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REVIEW ARTICLE

Improving water use efficiency of vineyards in semi-arid regions. A review

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Abstract Water is critical for viticulture sustainability since grape production, quality and economic viability are largely dependent on water availability. The total water consumption of vineyards, 300 to 700 mm, is generally higher than the annual average precipitation in many viticultural areas, which induces a risk for sustainability of vineyards. Improving vineyard water use efficiency (WUE) is therefore crucial for a sustainable viticulture industry in semi-arid regions. Increased sustainability of water resources for vineyards can be achieved using both agronomical technology and cultivar selection. Here, we review advances in grapevine water use efficiency related to changes in agronomical practices and genetic improvements. Agronomical practices focus on increasing green water use by increasing soil water storage capacity, reducing direct soil water loss, or limiting early transpiration losses. Cover crops for semi-arid areas show a favorable effect, but careful management is needed to avoid excessive water consumption by the cover crop. Canopy management practices to reduce excessive water use are also analyzed. This is a genetic based review focused on identifying cultivars with higher WUE.

Keywords Soil water availability · Irrigation · Drought · Genotypes · Carbon balance · Water economy · $\delta^{13}C$

Abbreviations

A_N	Net leaf photosynthesis
g_s	Stomatal conductance
WUE	Water use efficiency
WUEi	Intrinsic water use efficiency ($A_{N/}g_s$)
WUEc	Crop water use efficiency
WFP	Water foot print
ETc.	Crop evapotranspiration
$\delta^{13}C$	Carbon isotope discrimination

Contents

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1 General introduction

Sustainability in agriculture is an important goal for many farmers and agronomists. This is supported by a wide range of evidence showing the necessity and convenience of sustainable practices in agricultural lands for long-time exploitation of non-renewable natural resources, such as water and soil. This concern is commonly presented in current literature, which identifies water use efficiency as a general goal for different crops from the farm to regions and country scales (Deng et al. 2006; Geerts and Raes 2009; Katerji et al. 2008; Morison et al. 2008). Considering these society concerns, there is also a growing tendency to exhibit greener and cleaner food production. For viticulture, sustainability is becoming a serious concern due to the high extension of the crop in many different climatic conditions and high inputs required. Furthermore, the carbon and water footprint labels are having an increased importance within produces and wine trades. This is related to the wider positive appreciation of a minimal carbon and water footprint of the crop or to the "going greener" concept, which shows a certain salutary interest of grape growers and winemakers related to the whole sustainability of the vineyards and wineries.

Within these concerns, the water issue is the most important for environmental sustainability of viticulture with a 60 % presence in semi-arid areas (Flexas et al. 2010). However, the reduction of pesticide use could be more important in other climates. High water requirements are necessary to complete the growth cycle of grapevines, which coincides with the driest months, making irrigation scheduling and timing critical (Williams and Ayars 2005). In dry areas, water use by irrigation scheduling can be a compromise for environmental sustainability of the crop and sometimes be a competition with other critical human uses (Chaves et al. 2007). Moreover, evaporative demand is expected to increase as a consequence of increased global air temperature (Vicente-Serrano et al. 2014) and intensity of climatic anomalies, such as droughts and heat waves (IPCC 2013; Jones and Vaughan 2010). These effects could only be alleviated with higher transpiration rates to lower leaf temperature. All those circumstances are a prevalent condition for most of the semi-arid regions of grapevine production, as well as most of the "new world" viticulture due to the high irrigation volumes required to obtain a reasonable harvest.

Consequently, the optimization of water use for vineyards, by improving water use efficiency (WUE), is a core subject of interest to secure sustainability in viticulture. In consequence, an important volume of applied and fundamental research has been focused into the exploration of the capacity to optimize grapevine water use. An important part of these researches are related to the evaluation of irrigation timing and schedule by introducing new technologies to reduce water consumption (Chaves et al. 2010; Romero et al. 2010; Sadras 2009; Williams et al. 2010). Regarding the improvement of genetic capacities to enhance WUE, some works have been focused on the estimation of the genetic variation of grapevine rootstocks or cultivars (Alsina et al. 2007; Satisha et al. 2006; Tomás et al. 2012).

However, most of these researches reflect the increasing social interest and the necessity of optimizing water use by the grapevine crop. Related to this, increasing concerns about the water foot print (WFP) of grapes and wine production reinforces the importance of water economy as a convenient label for the grapevine fruit and wine industry. To determine WFP, three water categories have been considered: (i) green water, which is water coming from rain/snow or other natural sources directly to the cropped land; (ii) blue water, which is water used for irrigation, and (iii) gray water, related to industrial processes around the winery practices and agronomic practices.

Fortunately, for most of the wine regions, high grape yield is not the main concern for farmers since grape quality is routinely assessed and rewarded. Also, the highest fruit quality is negatively correlated to higher yields (Romero et al. 2013; Williams and Matthews 1990). In summary, it can be said that high-quality yield is generally achieved under suboptimal crop conditions. Therefore, water stress has become a management target to secure high fruit quality and improve sustainability of water use by rewarding crop quality over quantity.

In the present paper, we summarize different ways available to improve the WUE of grapevines on the basis of the WFP classification, thus increasing the green water consumption, reducing the blue water use, and improving genetically the capacity to achieve higher WUE allows the increased sustainability of vineyards. Figure 1 summarizes the different scales to measure WUE in grapevines.

2 Improving WUE by agronomic practices

2.1 Maximizing green water use

Management of water stored in the soil by accumulation of rainfall is crucial to reduce plant irrigation requirements. The ways to enhance total water availability to the plants can be related to the improved capacity of soils to store water. Improvements in soil physical and chemical structure and properties can be achieved by, for example, adding organic matter and avoiding soil water unnecessary losses, thus reducing direct soil water evaporation by mulching, and increasing water availability to plants with deeper and more extensive root systems (more drought adapted rootstocks).

2.1.1 Mulching

Organic mulching is a sustainable agronomic practice widely used to prevent soil erosion and improve general soil

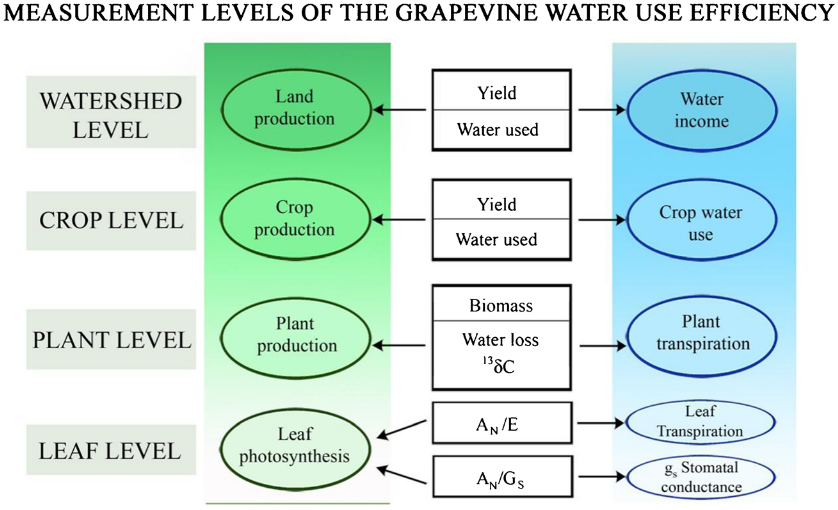


Fig. 1 Measuring water use efficiency in grapevine at different scales, from leaf to watershed level (adapted from Medrano et al. 2010)

properties. Straw mulch is an easily available and relatively cheap material, but so are crop residues or compost from waste products, which can also be used as mulching material (Fig. 2). Furthermore, besides waste products from other origins, vineyard and winery waste products can be incorporated into mulches.

