OENO One
VINE AND WINE
OPEN ACCESS JOURNAL

The influence of vine water regime on the leaf gas exchange, berry composition and wine quality of Arvine grapes in Switzerland

Vivian Zufferey[1,*], Thibaut Verdenal[1], Agnès Dienes[1], Sandrine Belcher[1], Fabrice Lorenzini[1], Carole Koestel[1], Marie Blackford[1], Gilles Bourdin[1], Katia Gindro[1], Jorge E. Spangenberg[2], Johannes Rösti[3], Olivier Viret[4], Christoph Carlen[1] and Jean-Laurent Spring[1]

[1] Agroscope, Swiss Agricultural Research Institute, Route de Duillier 50, CH-1260 Nyon, Switzerland
[2] Institute of Earth Surface Dynamics IDYST, University of Lausanne, Lausanne, CH-1015, Switzerland
[3] Service de l'Agriculture, station viticole et encavage de l'Etat, République et Canton de Neuchâtel, Rue des Fontenettes 37, CH-2012 Auvernier, Switzerland
[4] Service de l'Agriculture et de la Viticulture (SAVI), Avenue de Marcelin 29, CH-1110 Morges, Switzerland

*corresponding author: vivian.zufferey@agroscope.admin.ch

ABSTRACT

Aim: The aim of the present study was to analyze the impact of different water regimes, by means of various levels of irrigation, on the physiological and agronomical behavior of an aromatic white grapevine (cv. Arvine). The consequences of the plant water status were followed through to chemical (aromatic precursors) and sensorial analysis of resulting wines.

Methods and results: Adult vines of *Vitis vinifera* L. cv. Arvine grafted onto 5BB were subjected to different water regimes (various levels of irrigation) during the growing season. Physiological indicators were used to monitor the plant water status [the predawn leaf (Ψ_{PD}) and stem (Ψ_{STEM}) water potentials and the carbon isotope composition ($\delta^{13}C$) in the must]. Gas exchange (net photosynthesis A_N and transpiration E), stomatal conductance (g_s), yield parameters, berry composition at harvest, analysis of potential grape aromatic properties (glycosyl-glucose G-G, precursor 3-mercaptohexanol P 3-MH) and the sensorial quality of wines were analyzed over a period of 8 consecutive years (2009-2016) on the Agroscope experimental vineyard in Leytron under the relatively dry conditions of the Rhône valley, in Wallis, Switzerland.

In non-irrigated vines, the progressively increasing water deficit observed over the season reduced the leaf gas exchange (A_N and E) and g_s. The intrinsic water use efficiency (WUE_i, A/g_s) increased over the season and was greater in vines that had suffered water restriction than in irrigated vines. The rise in WUE_i was correlated with an increase in $\delta^{13}C$ in the must sugars at harvest. A decrease in plant vigor was observed in the water stressed vines over multiple years. Moderate to high water stress during fruit ripening lowered the contents of total and malic acidity in the musts and the content of yeast available nitrogen (YAN). On the other hand, contents in sugar and the aromatic precursor (P-3MH) in berries were not influenced by the vine water status. Values of G-G in berries increased with rising water stress in non-irrigated vines. Wines from plants subjected to water stress and to yeast available nitrogen deficiency (non-irrigated vines during hot and dry seasons) presented a less distinctive typicity, and developed a lower aromatic expression with a more bitter taste, than wines from non-stressed plants. Overall, and compared with stressed vines, the organoleptic characteristics and quality of Arvine wines coming from vines where no restrictions in water and nitrogen had been suffered during the growing season were better appreciated.

Conclusions: The vine's physiological behavior (leaf gas exchange, plant vigor) and agronomic parameters (yield, berry composition), together with the quality of white aromatic Arvine wines, were strongly influenced by vine water regimes during the growing season.

Significance and impact of the study: Vine water status and must nitrogen contents are key factors in grape composition and in the sensorial quality of resulting aromatic white wines.

KEYWORDS

water stress, gas exchange, water use efficiency (WUE), carbon isotope composition, berry composition, aromatic compounds, wine quality

INTRODUCTION

The vine water status derives from numerous pedoclimatic factors (soil properties, soil water reserves, mesoclimate (Seguin, 1975), from the rootstock's genetic characteristics (root density, for example) and grape variety (drought sensitivity), and from cultivation practices (cover crop, leaf-fruit ratio), including irrigation in some cases. Restrictions in water supply during the season may affect plant growth (Chaves *et al*., 2010), the canopy's photosynthetic capacity, yield components (floral initiation, the rate of fruit set, berry weight …) and the quality of grapes and wines (van Leeuwen and Seguin, 1994). Stomatal regulation of leaf transpiration provides a short-term response of controlling water losses in vines when edaphic water stress and/or atmospheric demands (water vapor deficit in the air, VPD) rise sharply during the day (Lovisolo *et al*., 2016). By limiting water flux in the plant (lowered transpiration) and canopy development (decreasing leaf area by leaf fall), the plant is able to maintain its water status and stabilizes the leaf water potential above the threshold required for avoidance of hydraulic rupture (cavitation phenomena with development of air bubbles in vessels) in cases of high water stress (Tyree and Sperry, 1988).

The effects of drought on yield components depend on the timing, the intensity and the duration of water deficit (Deloire *et al*., 2004). Water stress early in the season leads to a smaller number of berries per cluster; severe stress developing between the fruit set and veraison period causes a reduction in berry weight (Ojeda *et al*., 2001) and increases the heterogeneity of berry size. No water stress, combined with high soil water availability, often develops vigorous plant growth and increases the risk of fungal diseases, altering the harvest quality (increased yield, increased competition in the sugar allocation between the vegetative and reproductive vine parts, dilution phenomena, and reduced wine color). On the other hand, a progressively increasing and moderate water stress (after fruit set) leads to a slow stop in plant growth around the veraison, promoting the production of berries richer in sugars, anthocyanins and phenol compounds, with less acids (van Leeuwen *et al*., 2009; Zufferey *et al*., 2017). For the elaboration of high-quality white wines, it is well known that vines should experience no mineral nutrient deficiencies, particularly nitrogen deficiencies (Bell and Henschke, 2005; Lacroux *et al*., 2008). For this reason, vines should not be exposed to a water deficit that is too severe (Choné *et al*., 2006; Deluc *et al*., 2009) which may result in a loss of aromatic compounds and wine quality (Reynolds *et al*., 2010; Reynard *et al*., 2011; Verdenal *et al*., 2012).

TABLE 1. Monthly rates of precipitation (mm) at the experimental site in Leytron (Switzerland) during the eight-year study period (2009-2016) and long-term precipitation averages (1981-2010).

	2009	2010	2011	2012	2013	2014	2015	2016	Long-term
January	109	11	22	57	21	42	55	110	51
February	28	29	7	0	59	79	11	104	47
March	23	27	14	5	29	5	63	19	42
April	37	8	5	51	45	29	12	38	35
May	25	120	43	52	83	34	123	76	49
June	40	15	40	37	24	17	34	45	54
July	87	73	69	51	52	106	35	46	58
August	16	45	22	65	30	87	78	27	57
September	18	22	42	52	45	15	14	14	44
October	11	14	34	39	67	30	29	32	52
November	68	36	2	53	95	44	42	75	52
December	108	70	168	152	17	42	4	0	64
Year	570	470	468	614	567	530	500	586	603

TABLE 2. Monthly mean temperatures (°C) at the experimental site in Leytron (Switzerland) during the eight-year study period (2009-2016) and long-term temperature averages (1981-2010).

	2009	2010	2011	2012	2013	2014	2015	2016	Long-term
January	-2.7	-1.5	0.2	1.5	1.0	2.6	1.4	2.2	-0.1
February	1.0	1.5	2.9	-1.7	0.0	4.2	1.3	4.4	1.8
March	5.9	6.1	7.9	9.1	5.2	8.4	7.9	6.6	6.5
April	12.4	11.8	14.2	10.9	10.9	12.8	12.2	11.3	10.4
May	16.4	14.0	17.0	16.1	12.5	15.6	15.6	14.7	14.9
June	18.4	18.9	18.8	20.0	18.1	20.1	20.6	18.7	18.1
July	20.5	21.8	18.6	20.3	21.6	19.3	24.0	21.5	20.1
August	21.6	18.5	21.0	21.3	20.2	18.4	20.9	21.0	19.2
September	16.8	14.8	17.8	15.8	16.3	16.9	14.9	18.4	15.2
October	10.3	10.3	10.4	11.5	12.7	13.0	10.5	10.1	10.3
November	6.7	5.5	5.2	6.4	3.8	8.1	5.9	5.8	4.3
December	1.0	-0.6	1.9	0.6	0.4	2.7	2.2	-0.7	0.6
Year	10.7	10.1	11.3	11.0	10.1	11.7	11.5	11.2	10.1

The Arvine grape variety, cultivated mainly in the Swiss canton of Wallis, is well appreciated for the character and the complex fruity and floral bouquet of its wines (Spring *et al*., 2014). This aromatic typicity arises from sulphur compounds of the thiol family and in particular 3-mercapto-hexanol (Fretz *et al*., 2005), whose aromas are evocative of grapefruit, lemon, rhubarb and exotic fruits. These aromas are linked to glutathione and cysteine (P-3MH) in musts and liberated in volatile form during alcohol fermentation (Tominaga *et al*., 2000).

