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?

C. VAN LEEUWEN[1]*, O. TREGOAT[2], X. CHONÉ[3],
B. BOIS[4], D. PERNET[5] and J.-P. GAUDILLÈRE[6]

1: ENITA de Bordeaux, UMR EGFV, ISVV,
1 cours du Général de Gaulle, CS 40201, 33175 Gradignan cedex, France
2: Consultant viticulture, 11 rue William et Catherine Booth, 34500 Béziers, France
3: Consultant viticulture, 5 rue Eugène Delacroix, 33150 Cenon Bordeaux, France
4: Centre de Recherches en Climatologie, UMR 5210, CNRS
Université de Bourgogne, 6, boulevard Gabriel, 21000 Dijon, France
5: SOVIVINS, Site Montesquieu, 4 allée Isaac Newton, 33650 Martillac, France
6: INRA Centre de Bordeaux, BP 81, 33883 Villenave d'Ornon cedex, France

Abstract

Aims: The impact of water deficit stress on vine shoot growth, berry weight, grape composition and overall vintage quality was investigated in Bordeaux vineyards. Methods for assessing water deficit stress were compared.

Methods and results: Vine water status was assessed on three soil types during four vintages by means of stem water potential and carbon isotope discrimination measured on grape sugar. Regional water deficit was compared for a range of over 30 vintages by means of water balance modelling. It was shown that water deficit stress anticipated shoot growth slackening, limited berry weight and enhanced berry anthocyanin content. Berry sugar content was greatest when water deficit was mild. It was shown that stem water potential measurements and carbon isotope discrimination are accurate tools for assessing vine water status at plot scale. Seasonal water deficit at a regional scale can be correctly estimated by water balance models. Vintage quality in Bordeaux is determined by the intensity of water deficit stress rather than by the level of the temperatures.

Conclusions: Vine phenology and grape ripening are highly dependent on water uptake conditions. Mild water deficit stress enhances grape quality for the production of red wines. Vine water status can accurately be assessed by means of stem water potential or carbon isotope discrimination measured on grape sugars. Quality losses through severe water stress can be avoided through the use of drought-adapted plant material, appropriate canopy management, yield reduction or the implementation of deficit irrigation.

Significance and impact of the study: This study shows the key role of water deficits in the production of quality grapes for red wine production. Methods for assessing vine water status are compared and discussed. Among many existing methods, the accuracy of stem water potential, carbon isotope discrimination measured on grape sugar and water balance modelling are emphasized.

Key words: water status, water deficit stress, vine, grape, water potential, water balance, carbon isotope discrimination, ripening speed, irrigation

Résumé

Objectifs : L'incidence d'un déficit hydrique de la vigne sur la croissance des rameaux, le poids des baies, la composition du raisin à maturité et la qualité globale du millésime a été évaluée dans le vignoble de Bordeaux. Différentes méthodes pour mesurer le déficit hydrique de la vigne ont été comparées.

Méthodes et résultats : L'état hydrique de la vigne a été mesuré sur trois sols pendant quatre millésimes à l'aide du potentiel tige et de la discrimination isotopique du ^{13}C mesurée sur le sucre du moût. À l'échelle régionale, le déficit hydrique climatique a été comparé pour 30 millésimes par l'établissement d'un bilan hydrique. Il a été montré que le déficit hydrique provoque l'arrêt de croissance des rameaux, limite le poids des baies et augmente la teneur en anthocyanes des raisins. La teneur en sucre du raisin est le plus élevée lorsque le déficit hydrique est modéré. Le potentiel tige et la discrimination isotopique du ^{13}C mesurée sur les sucres du moût sont des indicateurs pertinents de l'état hydrique de la vigne à l'échelle parcellaire. Le déficit hydrique cumulé au cours de la saison d'une région peut être estimé à l'aide d'un bilan hydrique. La qualité du millésime à Bordeaux est davantage déterminée par l'intensité du déficit hydrique que par le niveau de températures.

Conclusions : La phénologie de la vigne et la maturation du raisin dépendent fortement de l'état hydrique de la vigne. Un déficit hydrique modéré augmente le potentiel qualitatif de raisins noirs pour la production de vins rouges de garde. L'état hydrique de la vigne peut être évalué avec pertinence à l'aide de la mesure du potentiel tige et de la discrimination isotopique du ^{13}C mesurée sur les sucres du moût à maturité. Les pertes de qualité par un déficit hydrique excessif peuvent être évitées par l'utilisation de matériel végétal et des systèmes de conduite adaptés ainsi que par une diminution du rendement. Lorsque cela n'est pas suffisant, l'irrigation peut également être envisagée, mais les apports d'eau ne doivent pas annuler le déficit hydrique.

Signification et importance de l'étude : Cette étude montre le rôle déterminant du déficit hydrique dans la production de vins rouges de qualité. Des méthodes pour évaluer l'état hydrique de la vigne sont comparées et discutées. Parmi les nombreuses méthodes qui existent, l'intérêt du potentiel tige, de la mesure de la discrimination isotopique du ^{13}C sur les sucres du moût et du calcul du bilan hydrique est souligné.

Mots clés : état hydrique, déficit hydrique, vigne, raisin, potentiel hydrique, bilan hydrique, discrimination isotopique du carbone, vitesse de maturation, irrigation

manuscript received the 17th of November 2008 - revised manuscript received the19th of August 2009

*Corresponding author: k-van-leeuwen@enitab.fr

INTRODUCTION

Unlike most plant crops, especially annuals, wine grape cultivars are often grown best under sub-optimal conditions. Historically, and particularly so in the Old World, farmers preferred to use fertile land for grazing livestock and growing annual crops. Shallow soils, stony soils and steep slopes were dedicated to vineyards or olive tree plantations (van Leeuwen and Seguin, 2006). It is acknowledged that a range of environmental constraints may restrict vigour and yield and thereby enhance the winemaking potential of the grape (Coipel *et al.*, 2006; van Leeuwen *et al.*, 2007). Of all these constraints, it is the restriction of water supply that plays the most significant role in vine behaviour and berry composition. A limitation in vine water uptake reduces shoot growth, berry weight and yield and increases berry anthocyanin and tannin content (Hardie and Considine, 1976; Matthews and Anderson, 1988; Matthews and Anderson, 1989; van Leeuwen and Seguin, 1994; Koundouras *et al.*, 2006). These effects are favourable to grape quality potential, particularly so in red wine production (Ribéreau-Gayon *et al.*, 1998). The effect of water deficit stress on berry sugar content is yield-dependent; for low yields, vine water deficit enhances berry sugar content and for high yields, it depresses berry sugar content (Tregoat *et al.*, 2002). In temperate climates, water deficit conditions are necessary to produce high quality red wine (Seguin, 1986). However, excessive water deficit stress may lead to yield and quality losses (Ojeda *et al.*, 2002). Vine water status is dependant on soil and climate characteristics (van Leeuwen *et al.*, 2004). Soil influences vine water status through its water-holding capacity. Climate acts on vine water status through rainfall and Reference Crop Evapotranspiration (ETo). Vines can be dry farmed or irrigated. Full irrigation increases yield but is detrimental for quality. Deficit irrigation strategies have been developed to produce high quality wines while limiting yield losses through severe water stress (Dry *et al.*, 2001). Deficit irrigation also allows increasing water use efficiency, compared to full irrigation.

