grapes. However, Casassa et al. [111] recently reported that early and full deficit irrigation applied at pre-*veraison* produced cv. Cabernet Sauvignon grapes and wines with higher concentrations of phenolic compounds. In general, moderate water stress increases the concentrations of these compounds in red grapes, improving berry quality. However, when a certain threshold of water stress is surpassed, these positive effects are reported to disappear [69]. Similarly, Delgado et al. [112] report that the use of less water can increase the chemical and sensorial quality of wine; this is of some significance in a climate change context in which water supplies may decline. Niculea et al. [113] report phenolic compound accumulation and composition responses to sustained deficit irrigation during berry growth and ripening to be variety-dependent.

Finally, Herrera et al. [114] suggest that the interaction between water availability and weather conditions plays a crucial role in modulating berry composition. A meta-analysis performed by Mirás-Avalos and Intrigliolo [115], using published data for red and white varieties, concludes that cultivar, the timing of water restrictions and rootstock type have a great influence on must and wine composition. The

effects of other factors, such as climate, the leaf surface/yield ratio and training systems, need to be examined in future research.

The effect of RDI on grape volatile and phenolic compounds remains incompletely understood, and further investigations are required to determine what compounds are influenced by irrigation. The timing, severity, duration of water stress, seasonal variations, the type of cultivar and the interaction of *genotype x environment* can all influence the response of vines to water stress, probably explaining the discrepancies seen in the results of different studies.

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