The reported advantages of mulching in vineyards include the following: (i) nutrient release efficiency and better plant nutrient status, enabling a reduction in fertilizer application (Agnew et al. 2002, 2005; Ross 2010; Nguyen et al. 2013); (ii) weed control, which enables reduction in herbicide application (Elmore et al. 1998; Frederikson et al. 2011; Steinmaus et al. 2008); (iii) prevention of soil erosion by improving soil structure and decrease soil compaction (Agnew et al. 2002; Göblyös et al. 2011; Némethy 2004), and (iv) increasing vineyard biodiversity, which can, in turn, encourage beneficial insects to prevent pests (Huber et al. 2003; Nicholls et al. 2001; Thomson and Hoffmann 2007). A recent review by Guerra and Steenwerth (2012) showed how the use of organic mulches increased yields and reduced pathogen and pest pressure. Furthermore, Nguyen et al. (2013) showed how natural compost mulch increased grape yield with no adverse effects on grape quality. Other studies also reported a higher yield of mulched grapevines compared to other soil management practices (Buckerfield and Webster 2001; Fourie 2011).

Fig. 2 Straw mulch in young grapevines (University of Balearic Islands, Mallorca, Balearic Islands, Spain)

So far, the mulching effect on the crop water retention, consumption, and consequently, on the crop water use efficiency (WUEc) has not been widely studied. WUEc can be defined as the ratio between crop production and total water used. Total crop water use includes the amount of water lost directly from the soil, without being used by the plant. The latter occurs through soil evaporation, runoff, and leaching, and, as pointed out by Gregory (2004), it can be avoided or reduced by agronomic practices such as mulching. Similarly, Davies et al. (2011) showed how, by applying mulches, it could affect more directly WUEc as they can modify soil reserves, minimizing soil evaporative losses and consequently improving water soil infiltration. These results are in agreement with some reviews showing how surface residue management or mulching can improve WUEc by reducing soil evaporation and runoff in other crops (Davies et al. 2011; Hatfield et al. 2001).

For grapevines, Pinamonti (1998) reported how compost-mulched soils presented better water permeability and water storage capacity and reduced evaporation compared to plastic mulches or bare soil in a Merlot vineyard (showing around 2 % increase of water availability in the soil). Agnew et al. (2002) found that mulches helped to retain soil moisture early in the season with moisture levels around 5 % higher under mulch in the upper part of the soil profile (0–30 cm). In Hungarian vineyards with sandy soils, the most favorable soil moisture was found under straw mulch compared to cover crops or mechanical tillage. On a yearly average, the soil moisture content between 0–60 cm was 3.4 % higher in the covered soil than in the tilled one. In addition, soil penetration resistance (related to the soil compaction) was reduced by 50 % (Némethy 2004). In a recent study, Zhang et al. (2014) showed interesting results on potted grapevines about improvements of WUEc and yield by applying rice-straw mulch. On the other hand, Nguyen et al. (2013) did not find higher soil water content in compost-mulched grapevines, but presented higher yield. Nevertheless, measurements by our group showed that direct soil evaporation can be up to 20 % of water consumption, so covered soil may result in greater plant water availability (Buckerfield and Webster 2001).

Summarizing, soil management using mulching can be seen as an efficient tool to control soil water loss and therefore improve WUE as can be seen in Table 1, which summarizes the referred literature on the effects of mulching on soil water content. However, there is still a lack of information about the quantification of the contribution of mulching to water savings and WUEc improvements for grapevines. The amount of saved water or reductions in irrigation water requirements are not easy to generalize since the effects of mulching largely varies with soil types, rainfall patterns, and evaporative demands (Jalota et al. 2001). On the other hand, different mulch materials can result in different water holding capacity and evaporative loss variability (Shaw et al. 2005). In this sense, more specific studies in different conditions are necessary to determine the effects of mulches on water conservation by soils, plant WUE, and plant growth.

2.1.2 Cover crops

With few exceptions, natural terrestrial ecosystems have a continuous cover of some amount of plant residue on the soil surface, and this residue can have some effects on seedling emergence and succession of vegetation communities (Facelli and Pickett 1991). Cover crops have been largely recommended to extract excessive water and nutrients within the effective root zone of plants, which can induce excessive vigor in grapevines. Nowadays, jointly with mulching, cover crops have been also used to reduce the risk of soil erosion and water runoff and to improve soil fertility and structure, mainly when cash crops are not actively growing (Folorunso et al. 1992a, b; Hartwig and Hoffman 1975; Shanks et al. 1998). However, only a small percentage of farmers are planting cover crops in semi-arid areas due to the disadvantages outweighing the advantages since the positive effects of using cover crops are not always clear and cost effective (Table 2). Although the off-season water used by a cover crop has positive effects in some climates, yield losses associated with water lost by the cover crop are often found in areas with less than 1000 mm of annual rainfall (Hartwig and Ammon 2002). So, it is necessary to have a complete account of the total and available water holding capacities of the soil and the potential, as well as actual, rooting depths of the crop to advise on the specific results. Furthermore, in order to maximize the potential benefits of specific cover crops and to avoid the undesirable ones, the accurate selection of species and varieties are key points in the decision-making process. For example, under Mediterranean conditions, early senescent and self-seeding or perennial species such as *Dactillys* sp., *Medicago* sp., and *Trifolium* sp., among others, can meet both these objectives by improving soil characteristics and by competing for water resources until mid-spring, helping in this way vigor control for grapevines (Pou et al. 2011).

Table 1 Soil water availability changes in response to cropping practices. Analysis of referred work showing the location, the soil type, variety, type of mulching or cover crop and changes in soil moisture

Reference	Location	Type of soil	Cultivar	Soil management	Percent of soil water availability changes
Pinamonti 1998	Adige Valley, Italy	Udorthents, medium sandy	Merlot	Compost mulch	2 % soil moisture increase
Agnew et al. 2002	Marlborough, New Zealand	Silty clay	Sauvignon blanc	Compost mulch	5 % soil moisture increase
Némethy 2004	Szigetcsép, Hungary	Sandy	Not described	Straw mulch	3.4 % soil moisture increase
Nguyen et al. 2013	Marlborough, New Zealand	Silty clay	Merlot	Compost mulch	Null soil moisture increase
Wheeler et al. 2005	Hawke's Bay, New Zeland	sandy-clay-loamy	Cabernet Sauvignon	Permanent sown cover crop	7 % soil moisture decrease
Gulick et al. 1994	Parlier, California	fine sandy loam	Thompson seedless	Perennial cover crop	46 % soil moisture decrease
Gulick et al. 1994	Parlier, California	fine sandy loam	Thompson seedless	Winter cover crop	19 % soil moisture decrease

Table 2 Comparison of cost and benefits of cover crops for vineyards under climates without water stress in respect to climates with typical summer drought