Vine water uptake conditions can be assessed through (i) soil water monitoring by means of tensiometers (Nadal and Arola, 1995), watermark probes (Hanson *et al.*, 2000), neutron moisture probes (Seguin, 1986) or Time Domain Reflectometry (Koundouras *et al.*, 1999), (ii) water balance modelling (Lebon *et al.*, 2003; Pellegrino *et al.*, 2006), or (iii) the use of physiological indicators (van Leeuwen *et al.*, 2001a; Jones, 2004; Cifre *et al.*, 2005). Among physiological indicators, two are particularly accurate and useful: stem water potential (Choné *et al.*, 2001a) and the $^{13}C/^{12}C$ ratio ($\delta^{13}C$ or carbon isotope discrimination) measured on grape sugar at ripeness (van Leeuwen *et al.*, 2001b; Gaudillère *et al.*, 2002).

In this article, precise data are presented about the impact of water status on vine development, yield parameters, grape ripening and vintage quality. Methods for assessing vine water uptake conditions and possible applications for water management in vineyards are discussed. Threshold values for water deficit stress levels are proposed. Vine water status has implications on yield and quality parameters and is therefore essential to the economics of vineyard management. Grape growers tend to focus on yields while grape buyers tend to focus on quality parameters. Hence, an accurate and easy-to-implement tool for assessing vine water status can clarify relations between grape growers and buyers in the wine industry.

MATERIALS AND METHODS

1. Experimental plots

Three experimental plots planted with *Vitis vinifera* cv. Merlot were chosen among existing dry-farmed blocks in a commercial vineyard in the Saint-Émilion region (44°56'N; 0°11'W). Soils and vine-rooting profiles were characterized by means of a soil pit study. Soil texture was gravelly (G), sandy (S) and clayey (C). The sandy soil had a water table within the reach of the roots. Soil water-holding capacities were highly variable among plots, so as to create a large range of vine water uptake conditions. The maximum distance between the experimental sites was 500 meters, on flat terrain, so that climate conditions can be considered identical. Rootstock was 3309C. Vines were Guyot pruned and trained with a vertical shoot positioned trellis, with two fixed and two movable wires. Vine density was 6000 vines/ha. The study covers the period 2004 – 2007.

2. Climate conditions

Temperature and rainfall data were collected by an automatic weather station in Saint-Émilion (Bordeaux area), and compared to 1970-1999 averages.

3. Vine water status

Vine water status was assessed with the pressure chamber technique (Scholander *et al.*, 1965) and by means of carbon isotope discrimination measured on grape sugar at ripeness (Gaudillère *et al.*, 2002).

Stem water potential (Choné *et al.*, 2001a) was measured with a pressure chamber several times during the season on leaves covered with an opaque plastic bag one hour prior to measurement. Each measurement was replicated 6 times, on 6 individual vines.

Stable isotope ratio in carbon ($^{13}C/^{12}C$) is modified by photosynthesis: ^{12}C is preferentially picked up by the enzymes involved in photosynthesis (Farquhar *et al.*, 1989). This process is called « isotope discrimination », because ^{12}C is preferred over ^{13}C. In water stress conditions, this discrimination is less severe and sugars produced contain more ^{13}C compared to those produced when plant water status is not limiting. Hence, an index called $\delta^{13}C$, based upon $^{13}C/^{12}C$ ratio in grape sugar, can be used as an integrative indicator of water deficit experienced by vine during grape ripening. $^{13}C/^{12}C$ ratio is expressed compared to a standard and ranges from -27 p. 1000 (no water deficit) to -20 p. 1000 (severe water deficit stress, van Leeuwen *et al.*, 2001b). For each plot, $\delta^{13}C$ measurements were carried out on 4 individual samples of grape juice at harvest by mass spectrometry.

4. Modelling of the water deficit of a vintage

In order to assess the water uptake conditions of a range of vintages in Bordeaux, average Water Deficit Stress Index (WDSI) between véraison and ripeness was calculated with the model published by Pieri and Gaudillère (2005). This model is based on a previous model of seasonal dynamics of soil water balance in vineyards (Lebon *et al.*, 2003) to which a non-linear function is added to account for the stomatal regulation. A Total Transpirable Soil Water (TTSW) content at field capacity of 200 mm was used, which corresponds to an average value for Bordeaux soils. The WDSI calculated by the model ranges between 0 (severe water deficit stress, i.e. stomata permanently closed) and 1 (no water deficit stress, i.e. no stomatal limitation).

5. Shoot growth slackening

Once every week, 50 apexes were sampled randomly on lateral shoots inside the canopy. Growth slackening was considered to have occurred when 50% or more of the apexes completely stopped their growth.

6. Yield parameters

Grape load was determined on 20 vines per plot so as to obtain the average yield per vine. Four replicates of eight hundred berries were sampled on each plot at harvest time and weighed to determine individual berry weight.

7. Leaf area

A correlation was established every year between the length of shoots and the leaf area they carried, for primary and secondary shoots, according to Mabrouk and Carbonneau (1996). Then, the length of all the shoots was measured for 10 vines on each plot. Leaf area was deduced from the previously established correlation.

