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REVIEW

How Could Cover Crops and Deficit Irrigation Improve Water Use Efficiency and Oenological Properties of Southern Chile Vineyards?

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Abstract

Vineyards started 20 years ago in Southern Chile, making viticulture a promising agricultural option for farmers in this area, increasing 7-fold during the last 5 years. However, vineyards of Southern Chile reach lower yields and lower sugar concentrations than those of the central zone, mainly due to the edaphoclimatic drivers such as low temperature, spring frost, and management constraints. Moreover, the impacts of climate change on rainfall have increased the water deficit in this area, mainly during grapevine phenological stages of high-water requirements (bloom, fruit set to *veraison*, and *veraison* to harvest). These antecedents support the urgency to validate strategies aimed at improving water use efficiency (WUE) of vineyards in Southern Chile through techniques such as the use of cover crops and regulated deficit irrigation (RDI). In addition, inter-row and intra-row cover crops can decrease both, plant water consumption and transpiration losses, as well as improve soil water infiltration. The high amount of winter rainfalls and fertility of soils in this zone, explaining also, the excessive vigor of vines, becomes possible through the adoption of these floor management techniques. Otherwise, RDI is currently proposed as a saving-water technique that controls vine vigor and increases fruit quality in vineyards. Nevertheless, currently, the findings are conflicting, and the most of studies have been performed in arid or semi-arid regions, but few in the neither Mediterranean nor humid regions such as those of Southern Chile. Therefore, according to the literature analyzed in zones with similar climatic conditions in Southern Chile, this review aimed to critically discuss how the strategies of cover crops and regulated deficit irrigation could improve the water use efficiency, vine balance, and enological properties in vineyards production of Southern Chile.

Keywords *Vitis vinifera* L. · Regulated deficit irrigation · Grape quality

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1 Southern Chile Vineyards: Opportunities and Constraints of Vitiviniculture in a Climate Change Scenario

Southern Chile has increased around 7-fold during the last 5 years the vineyards area, reaching ~140 ha in 2021 (SAG 2021). Grapevine production is mainly located (up to 80–90%) in the Rainfed Agroecological Zone of La Araucanía region, which is also known as Malleco Valley (37–39° S). The Araucanía Region has a Mediterranean climate with hot and dry summers, and rainfall strongly concentrated in 4 months during the winter season (Fig. 1A and B) (INIA 2023; Rouanet et al. 1988). The vine growers of the South of Chile are relatively small with an average vine surface of 0.5 ha and low tech in their fields (SAG 2021).

The viticulture in this area is based on a limited number of French cultivars well-adapted to the cool climate, including Chardonnay, Sauvignon Blanc, and mainly Pinot Noir; the data is presented in Table 1 (SAG 2021).

Interestingly, most wines produced with grapes of Southern Chile are recognized for their unique oenological properties. Whereas white wines have good acidity levels, minerality, and high aromatic intensity, red wines are recognized by their suitable acidity, freshness, and high amounts of fresh fruit aromas, being both mostly sold by export to Europe, Latin American, and Asian countries. Despite the high quality of these Southern Chilean wines, field experiences have shown that vines exhibit lower yields (up to 2-fold) compared to the central zone of Chile (33°1′21.73″ S-71°19′19.46″ to 34°36′32.32″S-70°59′53.87″ O*)*. The reasons explaining these low yields have different origins, from climatic to soil conditions, as well as viticultural

