ASSESSMENT OF PLANT HYDRAULICS IN GRAPEVINE ON VARIOUS « TERROIRS » IN THE CANTON OF VAUD (SWITZERLAND)

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Abstract

Aims: The aim of this paper is to study the relevance of different physiological indicators concerning vines hydraulic in relation to estimations of the soil water reservoir on various « terroirs » in Switzerland.

Methods and results: Different physiological indicators like leaf and stem water potentials, carbon isotope discrimination and a model of transpirable soil water were used. A close relationship was observed between pre-dawn leaf water potential and the soil water holding capacity (SWHC) from about thirty study sites over a period of three years.

Conclusion: The different assessments of plant hydraulics (leaf water potential, carbon isotope discrimination technique, model of transpirable soil water) were in good agreement with the soil water holding capacity.

Significance and impact of study:The results confirm the importance and the possibilities to estimate plant water ability in relation with soil water holding capacity and climatic factors.

Key words: « vine terroir », plant hydraulics, leaf and stem water potential, carbon isotope discrimination

Résumé

Objectif : L'objectif de ce travail est d'examiner la pertinence de différents indicateurs physiologiques concernant le régime hydrique de la vigne en relation avec les estimations de la réserve hydrique des sols sur divers terroirs en Suisse.

Méthodes and résultats : Divers indicateurs physiologiques comme les potentiels hydriques foliaires et de tige, la discrimination isotopique du carbone et un modèle de bilan hydrique ont été utilisés. Une relation étroite a été observée entre le potentiel hydrique de base et la réserve en eau des sols à partir d'un réseau de trente parcelles sur une période de trois années de mesure.

Conclusion : Les diverses estimations du régime hydrique de la plante (potentiel hydrique foliaire, discrimination isotopique du carbone, modèle de bilan hydrique) ont été en bon accord avec la capacité de réserve hydrique des sols.

Signification et impact de l'étude : Les résultats confirment l'importance et les possibilités d'estimer l'état hydrique des plantes en relation avec la réserve en eau des sols et les facteurs climatiques.

Mots clés : terroirs viticoles, alimentation hydrique de la vigne, potentiels hydriques foliaire et de tige, discrimination isotopique du carbone

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INTRODUCTION

Studies on the characteristics of vineyard territories tend to indicate that water supply conditions to the vine have a great influence on vine behaviour, grape composition and wine quality (SEGUIN, 1970; MORLAT, 1989; VAN LEEUWEN, 1991). Generally, it has been unanimously accepted that water supply to grapevines during the ripening process plays a key role in the grape and wine quality (DELOIRE *et al.*, 2005; TREGOAT *et al.*, 2002). Furthermore, grapevine sensitivity to water deficiency is a function of the vineyard's intrinsic parameters (soil type, mesoclimate) and varies according to genetic and agronomic factors.

Several techniques for the evaluation of grapevine water regimes exist (VAN LEEUWEN *et al.*, 2001) : some are based on the estimation of soil water quantities (gravimetry or neutron humidity) or its availability to the plant. Physiological indicators constitute an additional approach to assessing hydraulics status of the plant itself. Some techniques make use of leaf transpiration or leaf water potential measurements, for example, to give an instantaneous picture of the grapevine hydraulics. Other methods utilise meso- or microclimatic parameters, the crop water stress index, for instance. Lastly an overall assessment of the grapevine water regime during the phase of grape ripening (the sugar accumulation phase) can be obtained using the $^{13}C/^{12}C$ isotopic ratio in must sugars.

The present study endeavours to evaluate the pertinence of several physiological indicators of water stress (leaf water potential, leaf gas exchanges, carbon isotope discrimination and transpirable soil water) on about thirty sites where soil water reserves varied from 50 mm to over 250 mm. The present results form part of a wider study being conducted on soil-climate-plant relations and their impact on grape composition and wine quality (ZUFFEREY and MURISIER, 2004a).

MATERIALS AND METHODS

1. Pedological and climatic characteristics

a - Soil types

An earlier soil study of the viticultural areas of Vaud by LETESSIER and FERMOND (2004) has enabled a grouping of soils resulting in a map of pedological units

Table 1 - Viticultural areas in the Canton of Vaud (Switzerland), pedologicals units, experimental sites with their soil water holding capacity (SWHC).