	Benefits	Costs	Recommended cover crops
Rain boundless climates	- Protects soil from erosion and crusting - Improves soil fertility and structure increasing soil water retention capacity - Regulates vine growth (vigor) and yield by reducing water availability for the grape	- Cost of establishment and regular maintenance - Management of irrigation, fertilization, and other practices must meet the needs of both, crop, and cover crop	- Permanent or perennial cover crops of grasses and/or spontaneous herbs covering all vineyard surfaces all along the grapevine vegetative growth. - For deep soils with presumably adequate available soil moisture, the recommended crop includes rapid growing grass species.
Rain-limited climates	- Improves soil fertility and biological activity (mycorrhiza) implicated in water and nutrients uptake. - Improves soil water-holding capacity by decreasing soil mechanical resistance and increasing water infiltration - Diminishes direct soil evaporation during summer - In deep soils, increases vine root growth and limits direct competition for water resources - Early adjustment of plant leaf area reduces later water necessities	- Cost of establishment and regular maintenance - Competition with vines for water and nutrients. - Not recommendable for early vineyard establishment.	- Non-permanent or annual cover crops with no growth during summer. - Partial vineyard coverage (alternating rows with/without cover crop) - For shallow soils receiving limited rainfall and for hillside vineyards, the recommended mix contains a variety of fescues (*Festuca* spp.) - For semi-arid areas a mix of grasses and legume

A bulk of research has been done aiming to assess the effects of a particular mixture of Mediterranean legumes and grasses as inter-row cover crop to evaluate the impacts on soil structural stability and crop performance. Also, to improve leaf area development, leaf gas exchange, biomass stability, or productivity (Clark 2007; Fourie et al. 2006; Lopes et al. 2004; Monteiro et al. 2008; Teasdale 1996) were evaluated. For grapevines growing in water-limited areas, ground covers can be managed to compete with vines during the early vegetative growth, thus reducing their canopy leaf area and consequently reducing later transpiration losses (Dry and Loveys 1998; Monteiro and Lopes 2007). This management strategy also enhances grape and must quality (Ingels et al. 2005; Pinamonti 1998; Wheeler et al. 2005; Winkler et al. 1974). However, it is important to impose these strategies in a timely fashion to avoid excessive water stress to the plants that could reduce fruit set or cause even premature defoliation. For those areas, cover crops can finally result as disadvantageous when water competition occurs after spring, which could lead to severe vine water stress and consequently, negative effects on growth, yield, and berry quality (Lopes et al. 2011; Williams and Matthews 1990).

In the literature, there are several studies showing that cover crop interfere with grapevine water use by decreasing water resources and thus increasing grapevine water stress (mainly early during the spring) (Gulick et al. 1994; Monteiro and Lopes 2007; Morlat 1987; Pou et al. 2011). Whereas, in other studies, it has been shown that cover-cropped vineyards do not always exhibit higher water stress compared to those with bare soil (Celette et al. 2005; Ripoche et al. 2011). Nevertheless, what it is commonly shown is that cover crop clearly interacts with the vines by improving soil properties, including spatial and temporal modifications of the water within the soil profile (Celette et al. 2008). Furthermore, it has been shown that cover crop decreases vine vegetative vigor, as well as showing some increases in vine deeper root fraction, triggered by the competition with cover crop roots (Lopes et al. 2011; Wheeler et al. 2005). In a particular study, Pou et al. (2011) considered not just what happens at soil level, but also, at plant level. This was done by studying the effects of particular cover crops in Mediterranean vineyards on grapevine vegetative growth, intrinsic water use efficiency (WUEi, calculated as the ratio between net leaf photosynthesis (A_N) and stomatal conductance (g_s)), yield, and grape quality. In a 3-year experiment, three treatments were established as follows: (i) perennial grass and legume mixture; (ii) no tillage, i.e., with permanent resident vegetation; and (iii) traditional tillage or plowed soil (Fig. 3). This study concluded that at the early growing stage, even though sward treatments showed similar or higher g_s and A_N as compared to traditional tillage (likely due to reductions in total leaf area), WUEi did not significantly differ among treatments. However, later in the season, the cover cropped grapevines showed more stable (even higher values) of g_s, A_N, and WUEi likely due to a lower water consumption because of the lower plant leaf area (Pou et al. 2011).

Table 2 summarizes the possible pros and cons to use cover crops depending on growing conditions. For water-limited areas, current studies involving cover crops in grapevines showed some positive effects by reducing excessive vegetative growth associated with slight increases in deeper roots jointly with some mulching effect and soil characteristic

Fig. 3 Contrast soil management in grapevines. Cover crop with natural vegetation vs. traditional tillage ("Hereus de Ribas" vineyards at Consell, Mallorca, Spain)

improvements. The negative effects were clearly identified with the "excessive" plant consumption of available water, which can lead to even harder water stress in dry springs, thus severely reducing crop yield and final plant vigor. These results make a careful management necessary to minimize the risks by choosing appropriate cover crop species that are able to self-reseed and have minimal or complete lack of water consumption after mid spring.

2.2 Canopy management

Canopy management is an important agronomic technique being widely used in viticulture to regulate the microenvironment around the clusters, and hence, fruit sanitary conditions, yield, and quality. This effect occurs through the modified light interception in the fruit zone regulated by the training system and hence, orientation, shoot positioning, and leaf area are exposed. The effect of plant architecture on canopy radiation distribution and plant production has been largely studied (Carbonneau 1980; Prieto 2011). However, only few studies have focused on the effects of the canopy on leaf gas exchange (Escalona et al. 2003; Intrigliolo and Lakso 2011; Smart 1974; Williams and Ayars 2005) and WUEi. Medrano et al. (2012) confirmed that WUEi strongly and positively depends on incoming light interception. This study also showed that shaded leaves within the canopy displayed lowest WUEi. A deeper analysis on the relationship among leaf gas exchange parameters and microclimatic conditions for different canopy positions questioned optimization theory for leaf gas exchange (Buckley et al. 2014). These results not only pointed out the difficulties to estimate the whole plant WUE through WUE parameters at leaf level, but also suggested the possibility to improve the whole plant WUE throughout the canopy management (i.e. selective pruning).

2.3 Irrigation strategies and WUE

2.3.1 Deficit irrigation, partial root irrigation, or partial root drying

Grapevine has been cultivated under rain-fed conditions for a long time in Mediterranean countries linking higher grape and wine quality with the dryer years. During the last three decades, more frequent episodes of drought stress and their intensity required the incorporation of water by irrigation as a way to overcome such limitation and to secure more regular and predictable yields (Chaves et al. 2007, 2010; Flexas et al. 2010). However, two considerations need to be taken in account when irrigating grapevines: (i) water requirements are usually high in semi-arid areas thus potentially compromising water resources and sustainability of agricultural practices (FAO 2014) and (ii) yield increases are commonly associated to grape quality reductions, since grape quality usually decreases in response to an excess of vigor creating an unbalance between the reproductive and vegetative organs within plants (Bravdo et al. 1985; Dokoozlian and Kliewer 1996; Esteban et al. 2001; Matthews et al. 1990; McCarthy 1997). Such tradeoff between yield increase/quality decreases is clearly dependent on environmental conditions, cultivar, and agronomic practices thus requiring widespread experiments on the relationships among grapevine water status, yield, and quality with important presence in the technical and scientific literature (Table 3).