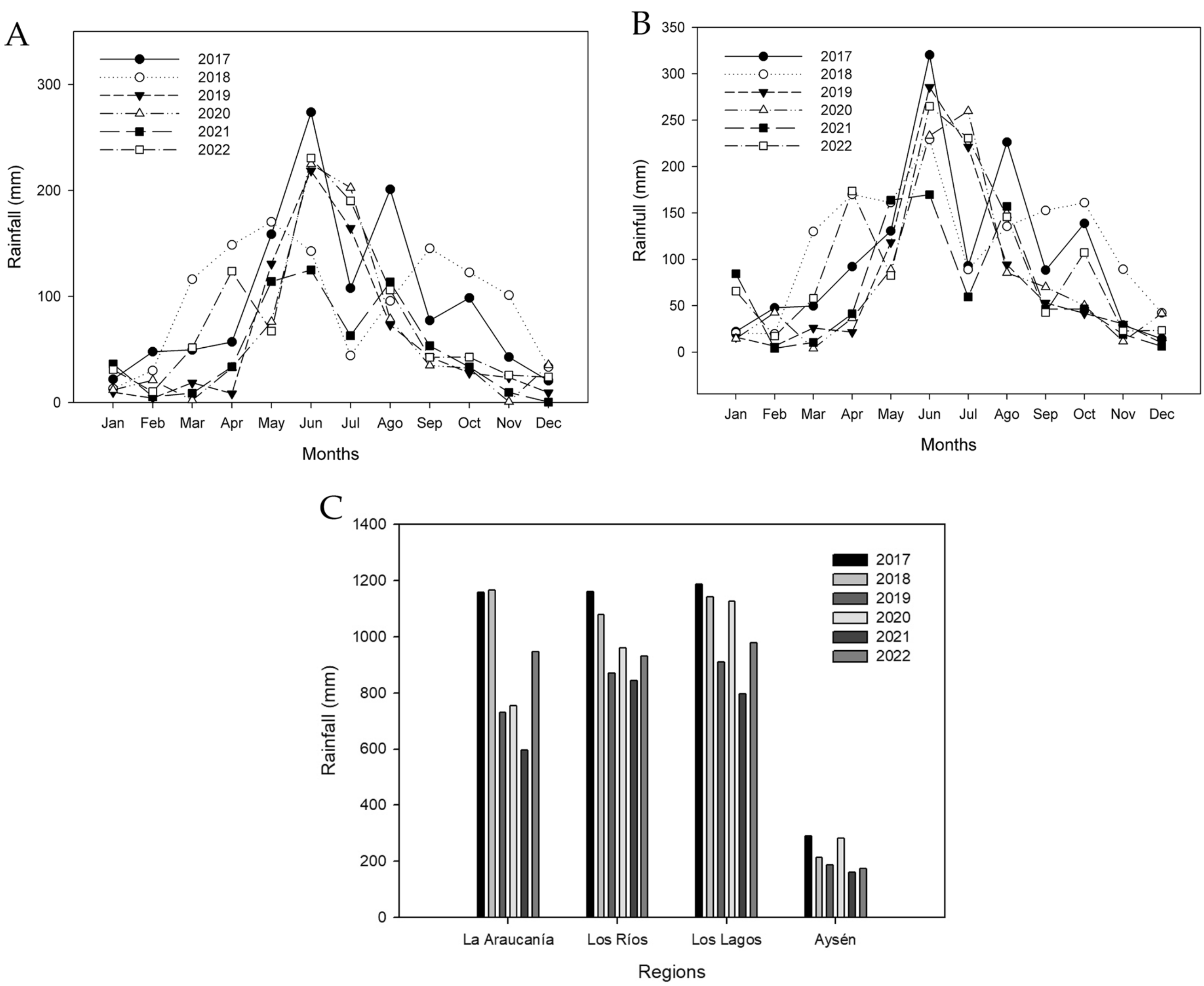

Fig. 1 Rainfall in Malleco Valley (**A**) and Cautín Valley (**B**) (Araucanía Region) between the 2017–2022 years (INIA 2023) and rainfall average per year of different regions of the South of Chile (**C**)

Table 1 The cultivar area (ha) of planted vineyards in different regions of Southern Chile. Data collected from SAG (2021)

Cultivars	Vineyards planted in Southern Chile regions (ha)			
	Araucanía	Los Ríos	Los Lagos	Aysén
Chardonnay	33.28	5.50	4.54	0.65
Gewurztraminer	0.46		1.06	
Pinot Gris	0.02		0.26	
Riesling	2.20	1.70	0.49	
Sauvignon Blanc	5.73	6.50	1.66	0.64
Viognier	1.00		0.18	
Pinot Meunier	0.30		0.30	
Pinot Noir	59.56	5.20	8.97	0.65
Syrah	0.04		0.19	

management. From the climatic point of view, low temperatures during bloom, events of spring rains, and the high incidence of spring frosts cause high levels of flower fall and a poor fruit set (Mosedale et al. 2015). On the soil side, major of them are derived from volcanic ashes (i.e., Andisols or Utilsols), which have a high organic matter percentage (around 4 to 14%), low apparent density (between 0.67 and 1.05 approximately), and textural classification to claim loam and sandy claim loam, depending to the location. These characteristics provide a high percentage of water retention at field capacity (around 34 to 50%) and a wilting point between 12.4 and 26.5% (Luzio et al. 2010) These percentages reflect the great structure and high macroporous structure in the soil which provide a higher infiltration of the water in the soil profile. Regarding chemical characteristics, the southern soils of Chile have a high aluminum (Al) saturation (Mora et al. 1999). Aluminum binds to phosphorus (P) affecting its uptake. Furthermore, root elongation and plant growth can be inhibited by high Al concentrations (Banados et al. 2012; Reyes-Diaz et al. 2009; González-Villagra et al. 2021). From an agricultural management point of view, a survey of 20 winegrowers (representing more than a third of all winegrowers in the La Araucanía region) showed that 30% of them produce grapes under rainfed conditions (Leiva and Soto 2016). Despite the amount of precipitations of all region of Southern Chile (Fig. 1B), the evident impacts of climate change on rainfall amount (low), intensity (high), and frequency (variable) have generated a water deficit condition in this zone, even during grapevine phenological stages susceptible to water stress such as bloom, fruit set to *veraison*, and to a lesser extent from *veraison* to harvest (Anon 2007). According to an unpublished data collected for our research team at the experimental Vineyard of La Frontera University (Table 2), the dates of grape bloom in La Araucanía region are between December 14th and December 20th depending on the cultivar, being Pinot Noir the earlier and Chardonnay the latest, and harvest usually being made in the second week of April, coinciding these phenological states with the dates of least incidence of rainfall (Fig. 1A). This rainfed condition combined with the high temperatures and strong winds at summer has forced the progressive adoption of irrigation systems in southern Chile vineyards.

Currently, several agricultural areas worldwide have been affected by a significant reduction of rainfall (mainly in spring-summer) as a result of global climate change (IPCC 2014). In Chile, 40–50% of the agricultural lands have reduced rainfall (Ortega-Farias et al. 2012). Indeed, the Araucanía region has suffered rainfall decreases of up to 250 mm per year (~20% of reduction) during the last 40 years (1975 to 2014) (DGA 2021; INIA 2020). At the end of the twenty-first century, 15–25% rainfall reductions are projected for Southern Chile (CONAMA 2006), whereas Valdés-Pineda et al. (2014) reported a 65% drop of the rainfall average between Maule and Los Lagos (34°41′S to 44°14′S) regions. This information was confirmed by the General Water Direction of Chile (DGA 2021). Noteworthy, crop evapotranspiration (ET) has also increased during the last years, raising the irrigation requirements for fruit species (Valdés-Pineda et al. 2014). To date, at least 70% of Southern Chile vineyards are drip-irrigated (SAG 2021). Field evidence indicates that non-irrigated grapevines of the La Araucanía region can reach at least 30–40% lower yields than irrigated ones. Additionally, grape growers of southern Chile frequently irrigate supplying the total atmospheric water demand, without considering the soil water content, or applying a moderate hydric stress at the end of the season (1 month after harvest), this last to increase the grape quality (mainly sugar content), with few impacts on fruit yields. Nevertheless, this water shortage in the previous month