Viticultural areas	Pedological units	Experimental sites	SWHC (mm)
LA CÔTE	lateral moraines (30-60% coarse elements)	Begnins 01	150
		Vinzel 03	120
	botton moraines (< 30% coarse elements)	Vinzel 02	80
		Luins 01	115
		Luins 03	80
	retraiting moraines gravelly-stony	Bursins 02	125
		Luins 02	65
		Dully 02	85
	colluvial deposits	Begnins 06	160
		Begnins 07	>150
BONVILLARS	botton moraines (< 30% coarse elements)	Concise 02	160
		Bonvillars 02	120
	Jurassic sandy stones	Bonvillars 01	95
		Champagne 02	70
	colluvial deposits	Nonvillars 93	> 220
CHABLAIS	lateral moraines (30-60% coarse elements)	Ollon 01	> 100
		Ollon 03	135
		Ollon 06	160
		Ollon 08	140
	flysch soils	Bex 01	75
		Bex 03	120
		Bex 03	155
LAVAUX	lateral moraines (30-60% coarse elements)	Chardonne 07	160
		Rivaz 02	130
	botton moraines (< 30% coarse elements)	Chardonne 04	75
		Rivaz 01	75
		Chexbres 01	130
	marly sandstones	Rivaz 05	240
		Corsier 02	75
		St-Saphorin 03	130
	colluvial deposits	Chardonne 03	180

(Table I). The majority of soils in the study area, that is approximately 80 % of the surface area, were made up of alpine moraines, a heterogeneous mixture of unevenly sized debris transported by the Rhone glacier. Moraines can be classified into three types of parent-rock (LETESSIER and FERMOND, 2004) : stony lateral moraines (30-60 % coarse siliceous and calcareous coarse elements), bottom moraines with few stones (< 30 % coarse elements) and gravelly-stony retreating moraines and/or of fluvio-glacial formation (glacifluvial deposits) (> 60 % large elements). In some places, a relatively thin layer of moraine (sometimes less than 60 cm thickness) has been observed lying on top of gritty-sandy or marly sandstones or Jurassic sandy limestones. Some colluvial deposits found at the foot of slopes originate from progressive erosion of the dominating slopes.

b - Soil water holding capacity

Soil water holding capacity (SWHC) was estimated from soil profiles in layers of 10 cm thickness (decimetric reserves), taking into account the soil texture, the amount of stones and root colonisation. SWHC estimations were conducted by LETESSIER and FERMOND (2004) who thus evaluated the water profile or the amount of water directly available to the grapevine on the different study sites (Table 1).

c - Climatic characteristics of years 2001 to 2003 (Table II)

The year 2001 was characterised by very heavy rainfall (1'248 mm at Changins for a mean annual rainfall of 945 mm and 1'565 mm at Pully for an average of 1'100 mm). From January to the end of June, precipitation was especially heavy with regular summer thunderstorms. As for temperatures, the months between May and August were particularly hot with temperatures between 2.5 and 3 °C above the average measured over the last 30 years. In 2002, rainfall measurements were slightly higher than the mean, particularly during the period of plant growth in Lavaux and the Chablais. In addition, low but frequent precipitation was recorded in these two regions during grape ripening. The vineyards of La Côte and Bonvillars enjoyed drier weather during the month of September. Annual temperatures everywhere were above the average for the previous 30 years by 2 to 2.5 °C. The month of June was particularly hot. Throughout the plant growth period, the balance of monthly temperatures was positive. In 2003, summer temperatures were well above the norm by 4 to 6.5 °C from June to August. In addition, this period was characterised by low rainfall and a significant water deficit (difference between rainfall and evapo-transpiration).

2. Experimental sites

A network of around thirty sites was set up in pilot zones covering 1,000 ha approximately, and chosen from reputable vineyards characteristic of the Vaudois wine territory (« terroirs »). The study sites were planted with *Vitis vinifera* L. cv. Chasselas grafted onto 3309C and trained in espalier (single Guyot with vertical shoot positioned foliage). In this paper, only the viticultural areas « La Côte » and « Bonvillars » are presented.

3. Experimental measurements

a - Wine water status measurements

Leaf water potential (ψ) was measured using a pressure chamber or Scholander's bomb (SCHOLANDER *et al.*, 1965). The pre-dawn leaf water potential (ψ_{PD}) measurements were made in the early hours of the morning (02 h 00 to 06 h 00) in total darkness on mature leaves centrally placed in the foliage. Leaf water potential (ψ_{leaf}) was measured during the day immediately following leaf gas-exchange measurements

Table 2 - Climatic characteristics (temperature, rainfall). Meteorological station of Changins in Nyon (Switzerland).