Within these experiments, different ways to establish irrigation scheduling regimes and timing were proposed based on yield and quality optimization and the concern about more sustainable use of water resources. These important issues lead to the development of irrigation strategies by which grapevines receive a certain fraction of the water required that allows maintaining them under mild or severe water stress conditions with associated effects on yield reductions, maintenance, or increments in berry quality and improved WUE (Costa et al. 2007; Flexas et al. 2010).

Some irrigation strategies that have been developed and used to reduce the amount of water applied to grapevines are deficit irrigation, which in general, corresponds to the classical irrigation strategy used to maintain some degree of water deficit usually leading to maintaining or increasing grape quality at the cost of some reduction of potential yield but with a substantial reduction of water applied. Specifically, deficit irrigation consists on the application of water at lower amounts to the water evapotranspired by the plants or crop (ETc.). Two variants of this strategy have been developed: regulated deficit irrigation and partial root zone drying.

Regulated deficit irrigation is based on the principle that plant sensitivity to water stress (yield, quality) is not constant during all the phenological stages. Therefore, irrigation at lower amounts from ETc. during specific periods may largely

Table 3 A compilation of studies about irrigation strategies (deficit irrigation, DI; regulated deficit irrigation, RDI; and partial root drying, PRD) on physiological and agronomic parameters and quality of grape and wine

		Irrigation strategy		
		DI	RDI	PRD
Physiological parameters	Soil water content	7, 12, 14, 17, 27	16, 20, 25, 27, 28	7, 12, 13, 15, 17, 21, 27, 28, 30
	Transpiration	6, 7, 14, 17, 19,24, 26, 27	16, 20, 27, 28	7, 8, 9, 17, 18, 26, 27, 28
	Net photosynthesis	5, 6, 14, 17, 24, 27, 32	2, 27, 28, 34	2, 5, 8, 9, 13, 17, 27, 28, 32
	Stomatal conductance	4, 5, 6, 17, 23, 24, 26, 27	27, 28	5, 8, 9, 15, 17, 21, 23, 26, 27, 28, 33
	Abscisic acid content	18, 23, 26, 27	28	18, 23, 26, 27, 28, 33
	Water potential	4, 5, 6, 10, 11, 12, 14, 17, 18, 19, 21, 23, 26, 31, 32	1, 2, 20, 22, 27, 28, 29, 35	2, 5, 9, 8, 10,11, 12, 13, 17,18, 21, 23, 26, 28, 30, 32, 33
	Intrinsic water use efficiency (A_N/g_s)	5, 6, 10, 14, 17, 24, 27, 32	27, 28	5, 8, 9, 10, 17, 27, 28, 32
	Carbon discrimination ($\delta^{13}C$)	5, 10	28, 29	5, 9, 10, 28
Agronomic parameters	Yield	5, 7, 11, 12, 14, 17, 19, 24, 31,	1, 2, 16, 20, 22, 25, 27, 29, 34, 35	2, 3, 5, 7, 8, 11, 12, 15, 17, 21, 30
	Growth (roots and aerial tissues)	5, 10, 11, 12, 17, 27, 32	16, 20, 22, 25, 28, 29, 34, 35	5, 8, 10, 11, 12, 13, 15, 17, 21, 27, 28, 30, 32
	Crop WUE	7, 11	16	7, 8, 11, 15, 30
Quality of grape	Must composition	5, 11, 12, 14, 17, 19, 24, 31	1, 2, 16, 20, 22, 25, 27, 29, 34, 35	2, 3, 5, 8, 11, 12, 15, 17, 21, 30
	Phenolic fraction	5, 11, 12, 17, 19, 24, 31	1, 2, 16, 27, 29, 35	2, 3, 5, 8, 11, 12, 17, 30
Wine	Wine attributes		22	8, 21

[1] Acevedo-Opazo et al. 2010; [2] Bassoi et al. 2005; [3] Bindon et al. 2008; [4] Centeno et al. 2010; [5] Chaves et al. 2007; [6] Cifre et al. 2005; [7] Collins et al. 2010; [8] De la Hera et al. 2007; [9] De Souza et al. 2003; [10] De Souza et al. 2005; [11] Dos Santos et al. 2003; [12] Dos Santos et al. 2007; [13] Dry and Loveys 1999; [14] Du et al. 2008; [15] Du toit et al. 2003; [16] Edwards and Clingeleffer 2013; [17] Fernandes de Oliveira et al. 2013; [18] Fuentes et al. 2014; [19] Girona et al. 2006; [20] Greven et al. 2005; [21] Intrigliolo and Castel 2009; [22] Intrigliolo and Castel 2010; [23] Marsal et al. 2008; [24] Medrano et al. 2003; [25] Myburgh 2003; [26] Rodrigues et al. 2008; [27] Romero et al. 2010, [28] Romero et al. 2014; [29] Santesteban et al. 2011; [30] Santos et al. 2005; [31] Sofo et al. 2012; [32] Souza et al. 2005; [33] Stoll et al. 2000; [34] Tarara et al. 2011; Terry and Kurtural 2011

reduce vigor and improve harvest quality, decreasing also the water amount used (Chalmers et al. 1981; Loveys et al. 2004; McCarthy et al. 2002). The regulated deficit irrigation technique can be applied to accomplish different objectives at different phenological stages, i.e., reducing the vigor of berry cell division/berry size (McCarthy et al. 2002) or to induce an accumulation of anthocyanin (Dry et al. 2001). This irrigation strategy requires maintaining the soil and plant water status in a narrow range by regulating irrigation on the basis of environmental information. An excessive reduction of water application can result in severe losses of yield and quality and an excessive irrigation suppresses the advantages of using this strategy by increasing vigor (Jones 2004).

In contrast, partial root zone drying involves wetting and drying approximately half of the root system of plants in cycles of 8–14 days depending on the soil type. This system requires a double irrigation line controlled by different valves that allows irrigating one half of the root system leaving the other half drying in one cycle and shifting sides for wetting and drying in the next cycle. The wet side provides enough water to the plant to avoid water stress, while the drying half is linked to the reduction of stomatal conductance (Zhang et al. 1987). This strategy is based on the knowledge that roots under water stress produce hormonal signals, mainly abscisic acid, a hormone responsible for the stomatal closure and inhibition of growth.

2.3.2 Effects on plant physiology

All the irrigation strategies mentioned above have been assessed in field experiments under a wide scope of environmental conditions (soil and climate) and in contrasting grapevine cultivars, thus providing a wide set of results, which sometimes are contradictory. The latter reflects the large genotype/environmental interactions of the plant-available water on the grape behavior. Therefore, a way to have a general overview of these results is to look on the physiological effects on grapevines. To better understand how these strategies affect plant physiology, some of the most general observations among the watering strategies in physiological parameters are described.