In this study, the impact of water supply to vines on plant behavior was analyzed by creating different water regimes during the growing season. The experiments included three levels of irrigation: a deficit irrigation that compensated approximately 30 % of evapotranspiration potential (ETP) from flowering to the onset of ripening (veraison); no water supply (no irrigation, rain-fed vines) throughout the whole season; and water stress imposed by covering the soil with a plastic, impermeable, non-reflecting sheet during the growing period (April-October). The vine water status was monitored by using physiological indicators, such as leaf and stem water potentials and carbon isotope composition in the must sugars at harvest. The influence of the water regime on the vine physiology (gas exchange, plant vigor, leaf and berry mineral nutrition) and agronomical behavior (yield components) and the quality of the resulting wines was observed in adult vines of the cultivar Arvine over a period of eight consecutive years on the experimental Agroscope vineyard, which is located in a relatively dry alpine region of Switzerland (Valais).

MATERIALS AND METHODS

1. Study site and plant material

The experiments were conducted from 2009-2016 at the Agroscope experimental station in Leytron, Switzerland (46°10' N, 7°12' E; 485 m asl), which is located in an alpine valley. The planting material was the cultivar Arvine, grafted onto *Vitis berlandieri* x *Vitis riparia* cv. Kober 5BB rootstock. Vines were trained in the Guyot system (vertical shoot-positioned) with a planting density of 5500 vines ha^{-1} (planting distance: 1.8 x 1.0 m). Six shoots per vine were maintained. The experimental site in Leytron lies on very stony (peyrosol > 60 % large elements, stones, blocks and gravel) and deep (> 2.5 m vine root depth) soil with a water-holding capacity estimated at 150 mm. Monthly rainfalls and temperatures from 2009 to 2016 (and long-term averages from 1981 to 2010) from the meteorological station in Leytron are presented in tables 1 and 2.

2. Irrigation treatments

Three irrigation treatments were established. In the first treatment, 9 L/m^2 of soil (16 L/vine)

was drip-fed weekly from bloom (~150 DOY) to fruit ripening (~215 DOY). This level of irrigation (deficit irrigation, DI) corresponded to an approximate weekly compensation of 30 % ETP. The second treatment applied no irrigation throughout the entire growing season (plants were rain fed). The third treatment also involved no irrigation; in addition, waterproof and non-reflecting plastic sheeting was placed on the soil from bloom (~150 DOY) to harvest (~280 DOY) to eliminate the infiltration of water from precipitation events. The trial was conducted using 40 plants per treatment, which were set out in four split-plot randomized blocks of ten vines each.

3. Measurements of plant water status and relative carbon isotope composition (δ13C)

Predawn leaf water (Ψ_{PD}) and midday stem water (Ψ_{STEM}) potentials were measured using a pressure chamber (Scholander *et al.*, 1965) according to Turner (1988). Ψ_{PD} was measured between 0400 and 0500 in the morning, in complete darkness, on eight mature, undamaged and non-senescent leaves. Midday Ψ_{STEM} measurements were performed between 1400 and 1500, when evapotranspiration was at a maximum. Midday Ψ_{STEM} values were determined for eight leaves bagged with a plastic sheet and covered with aluminum foil to stop transpiration at least one hour before the measurement (Fulton *et al.*, 2001).

The stable carbon isotope composition ($\delta^{13}C$) of the must sugars was determined at harvest at the Stable Isotopes Laboratory of the University of Lausanne by elemental analysis-isotope ratio mass spectrometry (EA-IRMS) using a Carlo Erba 1108 elemental analyzer connected to a Thermo Fisher Scientific (Bremen, Germany) DeltaV mass spectrometer. The stable isotope composition was reported as $\delta^{13}C$ values per mille (‰), with deviations of the isotope ratio relative to known standards as follows: $\delta = [(R_{sample} - R_{standard}) / R_{standard}] \times 1000$, where R is the ratio of heavy to light isotopes ($^{13}C/^{12}C$). The $R_{standard}$ value for ^{13}C in Vienna Pee Dee Belemnite limestone is 0.0112372 (Deléens *et al.*, 1994).

4. Leaf gas exchange measurements

Leaf gas exchange [net photosynthesis (A_N) and transpiration (E)], stomatal conductance (g_s) and mesophyll resistance (r_m) were measured
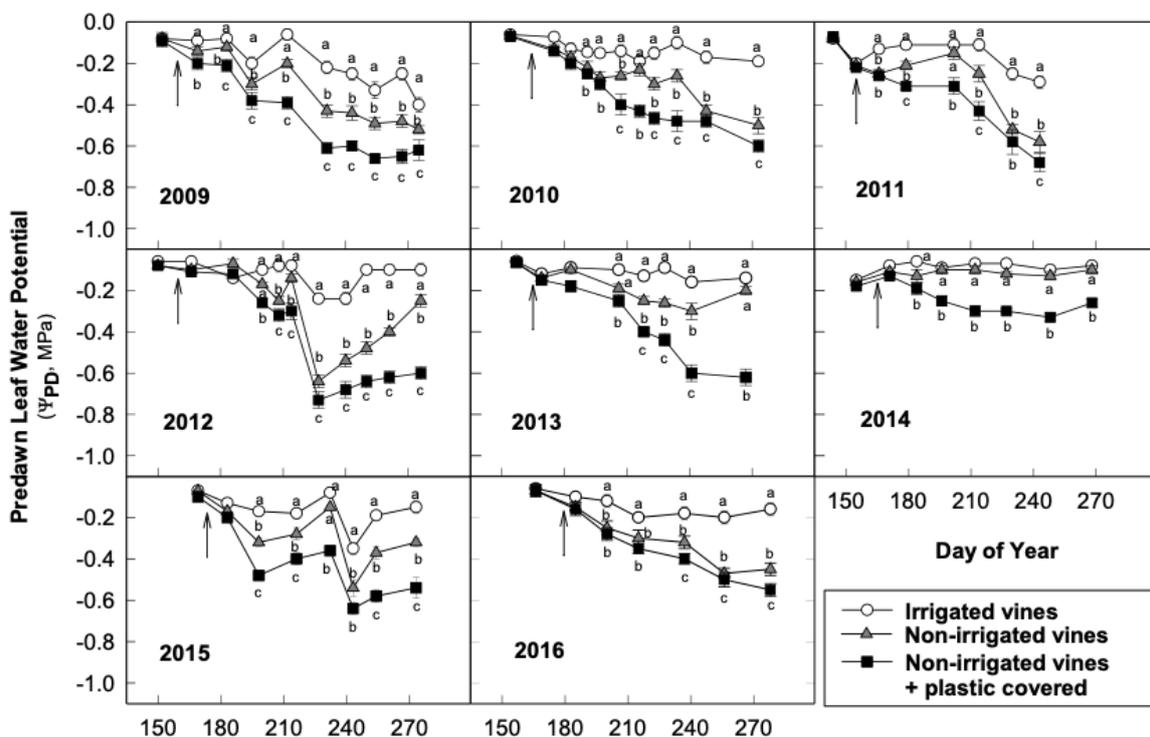
FIGURE 1. Seasonal evolution of the predawn leaf water potential (Ψ_{PD}) for different irrigation treatments. Arrows indicate irrigation onset.

Means ± SE for eight leaves. Letters indicate statistical significance at the 5 % level of probability. Arrows indicate start of irrigation. Arvine, Leytron (Switzerland), 2009-2016

on healthy, fully expanded, mature and non-senescent leaves well exposed to direct sunlight (PFD > 1800 $\mu mol\ m^{-2}s^{-1}$) from June to mid-October. Eight leaves per irrigation treatment were measured in the morning (1000) on days with clear skies. Gas exchange was measured using a portable photosynthesis system (LI-6400, LI-COR Inc., Lincoln, NE, USA). R_m was calculated as $r_m = (C_i-\Gamma)/A$, where C_i is the intercellular partial pressure of CO_2, Γ is the CO_2 compensation point (corresponding to 50 ppm for adult leaves with a leaf temperature between 20-25°C, Schultz, 1996), and A is net photosynthesis. The intrinsic water use efficiency (WUE_i, A/g_s) and instantaneous water use efficiency (WUE_{inst}, A_N/E) were determined from single leaf gas-exchange measurements that related the net photosynthesis rate (A) either to the stomatal conductance for water vapor (g_s), termed WUE_i (Osmond *et al.*, 1980), or to the leaf transpiration rate (E), termed WUE_{inst}.