Months	Temperature (°C)				Rainfall (mm)			
	2001	2002	2003	Ø 30 years	2001	2002	2003	Ø 30 years
January	3.1	1.3	1.1	**0.7**	161	47	80	**76**
February	4.5	5.9	-0.1	**1.7**	55	91	29	**66**
March	8.3	7.5	8.1	**5.3**	294	61	16	**68**
April	8.0	10.3	10.1	**9.0**	126	15	69	**64**
Mai	16.0	12.8	15.2	**13.4**	77	162	53	**73**
June	16.7	19.8	23.1	**16.6**	125	46	23	**83**
July	19.7	19.3	21.8	**18.6**	96	79	44	**81**
August	20.0	18.2	23.8	**17.6**	73	76	99	**93**
September	12.7	14.6	15.6	**14,3**	78	42	71	**90**
October	13.5	11.1	8.2	**9.2**	71	157	177	**79**
November	4.1	7.2	5.5	**4.5**	46	280	60	**88**
December	1.2	5.2	2.8	**1.6**	46	94	38	**84**
YEAR	10.6	11.1	11.3	**9.4**	1248	1150	760	**945**

on mature primary leaves. The water gradient (Δ_{leaf}) was calculated from ψ_{stem} and ψ_{leaf} measurements on the same shoot ($\psi_{stem} - \psi_{leaf} = \Delta\psi$). The levels of water stress (low, moderate, high) and the corresponding water potential critical values were used according to CARBONNEAU (1998). Stem water potential (ψ_{stem}) was measured on leaves bagged with a plastic sheet covered with aluminium foil to stop transpiration for one or two hours before measurement : ψ_{stem} was measured at the hottest time of the day (1,400 to 1,500 hr) on mature leaves. Additional details of measurements can be found in ZUFFEREY and MURISIER (2004b).

b - Carbon isotopic discrimination

Carbon isotopic discrimination in grape sugars, known as δ13C ($^{13}C/^{12}C$) and expressed in per thousand, was measured on a sample of must obtained from 300 mature grape berries per site (GAUDILLIÈRE *et al.*, 2002). The sample (a few millilitres) was autoclaved and then converted into CO_2 by combustion using pure oxygen. The isotopic content was determined by continuous flux mass spectrometry (Europe Scientif Ltd., Crewe, UK, AVICE *et al.*, 1996).

c - Transpirable soil water model

A transpirable soil water model, developed by RIOU and PAYAN (2001) and LEBON *et al.* (2003), was run on all the study sites. The model relies on the acquisition of simple, easily accessible data of climatic and agronomic properties of the site (rainfall, potential evapotranspiration (PET), stage of plant growth, size and shape of plants). The model considers the soil as a reservoir which fills up by precipitation and empties through plant transpiration and soil evaporation in relation to climatic demands. An estimation of the total transpirable soil water (TTSW) was determined by combining the model with pre-dawn leaf water potential measurements (LEBON *et al.*, 2003). The fraction of transpirable soil water (FTSW) represent the ratio between the available transpirable soil water (ATSW) at a given time and the total transpirable soil water (TTSW). According to LEBON *et al.* (2003) : FTSW = ATSW/TTSW. The relationship between FTSW and ψ_{PD} (LEBON *et al.*, 2003) was used to determine the TTSW in different sites.

RESULTS AND DISCUSSION

I - Soil water holding capacity

The study of root profiles enabled determination of the depth of soil colonized by roots, the quantity and nature of roots, as well as assessing the soil water holding capacity (SWHC). Root depth varied widely depending on soil type, moraine compactness and proximity to the conglomeratic or gritty-lime sandstone. Root penetration

Table 3 - Stem water potential measurements (ψ_{stem}) taken over the season from various sites with different SWHC. Mean ± standard error. Chasselas, Bonvillars (CH), 2002.

SWHC (mm)	Midday ψ_{stem} (MPa)				
	Pea size July 1st	July 22	Veraison August 14	Ripening September 18	Harvest October 2nd
< 70 mm	-0.66 ± 0.03	-0.54 ± 0.02	-0.46 ± 0.02	-1.65 ± 0.03	-1.34 ± 0.05
95 mm	-0.44 ± 0.01	-0.45 ± 0.02	-0.33 ± 0.02	-1.11 ± 0.05	-1.10 ± 0.08
120 mm	-0.43 ± 0.02	-0.47 ± 0.02	-0.35 ± 0.01	-	-0.60 ± 0.04
160 mm	-0.35 ± 0.01	-0.37 ± 0.01	-0.32 ± 0.02	-	-
> 220 mm	-0.37 ± 0.01	-0.38 ± 0.01	-0.30 ± 0.02	-	-0.40 ± 0.02

Table 4 - Estimation of soil water holding capacity (SWHC) by LETESSIER and FERMOND (2004) and total of transpirable soil water (TTSW) simulated by transpirable soil water model (RIOU and PAYAN, 2001; LEBON *et al.*, 2003) from different sites in the Canton of Vaud (CH). Means ± standard error. Chasselas, La Côte (CH), 2001-2003.