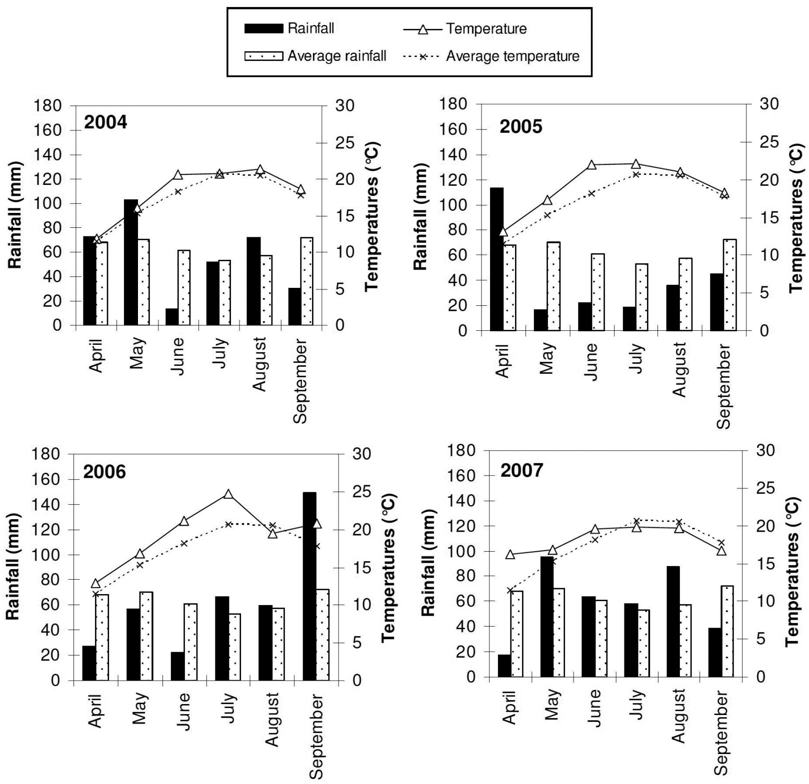

Figure 1 - Monthly temperatures and rainfall in Saint-Émilion (Bordeaux) in 2004, 2005, 2006 and 2007.
The average values correspond to the 30 years period 1970-1999.

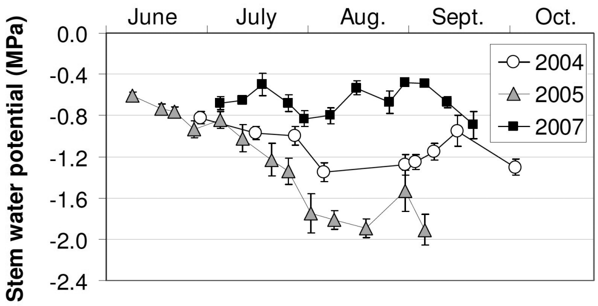

Figure 2 - Comparison of seasonal stem water potential on a gravelly soil in the Saint-Emilion region in three vintages (*Vitis vinifera* L. cv. Merlot, Bordeaux).
The error bars indicate the standard deviation of measurements.

8. Grape composition at ripeness

Grapes were considered ripe for the production of high quality red table wine when the technical staff of the commercial vineyard decided to harvest (generally at 13% potential alcohol). Harvest took place between 44 and 53 days after mid-véraison, depending on the year. Four replicates of eight hundred berries were sampled at ripeness and pressed at 0.5 MPa in a pneumatic laboratory press (BELLOT, 33170 Gradignan, France). Grape sugar was measured with a portable refractometer. Total acidity was measured by titrimetry. Malic acid was analyzed using an enzymatic kit (Bohringer, Mannheim, RFA; expressed in g.L^{-1}).

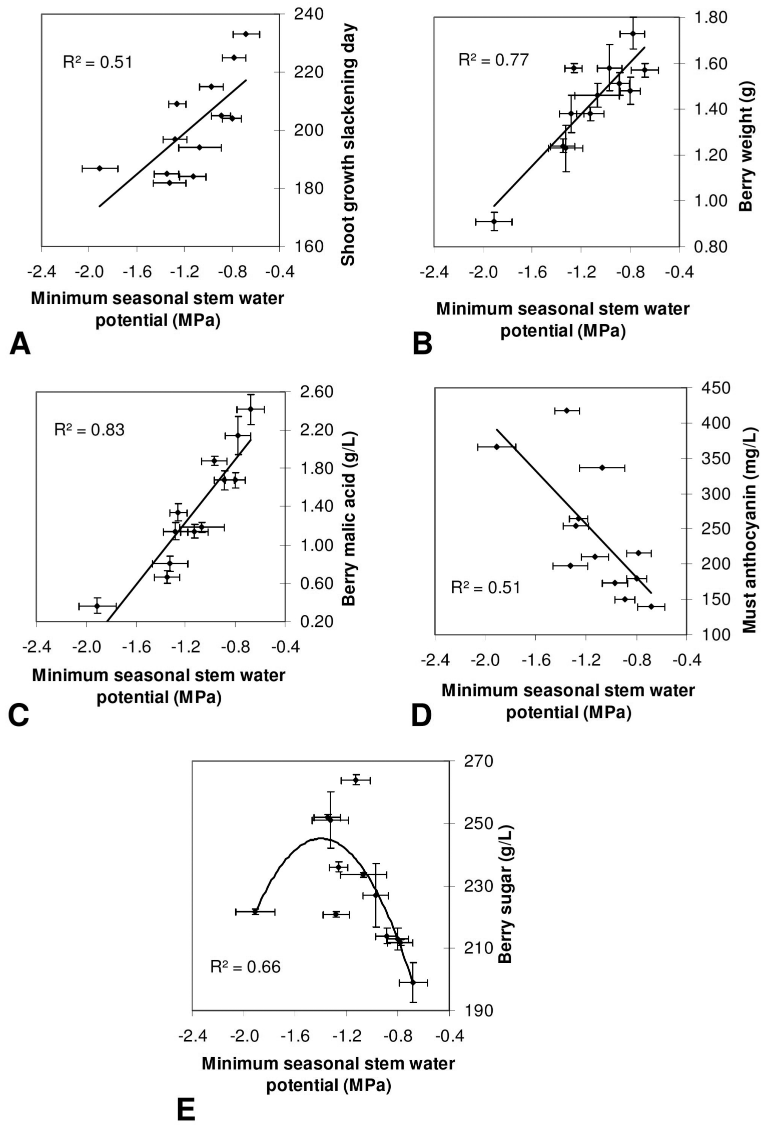

Figure 3 - Correlation between the intensity of vine water stress, assessed by the minimum seasonal stem water potential value, and several grapevine physiological characteristics: A: the date 50% of the shoot tips stopped growing; B: berry weight at ripeness; C: berry malic acid content at ripeness, D: must anthocyanin content at ripeness; E: berry sugar content at ripeness (*Vitis vinifera* L. cv. Merlot, 2004-2007, Bordeaux).
The error bars indicate the standard deviation of measurements.

9. Anthocyanin composition at ripeness

Four replicates of two hundred berries were sampled at ripeness and mixed during 2 minutes in a fruit mixer. Fifty mL of juice were centrifuged at 3500 rotations per minute during 10 minutes. Juice was diluted 50 times in a 1% HCl solution (A) and in purified water (B). Optic Density (OD) was measured at 520 nm through 1 cm. Anthocyanin content was obtained by the formula: Anthocyanin (mg/L) = OD520 (A-B) * 22.76 * 50 (Ribéreau-Gayon *et al.*, 1998).