Soil water content is reduced using the different irrigation strategies compared to a full irrigation control treatment. This enables grapevines to have a differential behavior in root growth depending on the strategy used. It has been demonstrated that partial root zone drying vines are able to stimulate root growth to deeper layers compared to grapevines under deficit irrigation (Dos Santos et al. 2007; Gu et al. 2004; Kriedemann and Goodwin 2003; Stoll et al. 2000). However, this effect was dependent on the soil type or soil water content where grapevines were grown (Collins et al. 2010). Root growth rates under partial root zone drying conditions can change the proportion of roots in a drying soil having implications for abscisic acid synthesis, water extraction, and also nutrient uptake. Partial root zone drying induces also lower canopy leaf area and consequently lowering water use (Chaves et al. 2007; 2010; Davies et al. 2002; Kang and Zhang 2004; Santos et al. 2003; Stoll et al. 2000). These physiological changes observed in partial root zone drying are not always found in all field experiments (Bravdo 2004; Dry et al. 2000a, b; Gu et al. 2004; Intrigliolo and Castel 2009; Marsal et al. 2008). Thus, these contradictory results demonstrate that partial root zone drying as an irrigation strategy is totally dependent on growing conditions (mainly soil characteristics) and genotypes. On the other hand, g_s play a critical role on the regulation of water loss. Under mild to moderate water stress, g_s reduction is the earliest response (Chaves et al. 2003; Medrano et al. 2003) and has been identified in grapevine as a suitable parameter to detect the degree of water stress (Cifre et al. 2005; Medrano et al. 2003). In general, no differences have been observed in g_s between partial root zone drying and deficit irrigation strategies when the same amount of water was applied to the soil (Sadras 2009). However, the dependency of g_s to vapor pressure deficit can be changed under partial root zone drying or deficit irrigation as demonstrated by Collins et al. (2010), likely due to different g_s regulation by abscisic acid.

As it is well known, abscisic acid is one of the main hormonal regulators described for stomatal conductance (Lovisolo et al. 2010; Pou et al. 2008; Rodrigues et al. 2008; Soar et al. 2004; Speirs et al. 2013). Also, it is the fundamental molecule behind the basis of the partial root zone drying strategy since roots under water stress produce abscisic acid and this signal is transported to leaves via xylem inhibiting stomatal conductance and growth rate. Recently, Romero et al. (2014) showed that abscisic acid production could be a function of plant-available water, i.e., of functional roots related to aquaporins. In this sense, some authors linked certain interconnection between abscisic acid signal transduction and aquaporin function (Tyerman et al. 2002). A possible mechanism for increasing root hydraulic conductance as an abscisic acid-induced increased activity of aquaporins was described by Kaldenhoff et al. (1993, 2008) and Thompson et al. (2007). Moreover, it is possible to speculate that abscisic acid loading by xylem to perivascular tissues acts as a signal to trigger the aquaporin-mediated parenchyma-to-xylem radial water flow during embolism refilling. In this putative mechanism, abscisic acid would play an indirect role in modulating hydraulic conductivity even in not-living xylem cells via complementary aquaporin-mediated cell pathways.

On the other hand, abscisic acid is believed to play an important role for the regulation of berry ripening, as the endogenous abscisic acid concentrations in the berries increase dramatically at the onset of ripening (Coombe and Hale 1973; Düring et al. 1978). Furthermore, exogenous abscisic acid applications on the berries were reported to improve the berry coloring of both table and wine grapes (Jeong et al. 2004; Koyama et al. 2010; Mori et al. 2005a, 2005b; Peppi et al. 2007; Wheeler et al. 2009).

Photosynthesis in grapevines has been demonstrated to be quite resilient to water stress (Chaves et al. 2007; Flexas et al. 2002; De Souza et al. 2003; Tomás et al. 2013) and dependent on the diffusion pathways of CO_2 (Flexas et al. 2008, 2012; Tomás et al. 2013, 2014a). Under mild water stress, as photosynthesis is moderately by stomatal closure or mesophyll conductance, an improved WUE_i is generally reported. This improvement leads to have more carbon assimilation for the same amount of transpiration. Thus, all deficit irrigation strategies improve WUE_i. However, even for a physiological analysis, when different irrigation strategies are compared in WUE_i terms, no differences were found between them (Cifre et al. 2005; Chaves et al. 2007; De la Hera et al. 2007). Moreover, WUE_i could not be an appropriate proxy for the real plant water use efficiency, since this value does not describe the whole canopy behavior of g_s during the whole day and at the whole plant level. There is the need to use more integrated measurements as stable carbon isotope composition ($\delta^{13}C$) (Chaves et al. 2007; De Souza et al. 2003, 2005; Romero et al. 2014; Santesteban et al. 2011). In general, differences between irrigation strategies have been found when the amount of water applied was different (De Souza et al. 2005; Santesteban et al. 2011). For some experiments, some differences have been found between partial root zone drying and regulated deficit irrigation with the same amount of irrigation (Romero et al. 2014) being $\delta^{13}C$ as a good proxy of integrated WUEc throughout the season. However, depending on the amount of water applied, these differences are not evident (Romero et al. 2014). Therefore, more work is needed to elucidate the whole plant response to identify the optimal WUE.

2.3.3 Effects on yield, grape, and wine quality

Deficit irrigation strategies are relatively new tools for managing grapevine growth, improving fruit quality and WUE, while maintaining or slightly reducing yields. One of these strategies as discussed before is regulated deficit irrigation, which has been explored to control vegetative growth (Edwards and Clingeleffer 2013; Greven et al. 2005; Intrigliolo and Castel 2010; Santesteban et al. 2011; Tarara et al. 2011;

Terry and Kurtural 2011). This technique improves vigor by reducing water application and yield per unit water supply (Acevedo-Opazo et al. 2010; Edwards and Clingeleffer 2013; Myburgh 2003; Tarara et al. 2011). On the other hand, partial root zone drying has the effect of controlling excessive vegetative growth in grapevines leading to a reduction in canopy density and a better plant balance with decreased input costs (water and nutrients). This effect leads to an increase of grape quality presumably without yield modification (Chaves et al. 2007; De la Hera et al. 2007; dos Santos et al. 2003, 2007; Dry and Loveys 1999; Intrigliolo and Castel 2009; Romero et al. 2010, 2014; Santos et al. 2005; Souza et al. 2005). However, when a big set of existing data is compared, no relationship between total water applied and yield is observed (Fig. 4a). This lack of correspondence can be explained due to yield having been affected not only by watering amount and irrigation management, but also by the environment and vineyard conditions, namely soil characteristics, cultivar, and viticultural practices (Fig. 4a). When comparing WUEc to yield or water used, the response is clearly different (Fig. 4b, c). Figure 4b shows the significant correspondence between WUEc and yield. However, a wider dispersion of data is observed when WUEc is plotted vs. water used (Fig. 4c). Nevertheless, as Fig. 4c shows, the highest values of WUEc for any water used data shows a clear line, which can be understood as that maximum WUEc and linearly drops when the amount of water used increases. In water-limited areas, the application of deficit irrigation practices can also provide growers with a tool to manipulate fruit composition to enhance and modulate the season-to-season variation in red wine quality attributes (De la Hera et al. 2007; Intrigliolo and Castel 2009, 2010) and to manipulate wine sensory characteristics (Matthews et al. 1990). Deficit irrigation, as compared to full irrigation, may also improve berry quality due to an increment in the contents of anthocyanins and total phenols (Chaves et al. 2007; Girona et al. 2006; Medrano et al. 2003; Santos et al. 2005; Sofo et al. 2012) even though this response is also cultivar dependent. The effects of regulated deficit irrigation on fruit growth and quality are neutral or positive, while keeping vineyard vigor in balance with potential production (Girona et al. 2006; Greven et al. 2005; Intrigliolo and Castel 2009). Understanding the effects of timing and amount of irrigation on berry composition is a key to achieve the desired berry quality. Moreover, partial root zone drying can also produce a significant modification on grape composition and wine spectral properties compared with that of a control (De la Hera et al. 2007; Intrigliolo and Castel 2009).