Sites	SWHC (mm)	TTSW (mm) 2003	TTSW (mm) Ø 2001-2003
Begnins 01	150	120	125 ± 30
Begnins 06	160	150	165 ± 35
Begnins 07	> 150	170	190 ± 40
Luins 01	115	130	110 ± 20
Luins 02	65	50	70 ± 25
Luins 03	80	90	100 ± 15
Vinzel 02	80	110	-
Vinzel 03	120	150	160 ± 30
Bursins 02	125	90	-
Dully 02	85	-	80 (en 2002)

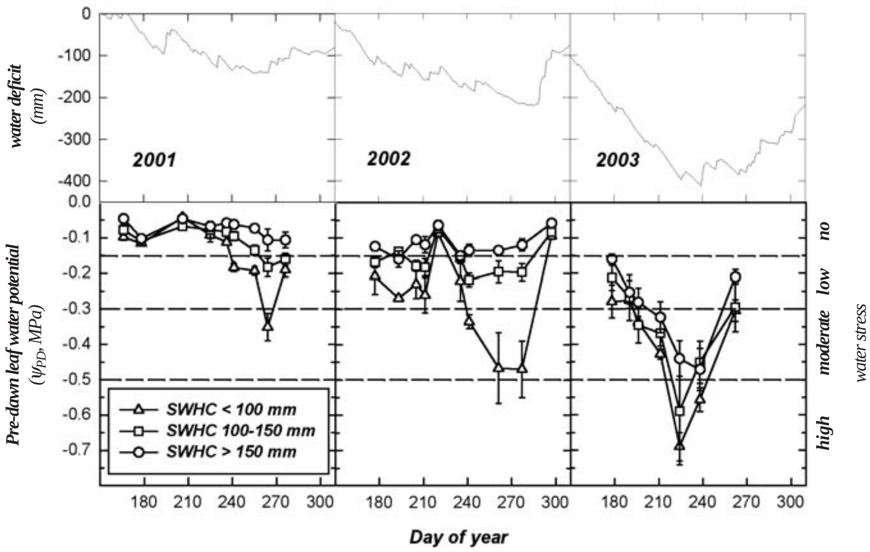

Figure 1 - Seasonal evolution of water deficit (rainfall-PET) and pre-dawn leaf water potential (ψ_{PD}) as affected by the soil water holding capacity (SWHC).

Vertical bars: standard error. Chasselas, La Côte (CH), 2001-2003.