RESULTS AND DISCUSSION

1. Climate conditions

Climatic conditions varied considerably during the four vintages studied (Figure 1). The year 2004 was slightly warmer and slightly drier than average, while 2005 was warm and exceptionally dry. The year 2006 was dry, except for September which was very rainy, and warm, except for August, which was cool. The 2007 vintage was cool and wet, after a dry and warm month of April.

2. Effect of vine water status on vine growth, yield and grape ripening

Water deficit stress may occur more or less rapidly, depending on the climatic conditions of the year, as shown by the development of stem water potential in the 2004, 2005 and 2007 vintages in the Saint-Émilion region (Figure 2). On the three soils and during the four vintages, shoot growth slackening was related to the intensity of water deficit stress (Figure 3A) and so was berry enlargement. Berry weight was reduced by as much as 50% in water stress conditions (Figure 3B). Grapes contained less malic acid (Figure 3C) and more anthocyanin (Figure 3D) when vines faced water deficit. The highest sugar level was reached when water deficit was mild (Figure 3E).

The occurrence of water deficit stress during the season has a profound effect on the physiological functioning of the vine. Water deficit will cause the stomata to close for a part of the day (Hsiao, 1973). This adjustment by the stomata restricts photosynthesis. Hence, dry matter production is reduced and yield is negatively affected. When roots are present in drying soils, they produce abscisic acid (Stoll *et al.*, 2000). This hormone promotes grape ripening. Hence, vine water restriction has a negative effect on the maturation of the grape (it restricts photosynthesis) and several positive effects (production of abscisic acid, restriction of competition for carbon substances by the shoot tips, smaller berry size). When the water deficit is mild, the positive effects outweigh the negative; grapes contain less malic acid and are higher in sugar, anthocyanin and tannin contents (van Leeuwen and Seguin, 1994; Trégoat *et al.*, 2002). When water stress is excessive, photosynthesis is overly restricted and fruit ripening may be delayed, particularly when the yield is high.

When the water supply is moderately restricted, it improves the quality of red wines by causing the grapes to achieve optimal sugar levels. When the water supply is not restricted at all, grape sugar levels are lower for two reasons: (i) due to competition for carbon between berry ripening and shoot growth and (ii) increased berry size (dilution of sugar in a greater berry volume). When water deficit is severe, grape sugar content is depressed due to limited photosynthesis. Anthocyanin content increases in a linear manner with water deficit stress (Figure 3D). The quality of a red wine depends more on its level of phenolic compounds (anthocyanins and tannins) than on sugar levels in the grape at maturity. Therefore, the winemaking potential of red grapes can still be excellent even if a severe water deficit slightly limits the amount of sugar in the must.

3. Effects of water deficit and soil characteristics on the timing of grape ripening

The moment at which grapes attain ripeness depends both on the precociousness of the phenological cycle (which may be assessed by the date of mid-véraison), and the ripening speed, which can be calculated according to the method published by Duteau (1990). The precociousness of the budding depends on air and soil temperatures (Morlat, 1989). Soil temperature is directly related to soil water content. Hence, budding, as well as the occurence of the following phenological stages, is delayed on wet soils. The grape ripening speed is largely determined by the water status of the vine (van Leeuwen and Seguin, 1994). Moderate water deficit encourages rapid ripening while it restricts the size of the berries (and thus the volume to be filled with sugars). It also reduces competition for carbohydrates between the berries and the shoots, allowing a greater percentage of the sugars produced by photosynthesis to be available for grape ripening (Lebon *et al.*, 2006).

Figure 4 shows an example of the effect of water uptake conditions on the ripening speed (as a function of temperature sum base of 10 °C, also referred to as « Growing Degree Days » by Winkler *et al.*, 1974). Vines were low yielding (<1.5 kg/vine) and source/sink ratio was not limiting (2.21 m^2 leaves/kg of fruit on the gravelly soil, 1.70 m^2 leaves/kg of fruit on the sandy soil and 1.57 m^2 leaves/kg of fruit on the clayey soil). The vines were affected by water deficit stress in the gravelly soil (minimum seasonal predawn leaf water potential -0.53 MPa; minimal seasonal stem water potential -1.60 MPa) and the clayey soil (minimum seasonal

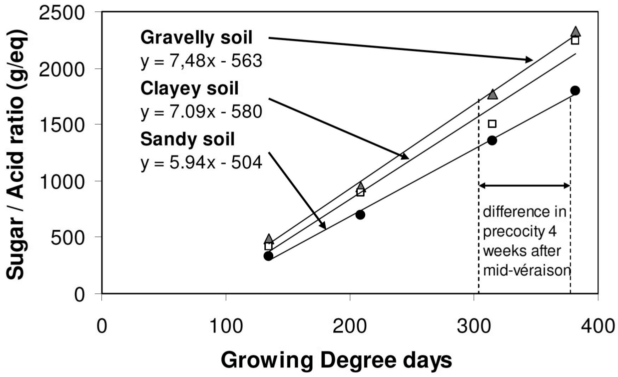

Figure 4 - Ripening speed on three soils of the Saint-Émilion region (*Vitis vinifera* L. cv. Merlot, 2001 vintage).
Sum of active temperatures (i.e. sum of each daily Celsius degrees over 10 °C) are expressed in degree.days (° days).

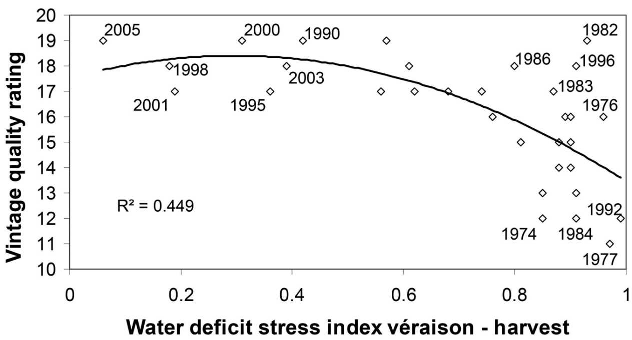

Figure 5 - Relationship between vintage quality rating and water deficit stress index (WDSI) for the period mid-véraison - ripeness.
WDSI = 1 means no water deficit stress;
WDSI = 0 means maximum water deficit stress.

predawn leaf water potential -0.58 MPa; minimal seasonal stem water potential -1.31 MPa), but not on the sandy soil (minimum seasonal predawn leaf water potential -0.24 MPa; minimal seasonal stem water potential -1.14 MPa). Berries ripened quicker (according to sugar/acid ratio of the pulp, figure 4) in the blocks that were subject to water deficit stress (gravelly soil and clayey soil). In the sandy soil, with a water table within reach of the roots the pulp ripened slowly. Despite each of these blocks having very close dates for mid-véraison (August 10 for the gravelly soil and August 11 for both the clayey soil and the sandy soil), similar « sugar / acid » ratios were reached about 8 days earlier (70 Growing Degree Days) on the gravelly soil than the sandy soil after four weeks of ripening.