Table 2 Average phenological stages occurrence (days of the year) of the main cultivars growing in the Central Valley of La Araucanía region by Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) scale (Lorenz et al. 1995)

Plant material	Budburst (09)	Bloom (60)	*Veraison* (83)	Harvest (89)
Chardonnay	286 to 293	350 to 355	52 to 53	105 to 115
Sauvignon Blanc	291 to 292	349 to 352	50 to 53	101 to 111
Pinot Noir	289 to 291	348 to 349	43 to 52	97 to 107

*Unpublished data

could be extended for a long period to improve the irrigation efficiency; the rain amounts in this zone can easily provide the vine water demand from 1 month before *veraison* (beginning of January). In this line, cover crops and a suitable strategy of regulated deficit irrigation, or the combination of both techniques, could be an excellent way to increase the use efficiency of irrigation water without reductions of vineyard grown and yield (Jones and Vaughan 2010; Webb et al. 2007) in southern Chile vineyards.

2 The Current Urgency to Improve Water Use Efficiency (WUE) in Vineyards

Most of the world's regions that produce wine exhibit seasonal drought (Corso et al. 2016). Global climate models (IPCC 2014) predict an increase in aridity and changes in phenology for grapevines in the near future (Webb et al. 2007). Thus, the impacts of global climate change including increased air temperature (Vicente-Serrano et al. 2014) and drought intensity (Jones and Vaughan 2010) allow expecting an increase of irrigation in vineyards at the world level. During the last years, water deficit has also occurred in cool-climate wine regions (Van Leeuwen and Seguin 2006). Water deficit is an important limiting factor for several physiological processes in higher plants (McDonald and Davies 1996), provoking a series of negative impacts on grapevine physiology, growth, and yield (Flexas et al. 2010; Medrano et al. 2003). It is reported that drought induces senescence of older leaves (Munné-Bosch and Alegre 2004), reducing plant water potential, increasing stomatal closure, and with this, a decrease of transpiration and photosynthetic rates (Villalobos-Gonzalez et al. 2019; Yordanov et al. 2000; Zufferey et al. 2020). Despite this impact, the grapevine is considered a "drought-avoiding" species, with an efficient stomatal control over transpiration; this stomatal control depends on the varieties (Schultz 2003; Villalobos-Gonzalez et al. 2019). Besides, leaf morpho-anatomy and morpho-biochemistry (i.e., epicuticular wax composition, lipid composition, mesophyll thickness) may also play an important role in grapevine adaptation to water stress (Cameron et al. 2006). Stomata closure is one of the earlier plant responses to drought restricting water loss and carbon assimilation in vineyards grown under moderate water deficit (Chaves et al. 2003; Villalobos-Gonzalez et al. 2019). Water deficit influences berry development, metabolism, and composition as well as wine color and flavor (Chaves et al. 2010; Balint and Reynolds 2017; Teles Oliveira et al. 2012). Water stress rarely occurs in vineyards during bud break and early shoot development due to low water consumption; however, from flowering to fruit set, water deficit triggers a decrease in flower-cluster development, reduced pistil, and pollen viability and subsequent berry set, then decreasing yields as a consequence (Vasconcelos et al. 2009). Besides, water deficit may reduce berry cell division and expansion after fruit set, resulting in small fruits and low yields. From fruit set to *veraison* as well as from *veraison* to harvest, vineyard water consumption reaches about 35% of the annual water requirements. Nevertheless, irrigation management strategies, such as regulated deficit irrigation (RDI), are considered a suitable way to increase grape quality without affecting yield when this is applied correctly (Chaves et al. 2010; McCarthy 1997).

WUE can be defined as the ratio between crop production and total water consumed by the plant (Zahoor et al. 2019). This definition assumes that total crop water used includes also the amount of water lost from the soil (soil evaporation, runoff, and/or leaching), which is not utilized by plants (Bacon 2009; Medrano et al. 2015a; Medrano et al. 2015b). Thus, WUE is the balance between gains (amounts of biomass produced or CO_2 assimilated) and costs (water used or transpired) (Medrano et al. 2015a). Some authors report to WUE as a non-dimensional output/input ratio for the single term efficiency, and to avoid confusion with other concepts such as water productivity (WP), the term WUE should only be used to measure the water performance of plants to produce assimilates, biomass, and/or harvestable yield (Pereira et al. 2012). At the leaf level, the ratio between net CO_2 assimilation (A_N) and transpiration (E) or stomatal conductance (g_s) allows determining both the "instantaneous WUE (A_N/E, WUE*inst*)" and the "intrinsic water use efficiency (A_N/g_s, WUE*i*)" (Wang et al. 2013). However, according to Poni et al. (2009), WUE*i* (A_N/g_s) and WUE*inst* (A_N/E) are concepts associated with instantaneous WUE. In any case, WUE at the leaf level can be easily determined (by instantaneous gas exchange measurements) but always at short-time intervals (Pereira et al. 2012). In general, when grapevines are subjected to moderate water deficits (from −1 to −1.2 MPa stem water potential), photosynthesis declines at lower pre-dawn water potentials than stomatal conductance, and in this condition, intrinsic WUE is usually higher in vines under deficit irrigation than vines cultivated under well-watered conditions (Chaves and Oliveira 2004). Most studies of WUE are performed on the basis of instantaneous measurements, assuming that they are representative of whole-plant WUE (Medrano et al. 2015a; Tarara et al. 2011). Poni et al. (2009) and Medrano et al. (2015b) suggested that it is better to study WUE at yield level, as the balance between the total vine harvested yield and the total water consumption during the season. Although the WUE concept is widely used in the literature, Fernández et al. (2020) indicated that at the crop level, the correct definition and calculation of WUE is the crop evapotranspiration (ETc) divided by the amount of water supplied by irrigation. On the other hand, the same authors indicated that the WUE depends on the crop, species, and how irrigation management must be combined with a productivity and profit approach to the considered crop, where some species generate more profit without an irrigation deficit. This change in the concept could be an effective approach when the mechanized management and higher extensions of the field are included in the equation; however, in the case of the vineyard grower in Southern Chile, it is not applicable because of their low mechanized and smaller productive areas (lower than 1 ha). For this reason, the use of WUE as a concept should be used with more precise and rigorous terminology and fundamentals since the improvement in this sector inherently will increase their profits and maximize the natural resources.