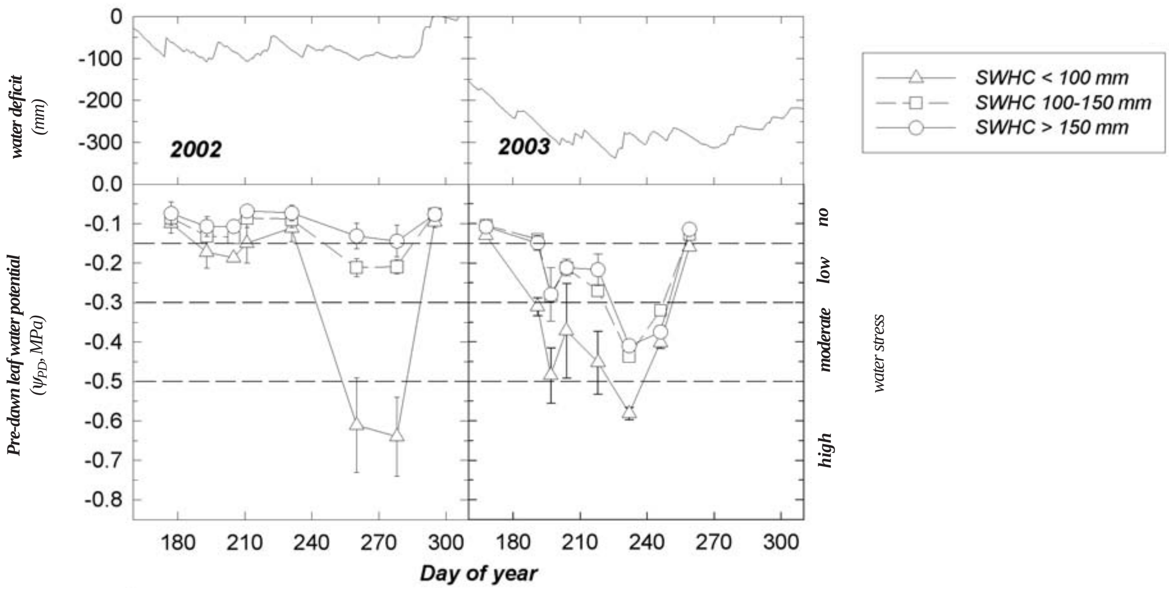

Figure 2 - Seasonal evolution of water deficit (rainfall-PET) and pre-dawn leaf water potential (ψ_{PD}) during growth seasons in relation to the soil water holding capacity (SWHC).

Vertical bars: standard error. Chasselas, Bonvillars (CH), 2002-2003.

was less than 80 cm in very compact moraines, but was deeper than 250 cm in loose moraines on slopes or very stony moraines (fluviglacial deposits). Estimations of the SWHC indicated that water reservoir potential differed greatly from one soil type to another because of differences in texture, quantity of stones and depth of root penetration. The SWHC values varied from 50 mm to over 250 mm in the largest water reservoirs of the present experimental sites.

2 - Seasonal water status

a - Predawn leaf water potential measurements (ψPD)

Figures 1 and 2 illustrate the ψ_{PD} in the various sites of La Côte (Fig. 1) and in Bonvillars (Fig. 2). The study shows that no water stress or only low water stress was found in sites with high SWHC (> 150 mm) during the seasons of 2001 and 2002, in spite of any accumulated climatic water deficit during the year (rainfall-PET < -100 mm). On the other hand, moderate to high water stress was recorded at the end of the growth season in sites with low SWHC (< 100 mm), mainly in 2002, when the climatic water deficit reached 220 mm at the end of September in La Côte (DOY 270).

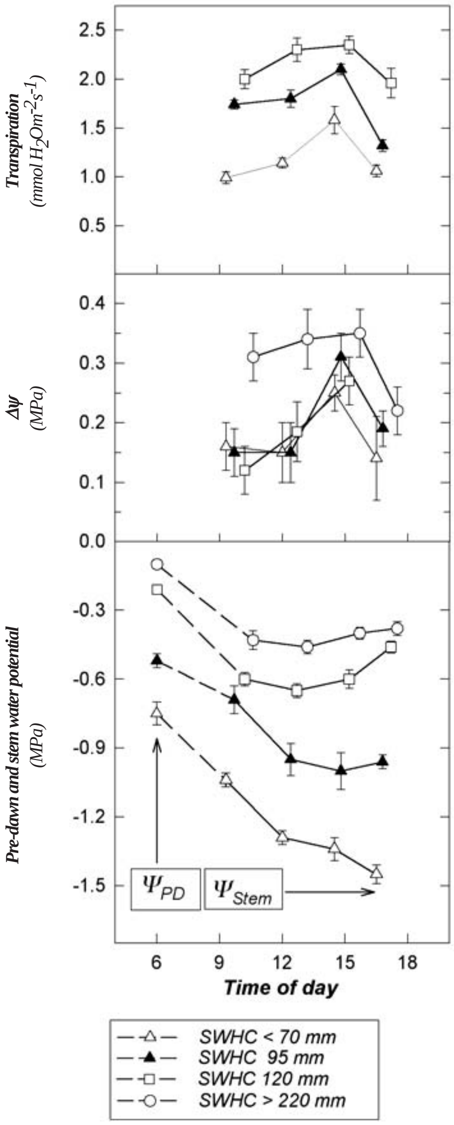

Figure 3 - Daily evolution (02/10/2002) of leaf transpiration, of water potential gradient between the stem and leaves ($\Delta\psi$), and of stem water potential (ψ_{stem}) from 4 sites with different SWHC values.
Vertical bars : standard error; fine sunny day, °Cmax : 19,9; minimum relative humidity in the afternoon : 52 %. Chasselas, Bonvillars (CH).

When soil water reserves were low, the evolution of ψPD depended largely on the water deficit throughout the season, or, in other words, on the balance between summer rainfall and PET. An intermediate situation of minor water stress was observed in vineyards where soil water reserves were between 100 and 150 mm during the plant growth periods in 2001 and 2002.