4. Water deficit stress and vintage quality in Bordeaux

In order to assess vineyard water availability of 32 vintages in Bordeaux (1974 – 2005), average Water Deficit Stress Index (WDSI) between véraison and ripeness was calculated by the model published by Pieri and Gaudillère (2005). The WDSI calculated by the model ranges between 0 (severe water deficit stress, i.e. stomata permanently closed) and 1 (no water deficit stress, i.e. no stomatal limitation). A correlation between WDSI values and vintage quality ratings by Bordeaux wine brokers Tastet and Lawton (33000 Bordeaux, France) shows that 45% (significant at $\alpha = 0.001$; n = 32) of the quality of red Bordeaux vintages is explained by the intensity of the water deficit stress (Figure 5). Thus, vine water status can be considered an important factor for red wine vintage quality in Bordeaux. Poor quality vintages are without exception wet vintages: 1974, WDSI = 0.85; 1977, WDSI = 0.97; 1984, WDSI = 0.91; 1992, WDSI = 0.99. Vintages where the vines were subjected to moderate to severe water deficit stress correspond without exception to very good or great vintages: 1990, WDSI = 0.42; 1995, WDSI = 0.35; 1998: WDSI = 0.18; 2000, WDSI = 0.31; 2001, WDSI = 0.19; 2003, WDSI = 0.39; 2005, WDSI = 0.05. In not one vintage during these 32 years has the overall quality of wine suffered due to excessive water deficit stress in Bordeaux. Even if during a dry summer excessive water deficit stress might have occurred on some blocks with negative consequences on the wine quality (particularly in blocks with young vines with superficial root systems), the overall quality of the vintage did not suffer.

Temperature is a less decisive factor on vintage quality in Bordeaux than water deficit stress. During the period 1974 - 2005, vintage ratings are neither well-correlated to the sum of active temperatures ($R^2 = 0.20$, data not shown), nor with the average growing season temperature (April – October, $R^2 = 0.26$, data not shown). Although some very warm vintages produced high quality red Bordeaux wines (1989, 1990, 2003, 2005), other warm vintages were not outstanding (1994, 1997). Some cool vintages (1978, 1985, 1988, 1996) were among the finest over the last three decades. However, temperature and water deficit stress are not completely independent factors: high net radiation generates high temperatures as well as high Reference Evapotranspiration rates (ETo).

That said, vintage quality in Bordeaux cannot be explained by vine water status alone: some very good vintages, such as 1982, were vintages without significant water deficit.

5. Managing vine water deficits to optimize berry quality

The ideal water uptake conditions for producing high-quality grapes for making red wine corresponds to a moderate water deficit early in the season (before véraison). Early water deficit stress has a greater effect on the reduction of berry size than late water deficit stress

(Becker and Zimmermann, 1984). The winemaking potential of the grape will suffer in the cases of both no water deficit and excessive water stress.

The loss of quality through excessive water deficit stress occurs much less frequently than the loss of quality due to insufficient water deficit, even though the latter consequence is often overlooked. If vines face excessive water deficit stress, berry shrinkage and leaf drop may occur, a consequence that is particularly visible and striking to growers. In the case of unlimited water uptake conditions, berries tend to be large and constituents diluted and though no damage to the vines is visible, the negative impact on grape quality potential can be significant. When summer rainfall and water reserves in the soil prevent a regular occurence of water deficit, it is necessary to increase the leaf area per hectare in order to increase evapotranspiration. This can be achieved in short term by increasing the trimming height and in long term by changing the trellis system (higher posts) or to increase vine density (number vines.ha^{-1}). Another solution is to select a rootstock which only partially uses water reserves of the soil (Riparia Gloire de Montpellier for example). Insufficient water deficit can also be addressed by choosing to plant specific grape varieties (i.e. white varieties or early ripening red varieties, van Leeuwen, 2001).

In situations where a loss of quality occurs in some years due to excessive water deficit stress (i.e. in very dry climates, in soils with low water reserves), it is possible to limit the negative effects on the vine by adapting the training system (i.e. to train the vines as spur-pruned bush vines) and by using appropriate plant material (Choné *et al.*, 2001b). The most effective protection against harmful effects of water stress is yield restriction. A moderate yield per hectare allows a moderately low leaf surface area per hectare without altering the leaf / fruit ratio. Mediterranean bush vines are adapted to arid regions when irrigation is not an option due to water restrictions. Rootstocks mediate vine responses to soil water restrictions through chemical signaling (Soar *et al.*, 2006). Choosing drought-resistant rootstocks (for example 110 Richter) is an efficient and cost-effective way of adaptation to dry conditions. Resistance to drought can also be achieved by choosing varieties adapted to arid regions. Drought resistance is highly variable among cultivars. For example, *Vitis vinifera* cv. Merlot is sensitive to drought, while *Vitis vinifera* cv. Grenache and Carignane are more resistant. Fertilization practices impact drought resistance. Low vine nitrogen status reduces water requirements by limiting vigour and leaf area.

Severe water deficits may compel viticulturists to resort to irrigation, although irrigation is restricted in most high-quality wine producing areas in Europe. Due to increasingly limited water resources and the harmful effects of irrigation on soil quality (salinity), vineyard design for dry farming is recommended over irrigation when possible (i.e. when economically sustainable). However, cultivating vines without irrigation while maintaining economically viable yields is difficult when the annual rainfall is less than 400 mm. This value however needs to be adjusted depending on the distribution of rainfall throughout the year and the soil water-holding capacity. In very dry climates, well-managed irrigation can enhance quality, but poorly conducted irrigation may cause significant losses in grape quality potential. When irrigation is necessary, it should ideally lead the vine progressively into a situation of moderate water deficit while avoiding a situation of excessive water stress (Choné *et al.*, 2001b).

Historically, grapevines are cultivated amidst challenging environmental conditions. The idea of the necessity of a limiting factor in the production of high quality wines is now making its way into irrigation management which strategically reduce water supply to the vines. In the case of Regulated Deficit Irrigation (RDI), water deficit is deliberately provoked in the early part of the season by withholding irrigation with the specific intent of reducing berry size (McCarthy, 1997; Dry *et al.*, 2001). The second method, Partial Rootzone Drying (PRD), draws on an alternating system of irrigation. Approximately every two weeks, each side of a row is alternately irrigated. In this way, half of the root system is always in a zone of the soil which is in the process of drying out. This method produces a positive effect in the winemaking potential of the grape, which may be partially explained by a greater synthesis of abscisic acid compared to vines irrigated without any water deficit stress (Stoll *et al.*, 2000). Another method of deficit irrigation, called « Sustained Deficit Irrigation » (SDI) has also proven to be effective for reducing water use (Fereres and Soriano, 2007).