5. Leaf and berry mineral nutrition, pruning weight measurements

A foliar analysis was performed to determine the levels of leaf nitrogen (Kjeldahl method), potassium, phosphorous, calcium and magnesium. The samples consisted of 25 leaves gathered in the cluster zone at veraison. Leaves with petioles were washed, over-dried, ground and analyzed. The leaf chlorophyll index was measured using an N-tester apparatus (Yara, Nanterre, France) on adult leaves situated at the middle of shoots.

Yeast available nitrogen (YAN) was estimated by NIR spectroscopy (WineScan®, FOSS NIRSystems, USA). This method quantifies the N-compounds of juice available to yeasts during fermentation. YAN corresponds to the concentration of ammonium ions and primary amino acids, excluding proline. In winter, the total weight of the pruned vine shoots was recorded (six shoots per vine), representing ten plants per replicate and 40 plants per treatment.

6. Yield components, berry composition and wine analytics and testing

Bud fertility (number of clusters per shoot) was observed each year shortly before flowering. At harvest, 50 berries per replica were randomly selected and weighed to determine the berry weight. The yield per plant (kg/vine) divided by the number of clusters per plant enabled the average weight of the clusters at harvest to be estimated. The fruit composition parameters at harvest included soluble solids content (g/L), pH, titrable acidity (g tartrate/L) expressed as tartaric acid (g/L), and malic acid (g/L). Microvinification (60 kg of grape) was conducted in an identical fashion for all irrigation treatments by the same winemaker. The aromatic potential of the Arvine grape variety was evaluated by the Glycosyl-Glucose (G-G) method, according to Williams *et al.* (1995), and the precursor 3-mercaptohexanol (P-3MH) was analyzed according to the Luisier *et al.* (2008) method on musts, after crushing and the addition of sulphites.
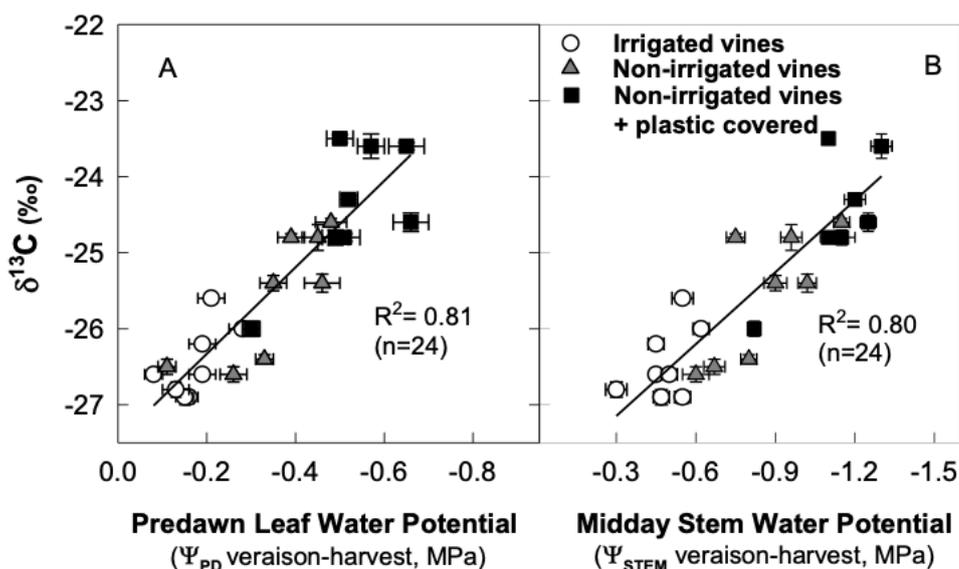
FIGURE 2. Relationship between the predawn leaf water potential (Ψ_{PD}, A), the stem xylem water potential (Ψ_{STEM}, B) measured during the period of veraison-harvest and the relative C isotope composition ($\delta^{13}C$) in must sugars at harvest for different irrigation treatments.
Means ± SE. Arvine, Leytron (Switzerland), 2009-2016.

Wine composition was assessed at bottling by using infrared spectroscopy. A sensory analysis was conducted two months after bottling by a panel of 12 experienced tasters. The panelists rated the intensities with 16 sensory attributes, including wine appearance, bouquet and palate. Wines were evaluated on an unstructured line scale from 1 (no perception) to 7 (very intense perception).

7. Statistical analysis

The significance of each treatment was evaluated with analysis of variance ($P < 0.05$) followed by a single-comparison Newman–Keuls test using XLSTAT 2011.2.04 (Addinsoft, Paris, France). The linear and non-linear regressions of Ψ_{PD} and Ψ_{STEM} and the different physiological parameters were determined using SigmaPlot software (version 13.0) and were statistically analyzed using the SigmaStat program package.

RESULTS AND DISCUSSION

1. Climatic conditions

Tables 1 and 2 present monthly and annual rainfall and temperatures for the period under study, from 2009 to 2016. The experimental wine-growing area is situated in a relatively dry Alpine region where long-term mean rainfall (1981-2010) is around 600 mm per year. During the study period, rainfall amounts were a little below the long-term average, especially in 2010, 2011 and 2015 when measured precipitation was approximately 100-130 mm less per year. Particularly dry summer periods (August-September) were recorded in 2009, 2010, 2011, 2015 and 2016. The year 2014 was an exception when rainfall was higher in July (106 mm) and August (87 mm) than normal (1981-2010). Annual temperatures were greater by about 0.6 to 1.6°C than the long-term means (1981-2010), except for the years 2010 and 2013 when average annual temperatures were equivalent to the long-term figures. In comparison with the 30-year mean figures, particularly high summer temperatures (July-September) were recorded in the region in 2009, 2011, 2012, 2015 and 2016.

2. Plant water status

Seasonal monitoring of vine water status was carried out by means of predawn leaf water potential measurements (Ψ_{PD}) throughout the study period 2009-2016 (Figure 1). In irrigated vines from bloom to fruit ripening, no water stress was recorded, and values of Ψ_{PD} varied between -0.05 and -0.25 MPa throughout the season and according to the year. Non-irrigated vines, however, showed a gradual increase in water stress from the end of July (DOY 2010), with Ψ_{PD} values fluctuating between -0.3 and -0.5 MPa, indicative of moderate water stress.

An exception was noted for the year 2014 when any manifestation of water stress was absent for the whole season. Soil-covering associated with no irrigation resulted in moderate to high water stress towards the end of berry ripening (values of $\Psi_{PD} < $ -0.5 MPa), especially during the hot, dry summers of 2009, 2011, 2015 and 2016. Water stress remained more moderate during the summers of 2010, 2013 and 2014 due to the cooler temperatures and regular rainfall in July and August, which meant lower water vapor deficits (VPD) and a reduced rate of soil water depletion. The measurement of Ψ_{PD} in darkness provides an estimate of vine water status when leaf transpiration is greatly reduced, and thus reflects the soil water availability (edaphic stress) in the wettest part of soil colonized by roots (Améglio *et al*., 1999). When measured during the hottest hours of the day (solar midday), Ψ_{STEM} allows not only an estimation of edaphic stress, but also of climatic stress resulting from the evaporative demand of the air (i.e. VPD). These two physiological approaches of Ψ_{PD} and Ψ_{STEM} provide valuable information concerning the supply of water to vines (Choné *et al.,* 2001, van Leeuwen *et al*., 2001a; van Leeuwen *et al*., 2001b; van Leeuwen *et al*., 2009). Values of Ψ_{PD} and of Midday Ψ_{STEM} are notably correlated ($R^2 = 0.85$, $P < 0.01$) throughout the 2009-2016 study period.

A correlation ($R^2 = 0.81$, $P < 0.01$ and $R^2 = 0.80$, $P < 0.01$, respectively) was observed between these two indicators of vine water status, Ψ_{PD} et Ψ_{STEM}, recorded during the fruit-ripening to harvesting period, and the carbon isotopic composition ($\delta^{13}C$) in musts at harvest-time (Figure 2A, B). Values of $\delta^{13}C$ varied from -23 ‰ (high water stress) in non-irrigated vines, to -27 ‰ (no water stress) in irrigated vines. Measurement of C isotopic composition in musts has the advantage of providing an integral overview of the vine water regime during the phase of sugar accumulation, that is, between the time of fruit-ripening and harvesting (Gaudillère *et al*., 2002).