A very high climatic water deficit was measured during the summer period of 2003, reaching 400 mm at the end of August (DOY 240) in La Côte and 320 mm at Bonvillars (Figures 1 and 2). The sites with high SWHC

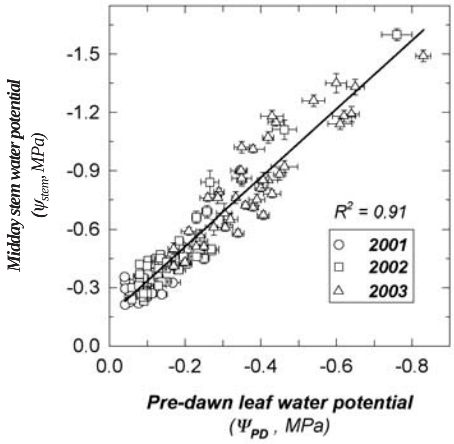

Figure 4 - Relationship between the pre-dawn leaf water potential (ψ_{PD}) and stem water potential (ψ_{stem}) at Midday of the various study sites.
Vertical and horizontal bars : standard error; air temperature between 25-32 °C; relative air humidity measured between 35-50 %; saturated light PAR >1200 µmol photons $m^{-2}s^{-1}$; PET between 4.5 and 5.5 mm/day. Chasselas, Canton of Vaud (CH), 2001-2003.

(> 150 mm) showed moderate level of wine water stress during July and August. In sites where the SWHC was situated between 100 and 150 mm, grapevines proved to be more sensitive to water deficits than those in sites with a large reservoir. Stress was high in mid-August (DOY 225), then became again during berry ripening. Finally, stress levels in sites with small water reserves (SWHC < 100 mm) were moderate early in the growth season (beginning of June, DOY 155) and high during the months of July and August. On sites with highly restricted water reserves, falling leaves were observed in the zone around clusters.

b -Stem water potential measurements (ψ_{stem})

The ψ_{stem} measurements which were recorded during the hottest time of day systematically gave more negative values in grapevines planted in low SWHC soils at Bonvillars (Table 3). This measuring technique enabled highlighting variations in water supply to the vines during periods of highest evaporative demand, and this at a point in the growth cycle when no water stress had yet been noted from ψ_{PD} measurements. The first signs of falling leaves (yellowing leaves at the base of the foliage) were observed when ψ_{stem} values were close to -1,1 MPa. These results are in line with observations made by CHONÉ (2001) and CHONÉ *et al.* (2001).

The daily evolution of ψ_{stem} reflected the overall water stress levels observed by ψ_{PD} measurements from four sites representing different SWHC values (Fig. 3). The extremely low ψ_{stem} recorded late afternoon on a very low SWHC site suggest to a decrease in water availability from the soil and a sharp increase in hydraulic resistances

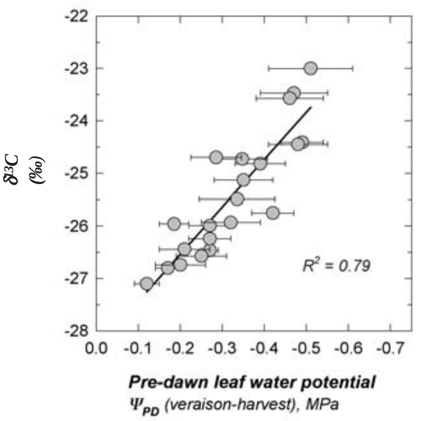

Figure 5 - Relationship between the C isotopic ratio (ψ13C) in must sugars at grape harvesting and (ψPD) measurements taken during the period between ripening and harvesting over a network including 21 sites.
Horizontal bars : standard error ψ_{PD}. Chasselas, Canton of Vaud (CH), 2003.

to water transfer from the soil to leaves. A loss in hydraulic conductivity and a progressive decrease in leaf stomatal conductance would explain the lower daily values of transpiration and water potential gradient between the stem and leaves ($\Delta\psi$) in the site with the lowest SHCW in comparison to other two sites. Furthermore, a relationship between the state of xylem water tension and cavitation has been shown to exist in various studies. In grapevine, the formation of an embolism has frequently been suspected during times of severe water stress which would then lead to, among other things, a cessation of apex growth and initial signs of defoliation (SCHULTZ and MATTHEWS, 1988).