6. Methods for assessing the water requirements of the vine

Given the importance of water relations in vines on yield and quality parameters, the measurement of vine water status is very important for vineyard management and research in both irrigated and non-irrigated vineyards. Many methods have been developped over the last five decades. Most of them were first implemented on annual crops and then adapted to vineyards. The vine is a perennial crop, which is often cultivated in stony soils, and which may have deep roots (up to several meters). Because of these particularities, some methods that give satisfactory results on annual crops or fruit orchards do not really work well on vines. Hence, one has to be very prudent when choosing a method for monitoring water supply to the vines. Measurements of vine water uptake can be grouped according to three different approaches: (i) measurements of soil water, (ii) water balance modelling or (iii) physiological indicators. Some methods are more suitable for research purposes, others for practical vineyard management.

a. (i) Assessment of soil water

Soil matric potential indicates the availability of soil water. It can be monitored with tensiometers (Nadal and Arola, 1995). Tensiometers are succesfully implemented for irrgation management in annual crops and fruit tree crops. However, this technique has major drawbacks when used in vineyards. A first limitation of this technique is the rooting depth of vines, generally over one meter. Vines explore several soil layers, each of which has its own matric potential. Tensiometers have thus to be installed at several depths. A second technical limitation is the narrow range of soil matric potential that can be measured: from 0 to –70kPa for classic tensiometers. Watermark probes (Hanson *et al.*, 2000) can assess a greater range of soil matric potentials: 0 to –0.2MPa. However, even at –0.2MPa there is almost no limitation in vine water uptake. Tensiometers and watermark probes can thus only be used for vine water status control when water deficit is weak or when there isn't any water deficit stress. Hence, deficit irrigation cannot be managed with these tools.

Vine water consumption can be determined and soil water balance established through regular monitoring of soil volumetric water content. Soil volumetric water content can be measured by means of a neutron moisture probe (Seguin, 1986) or Time Domaine Reflectometry (TDR, Koundouras *et al.*, 1999). Studies using a neutron moisture probe have provided details of vine water uptake in gravely soils (e.g. Haut-Medoc: Seguin, 1975), in clayey soils in Pomerol (Duteau *et al.*, 1981), as well as in the calcareous soils of the limestone plateau at Saint-Émilion (Duteau, 1987). However, the neutron moisture probe has some drawbacks when implemented in vineyards. Water assessments conducted in this way do not take into account water coming in laterally when a water table is present in the soil; run-offs from sloping sites are not taken into account either. Eventually, root development can reach the access tube, which would alter the results (van Leeuwen *et al.*, 2001a). Vine rooting can be very deep and neutron moisture probe readings can only be interpreted when the access tube covers the whole root zone, which is rarely the case. Moreover, the types of soils typically found in vineyards (gravelly, rocky) can make it very difficult to insert the access tube. Neutron moisture probes measure soil water content in a sphere with a diameter of less than 50 cm. Many access tubes per plot are necessary to take spatial soil moisture variations into account. Even if the neutron moisture probe is used in certain countries to control vine irrigation, the unwieldiness of this tool will be an obstacle to its widespread use. The use of TDR probes (Time Domain Reflectometry) for establishing vine water uptake assessments presents similar drawbacks.

b. (ii) Water balance modelling

Water balance modelling is a way to estimate soil water availability (Riou and Lebon, 2000; Lebon *et al.*, 2003; Pieri and Gaudillère, 2005). The idea is to simulate the amount of water remaining in the soil throughout the summer by using data regarding the amount of available water in the soil at the beginning of the season (total transpirable soil water at field capacity). The inputs (rainfall, irrigation) are added to this number and the outputs (crop transpiration, evaporation at soil surface) are subtracted (I):

$$ASW = TTSW + R + I - CT - SE \quad (I)$$

ASW = Available Soil Water (mm)
TTSW = Total Transpirable Soil Water at Field Capacity (mm)
R = Rainfall (mm)
I = Irrigation (mm)
CT = Crop Transpiration (mm)
SE = Soil Evaporation (mm)

Soil water content is most precisely modelled at daily time step, but water balance models can also be run with a time step of a decade or a month. Rainfall can easily be determined by using a weather station. Crop transpiration and soil evaporation can be accurately estimated by using ETo (reference crop evapotranspiration) and rainfall data from a weather station and also from taking canopy size into account. The main problem with the modelling approach is in estimating the total transpirable soil water at field capacity which is extremely difficult due to varying conditions in vine cultivation (rooting depth, amount of stones in the ground, variations in soil texture, variations in soil bulk density, etc.). Hence, application of these models at plot level provides inconsistent results (Pellegrino *et al.*, 2006). However, these models are useful for describing the climatic and plant-related aspects of vine water deficits at a regional scale and they are powerful tools for classifying vintages according to their dryness.

c. (iii) Physiological indicators

Vine water status can also be monitored by the use of physiological indicators (Cifre *et al.*, 2005). These indicators are based on the principle that vine physiology is modified by water deficit. Many physiological indicators have been developed over the last four decades: (1) transpiration (Hsiao, 1973), (2) water potentials (Begg and Turner, 1970), (3) microvariations in stem or berry diameter (Garnier and Berger, 1986; Greenspan *et al.*, 1994; van Leeuwen *et al.*, 2001a), (4) differences between leaf and air temperatures (Jones, 1999), (5) carbon isotope discrimination measured on grape sugars (Farquhar *et al.*, 1989; van Leeuwen *et al.*, 2001b; Gaudillère *et al.*, 2002), (6) sap flow measurement (Escalona *et al.*, 2002) and (7) growth parameters (Pellegrino *et al.*, 2005). Among these accurate physiological indicators, two are practical tools for determining vine water status: stem water potential and carbon isotope discrimination measured on grape sugars.

Predawn, leaf and stem water potentials

Water potentials in vascular plants can be measured by means of a pressure chamber (Scholander *et al.*, 1965). These potentials are generally measured on leaves. The pressure chamber technique is applied to: (i) leaf water potential, (ii) pre-dawn leaf water potential and (iii) stem water potential. The range of midday leaf water potential values, pre-dawn leaf water potential values and midday stem water potential values with regard to vine water deficit are presented in table 1. However, these values are average thresholds which may vary from block to block depending on root distribution, vine vigour and yield.