In summary, deficit irrigation strategies can help to reduce plant water use by adjusting total leaf area, and at the same time, to maintain or improve fruit quality with almost no changes in yield. However, the effects of deficit irrigation strategies in WUE are not conclusive and the results are in some cases, contradictories. Many factors as genotypes, environment, soil management (fertilization, tillage system, cover crop, and mulching) and crop management (pruning, trellis system, partial defoliation), can influence in plant behavior to deficit irrigation strategies, mainly in relation to water use efficiency.

3 Genetic variability of water use efficiency

3.1 Cultivar influence in WUE

Genetic improvement of crops has been an important basis of the general increase of productivity in the last decades on the basis of a different selection criteria and existing genetic variability. In the case of grapevines, the result of this large selection is a great variety of commercial cultivars, which can be considered as one of the biggest among actual crops.

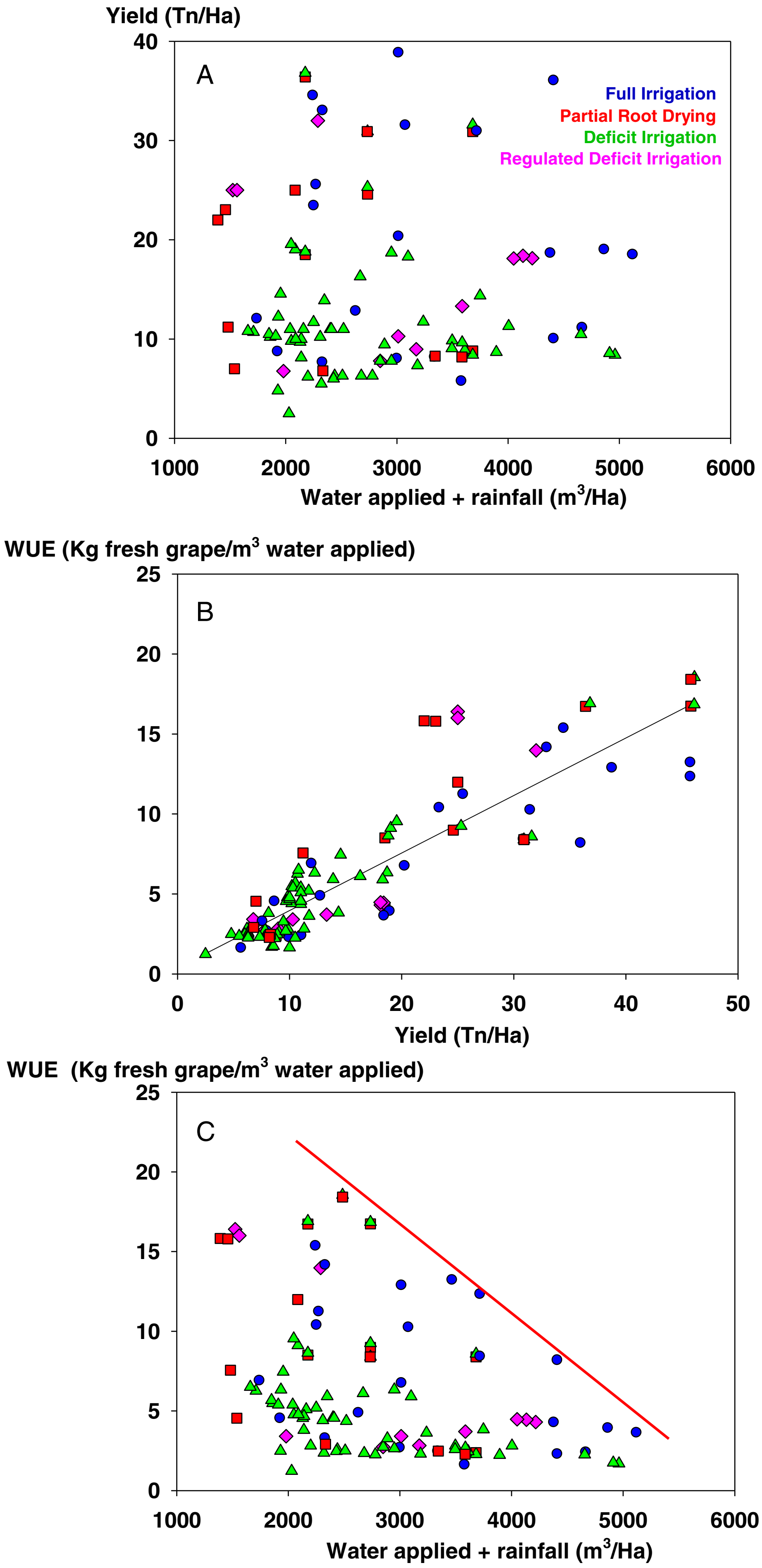
Thousands of grapevine cultivars have been described around the world (OIV 2009; This et al. 2006) showing an impressive genetic variability and plasticity of the grapevine genome. This variability offers an invaluable genetic resource to cope with crop adaptation to the different environmental conditions and potentially to climate change. There is no reference about the use of WUE as selection criteria, but there are cultivars reputed as more adapted to drought-prone conditions, which presumably should also present high WUE. Nowadays, the importance of this character and the necessity of a more sustainable crop forces the necessity to evaluate the variability of WUE among existing cultivars.

The existence of genetic variability in WUEi was demonstrated earlier by Bota et al. (2001) and Gaudillère et al. (2002), which measured WUEi and the surrogate character $\delta^{13}C$, respectively. However, as mentioned before, there are difficulties to estimate the whole plant WUE through WUEi. A recent study performed in different cultivars of grapevine confirmed previous results by showing that there is no consistent correlation between parameters measured at leaf and whole canopy levels (Tomás et al. 2012). The possible causes of this lack of correlation, explained in detail in different reviews (Flexas et al. 2010; Medrano et al. 2012; Schultz and Stoll 2010; Tarara et al. 2011; Tomás et al. 2014a) are associated to the complexity of the canopy structure, and two physiological mechanisms, leaf night transpiration and plant respiration.

In consequence, it seems necessary to amplify our knowledge about the variation of those components for plant WUE in order to assess properly leaf WUE variability within the canopy.