A linear relationship between ψ_{PD} and ψ_{stem} (Fig. 4) has been shown to exist from observations made in the present study on different sites between the years 2001-2003. As far as the ψstem measurements are concerned, this relationship was established under well-defined and comparable climatic conditions between the sites (air temperatures between 25 and 32 °C, relative air humidity between 35 and 50 %, PAR > 1200 PPFD, PET between 4.5 and 5.5 mm/day). Additional observations, however, would prove to be necessary in order to establish the influence of plant variety and pedoclimate on this relationship.

3 - Carbon isotopic discrimination δ13C)

Figure 5 illustrates a close correlation between carbon isotopic discrimination ($\delta^{13}C$) in grape sugars at harvest and plant hydraulics observed in vine during ripening (mean ψ_{PD} of five measurements). Observations made by several authors (GAUDILLÈRE *et al.*, 2002; TREOGAT *et al.*, 2002; VAN LEEUWEN *et al.*, 2001) are confirmed in all aspects by the present results. In addition, a relationship between ψ_{stem} and the ratio $\delta^{13}C$ was established (data not shown). It is nevertheless important that investigations continue so that this indicator can be proved reliable for different vine varieties and under varying pedoclimatic conditions.

4. Transpirable soil water model

In order to test the pertinence and validity of the present methodology, a transpirable soil water model (RIOU and PAYAN, 2001; LEBON *et al.*, 2003) was run on various sites (Fig. 6). The model parameters utilise the vine as an indicator of the environment's water availability through the ψ_{PD} measurements. In figure 6, the evolution over the growing season of the fraction of transpirable soil water (FTSW) is presented from ten sites

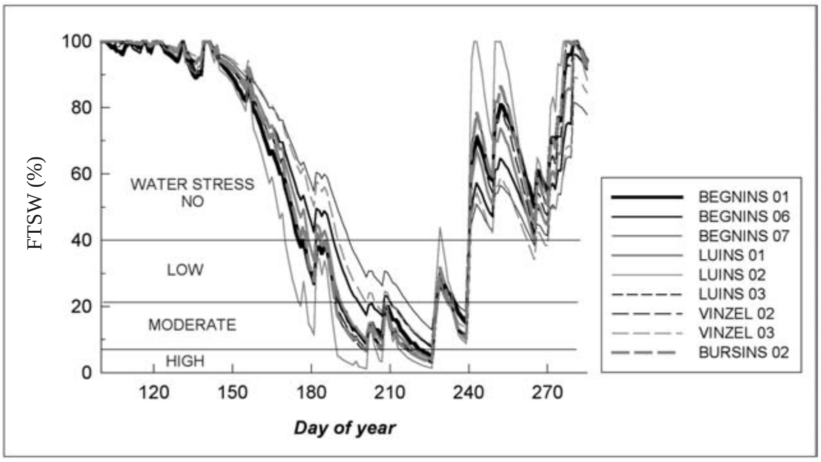

Figure 6 - Evolution of FTSW (fraction of transpirable soil water) over the 2003 growing season from various experimental sites according to water balance model proposed by RIOU and PAYAN (2001) and LEBON *et al.* (2003). Chasselas, La Côte (CH), 2003.

in La Côte. The advantage of this water assessment model lies in being able to discriminate levels of water stress by means of its three components, namely, precocity, duration and intensity.

Estimations of TTSW (total of transpirable soil water) were made by combining the water model with ψ_{PD} measurements, and then compared with SWHC measurements provided by pedologists (LETESSIER and FERMOND, 2004). Initial results gave good agreement between SWHC estimations and the TTSW values obtained from the 2003 season's simulation (R^2 = 0.68), as well as from the 2001-2003 mean seasonal values (R^2 = 0.80) (Table 4). In general, the TTSW values were slightly higher than the SWHC estimations. These preliminary observations are encouraging. Improvement of the model is envisaged by further taking into account transpiration of intercalary vegetation and water flux by streaming, for example, which would increase the reliability of this diagnostic tool for water stress.

CONCLUSION

A close relationship was observed between vine hydraulics estimated by pre-dawn leaf water potential or stem water potential and soil water holding capacity on different sites in the canton of Vaud (Switzerland). The carbon isotope discrimination in grape sugars was correlated to vine hydraulics during the ripening period. The assessment of the total transpirable soil water estimated by combining the model with values of pre-dawn leaf water potential according to LEBON *et al.* (2003) was in good agreement with estimation of the soil water holding capacity in our study.

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BIBLIOGRAPHY

AVICE J., OURRY A., LEMAIRE G. and BOUCAUD J., 1996. Nitrogen and carbon flows estimated by ^{15}N and ^{15}C pulse-chase labeling regrowth of alfafa. *Plant physiol*., **112**, 281-290.