Leaf water potential can be measured during the course of the day. The more negative the water potential in the leaf, the greater the water deficit in the vine. Leaf water potential reaches a minimum in the early afternoon and it is this time of day that is generally chosen for comparing measurements. Although it has been shown that leaf water potential varies with vine water status, it is also highly variable depending on the microclimatic environment of each particular leaf (Jones, 2004). Moreover, vines may have an isohydric behaviour (Schultz, 2003) and they limit variations in water potential of their leaves by stomatal regulation. For these two reasons, midday leaf water potential is not the most accurate indicator of vine water status.

When water potential is measured on leaves at the end of the night (so-called pre-dawn leaf water potential), microclimatic conditions are homogeneous among leaves and vines are not transpiring. At this time of day, each single leaf of a vine has a similar water potential. This water potential is in equilibrium with the most humid soil layer explored by the root system. Although pre-dawn leaf water potential better represents vine water status in relation to soil water availability than midday leaf water potential does, it underestimates water deficits when soil water is heterogeneous (Améglio *et al.*, 1999). For a given level of pre-dawn leaf water potential, vines will be more subject to water deficit stress during the day when soil water content is heterogeneous. A small humid soil layer might be able to rehydrate a vine overnight (with pre-dawn leaf water potential values close to zero), but might not be able to provide enough water to the vine during the day to meet evaporative demand, particularly when the canopy is large. This is typically the case with regard to irrigated vines and therefore, pre-dawn leaf water potential is not an accurate indicator of vine water status for irrigation management (Améglio *et al.*, 1999).

Stem water potential is measured during the day on a leaf that is bagged with an opaque plastic bag at least one hour prior to measurement (Begg and Turner, 1970). The opaque bag prevents the leaf from transpiring. During the hour between bagging and taking the water potential measurement, the water potential in the leaf balances with the water potential in the stem xylem. Although the measurement is carried out on a single leaf, the obtained value represents whole vine water potential. Hence, when measurements are carried out on several leaves of the same vine, the coefficient of variation (%) of stem water potential is consistently lower compared to pre-dawn leaf water potentials or leaf water potentials (van Leeuwen *et al.*, 2007). Stem water potential values reach a minimum in the early afternoon. This moment is generally chosen for comparing measurements among sites. Stem water potential values reflect soil water availability, but they also depend on climatic parameters. Any comparisons of soil water availability through stem water potential readings should therefore be carried out in similar climatic conditions, for example on sunny days without extreme temperatures. Stem water potential is consistently well-

Table 1 - Water potential and $\delta^{13}C$ values with respect to vine water deficit thresholds

	Midday Stem Water Potential (MPa)	Midday Leaf Water Potential (MPa)	Pre-dawn Leaf Water Potential (MPa)	$\delta^{13}C$
No water deficit	> -0.6	> -0.9	> -0.2	< -26
Weak water deficit	-0.6 to -0.9	-0.9 to -1.1	-0.2 to -0.3	-24.5 to -26
Moderate to weak water deficit	-0.9 to -1.1	-1.1 to -1.3	-0.3 to -0.5	-23 to -24.5
Moderate to severe water deficit	-1.1 to -1.4	-1.3 to -1.4	-0.5 to -0.8	-21.5 to -23
Severe water deficit	< -1.4	< -1.4	< -0.8	> -21.5

correlated to vine transpiration which is not always the case for midday leaf water potential (Choné *et al.*, 2001a). Stem water potential is closely related to other physiological parameters of the plant (McCutchan and Shackel, 1992).

Because stem water potential represents whole vine water status during the day, it is a particularly useful tool for irrigation management. It accurately represents vine water status, even if soil water content is heterogeneous, which is the case in irrigated vineyards (Shackel, 2006). It can also be used in dry-farmed vineyards for measuring residual water deficits after rainfall (Choné *et al.*, 2000). However, the specific threshold of stem water potential that gives way to irreversible damage on canopy and grapes varies with the vigor of the vines. Water deficit damage is caused by vascular embolism (Schultz and Matthews, 1988). Xylem vessels are small in vines that have been exposed to early water deficit stress and large in vines that developed under unlimited water uptake conditions (Lovisolo and Schubert, 1998). On vigorous vines with large xylem vessels that are suddenly exposed to excessive water deficit, irreversable embolism might occur at stem water potential readings of -1.2 MPa. Low vigor vines that are progressively exposed to water deficits might resist to stem water potential levels of -1.6 MPa (no excessive leaf drop of, no berry shrivel). In dry-farmed, Bordeaux vineyards, it is a current observation that vines are remarkably resistant to drought conditions when water deficits develop progressively during the season. This happened during the 2005 vintage. Although it was the dryest ever recorded in Bordeaux, no major water stress damage was recorded on vines.

Carbon isotope discrimination

Ambient CO_2 contains 98.9% of ^{12}C isotope and 1.1% of ^{13}C isotope. ^{12}C is more easily used by the enzymes of photosynthesis in their production of hexoses. Therefore, the sugar produced by photosynthesis contains a higher rate of the ^{12}C isotope than ambient CO_2. This process is called « isotope discrimination ». When plants face water deficit conditions, isotope discrimination is reduced because of stomatal closure (Farquhar *et al.*, 1989). Therefore, the $^{12}C/^{13}C$ ratio in products of photosynthesis forms a signature of plant water uptake conditions over the period in which they were synthesised. When measured on grape sugar at ripeness, the $^{12}C/^{13}C$ ratio (so-called $\delta^{13}C$) indicates average vine water status during grape ripening (van Leeuwen *et al.*, 2001b, Gaudillère *et al.*, 2002).

$\delta^{13}C$ can easily be measured by mass spectrometry in specialized laboratories. The $^{12}C/^{13}C$ ratio in the sample is compared to that in an international standard, the so-called PDB standard which is a rock in which this ratio is particularly stable. The results vary from –20 p. 1000 (severe water deficit stress) to –27 p. 1000 (no water deficit stress, table 1). $\delta^{13}C$ is well-correlated to stem water potential (Figure 6).

The advantage of the carbon isotope discrimination method lies in the fact that it does not require any field measurements other than sampling the grapes at maturity (van Leeuwen *et al.*, 2001b; Gaudillère *et al.*, 2002). Hence, many measurements can easily be carried out. This is not the case with a pressure chamber, which is a more time consuming and labour intensive tool. In dry farmed vineyards, $\delta^{13}C$ is a valuable tool for determining water deficits at block scale or even at intra-block scale (van Leeuwen *et al.*, 2006). On the Bordeaux estate presented in figure 7A, dry blocks (high $\delta^{13}C$ values) correspond to gravelly soils with low water-holding capacity. On these blocks, soil resistivity is high (Figure 7B). Blocks with higher water-holding capacities (due to a higher clay content in the soil) show more negative $\delta^{13}C$ values (Figure 7A). On these blocks, soil resistivity is low (Figure 7B). However, the fact that the result of carbon isotope discrimination is only available after harvest date makes this tool unsuitable to assess day-to-day vineyard irrigation requirements.