3. Physiological behavior in response to progressive water deficit

3.1 Water and gas exchange relationships

Figure 3 shows the impact of the different water regimes, estimated by night-time Ψ_{PD} (Figure 3A),
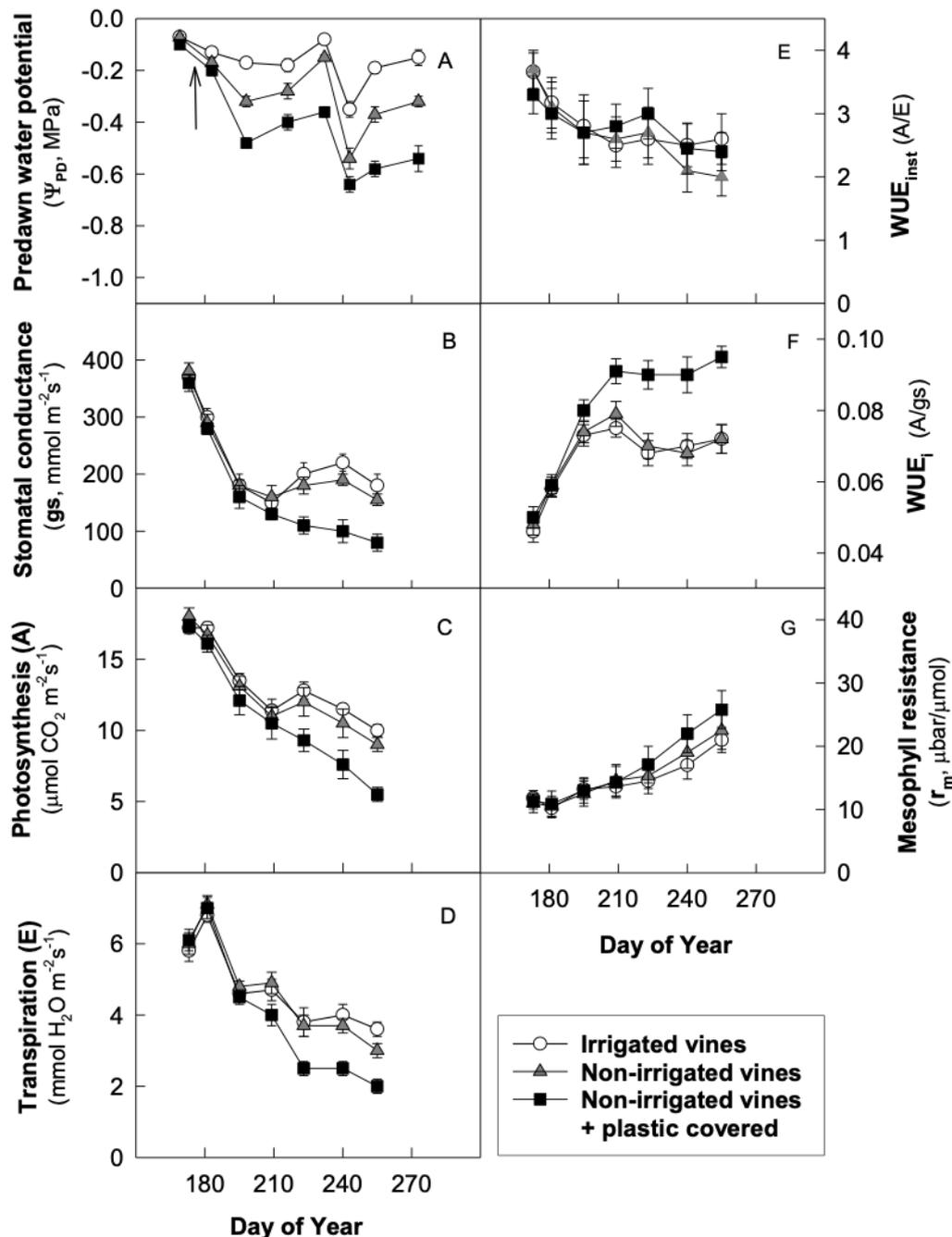
FIGURE 3. Changes in the predawn leaf water potential (Ψ_{PD}, A), stomatal conductance (g_s, B), net photosynthetic rate (A_N, C), transpiration rate (E, D), instantaneous water use efficiency (WUE_{inst}, E), intrinsic water use efficiency (WUE_i, F) and mesophyll resistance (r_m, G), during the 2015 season. Means ± SE for eight leaves. Arvine, Leytron (Switzerland).

on stomatal conductance g_s (Figure 3B), net photosynthesis A (Figure 3C), transpiration E (Figure 3D), mesophyll resistance r_m (Figure 3G) and water use efficiency WUE (Figure 3 E, F).

Taking the 2015 season as an example, increasing water stress observed in non-irrigated vines was accompanied by a decrease in g_s, A and E. The

values of g_s measured were below 100 mmol m^{-2}s^{-1} at the end of the season in non-irrigated vines with covered soils, corresponding to half of the rates observed in well-watered vines (irrigated vines). From the end of July (DOY 2010) net photosynthesis was reduced by 30 to 50 % in vines suffering from water restrictions, in comparison with irrigated vines, where levels of almost

5 µmol CO_2 $m^{-2}s^{-1}$ were reached by the end of the season. In addition, leaf transpiration decreased by nearly a half during grape ripening in vines with plastic-covered soils and no irrigation, compared with the well-watered vines. Under increasing water stress conditions, the plant can respond rapidly by stomatal regulation of gas exchange (photosynthesis and transpiration), a process which has been well described by many studies (Chaves *et al.*, 2007; Chaves *et al.*, 2010, Medrano *et al.,* 2002; Medrano *et al.,* 2003). Effectively, stomatal control of transpiration allows a rapid response to edaphic and atmospheric water deficits, while managing risk of hydraulic rupture in vessels which, in extreme cases, could lead to embolism (Lovisolo *et al.*, 2002, Zufferey *et al.*, 2011).

Under the conditions of moderate to strong water stress of the present study (non-irrigated vines with plastic-covered soils), net photosynthesis dropped off less markedly than g_s during the growing season. Consequently, intrinsic water use efficiency (WUE_i, A/g_s) rose during the growth period, stabilizing at the end of fruit ripening. WUE_i was higher in vines which were stressed during ripening, compared with well-watered vines. As previously demonstrated by numerous studies in Mediterranean climates (Schultz 1996, Chaves *et al.*, 2007; Pou *et al.*, 2008, Flexas *et al.*, 2007, Tomas *et al.,* 2014), the WUE_i tends to increase under drought conditions. However, it has been noted that, when water stress becomes very high, there is a reduction in WUE_i (Prieto *et al.*, 2010), suggesting an increase in mesophyll resistance, as observed in the present study, thus reducing assimilation (Flexas *et al.*, 2007). Moreover, a correlation between WUE_i and $\delta^{13}C$ in grape sugars (results not presented) would confirm findings from other research (de Souza *et al.*, 2005a, de Souza *et al.*, 2005b; Bchir *et al.*, 2016). Non-irrigated vines demonstrated higher $\delta^{13}C$ values than irrigated vines without water stress. This result is probably associated with a lower discrimination with regard to ^{13}C and to enrichment of ^{13}C in musts, which correlates with an increase in WUE_i. There is generally an enrichment of ^{13}C in berries compared to leaves due to the import of carbon assimilates from the leaves after the onset of ripening, when water stress is high (stomata closed), thus supplying carbon assimilates enriched in ^{13}C. Lastly, recent studies (Spangenberg *et al.*, 2017, Spangenberg and Zufferey, 2018; Spangenberg and Zufferey, 2019) have shown that the analysis of carbon isotopes, undertaken in the solid residues and volatile organic components of wine, constitutes a very effective tool for estimating variations in the water status of plants and soils in different vineyards.

The decline in g_s and in A_N during the growth season was followed by an almost linear decrease in E. In this way, the A_N/E ratio, named instantaneous water use efficiency (WUE_{inst}), diminished over the season (Figure 3E) but remained, nevertheless, practically identical among the different vine water regimes. Stomatal conductance g_s is sensitive not only to water stress but also to environmental factors, such as, for example, the water vapor deficit of the air or VPD (Prieto *et al.*, 2010; Zufferey and Smart, 2012). A rise in VPD generally leads to the progressive closure of stomata but an increase in E, resulting finally in a fall in WUE_{inst}. The rise in VPD tends to diminish WUE_{inst} over a wide range of water deficits as a result of decreasing g_s and A_N, but not the WUE_i.

TABLE 3. Mineral supply to the vine: leaf nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) content at veraison; leaf chlorophyll index (N-tester measurements) at veraison; and yeast available nitrogen (YAN) content in the must at harvest.