3 Cover Cropping as Sustainable Strategy to Enhance WUE in Vineyards

Cover crops have an old history in vineyards, where they have been widely used to prevent soil erosion and increase fertility, improve soil structure, as well as to control weeds and pests (Altieri et al. 2005; Altieri and Schmidt 1985; Vance 2012; Wheeler and Pickering 2003). Nevertheless, in some cases, certain constraints related to the permanent use of cover crops in vineyards, which can include yield reduction (Rodriguez-Lovelle et al. 2000), higher water consumption (Caspari et al. 1993; Celette et al. 2005; Celette et al. 2008; Celette and Gary 2013), competition for nutrients (Celette and Gary 2013; Rodriguez-Lovelle et al. 2000), and an increase in the crop frost risk (McGourty and Christensen 1998). This increase of the risk of frost damage is because of a reduction in the amount of solar radiation reaching the soil during daylight hours. This reduces the amount of solar radiation that can be stored by the soil and then released during cooler hours. In addition, the waiting time for lower temperatures may be longer in vineyards with cover crops than in vineyards with bare soil. However, if cover crops can be cut as low as possible, the difference with bare soil is very small. Therefore, it is not recommended to use species that cannot be cut very low to the ground or removed before bud break. Therefore, the reduction of the ground cover biomass after bud break could be an interesting strategy to reduce the effect of the spring frost in the early spring. Nevertheless, after fruit set, cover crops should not have to be removed or cut in order to improve the WUE of the wine grapes, and with this decrease the vine vigor of the plants after veraison.

Vine vigor reductions caused by some cover crops can have important positive effects on grapevines, such as decreased sensitivity to fungal diseases and increased fruit and wine quality (Celette et al. 2005; Jacometti et al. 2010; Valdés-Gómez et al. 2011). Nowadays, cover crop use is recognized as one of the most recommended ways to overcome climate change impacts and to promote sustainability in vineyards (Mozell and Thach 2014) by improving grapevines WUE (Medrano et al. 2015a). The improvement of vineyard WUE can possibly be achieved due to a decrease in water consumption when cover crops have decreased the leaf area of the vineyard, i.e., due to competition with the vine.

Comprising tilled or non-tilled soil, spontaneous vegetation, or cultivated cruciferous, legume, or grass species, cover crops constitute an effective way to regulate vine vigor, reducing transpiration losses, and increase soil water infiltration and holding capacity; additionally, these are capable to enhance the organic matter in the soil surface, improving its physical, chemical and biological properties, and soil water retention capacity (Hofman 2000; Ingels 1998; McGourty and Christensen 1998; Medrano et al. 2015a). According to Gaudin et al. (2010), cover crops may increase water infiltration rates in soils (mainly in winter), thus increasing water storage capacity and decreasing runoff. Otherwise, the control of vine vigor caused by cover crops in Mediterranean vineyards (Portugal) reduced water consumption during ripening, improving WUE, mainly in spring (Monteiro and Lopes 2007).

Despite its potential benefits on vineyards water consumption, the use of cover crops in vineyards is still hampered due to both, the conflicting results and the uncertainty about the competition between vines and cover species for nutrients and water (Mercenaro et al. 2014; Porqueddu et al. 2000), mainly in rainfed semi-arid and Mediterranean areas (Medrano et al. 2015a). In contrast, in humid and subhumid zones, this competition may represent an advantage for reducing vine vegetative growth and improving berry quality (Córdoba et al. 2015). According to Hartwig and Ammon (2002), the off-season use of water by cover crops has positive effects in some climates, whereas yield losses can be found in areas with less than 1000 mm of annual rainfall. In dry areas and in low-vigor vineyards, the combination of cover crops with deficit irrigation practices should be carefully used as it can reduce yields without benefits on grape quality (Lopes et al. 2011). Ingels (1998) found that the use of cover crops in grapevines in Mediterranean conditions (less than 600 mm of annual rainfall) decreased grapevine's leaf area, helping to avoid strong reductions of stomatal conductance in mid-summer, but decreasing yield and only slightly increasing grape quality. Moreover, the water competition by cover crops can be reduced by keeping the inter-rows free of vegetation during summer, decreasing cover crop water uptakes during the peak of grapevine growth (Curtis 2013). Giese et al. (2015) showed that complete vineyard cover crops with perennial ryegrass were an effective tool to reduce the vigor of Cabernet Sauvignon vines grown at Yadkin Valley located in North Carolina. According to Biddoccu et al. (2016), cover crops improve soil properties in vineyards through higher aggregate stability and pore connectivity, which can explain the higher values of field-saturated hydraulic conductivity appearing in soils of cover-cropped vineyards compared to those under conventional tillage.