Many studies performed at the leaf level have shown a wide range of intra-specific variability of WUEi among cultivars, (Gómez-Alonso and García-Romero 2010; Bota et al. 2001; Costa et al. 2012; Gaudillère et al. 2002; Gómez-

Fig. 4 Relation between total water applied (rainfall from April to September + irrigation) and yield and crop water use efficiency. Data are collected from Acevedo-Opazo et al. 2010; Bassinger and Hellman 2007; Bindon et al. 2008; Chaves et al. 2007; De la Hera et al. 2007; Edwards and Clingeleffer 2013; Girona et al. 2006; Greven et al. 2005; Intrigliolo and Castel 2010; dos Santos et al. 2007; Romero et al. 2010; Santos et al. 2005; Tarara et al. 2011. *Circles* full irrigation, *squares* partial root zone drying, *triangles* deficit irrigation, *diamonds* regulated deficit irrigation. *Red line* represents the theoretical maximum water use efficiency (WUE) for each soil total water availability level. *Black line* in **b** represents linear regression (r^2= 0.76)



Koundouras et al. 2008; Pou et al. 2008; Prieto et al. 2010; Rogiers et al. 2011; Schultz 2003; Souza et al. 2005; Tomás et al. 2012, 2014b; Zsófi et al. 2009). This variability is mostly associated to different g_s responses, as shown by Tomás et al. (2014a), which assessed 74 different cultivars under irrigation and drought conditions. In Table 4, a large range of WUEi is shown among the different cultivars under irrigation, ranging from 12 μmol $CO_2 mol^{-1}$ H_2O in Syrah to 117.6 μmol CO_2 mol^{-1} H_2O in Monastrell. Under drought conditions, the WUEi values are higher in all cultivars. Minimum values are similar to irrigated conditions with the cultivar Tas-A-Ganesh presenting the lowest values (16 μmol $CO_2 mol^{-1}$ H_2O). However, WUEi under drought was the maximum for Syrah and Rosaki (200 μmol $CO_2 mol^{-1}$ H_2O in both cultivars). Focusing only in widely grown wine cultivars, there is also a considerable range of variation under irrigation (around 70 %), which increased under drought to 84 %. It is worthy to point out that within a single cultivar, a large variability of WUEi was also observed depending on the environmental conditions of each experiment (Table 4). In fact, it has been shown by different studies that the same cultivar can behave different significantly with water economy parameters being qualified as iso- or anisohydric cultivar along the growing season (Poni et al. 1993) or between experimental years (Pou et al. 2012) or by changing the irrigation strategy (Collins et al. 2010). Therefore, the classification of cultivars in two different categories, iso- and anisohydric behaviors, based on the different g_s behaviors related to water potential, is not always helpful, as reported in different comparisons (Chaves et al. 2010; Pou et al. 2012; Tomás et al. 2014a).

Besides genetic variability of WUEi in the short term, substantial differences in long-term measurements ($\delta^{13}C$) have also been reported for grapevines. More than 3 % variations under irrigation and drought conditions in $\delta^{13}C$ has been reported; however, less cultivars have been studied using this parameter (Costa et al. 2012; Flexas et al. 2010; Gaudillère et al. 2002; Tomás et al. 2014a). Different types of whole plant measurements are used to estimate plant WUE depending on the specific study. These measurements are based on the vegetative growth rate and water consumption (g dry matter/kg H_2O) or whole canopy gas exchange measurements (mmol CO_2/mol H_2O), performed in potted plants or in the field, respectively. Gibberd et al. (2001) and Tomás et al. (2012) measured 19 and 9 different potted cultivars, respectively, showing important differences among cultivars as was shown by Poni et al. 2009 and Tomás et al. (2014b) demonstrating the existence of genetic variability in the whole plant WUE.

The large variability of WUE identified among cultivars and within a single variety at the leaf and whole plant level offers an opportunity to select the most appropriate cultivar depending on the environmental crop conditions.

3.2 Rootstock influence in WUE and rootstock-scion interactions

Although most studies are restricted to cultivated grapevine, it is important to deem the variability observed in plants included in the genus *Vitis*, which can provide a potential genetic resource to improve WUE or at least the green water consumption by rootstocks. In Table 4, it is shown that 19 *Vitis* species with significant differences in WUEi among them, from 11.2 to 154 μmol $CO_2 mol^{-1}$ H_2O under irrigation; and ranging between 13 and 132.1 μmol $CO_2 mol^{-1}$ H_2O under drought conditions. *Vitis berlandieri* and *Vitis labruscana* presented the minimum and maximum values, respectively. It is important to take into account that the genetic variability of WUEi observed in different studies, most of them performed with grafted plants, could partly be explained by a rootstock effect (Koundouras et al. 2008; Serra et al. 2014).

Interest in rootstock studies was initially triggered by the need to introduce resistance to the phylloxera plague and the fungal pathogens that were devastating European viticulture (Bouquet 2011). Later, tolerance to abiotic stresses of rootstocks became a priority owing to the impact on plant production (Webb et al. 2011). Tolerance to cold, drought, salinity, calcareous soils, low pH soils, and aluminum toxicity are some of the tolerance traits that have been demonstrated in rootstocks (Bavaresco et al. 1995; Cançado et al. 2009; Himelrick 1991; Padgett-Johnson et al. 2003). The studies about rootstocks effect on plant adaptation to water stress conditions have recently increased due to the rootstock capacity to extract water from the soil and to control and adjust the water supply to shoot transpiration demand (Alsina et al. 2011; Marguerit et al. 2012; Tramontini et al. 2013). However, studies about variability of WUE in rootstocks are scarce. Satisha et al. (2006) showed significant differences in WUE is studied in ten different rootstocks, ranging from 1.21 to 1.57 μmol $CO_2 mol^{-1}$ H_2O, while Jacobs (2014) did not find differences WUEi between four different rootstocks.

On the other hand, the interactions of rootstock scion have shown different WUE results in comparison with ungrafted plants. Differences in the horizontal and vertical distribution of rooting depth, root hydraulic capacity through the anatomical characteristics of the xylem vessels (Alsina et al. 2011; Pongrácz and Beukman 1970), and root aquaporin gene expression (Fouquet 2005; Gambetta et al. 2013; Lovisolo et al. 2008; Vandeleur et al. 2009), are the possible causes associated to the variability of scion's gas exchange parameters observed on grafted plants (Serra et al. 2014). However, the scarce and contradictory results show the need to increase studies about genetic variability of WUE in rootstocks-scion interaction that could play a fundamental role in the plant adaptation to future climate change.

Table 4 List of references on genetic variability of the leaf water use efficiency estimated as WUEi (A_N/g_s) characterized by the water potential (Ψ) range corresponding to irrigation and water stress treatments. In the case of cultivars studied by more than one report, the range of WUEi is showed