	Foliar analysis (% D.M)					N-tester	YAN (mg N/L)
	N	P	K	Ca	Mg		
Irrigated vines	2.58a	0.26a	1.04a	4.29a	0.29a	524a	231a
	(±0.15)	(±0.02)	(±0.07)	(±0.17)	(±0.02)	(±15)	(±14)
Non irrigated vines	2.46a	0.25a	0.97ab	4.14a	0.33ab	509a	215ab
	(±0.17)	(±0.02)	(±0.05)	(±0.15)	(±0.02)	(±13)	(±12)
Non irrigated vines + plastic covered	2.35a	0.22a	0.84b	4.10a	0.36b	483a	189b
	(±0.16)	(±0.03)	(±0.07)	(±0.12)	(±0.02)	(±15)	(±15)

Letters indicate statistical significance at the 5 % level of probability. Averages 2009-2016, Arvine, Leytron (Switzerland).
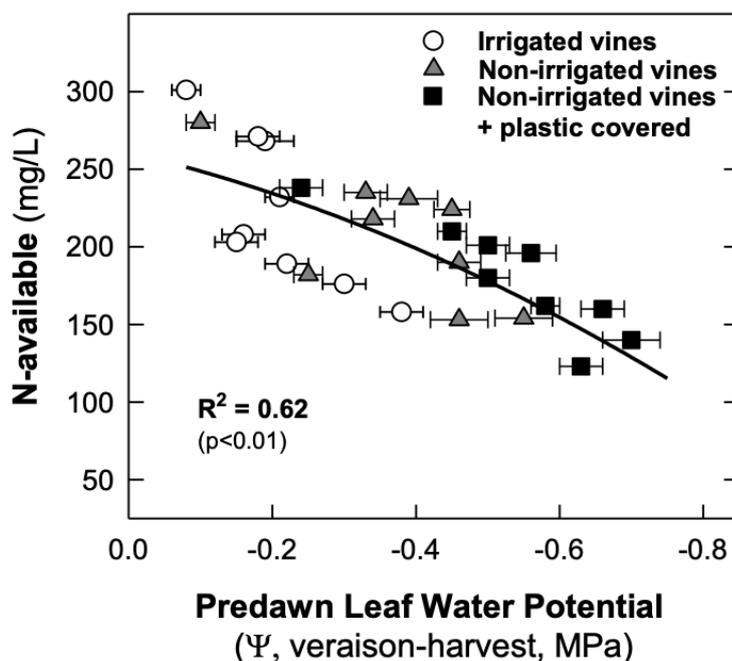
FIGURE 4. Relationship between the predawn water potential (Ψ_{PD}) and the yeast available nitrogen (YAN) in the must at harvest for different irrigation treatments.
Means ± SE. Arvine, Leytron (Switzerland), 2009-2016.

(Schultz and Stoll, 2010). Under conditions of water stress and high VPD, the opposite tendency between WUE_i et WUE_{inst} is sometimes observed, which was the case in this study.

Mesophyll resistance (r_m) increased during the growing season (Figure 3G), whatever the vine water status. Water stress did, nevertheless, accentuate r_m, showing that resistance increased to CO_2 transfer from sub-stomatal cavities towards carbon fixation sites or chloroplasts (Flexas *et al.*, 2002). The increase in r_m coupled with the decrease in g_s in non-irrigated vines subjected to water stress, leads to a fall in leaf photosynthesis, as was observed in this study.

3.2 Mineral supply and pruning weight

The leaf content of N, P, K and Ca had a tendency to diminish with rising water stress, especially in the non-irrigated vines with plastic-covered soils when compared with well-watered vines (Table 3); this tendency was not, however, significantly different in the study period. The leaf content of Mg did however increase with water stress, and in a significant way. These results confirm those obtained from other grape varieties under the same study conditions (Zufferey *et al.*, 2017, 2018). No significant differences in leaf chlorophyll content was found among the different water regimes imposed on vines. The content of yeast available

nitrogen in musts (YAN), however, dropped as water stress increased in non-irrigated vines with plastic-covered soils (Table 3, Figure 4).

A relationship between plant water status, measured by Ψ_{PD} during the period between fruit-ripening and harvesting, and the YAN ($R^2 = 0.62$, $P < 0.01$) was highlighted: the latter decreased as water stress rose. The reduced availability of soil water and the increased plant water stress caused weakening of leaf transpiration, the process which drives minerals uptake (including nitrogen) at the root level and their subsequent transport through the canopy transpiration flow (Gonzalez-Dugo *et al.*, 2010). Nitrogen mineralization and soil microbial activity are both negatively influenced by the soil drying conditions (Celette and Gary, 2013). Studies, carried out in different wine-growing "terroirs" by Reynard *et al.* (2011), have also brought to light the major role played by water supply to vines on the nitrogen content in leaves and berries. Verdenal *et al.* (2012) further observed that water and nitrogen supplies constitute a marker of the « terroir » effect, related to wine quality of Arvine wines, under pedoclimatic conditions of the Swiss canton Wallis.

Plant vigor, estimated by pruning weight in winter, was greatly influenced by the vine water status (Table 4). Water-stressed vines (non-irrigated vines with plastic-covered soil) showed the lowest

TABLE 4. Pruning weight (g/vine) per year and the 2009-2016 mean.

	Pruning weight (g/vine)								Mean
	2009	2010	2011	2012	2013	2014	2015	2016	2009-2016
Irrigated vines	643a	650a	640a	696a	644a	626a	540a	479a	615a
	(±45)	(±27)	(±25)	(±37)	(±27)	(±30)	(±22)	(±17)	(±37)
Non irrigated vines	555ab	630a	574b	647a	638a	585a	546a	489a	579a
	(±25)	(±30)	(±27)	(±34)	(±30)	(±30)	(±25)	(±22)	(±30)
Non irrigated vines + plastic covered	503b	590a	407c	566b	490b	453b	506a	474a	500b
	(±24)	(±20)	(±30)	(±40)	(±20)	(±27)	(±25)	(±27)	(±35)

Letters indicate statistical significance at the 5 % level of probability. Averages 2009-2016, Arvine, Leytron (Switzerland).

TABLE 5. Yield components: bud fertility (number of inflorescences per shoot), cluster removal per vine, berry and cluster weight at harvest, and yield (per m^2).

	Bud fertility (inflo/shoot)	Cluster removal (-x clusters per vine)	Berry weight (g)	Cluster weight (g)	Yield (kg/m2)
Irrigated vines	1.8a	-5.2a	1.3a	240.4a	0.93a
	(±0.05)	(±0.1)	(±0.1)	(±15)	(±0.13)
Non irrigated vines	1.8a	-5.2a	1.2a	225.2a	0.91a
	(±0.04)	(±0.2)	(±0.1)	(±20)	(±0.12)
Non irrigated vines + plastic covered	1.8a	-5.2a	1.0b	208.4a	0.86a
	(±0.05)	(±0.2)	(±0.1)	(±21)	(±0.10)

Letters indicate statistical significance at the 5 % level of probability. Averages 2009-2016, Arvine, Leytron (Switzerland).

weights of pruned wood, compared with irrigated vines. When compared with well-watered vines (irrigated vines), the loss in pruned wood weight reached 19 % on average in the 8 years of study in non-irrigated vines with plastic-covered soil, and 5 % in non-irrigated vines (rain fed).

3.3 Yield components and must characteristics at harvest

Arvine bud fertility (number of inflorescences per shoot) remained uninfluenced by vine water regimes on average over the 8-year study period (Table 5). Water stresses suffered by non-irrigated vines with plastic-covered soils had no impact on the fruiting of buds. The replenishment of carbon (starch) and nitrogen reserves was most likely to have been sufficient from one year to the next during the study period, in both irrigated and non-irrigated vines (Zufferey *et al.*, 2015). The yield regulation was carried out identically between the different irrigation treatments, where

5 clusters per plant were removed. In non-irrigated vines with plastic-covered soils, subjected to the highest water restrictions, lower berry weights were observed than from irrigated vines, or non-irrigated vines where water stresses were weak to moderate (Table 5). Finally, vine water status had no impact on cluster weights and yield per m^2 of soil (and per vine) at harvest time (Table 5). The water stress, which made its appearance relatively late during the ripening period in non-irrigated vines, generally had no major effect on yield (Ojeda *et al.*, 2001; Zufferey *et al.*, 2018), in contrast with early water deficits during the season (before veraison) (Ollat *et al.*, 2002).

Table 6 presents must characteristics at harvest time, such as sugar content, total acidity, tartaric and malic, pH and values of glycosyl-glucose (G-G) and of aromatic precursor (3 mercapto-hexanol, P-3MH). The vine water regime did not exert any major influence on sugar contents, nor on the pH in must. Malic acid content and total

TABLE 6. Harvest characteristics: sugar content, pH, titratable acidity (total acidity, tartaric and malic acid), glycosyl glucose (G-G) and aromatic precursor (P-3MH) in must.