The positive influence of cover crops on grape yield, quality, and WUE under Mediterranean conditions, where water competition can cause middle water stress, has been previously reported (Celette et al. 2005). These authors found that pre-dawn leaf water potential and stomatal conductance were not affected, suggesting that the reduction of vine vigor in intercropped vineyards did not occur by water competition. Likewise, Monteiro and Lopes (Monteiro and Lopes 2007) showed that the use of cover crops improved WUE, total phenols, and anthocyanins in grape skin, without negative impacts on either yield or berry sugar accumulation in the Cabernet Sauvignon vines grown in the Estremadura Region of Portugal (Mediterranean Oceanic Climate). Similar findings were observed by Mercenaro et al. (2014) in irrigated Carignan vineyard cultivated in a hot/dry region of Italy (Sardinia). Celette et al. (2008) highlighted that in areas where runoff is an important water flux, a reduction of this parameter by cover crops partially compensated water losses due to the cover crop transpiration. Cover crops can provoke a reduction of grapevine water consumption late in the season (just when water is more limited) by the reduction of vine vigor (as discussed by Flexas et al. 2010). Furthermore, after some years of grapevine-cover crop association, vines can be able to develop deeper roots, increasing the capacity of water extraction from deeper soil layers (Anón 2007). Moreover, the positive impacts of cover crops on water conservation have been reported in Mediterranean vineyards of Italy, Spain, and France (Ben-Salem et al. 2018; Ferrero et al. 2005; Ruiz-Colmenero et al. 2013).

Therefore, an accurate selection of species (and varieties) of cover crops is key to maximizing the profits of cover crops and avoiding their undesirable impacts. According to Ingels (1998), cover crop species should ensure a quick and homogeneous covering of vineyard soil, being a good option for Southern Chile the use of grasses-legume mixtures (perennial ryegrass plus white clover), with the highest proportion of grasses compared to legumes. Related studies have shown that increasing the surface area of perennial grass cover causes decreased grape yield (Zadabal and Ditmer 2001) and tissue nitrogen (N) (Rodriguez-Lovelle et al. 2000). When N-fixing legumes are included in the cover crop mixtures, nutrient competition is reduced (Ingels 1998). Under Mediterranean conditions, early senescent and self-seeding or perennial species such as *Dactillys* sp., *Medicago* sp., and *Trifolium* sp. can improve soil characteristics and help to control grapevine excessive vigor (Ingels 1998). In fact, perennial grasses have been successfully used in mature vineyards to compete for soil resources, decreasing the vigor of overly vegetative vines (Vance 2012; Wheeler et al. 2005). It is well-known that the addition of legumes as cover crops may increase N availability to young vines (Ingels 1998). In this way, Porqueddu et al. (2000) did not find any negative effects on grape yield and must quality by using annual self-reseeding legumes (inter-rows) compared to the tillage treatment. The same authors found that subterranean clover (*Trifolium subterraneum*) was more able than any other legume species to control weeds and increase grape yield. According to the same authors, winter annual self-reseeding legumes initiate growth in late summer or early fall, grow until the following spring when they flower, produce the burrs and seed, and then die; in summer, there is a dense mulch of dead herbage; in the next autumn, the seeds produced in spring begin to germinate and a green cover is again produced. This growth dynamic avoids the risk of water competition with vineyards in an intercropping system. Likewise, similar or even higher yields were observed in Pinot Noir vineyards cultivated with inter-rows cover crops based on grasses, legumes, or a mix of them (Mercenaro et al. 2014). Moreover, a study on this topic has revealed that cover crops such as white clover, alfalfa, and tall fescue can improve wine quality, including positive effects on wine aroma (volatile) compounds and sensory parameters (Xi et al. 2011). Córdoba et al. (2015) found that the vigour of Mencía vines was reduced when ryegrass or sub clover were used as cover crops in a humid region of Spain (Galicia) and that wines were positively affected by the use sub clover. Recently, Coniberti et al. (2018) studied the use of under-trellis cover crops on water availability and sensory attributes of Tannat wine in a humid climate, showing that cover crops regulated vine vigor and final canopy size, reducing bunch rot incidence as well as increasing fruit sugar and anthocyanin contents in grapes and wines. Besides, wines from vines cultivated with cover crops displayed increased fruit and aroma revealing distinctive sensory characteristics. A summary of the effect of the cover crops on yield components, fruit quality, and composition of grapes is presented in Table 3.

4 Improving WUE in Vineyards by Using RDI

RDI consists of applied lower amount of water than the real water demand of crops, being based on the principle that plant sensitivity to water deficit is not constant during all the phenological stages (McCarthy and Loveys 2002). However, the effects of RDI on grape growth and quality are frequently neutral or positive, while keeping vineyard vigor in balance with suitable production potential results are usually constant (Chaves et al. 2010; Dos Santos et al. 2007; Intrigliolo and Castel 2008; Uriarte et al. 2016).