CARBONNEAU A., 1998. Irrigation, vignoble et produits de la vigne. Chapitre IV, *In Traité d'irrigation*, Jean-Robert Tiercelin. Editions TEC DOC Lavoisier, Paris, 257-276.

CHONÉ X., 2001. Contribution à l'étude des terroirs de Bordeaux : Étude des déficits hydriques modérés, de l'alimentation en azote et de leurs effets sur le potentiel aromatique des raisins de *Vitis vinifera* L. cv. Sauvignon blanc. *Thèse de Doctorat* de l'Université de Bordeaux 2. 188 p.

CHONÉ X., VAN LEEUWEN C., DUBOURDIEU D. and GAUDILLÈRE J.-P., 2001. Stem water potential is a sensitive indicator for grapevine water status. *Annals of Botany*, **87**, n° 4, 477-483.

DELOIRE A., VAUDOUR E., CAREY V., BONNARDOT V. and VAN LEEUWEN C., 2005. Grapevine responses to terroir : a global approach. *J. Int. Sci. Vigne Vin*, **39**, n° 4, 149-162.

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**, n° 369, 757-763.

LEBON E., DUMAS V., PIERI Ph. and SCHULTZ H.-R., 2003. Modelling the seasonal dynamics of the soil water balance of vineyards. CSIRO Publishing. *Functional Plant Biology*, **30**, 699-710.

LETESSIER I. and FERMOND C., 2004. Étude des terroirs viticoles vaudois (Suisse), Géo-pédologie. Zone pilote de La Côte : Appellations Bursinel, Vinzel, Luins et Begnins. Rapports SIGALES, Études de sols et de terroirs, Letessier-Fermond, 38410 St Martin d'Uriage, 70 p.

MORLAT R., 1989. Le terroir viticole : contribution à l'étude de sa caractérisation et de son influence sur les vins. Application aux vignobles rouges de la moyenne vallée de la Loire. *Thèse Doct. État*, Bordeaux II, texte 289 p. + annexes.

RIOU C. and PAYAN J.C., 2001. Outils de gestion de l'eau en vignoble méditerranéen. Application du bilan hydrique au diagnostic du stress hydrique de la vigne. *C.R. GESCO. 12e journées*, Montpellier 3 au 7 juillet 2001, 125- 133.

SCHOLANDER P.F., HAMMEL H.T., BRADSTREET E.D. and HEMMINGZEN E.A., 1965. Sap Pressure in Vascular *Plants. Sci*., *148*, 339-346.

SCHULTZ H.-R. and MATTHEWS M.A., 1988. Resistance to water transport in shoots of *Vitis vinifera* L. *Plant physiology*, **88**, 718-724.

SEGUIN G., 1970. Les sols viticoles du Haut Médoc. Influence sur l'alimentation en eau de la vigne et sur la maturation du raisin. *Thèse de doctorat*, Université de Bordeaux, institut d'œnologie, 141 p.

TREGOAT O., GAUDILLÈRE J.-P., CHONÉ X. et VAN LEEUWEN C., 2002. Étude du régime hydrique et de la nutrition azotée de la vigne par des indicateurs physiologiques. Influence sur le comportement de la vigne et la maturation du raisin (*Vitis vinifera* L. cv. Merlot, 2000, Bordeaux). *J. Int. Sci. Vigne Vin*, **36**, n° 3, 133-142.

VAN LEEUWEN C., 1991. Le vignoble de Saint-Émilion : Répartition des sols et fonctionnement hydrique, incidences sur le comportement de la vigne et la maturation du raisin. *Thèse Doct. Nouveau régime*, Université Bordeaux II, 154 p.

VAN LEEUWEN C., GAUDILLÈRE J.-P. and TRÉGOAT O., 2001. L'évaluation du régime hydrique de la vigne à partir du rapport isotopique 13C/12C. L'intérêt de sa mesure sur les sucres du moût à maturité. *J. Int. Sci. Vigne Vin*, **35**, n°4, 195-205.

ZUFFEREY V. and MURISIER F., 2004a. Étude des terroirs viticoles vaudois. *Comportement de la vigne en fonction des conditions pédo-climatiques. Rapport final*. Agroscope RAC Changins, Centre viticole du Caudoz, CH-1009 Pully, 221 p.

ZUFFEREY V. and MURISIER F., 2004b. Étude des terroirs viticoles vaudois. 4. Comportement physiologique et agronomique de la vigne. *Rev. suisse Vitic. Arboric. Hortic*., **36** (4), 14-20.