	Sugar (g/L)	pH	Total acidity (g/L)	Tartric acid (g/L)	Malic acid (g/L)	G-G (mg/L)	P-3MH (mg/L)
Irrigated vines	239a	3.07a	10.9a	8.1a	4.8a	41.1a	48a
	(±11)	(±0.05)	(±0.4)	(±0.3)	(±0.5)	(±3.1)	(±4)
Non irrigated vines	239a	3.06a	10.4a	8.3a	4.0ab	43.6ab	47a
	(±10)	(±0.04)	(±0.3)	(±0.2)	(±0.4)	(±2.5)	(±3)
Non irrigated vines + plastic covered	237a	3.04a	9.7b	8.7b	2.9b	47.8b	48a
	(±8)	(±0.05)	(±0.3)	(±0.2)	(±0.6)	(±2.2)	(±4)

Letters: statistically significant at the 5 % level of probability. Averages 2009-2016, Arvine, Leytron (Switzerland).

acidity in musts were found to be lower from vines where moderate to high water stress had been experienced (non-irrigated vines), compared with well-watered vines (irrigated vines). During the hot and dry years of 2009, 2011 and 2015, the water stress observed in non-irrigated vines with plastic-covered soils led to the yellowing and loss of leaves from the basal zone of shoots: consequently, the microclimate of the cluster zone was modified, and clusters were more exposed to direct sunlight and berry temperatures rose. Such conditions may well have led to the degradation of malic acid in berries and a reduction in total acidity of musts (Ruffner, 1982a; Ruffner, 1982b). Conversely, tartaric acid increased with rising water stresses.

The aromatic potential of the Arvine grape variety was evaluated by global analysis of glycosylate compounds (G-G method) and direct quantification of the precursor 3-mercaptohexanol (P-3MH) in musts. G-G values were higher in non-irrigated vines where a moderate to strong water stress had been experienced, than in irrigated vines. Identical results had been obtained by Dienes-Nagy *et al.* (2016) in a study over several years and in varying climatic conditions: in hot and dry seasons, the G-G content of musts was higher than in cooler, rainy years. Observation of P-3MH concentration in musts, however, showed no significant differences between irrigated and non-irrigated vines. Furthermore, the quantity of P-3MH in musts may be influenced by the presence of *Botrytis cinerea* on grapes (Thibon *et al.*, 2011, Spring *et al.*, 2014), this fungus may provoke over-production of P-3MH in this case. During the present trial period, *Botrytis cinerea* was inexistent, whatever the year or the water regime imposed on vines.

In wines, values of pH, total acidity and tartaric acid were very similar among the different irrigation treatments, and no significant differences were observed (results not presented).

4. Wine tasting

Figure 5 presents sensorial analysis notes conferred on wines (noted from 1 to 7), carried out a few weeks after bottling, and covering the main wine characteristics: wine bouquet (quality of aromas), structure, bitterness and global appreciation of the wine.

The quality of the Arvine wine bouquet (typicality and finesse of aromas) was judged to be slightly less attractive in wines whose grapes came from non-irrigated vines, where a strong water stress had been experienced, particularly in the years 2010 and 2011, compared with well-watered (irrigated) vines. Taking into consideration the whole period, however, differences were not always significant. Poorer supplies of nitrogen to musts (concentration of yeast available nitrogen in musts below 200 mg/L, Spring et Lorenzini, 2006), which were observed in water-stressed vines, most certainly influenced bouquet appreciations, and also the perception of bitterness and astringency on the palate. Indeed, wines from water-stressed vines and from musts deficient in yeast available nitrogen (non-irrigated vineyards with plastic-covered soils) were distinguished by higher notes of bitterness, in comparison with vines well supplied with water and nitrogen (irrigated vines). These results corroborate the conclusions reached by Verdenal *et al.*, (2012) with regard to the importance of water and nitrogen supplies to Arvine vineyards and their impact on the wine quality from different pedo-climatic conditions. The global appreciation – or hedonic impression – of wines tasted in the present study was judged
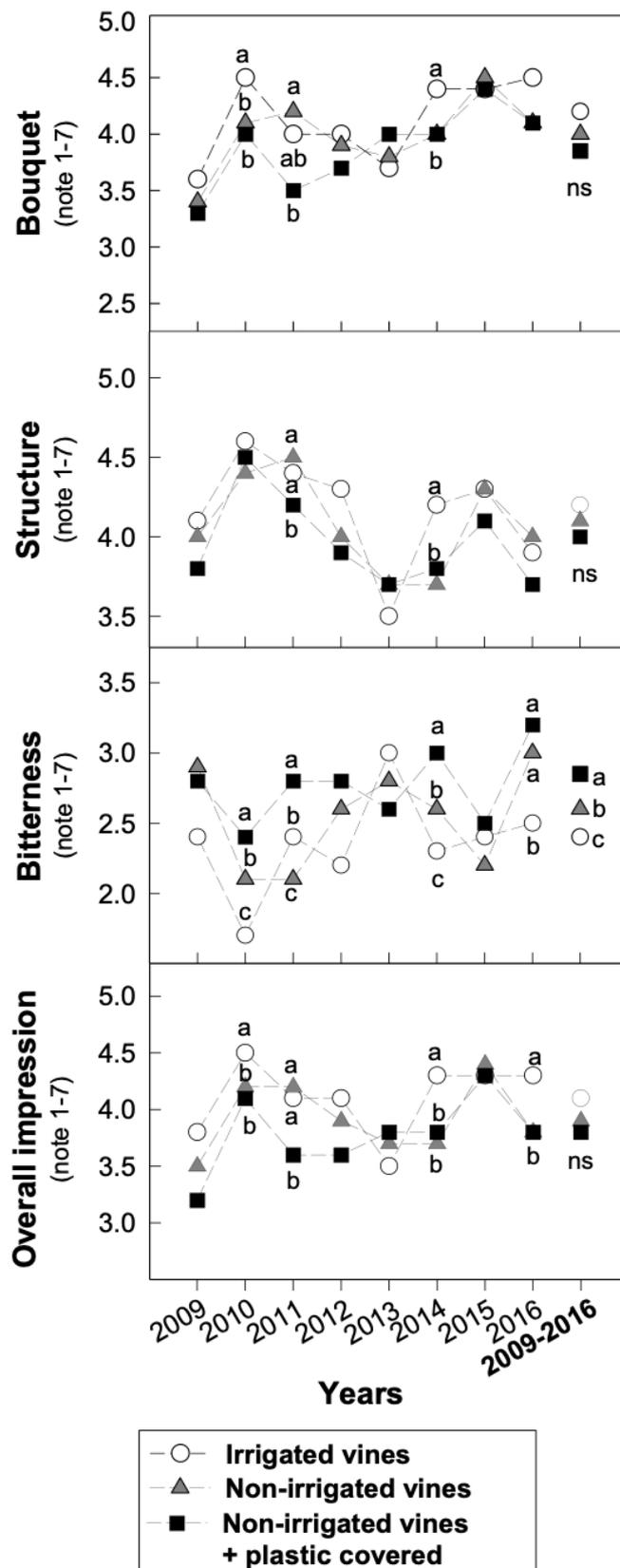
FIGURE 5. Evaluation of wine quality by tasting according to different sensory variables: olfactive (bouquet), gustatory (structure, bitterness) and overall impression for the different irrigation treatments.

The notation scale ranges from 1 (poor) to 7 (high). Letters indicate statistical significance at the 5 % level of probability. Arvine, Leytron (Switzerland), 2009-2016.

to be superior in wines coming from irrigated vines, well-supplied with nitrogen, as opposed to vines with high water deficits and yeast available nitrogen deficiency in musts. This was especially true for the hot and dry years, such as 2009, 2010 and 2011. Research led by Spring *et al*., (2014) into the effects of nitrogen supply and the characteristics of Arvine wines, demonstrated that available nitrogen content in musts, below 180-200 mg/L, brought about a decrease in aromatic precursor concentrations in must (P-3MH) and in aromas in wines. The YAN content observed over the years of the present study remained on average above 180 mg/L, including non-irrigated vines with plastic-covered soils. In this study, P-3MH content was equivalent in musts from both irrigated and non-irrigated vines.

In white cultivars, a low to slightly moderate water stress benefits the development of aromatic components (Choné *et al*., 2006; Reynolds *et al*., 2010). A severe or sometimes even moderate water stress can have a negative impact on white wine quality, particularly affecting the finesse and the typicality of aromas and the perception of bitterness (van Leeuwen and Vivin, 2008; Spring and Zufferey, 2011). Furthermore, high water stress is often accompanied by a reduction in the available nitrogen content of must. According to the vineyard, year, vintage, and grape variety, this reduction may impair the aromatic expression (Tominaga *et al*., 2000), the quality and the characteristics of white wines (Peyrot des Gachons *et al*., 2005; Reynard *et al*., 2011).

REFERENCES

Améglio T., Archer P., Cohen M., Valancogne C., Daudet F.A., Dayau S., Cruiziat P. 1999. Significance and limits in the use of predawn leaf water potential for tree irrigation. Plant Soil 207, 155-167.