Specifically, RDI for vineyards considers a water deficit applied during a critical period (i.e., after fruit set and up to *veraison*), which has shown improvements in vineyard

Table 3 Effects of cover crops on yield components, fruit quality, and composition of grapes and water use efficiency (WUE) in vineyards

Species	Cover species	Treatments	Effects	References
Vitis Vinifera L./“Aranel”	*Festuca arundinacea* Shreb., *lolium perenne* L., *hordeum vulgare* L.	T1: *Festuca arundinacea* + *Lolium Perenne* L.; T2: *Hordeum Vulgare* L.; T3: Chemical Control	T1 and T2 increased water consumption, drainage and capillary of soil and also WUE	Celette et al. (2008)
Vitis Vinifera L./“Aranel”	*Festuca arundinacea, Lolium Perenne* L.	T0: Chemical weed control; T1: permanent intercrop and T2: temporary intercrop	Cover crops improve water refilling in winery, T0 and T1 not differ in water stress T1 and T2 higher nutrient competition. Higher WUE	Celette and Gary (2013)
Vitis Vinifera L./“Aranel”	*Festuca arundinacea* Shreb., *Lolium Perenne* L.	T0: Perennial cover mixture of (*Festuca arundinacea* Shreb.) and Perennial ryegrass (*Lolium perenne* L.) (PI); T1: Annual cover crop of barley (*Hordeum vulgare* L.) (NPI); T2: Chemical weed control (WC); and Chemical weed control as above and drip irrigation in the row (WCI).	T1 and T2: lower canopy density and unfavorable condition to mildew development.	Valdés-Gómez et al. (2011)
Vitis vinifera L./Cabernet Sauvignon	*Lolium perenne* L., *Festuca ovina* L., *Trifolium incarnatum* L.	T0: Soil tillage between rows; T1: Permanent resident vegetation between row; T2: Permanent Sown cover crop	T1 and T2: increased total phenols and anthocyanin content. Increased WUE.	Monteiro and Lopes (2007)
Vitis vinifera L./Caringnano	Legume mixture, *Dactilys glomerata*, complex commercial grass-legume.	T0: soil tillage; T1: natural covering; T2: grass-legume mixture; T3: perennial grass	Cover crops reduce vigor but not yield. Perennial grass influenced positively the concentration of total anthocyanins. Increased WUE.	Mercenaro et al. (2014)
Vitis vinifera L./Mencia	*Lolium perenne* L., *Trifolium subterraneum* L.	T0: soil tillage; T1: native vegetation; T2: English ryegrass; T3: subterranean clover	T3, increased tannin content, color intensity, and lower malic acid. The yield was unaffected by the cover crops and reduced vegetative vigor.	Córdoba et al. (2015)
Vitis vinifera L./Cabernet Sauvignon	*Festuca arundinacea* Shreb. cv. KY-31, *Festuca arundinacea* Shreb. cv. Elite II; *Festuca ovina* L.; *Lolium perenne* L.; *Dactylis glomerata* L.	Different factors between root pruning and cover crops	Cover crops reduce vine vigor, with no effects on yield. Increased WUE	Giese et al. (2015)
Vitis vinifera L./Cabernet Sauvignon	*Chicorium intybus* L.	T0: Bare soil- herbicide; T1: Bare soil-cultivation; T2: Sawdust; T3: Chicory-herbicide; T4: Chicory-permanent	Non-differences in productive parameters between treatments, T3 and T4 higher anthocyanins content	Wheeler et al. (2005)
Vitis vinífera L./Syrah	*Sulla coronaria* L.	T0: Soil Tillage and T1: Sulla Cover Crop	Zulla cover crop (T1) did not produce negative effects on volatile profile	Valero et al. (2022)
Vitis vinífera L./Carbernet Sauvignon	*Portulaca oleracea* L.	T0: Clean Tillage; T1: Cover Cropping, T2: Plastic mulch.	T1: increase the accumulation of terpenes and C_{13}- nor isoprenoids in grape berries	He et al. (2023)

Table 3 (continued)

Species	Cover species	Treatments	Effects	References
Vitis vinifera L./Cabernet Sauvignon	*Portulaca oleracea L.*	T0: Clean tillage; T1: *P. oleracea* L. between rows	T1: decrease the temperature around the vines, lower TSS and higher TA, increase anthocyanin and flavonol in grapes.	Peng et al. (2022)
Vitis vinifera L./	*Lolium perenne L. and Trifolium subterraneum L.*	T0: Soil tillage; T1: Native vegetation; T2: English ryegrass; T3: Subterranean clover	Treatments T2 and T3, tended to have a higher concentration of ethyl esters, volatile fatty acids, and free terpenes.	Bouzas-Cid et al. (2018)
Vitis vinifera L./Muscat	*Lolium perenne* L. and *Medicago Sativa* L.	T0: Control; T1: *Lolium perenne* L.; T2: *Medicago sativa* L.;	T1: decrease nutrient in soil Pb concentration in grape vines was reduced; T2: increase nitrogen in soil and trace metal concentration.	Vystavna et al. (2020)

Abbreviations: *T0, T1, T2*, and *Tn* are treatments 0, 1, 2, and n, respectively; *WUE*, water use efficiency

profitability and sustainability. Under RDI before *veraison*, grapevines adjust total leaf area and frequently increase grape quality at the cost of some decreases in yield, but with a substantial reduction of water applied, improving WUE (Chaves et al. 2010; Costa et al. 2007; McCarthy 1997; Medrano et al. 2015a). In fact, RDI is one of the most used strategies for improving water use in grapevines (McCarthy 1997; Ortega-Farias et al. 2012; Romero et al. 2014; Zúñiga et al. 2018).