Reference	Cultivar	Irrigation treatment		Water stress treatment	
		Ψ (−MPa)	A_N/g_s (μmol CO_2#mol^{-1} H_2O)	Ψ (−MPa)	A_N/g_s (μmol CO_2 mol^{-1} H_2O)
Gómez-del-Campo et al. 2002, 2004, 2007	Airen	0.11–0.17	28.1–68.2	0.25–0.46	30.6–48.8
Bota et al. 2001	Aleluya	0.057	47.3	0.41	39
Costa et al. 2012; Maroco et al. 2002	Aragonez	0.13–0.8	35–60	0.25–1	55.5–200
Bota et al. 2001	Argamussa	0.035	44.7	0.45	111
Patakas et al. 2003a	Asirtiko	0.4	62.2	1	52.9
Ghaderi et al. 2011	Askari	0.2	36.1	0.6–1	55.4–95.1
Patakas et al. 2003a	Athiri	0.4	62.2	1	53
Bota et al. 2001	Batista	0.092	51.33	0.2	58.6
Ghaderi et al. 2011	Bidane-Sefid	0.2	19.7	0.6–1	50.8–77.9
Bota et al. 2001	Boal	0.13	40.7	0.46	57.1
Dobrowsky et al. 2005; Bota et al. 2001; Rogiers et al. 2009; Santesteban et al. 2009; Tomás et al. 2012	Cabernet Sauvignon	0.037–0.31	42–84.2	0.21–1.73	89.8–145.8
Bota et al. 2001; Tomás et al. 2012, 2014a, b	Callet	0.06	37.8–73.2	0.2	38.8–114.5
Bota et al. 2001	Calop Blanc	0.08	68.8	0.44	72.6
Winkel and Rambal 1993; Padgett-Johnson et al. 2000	Carignane	0.1–0.2	36	0.4	42.8
Chaves et al. 2007; Rodrigues et al. 2008; Souza et al. 2005	Castelao	0.25–0.26	60–81.8	0.78–0.8	50–80
Bota et al. 2001; Gómez-del-Campo et al. 2002, 2004, 2007; Flexas et al. 1999; Pou et al. 2012; Rogiers et al. 2009	Chardonnay	0.063–0.34	26.4–76	0.28–0.4	30.8–161.3
Zufferey et al. 2000	Chasselas	0.075	71.4	0.63	85.2
Bota et al. 2001; Tomás et al. 2012, 2014a, b.	Escursac	0.025	62.2–71.7	0.21	60.2–113.2
Bota et al. 2001	Esperó de gall	0.063	48.7	0.39	44.2
Satisha et al. 2006; Rogiers et al. 2009	Flame seedless	0.32	17.5–52.5	0.39	22.2–44.2
Bota et al. 2001	Fogoneu	0.047	56.3	0.24	65
Bota et al. 2001	Gorgollassa	0.053	58	0.27	65.15
Gómez-del-Campo et al. 2002, 2004; Pou et al. 2012; Santesteban et al. 2009; Schultz 2003; Tomás et al. 2012, 2014a, b	Grenache	0.1–0.34	57.4–83.3	0.46–0.85	50.2–151
Bota et al. 2001	Giró	0.06	56.1	0.32	64
Flexas et al. 1999	Gordot		53.1		21.4
Bota et al. 2001	Grumiere	0.06	41.6	0.37	63.3
Patakas et al. 2003b	Isabella (V. labrusca)	0.05	93.3		
Zsófi et al. 2009	Kekfrankos	0.15	47.8	0.32	55.3
Ghaderi et al. 2011	Koshnave	0.2	26.4	0.6–1	52.3–98.6
Poni et al. 2009	Lambrusco		63		103
Patakas et al. 2005	Melagouzia	0.15	90	0.4–0.42	80–85.7
Bota et al. 2001; Tomás et al. 2012, 2014a, b	Malvasia	0.053	48.7–64.8	0.43	71–121
Bota et al. 2001	Mancín	0.082	52.2	0.32	52.7
Bota et al. 2001; Escalona et al. 1999, 2003; Tomás et al. 2012, 2014a, b	Manto Negro	0.04–0.13	41.6–68.2	0.18–0.45	66.7–97
Rogiers et al. 2009; Sivilotti et al. 2005; Santesteban et al. 2009	Merlot	0.15–0.31	45.7–71	0.15–1.25	51.4–120
Bota et al. 2001; De la Hera et al. 2007	Mollar	0.08	41.3	0.34	59.3

Table 4 (continued)

Reference	Cultivar	Irrigation treatment		Water stress treatment	
		Ψ (−MPa)	A_N/g_s (μmol CO_2#mol^{-1} H_2O)	Ψ (−MPa)	A_N/g_s (μmol CO_2 mol^{-1} H_2O)
Romero et al. 2012	Monastrell	0.065–0.98	44.3–117.6	0.26–0.9	42.4–112.4
Chaves et al. 2007; Rodrigues et al. 2008; Souza et al. 2005	Moscatel	0.2	50–60.9	0.6–0.64	63.6–77
Poni et al. 1993; Rogiers et al. 2009; Tomás et al. 2012; 2014a, b	Pinot Noir	0.16–0.32	37.8–66.7	0.18–0.62	83.2
Bota et al. 2001	Prensal Blanc	0.063	38.5	0.23	38
Bota et al. 2001	Quigat	0.06	55.7	0.25	52.1
Patakas et al. 2003b	Ribier	0.05	71.4		
Downton et al. 1987; Flexas et al. 1999; Rogiers et al. 2009	Riesling	0.32–0.9	27.1–43.4	0.83	33.3–91.3
Quick et al. 1992; Rodrigues et al. 1993	Rosaki	0.1	100–110	0.06–1.1	60–200
Bota et al. 2001	Sabater	0.043	49.4	0.18	71.2
Naor and Wample 1994; Rogiers et al. 2009	Sauvignon Blanc	0.28	26.9–51.7		
Rogiers et al. 2009, 2011	Semillon	0.45	35.7–54.3		71.4
Satisha et al. 2006	Sharad seedless		17.8		18.1
Patakas et al. 2003a; Pou et al. 2012; Rogiers et al. 2009; Schultz 2003; Schultz and Stoll 2010	Syrah	0.1–0.34	46.5–70	0.19–1.15	50.5–200
Rogiers et al. 2009	Sultana	0.28	40.5		
Satisha et al. 2006	Tas-A-Ganesh		18.2		16
Escalona et al. 1999, 2003; Gómez-del-Campo et al. 2002, 2004; Santesteban et al. 2009; Tomás et al. 2012, 2014a, b	Tempranillo	0.03–032	44–84	0.31–0.49	52.1–120
Satisha et al. 2006	Thomson seedless		18.5		20
Moutinho-Pereira et al. 2004	Touriga Nacional	0.25	26.6	0.1–0.8	80–135.6
Correia et al. 1990, 1995; Costa et al. 2012	Tricadeira Preta	0.2–0.42	25–78	0.1–0.68	50–190.5

4 Concluding remarks

The sustainability of grapevine production largely needs a serious consideration regarding the environmental impact of the large amount of irrigation volume and the foreseeing increases of irrigation necessities according to future climate change scenarios. In this way, this work summarized the efforts to improve WUEc considering two main approaches: agronomic and genetic.

Even though there is an important volume of work that aims at reducing irrigation water consumption by using different irrigation methodologies, the meta-analysis of this literature clearly shows that increasing WUEc can only be achieved by reducing the total amount of water used, which generally means a certain reduction of yield. Fortunately, increasing fruit quality characteristics can compensate yield losses. However, the large variation in WUEc below the roof of the water consumption vs. WUEc shows that results are highly dependent on the environmental and genetic components reducing the determinism of this relationship and offering at time a wide opportunity to improve the WUEc according to the particular cropping conditions.

The capacity to improve the proportion of the green water use relies on the introduction of mulching and cover crops practices, which needs further work mainly to achieve a comparative water-saving quantification under different environmental conditions. On the other hand, the genetic improvement strategy is just starting to be explored in recent researches, showing important variability both for the rootstock's capacity to extract water from the soil as for the scions to a more economic use of water. In both cases, there is a paucity of information on the heritability and genetic basis of the observed differences in WUE, which should be solved before starting a wide selection program. A main limitation pending on this subject is also the representativeness or links among the surrogate characteristics of the WUEc, and the WUEi or the $\delta^{13}C$.

As a general conclusion, the present work showed a clear necessity of wider efforts to progress in the field of WUE improvement at the needed timing to secure the sustainability of this important crop in the near future.

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