Bchir A., Escalona J.M., Gallé A., Hernandez-Montes E., Tortosa I., Braham M. and Medrano H., 2016. Carbon isotope discrimination ($\delta^{13}C$) as an indicator of vine water status and water use efficiency (WUE): looking for the most representative sample and sampling time. *Agric. Water Manage.* 167, 11-20. doi:10.1016/j.agwat.2015.12.018

Bell S-J. and Henschke P.A., 2005. Implications of nitrogen nutrition for grapes, fermentation and wine. *Aust. J. Grape Wine Res.* 11, 242-295. doi:10.1111/j.1755-0238.2005.tb00028.x

Celette F. and Gary C., 2013. Dynamics of water and nitrogen stress along the grapevine cycle as affected by cover cropping. *Eur. J. Agron.* 45, 142-152. doi:10.1016/j.eja.2012.10.001

Chaves M.M., Santos T.P., Souza C.R., Ortuño M.F., Rodrigues M.L., Lopes C.M., Maroco J.P. and Pereira J.S., 2007. Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. *Ann. Appl. Biol.* 150, 237-252. doi:10.1111/j.1744-7348.2006.00123.x

Chaves M.M., Zarrouk O., Francisco R., Costa J.M., Santos T., Regalado A.P., Rodrigues M.L. and Lopes C.M., 2010. Grapevine under deficit irrigation: hints from physiological and molecular data. *Ann. Bot.* 105, 661-676. doi:10.1093/aob/mcq030

Choné X., van Leeuwen C., Dubourdieu D. and Gaudillère J.-P., 2001. Stem water potential is a sensitive indicator of grapevine water status. *Ann. Bot.* 87, 477-483. doi:10.1006/anbo.2000.1361

Choné X., Lavigne-Cruège V., Tominaga T., van Leeuwen C., Castagnede C., Saucier C. and Dubourdieu D., 2006. Effect of vine nitrogen status on grape aromatic potential: flavor precursors (S-cysteine conjugates), glutathione and phenolic content in *Vitis vinifera* L. cv. Sauvignon blanc grape juice. *J. Int. Sci. Vigne Vin* 40, 1-6. doi:10.20870/oeno-one.2006.40.1.880

Deléens E., Cliquet J.B. and Prioul J.L., 1994. Use of ^{13}C and ^{15}N plant label near natural abundance for monitoring carbon and nitrogen partitioning. *Aust. J. Plant Physiol.* 21, 133-146. doi:10.1071/PP9940133

Deloire A., Carbonneau A., Wang Z. and Ojeda H., 2004. Vine and water: a short review. *J. Int. Sci. Vigne Vin* 38, 1-13. doi:10.20870/oeno-one.2004.38.1.932

Deluc L.G., Quilici D.R., Decendit A., Grimplet J., Wheatley M.D., Schlauch K.A., Mérillon J.M., Cushman J.C. and Cramer G.R., 2009. Water deficit alters differentially metabolic pathways affecting important flavor and quality traits in grape berries of Cabernet Sauvignon and Chardonnay. *BMC Genomics* 10, 212. doi:10.1186/1471-2164-10-212

de Souza C.R., Maroco J.P., dos Santos T.P., Rodrigues M.L., Lopes C.M., Pereira J.S. and Chaves M.M., 2005a. Impact of deficit irrigation on water use efficiency and carbon isotope composition ($\delta^{13}C$) of field-grown grapevines under Mediterranean climate. *J. Exp. Bot.* 56, 2163-2172. doi:10.1093/jxb/eri216

de Souza C.R., Maroco J.P., dos Santos T.P., Rodrigues M.L., Lopes C.M., Pereira J.S. and Chaves M.M., 2005b. Grape berry metabolism in field-grown grapevines exposed to different irrigation strategies. *Vitis* 44, 103-109.

Dienes-Nagy A., Nardone D., Cléroux M., Riesen R., Frey U., Lorenzini F., 2016. Méthodes analytiques de mesure du potentiel aromatique des raisins. *Revue suisse Viticulture, Arboriculture, Horticulture* 48 (2), 102-109.

Flexas J., Bota J., Escalona J.M., Sampol B. and Medrano H., 2002. Effects of drought on photosynthesis in grapevines under field conditions: an evaluation of stomatal and mesophyll limitations. *Funct. Plant Biol.* 29, 461-471. doi:10.1071/PP01119

Flexas J., Diaz-Espejo A., Galmes J., Kaldenhoff R., Medrano H. and Ribas-Carbo M., 2007. Rapid variations of mesophyll conductance in response to changes in CO_2 concentration around leaves. *Plant Cell Environ.* 30, 1284-1298. doi:10.1111/j.1365-3040.2007.01700.x

Fretz C.B., Luisier J.-L., Tominaga T., Amado R., 2005. 3-Mercaptohexanol: An Aroma Impact Compound of Petite Arvine Wine. *Am. J. Enol. Vitic.* 56 (4), 407-410.

Fulton A., Buchner R., Olson B., Schwankl L., Gilles C., Bertagna N., Walton J. and Shackel K., 2001. Rapid equilibration of leaf and stem water potential under field conditions in almonds, walnuts and prunes. *HortTechnology* 11, 609-615. doi:10.21273/HORTTECH.11.4.609

Gaudillère J.-P., van Leeuwen C. and Ollat N., 2002. Carbon isotope composition of sugars in grapevine, an integrated indicator of vineyard water status. *J. Exp. Bot.* **53**, 757-763. doi:10.1093/jexbot/53.369.757

Gonzalez-Dugo V., Durand J.-L. and Gastal F., 2010. Water deficit and nitrogen nutrition of crops. A review. *Agron. Sustain. Dev.* 30, 529-544. doi:10.1051/agro/2009059

Lacroux F., Tregoat O., van Leeuwen C., Pons A., Tominaga T., Lavigne-Cruège V. and Dubourdieu D., 2008. Effect of foliar nitrogen and sulphur application on aromatic expression of *Vitis vinifera* L. cv. Sauvignon blanc. *J. Int. Sci. Vigne Vin* 42, 125-132. doi:10.20870/oeno-one.2008.42.3.816

Lovisolo C., Hartung W. and Schubert A., 2002. Whole-plant hydraulic conductance and root-to-shoot flow of abscisic acid are independently affected by water stress in grapevines. *Funct. Plant Biol.* 29, 1349-1356. doi:10.1071/FP02079

Lovisolo C., Lavoie-Lamoureux A., Tramontini S. and Ferrandino A., 2016. Grapevine adaptations to water stress: new perspectives about soil/plant interactions. *Theor. Exp. Plant Physiol.* 28, 53-66. doi:10.1007/s40626-016-0057-7

Luisier J.L., Buettner H., Völker T., Rausis T., and Frey U., 2008. Quantification of cysteine S-conjugate of 3-sulfanylhexan-1-ol in must and wine of Petite Arvine vine by stable isotope dilution analysis. *J. Agric. Food Chem.* 56 (9), 2883-2887. doi:10.1021/jf072963o

Medrano H., Escalona J.M., Bota H., Gulias J., and Flexas J., 2002. Regulation of photosynthesis of C_3 plants in response to progressive drought: stomatal conductance as a reference parameter. *Ann. Bot.* 89, 895-905. doi:10.1093/aob/mcf079

Medrano H., Escalona J.M., Cifre J., Bota J., and Flexas J., 2003. A ten-year study on the physiology of two Spanish grapevine cultivars under field conditions:

effects of water availability from leaf photosynthesis to grape yield and quality. Functional Plant Biology 30, 607–619. doi:10.1071/FP02110

Ojeda H., Deloire A. and Carbonneau A., 2001. Influence of water deficits on grape berry growth. *Vitis* 40, 141-145.