The effects of RDI on gas exchange variables, such as stomata conductance, net photosynthesis, and transpiration of vineyards, have been previously reported (Balint and Reynolds 2017; Intrigliolo et al. 2016; Merli et al. 2016; Romero et al. 2014; Santesteban et al. 2011; Zúñiga et al. 2018). Under slight water stress, improved intrinsic water use efficiency is generally reported (Medrano et al. 2015b). Nevertheless, gas exchange parameters can be also affected by the cultivar, agronomical practices such as the use of cover crops, and the season; moreover, the impacts of RDI on yield and grape quality strongly depend on the phenological stage at which RDI will be used (Medrano et al. 2015a; Romero et al. 2010; Romero et al. 2014, 2015; Zúñiga et al. 2018). However, this change in the stomatal conductance could be greater or lower depending on the strategies of different cultivars, which could be classified into two categories: (i) Isohydric plants have a strong stomatal control decreasing their transpiration to try to avoid the hydric stress; (ii) anisohydric, which keep higher levels of stomatal conductance product of constant transpiration (Domec and Johnson 2012; Schultz 2003). Nevertheless, some authors indicated that these categories can appear in the same cultivar depending on the conditions (year, weather conditions, and hydric deficit moment) (Liu et al. 1978; Medrano et al. 2003; Naor and Wample 1994; Poni et al. 1993; Villalobos-Gonzalez et al. 2019).

The RDI is frequently evaluated by the stem water potential or, less used, the pre-dawn potential, measuring the water status of the xylem and matric potential of the soil, respectively. Some ranges of values of stem water potential are from 0 to −0.9 MPa indicating no water stress, from −1 to −1.2 MPa indicating moderate stress, and below −1.4 MPa indicating severe water stress, independently of the phenological stage (Ferreyra et al. 2003; Lampinen et al. 2001; Sibille et al. 2007; Treogat et al. 2002; Williams and Araujo 2002). The pre-dawn values for the different levels of water stress are in a range between 0 and −0.34 MPa, −0.35 and −0.42 MPa, and < −0.42 MPa for without, moderate, and severe water stress, respectively (Williams and Araujo 2002).

Frequently, RDI is applied to vineyards at three phenological stages: from fruit set to *veraison*, from *veraison* to harvest, or from fruit set to harvest. According to Goldammer (2015) and Moyer et al. (2013), (i) RDI applied before *veraison* reduces vegetative growth and grapes size and increases soluble solids, being this the period at which this technique offers the greatest potential to reduce excessive vine vigor; (ii) with moderate water stress applied from fruit set to *veraison*, vegetative growth can be greatly reduced without significant effects on yield; (iii) slight water stress after *veraison*, when vegetative growth is stopped, tends to reduce yield by decreasing grapes size, whereas an increase in grape phenolics can occur. In the *veraison* of grapes, cell division stops but cell elongation begins (Basile et al. 2011). There are several works about water use, yield, and quality of vineyards as affected by RDI applied during pre-*veraison* (McCarthy and Loveys 2002), post-*veraison* (Intrigliolo et al. 2016), or both periods (Basile et al. 2011; Chaves et al. 2010; Zúñiga et al. 2018). Munitz et al. (2017) showed that water deficit during the early season (pre-*veraison*) had a negative effect on canopy growth, berry mass, and yield compared with late water deficit (post-*veraison*) in Merlot vines cultivated in a semi-arid region of Israel. In this way, it was shown that RDI strategies improved the harvest quality of Tempranillo vines grown in semiarid but reduced grape weight (Santesteban et al. 2011). Differently, Intrigliolo and Castel (2008) did not detect any significant impact of early or late drought on grapes in Tempranillo grapevines cultivated in Eastern Spain. In a related study conducted in Southern France, late water deficit reduced final grape weight in the cultivar Shiraz, whereas no differences were found when water shortage occurred at pre-*veraison* (Ollé et al. 2011). Regarding grape quality, RDI generally decreased the total titratable acidity at harvest, whereas grape total phenolics and anthocyanins increased in both moments (almost between 15 and 30%), pre- and post-*veraison* water-stressed vines (Acevedo-Opazo et al. 2010; Chaves et al. 2010; Edwards and Clingeleffer 2013; Girona et al. 2006; Medrano et al. 2003; Romero et al. 2010). Otherwise, there is a concern about the effect of water shortages on soluble solids accumulation in berries, due to results significantly vary depending on the intensity of water deficit and the cultivar (dos Santos et al. 2007; Edwards and Clingeleffer 2013; Romero et al. 2010). Finally, Zúñiga et al. (2018) showed that RDI needs to be applied at post-*veraison* in order to improve plant water status and use, without affecting grape yield in Carmenere vines grown in the semi-arid zone of Chile. The same authors found that pre-*veraison* water stress significantly reduced cluster volume and grape diameter and weights.

Despite its potential benefits, an excessive reduction of water supply by using RDI can result in severe losses of yield and quality in vineyards (Jones 2004). Nonetheless, these constraints will be solved by the combination of RDI, and soil management practices aimed to improve vine performance, such as cover cropping. Indeed, crop (pruning, trellis system, canopy management) and soil (fertilization, tillage system) management can influence the impacts of RDI on WUE in grapevines (Medrano et al. 2015a). Finally, it is important to mention that to date, most of the available research evidence about RDI in grapevines has been conducted in arid or semi-arid regions (Bota et al. 2016; Dos Santos et al. 2007; Edwards and Clingeleffer 2013; Zúñiga et al. 2018). As was described above, soils of Southern Chile have high fertility levels and low physical restrictions which commonly allow the production of very vigorous vines, then; early RDI practices can be useful to reduce vine vigor, transpiration levels, and then, water requirements, without significant impact of yield, thus increasing water use efficiency. Therefore, it is important to increase evidence about the benefits of this interesting practice on semi-humid and humid regions.