Ollat N., Diakou-Verdin P., Carde J.P., Barrieu F., Gaudillère J.P. and Moing A., 2002. Grape berry development: a review. *J. Int. Sci. Vigne Vin* 36, 109-131. doi:10.20870/oeno-one.2002.36.3.970

Osmond C.B., Björkman O. and Anderson D.J., 1980. Physiological Processes in Plant Ecology (Springer-Verlag: Berlin). doi:10.1007/978-3-642-67637-6

Peyrot des Gachons C.P., van Leeuwen C., Tominaga T., Soyer J.P., Gaudillère J.P. and Dubourdieu D., 2005. Influence of water and nitrogen deficit on fruit ripening and aroma potential of *Vitis vinifera* L. cv Sauvignon blanc in field conditions. *J. Sci. Food Agric.* 85, 73-85. doi:10.1002/jsfa.1919

Prieto J.A., Lebon E. and Ojeda H., 2010. Stomatal behavior of different grapevine cultivars in response to soil water status and air water vapor pressure deficit. *J. Int. Sci. Vigne Vin* 44, 9-20. doi:10.20870/oeno-one.2010.44.1.1459

Pou A., Flexas J., Alsina M., Bota J., Carambula C., Herralde F., Galmes J., Lovisolo C., Jiminez M., Ribas-Carbo M., Rusjan D., Secchi F., Tomas M., Zsofi Z., Medrano H., 2008. Adjustments of water use efficiency by stomatal regulation during drought and recovery in the drought-adapted *Vitis* hybrid Richter 110 (*V. berlandieri x V. rupestris*). *Physiologia Plantarum* 134, 313-323. doi:10.1111/j.1399-3054.2008.01138.x

Reynard J.-S., Zufferey V., Nicol G.C. and Murisier F., 2011. Soil parameters impact the vine-fruit-wine continuum by altering vine nitrogen status. *J. Int. Sci. Vigne Vin* 45, 211-221. doi:10.20870/oeno-one.2011.45.4.1502

Reynolds A., De Savigny C. and Willwerth J., 2010. Riesling terroir in Ontario vineyards. The roles of soil texture, vine size and vine water status. *Prog. Agric. Vitic.* 127, 212-222.

Ruffner H.P., 1982a. Metabolism of tartric and malic acids in *Vitis*: a review-part a. *Vitis* 21, 247-259.

Ruffner H.P., 1982b. Metabolism of tartric and malic acids in *Vitis*: a review-part b. *Vitis* 21, 346-358.

Scholander P.F., Hammel H.T., Bradstreet E.D. and Hemmingsen E.A., 1965. Sap pressure in vascular plants. *Science* 148, 339-346. doi:10.1126/science.148.3668.339

Schultz H.R., 1996. Water relations and photosynthetic responses of two grapevine cultivars of different geographical origin during water stress. *Acta Hortic.* 427, 251-266. doi:10.17660/ActaHortic.1996.427.30

Schultz H.R., Stoll M., 2010. Some critical issues in environmental physiology of grapevines: future challenges and current limitations. *Australian Journal*

of Grape and Wine Research 16, 4-24. doi:10.1111/j.1755-0238.2009.00074.x

Seguin G., 1975. Alimentation en eau de la vigne et composition chimique des moûts dans les Grands Crus du Médoc. Phénomènes de régulation. Conn. Vigne Vin 9, 23-34. doi:10.20870/oeno-one.1975.9.1.1675

Spangenberg J.E., Vogiatzaki M. and Zufferey V., 2017. Gas chromatography and isotope ratio mass spectrometry of Pinot noir wine volatile compounds (d13C) and solid residues (d13C, d15N) for the reassessment of vineyard water-status. J. Chromatogr. A 1571, 142-155. doi:10.1016/j.chroma.2017.08.038

Spangenberg J.E., Zufferey V., 2018. Changes in soil water availability in vineyards can be traced by the carbon and nitrogen isotope composition of dried wines. Science of Total Environment 635, 178-187. doi:10.1016/j.scitotenv.2018.04.078

Spangenberg J.E., Zufferey V., 2019. Carbon isotope compositions of whole wine, wine solid residue and wine ethanol determined by EA/IRMS and GC/C/IRMS record the vine water status: A comparative reappraisal. Analytical and Bioanalytical Chemistry, 411, 2031-2043. doi:10.1007/s00216-019-01625-4

Spring J.-L., Lorenzini F., 2006. Effet de la pulvérisation foliaire d'urée sur l'alimentation azotée et la qualité du Chasselas en vigne enherbée. Rev. Suisse Vitic. Arboric. Hortic. 38 (2), 105-113.

Spring J.-L. and Zufferey V., 2011. Irrigation : comportement de la vigne et qualité des vins de cépages blancs dans le Valais central. Rev. Suisse Vitic. Arboric. Hortic. 43, 162-173.

Spring J.L., Zufferey V., Dienes-Nagy A., Lorenzini F., Frey U., Thibon C., Darriet P., Viret O. 2014. Effet de l'alimentation azotée sur le comportement et la typicité des vins de l'Arvine. Rev. Suisse Vitic. Arboric. Hortic. 46 (4), 244-253.

Thibon C., Cluzet S., Mérillon J.-M., Darriet P., Dubourdieu D., 2011. 3-sulfanylhexanol precursor biogenesis in grapevine cells: the stimulating effect of Botrytis cinerea. J. Agric. Food Chem. 59 (4), 1344-1351. doi:10.1021/jf103915y

Tomas M., Medrano H., Escalona J.M., Martorell S., Pou A., Ribas-Carbó M., Flexas J. 2014b. Genetic variability in water use efficiency in grapevines. Environ. Exp. Bot. 103,148–157. doi:10.1016/j.envexpbot.2013.09.003

Tominaga T., Baltenweck-Guyot R., Peyrot des Gachons C.P. and Dubourdieu D., 2000. Contribution of volatile thiols to the aromas of white wines made from several Vitis vinifera grape varieties. Am. J. Enol. Vitic. 51, 178-181.

Turner N.C., 1988. Measurement of plant water status by the pressure chamber technique. Irrig. Sci. 9, 289-308. doi:10.1007/BF00296704

Tyree M.T. and Sperry J.S., 1988. Do woody plants operate near the point of catastrophic xylem dysfunction caused by dynamic water stress? Answers from a model. Plant Physiol. 88, 574-580. doi:10.1104/pp.88.3.574

van Leeuwen C. and Seguin G., 1994. Incidences de l'alimentation en eau de la vigne, appréciée par l'état hydrique du feuillage, sur le développement de l'appareil végétatif et la maturation du raisin (Vitis vinifera variété Cabernet franc, Saint-Emilion, 1990). J. Int. Sci. Vigne Vin 28, 81-110. doi:10.20870/oeno-one.1994.28.2.1152

van Leeuwen C. and Vivin P., 2008. Alimentation hydrique de la vigne et qualité des raisins. Innov. Agron. 2, 159-167.

van Leeuwen C., Choné X., Trégoat O. and Gaudillère J.P., 2001a. The use of physiological indicators to assess vine water uptake and to manage vineyard irrigation. Aust. Grapegrow. Winemak. 449, 18-24.

van Leeuwen C., Gaudillère J.P. and Trégoat O., 2001b. L'évaluation du régime hydrique de la vigne à partir du rapport isotopique 13C/12C. J. Int. Sci. Vigne Vin 35, 195-205. doi:10.20870/oeno-one.2001.35.4.984

van Leeuwen C., Trégoat O., Choné X., Bois B., Pernet D. and Gaudillère J.P., 2009. Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? J. Int. Sci. Vigne Vin 43, 121-134. doi:10.20870/oeno-one.2009.43.3.798

Verdenal T., Zufferey V., Spring J.L., Jourjon M., Viret O. 2012. Comportement du cépage Arvine dans le vignoble de Fully (Valais, Suisse). Rev. Suisse Vitic. Arboric. Hortic. 44 (6), 378-384.

Williams P.J., Cynkar I., Francis I.L., Gray J.D., Iland P.G., Coombe B.G., 1995. Quantification of Glycosides in grapes, Juices and Wines through a determination of Glycosyl Glucose. J. Agric. Food Chem. 43, 121-128. doi:10.1021/jf00049a023

Zufferey V., Cochard H., Ameglio T., Spring J.-L. and Viret O., 2011. Diurnal cycles of embolism formation and repair in petioles of grapevine (Vitis vinifera cv. Chasselas). J. Exp. Bot. 62, 3885-3894. doi:10.1093/jxb/err081

Zufferey V., Smart D.R., 2012. Stomatal behavior of irrigated Vitis vinifera cv. Syrah following partial root removal. Functional Plant Biology 39, 1019-1027. doi:10.1071/FP12091

Zufferey V., Murisier F., Belcher S., Lorenzini F., Vivin P., Spring J.-L. and Viret O., 2015. Nitrogen and carbohydrate reserves in the grapevine (Vitis vinifera L. 'Chasselas'): the influence of the leaf to fruit ratio. Vitis 54, 183-188. doi:10.5073/vitis.2015.54.183-188

Zufferey V., Spring J.-L., Verdenal T., Dienes-Nagy A., Belcher S., Lorenzini F., Koestel C., Rösti J., Gindro K., Spangenberg J. and Viret O., 2017. Influence of water stress on plant hydraulics, gas exchange, berry composition and quality of Pinot noir wines in

Switzerland. *OENO One* 51, 17-27. doi:10.20870/oeno-one.2017.51.1.1314

Zufferey V., Verdenal T.; Dienes-Nagy A.; Belcher S., Lorenzini F. Koestel C.;Gindro K., Spangenberg J.,

Viret O., Spring J.L., 2018. The Impacts of plant water status on gas exchange, berry composition and quality of Chasselas wines in Switzerland. *OENO One* 52, 4, 333-347. doi:10.20870/oeno-one.2018.52.4.2181.