5 Regulated Deficit Irrigation: Improving the Quality Composition of the Grapes

Phenolic compounds are the main components responsible for the coloration of grapes and provide characteristics important for wine color, flavor, and astringency (Conde et al. 2007). Polyphenols of the grape are classified in flavonoids and non-flavonoids groups. In the first group are the anthocyanins, responsible for the characteristics of color tissues such as red, blue, and purple. Besides, anthocyanins play an important role in plant reproduction and also in protection from different stresses, including photooxidative stress (Winkel-Shirley 2002). These compounds are principally accumulated in the berry skin, and their concentration depends on the cultivar and the environmental conditions where the grapes are cultivated (Keller and Torres-Martinez 2002; Keller 2005, Robinson et al. 2014). Environmental conditions such as drought, temperature, and light are the main factors that affect biosynthesis in grapefruit (Spayd et al. 2002; Castellarin et al. 2007b).

The biosynthesis of the phenolic compounds is mediated by abscisic acid (ABA) to abiotic stress, providing a line defense to the cells against abiotic stress (Cramer et al. 2011). Many key genes (*VvMybA1* and *VvUFGT*) of the Shikimic Acid Pathway were proved to be up-regulated under stress conditions (Cáceres-Mella et al. 2017; Casassa et al. 2015), would increase the ABA accumulation and inducing the activation of key genes of the flavonoid biosynthesis, resolve in a berry quality increase, by the accumulation of secondary metabolites and polyphenols in particular (Castellarin et al. 2007a; Deluc et al. 2009; Intrigliolo et al. 2012; Koundouras et al. 2009; Matthews and Anderson 1988; Savoi et al. 2017). Also, it is reported that the expression of genes involved in the biosynthesis of anthocyanins, proanthocyanins, and flavonols (*F3H, F305' H, LDOX,* and *DFR*) increased in water deficit conditions (Castellarin et al. 2007a, 2007b). Ageorges et al. (2006) and Deluc et al. (2009) reported a strongly upregulated expression of genes UFGT and GST involved in the accumulation of anthocyanins in the vacuole under water stress conditions. Based on these observations, it is often assumed that root ABA synthesis in response to water stress and transport through the xylem to leaves, or stress-induced ABA mobilization in leaves, mediated most of the stomatal response in grapevines (Liu et al. 1978; Loveys 1984; Loveys and Kriedemann 1974; Buckle 2019). ABA controls both transpiration and assimilation enhancing expansive cell growth by saving leaf water and reducing xylem tension, likely altering structural growth by limiting CO_2 entry (Pantin et al. 2012). The effect of RDI in the increase of the phenolic composition in grape berries has been highly reported in different varieties (Basile et al. 2011; Romero et al. 2010), where the main effect observed was an increase in the concentration of anthocyanins, polyphenols, and aromas. The main effect of the increase of phenolic composition in grapes has been reported when the RDI is applied from *veraison* to harvest, affecting the berry size, synthesis of phenolic compounds, and water content of the grape berries without a negative effect in yield parameters.

Moreover, the ability of berries to accumulate sugars depends on leaf photosynthetic activity and carbon allocation priorities (Dai et al. 2010). Both solar radiation and temperature partially determine plant photosynthetic potential, and a linear relationship has been shown between the evolution of soluble solids, mainly sugars, and heat accumulation (Duchêne et al. 2012). One of the limitations in the south area of the Araucanía region and the south of Chile (Cautín valley to the south) is to obtain an adequate ripening because of the low thermal accumulation that exists in these areas (between 850 and 900 GDD) (INIA 2023). Therefore, RDI and cover crops are presented as alternatives to have a higher accumulation of sugars in the berry by reducing plant vigor (Cortell et al. 2007).

6 Conclusions

During the last 20 years, the wine frontier in Chile has extended to the south with promising expectations, where it is possible to produce high-quality grapes with good and unique oenological traits of some French cultivars adapted to cool climates. Nonetheless, Southern Chile vineyards, mainly located in the unirrigated areas of the La Araucanía region, exhibit significantly lower yields than those of the central zone of Chile. These yield gaps are related to edaphoclimatic (low temperature, high fertility of the soils, and spring frost) and management constraints. Otherwise, the impact of climate change on rainfalls has provoked a water deficit condition in this area, then increasing the irrigation budgets, one of the most expensive issues of grapevine management. Thus, the generation and validation of strategies is a crucial challenge to optimize water resources and water relations in the vineyards of this zone. Improved water status and use in vineyards could be achieved by both the use of cover crops and RDI strategies. Cover crops can have a positive influence on vineyards WUE by a decrease in water consumption when cover crops have decreased the leaf area of the vineyard (i.e., due to competition with the vine) as well as by maximizing the volume of soil explored by roots through increments of the use of soil water reserves. Otherwise, RDI is currently proposed as a saving-water technique that, besides controlling vine vigor and increasing fruit quality, can improve water use in vineyards without detrimental effects on yield when it is applied to vigorous vines. However, to date, the findings are conflicting, and the most of studies have been performed in arid or semi-arid regions, but few in the Mediterranean nor humid regions such as those of Southern Chile. According to the literature cited in this review and the edaphoclimatic conditions of the south of Chile, cover crops could be an effective strategy to decrease the vegetative vigor from fruit set to forward, and this technique should be complemented with RDI 1 month before *veraison* to increase the organoleptic quality, decrease vegetative vigor, and with this increase WUE without affect yield parameters. Nevertheless, the occurrence of forest fires in the last 5 years in the South-Central zone could make a change in the management of the cover crops during the growing season.

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Declarations

Competing Interests The authors declare no competing interests.

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