In many countries, the wine industry buys grapes from independent growers. Buyers of red grapes generally ask growers to deficit irrigate their vines in order to enhance grape quality potential (reduced berry size, increased anthocyanin and total phenolic content). Growers might be reluctant to reduce irrigation however, because deficit irrigation tends to reduce yields. It is overly labour intensive for grape buyers to control irrigation in the field. However, the $\delta^{13}C$ measurement provides a tool with which grape buyers can, at a reasonable cost, control the level of irrigation performed on the purchased grapes. In cooperatives, the $\delta^{13}C$ measurement can be a useful tool for block selection or for differential payment of grapes depending on vine water status.

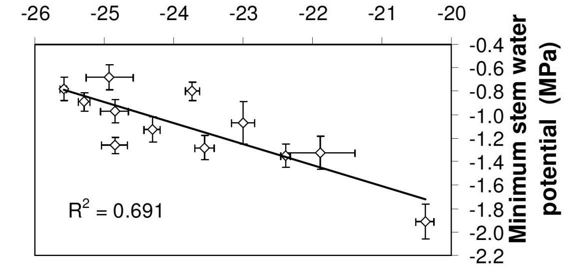

Figure 6 - Correlation between minimum stem water potential measured during the season and carbon isotope discrimination ($\delta^{13}C$) measured on grape sugar at ripeness (*Vitis vinifera* L. cv. Merlot).
The error bars indicate the standard deviation of measurements.

CONCLUSIONS

Vine phenology and grape ripening are highly dependent on water uptake conditions. Moderate water deficits reduce shoot growth, berry size and yield and enhance fruit ripening and phenolic compound synthesis in the berries. These factors generally enhance grape quality for the production of red table wines. The quality of red Bordeaux wine can be better correlated to the dryness of the vintage (calculated by means of a water balance model) than to the sum of active temperatures.

Although the vine is a very drought-resistant species, severe water stress can sometimes alter grape quality potential. In many situations, however, quality losses through severe water stress can be avoided if growers use drought-adapted plant material, practice accurate canopy management, reduce nitrogen fertilization to avoid excessive vigour and reduce yield. If rainfall is particularly low (<400 mm/year) or irregularly distributed over the year and soils are shallow or stony, irrigation might be necessary. The manner in which irrigation is managed is crucial to grape quality. Excessive irrigation, which is common due to poor assessment of vine water requirements, can provoke quality losses caused by yield increase, vigorous canopy growth and berry dilution. Quality production in irrigated vines can only be achieved when moderate water deficits are maintained which is difficult to achieve. For this type of finely-tuned irrigation management to yield positive results, accurate physiological indicators for assessing vine water status are needed.

A large range of methods for assessing vine water uptake conditions have been developed over the years. Some of them are more accurate and more easily

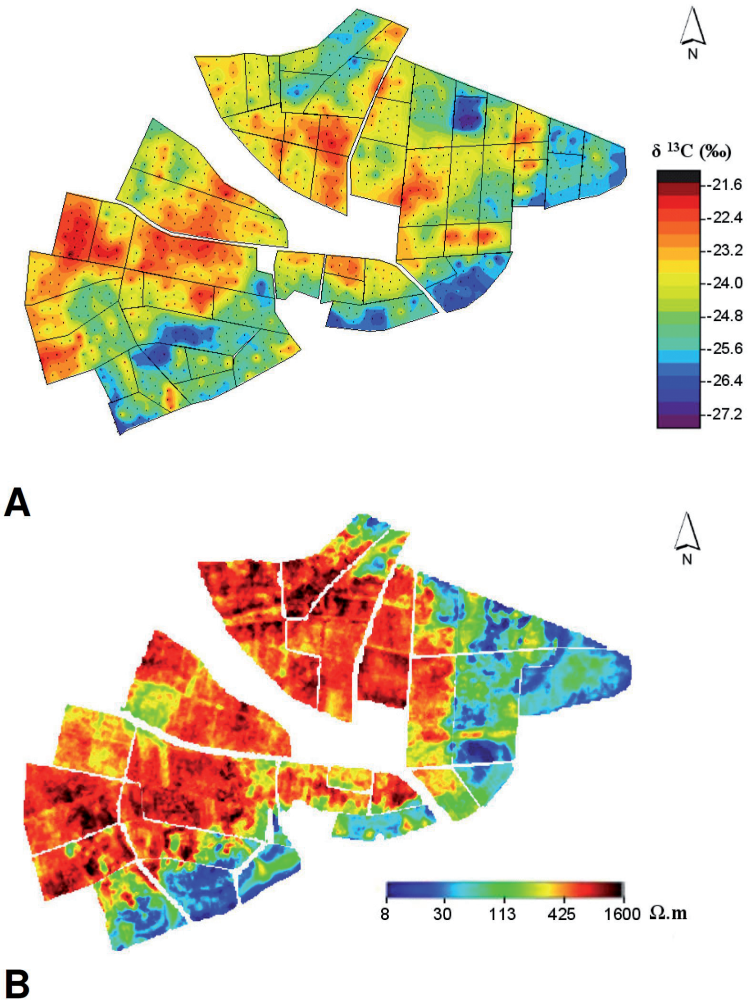

Figure 7 - Spatial representation of vine water status, assessed by $\delta^{13}C$ measurements on grape sugar (A), in a Bordeaux estate in 2006 compared with soil resistivity mapping carried out in the same estate (B). Cold colours represent low water deficit (A) or low soil resistivity (B) while warm colours represent high water deficit (A) or high soil resistivity (B).

performed than others. Vine water status is most accurately assessed by using physiological indicators. In our experimental conditions, stem water potential is one of the best ways to assess plant water status. Stem water potential may be the most accurate tool for irrigation management.

Carbon isotope discrimination ($\delta^{13}C$), measured on grape sugar at ripeness, indicates the average water deficit stress experienced by the vines during grape ripening. Because carbon isotope discrimination facilitates the execution of many measurements, it is a useful tool for block characterisation (for example in terroir studies). While grape quality potential is closely related to the occurence of water deficits during grape ripening, $\delta^{13}C$ can be used as a quality predictor in viticulture. Because the carbon isotope discrimination measurement takes place at ripeness, it cannot be used for irrigation management during the growing season. However, it can be used at harvest to validate irrigation strategies.

Acknowledgements : The authors are very grateful to Joy de Vink for help with proofreading and editing and Philippe Friant for technical assistance.

REFERENCES

AMÉGLIO T., ARCHER P., COHEN M., VALANCOGNE C., DAUDET F.-A., DAYAU S. and CRUIZIAT P., 1999. Significance and limits in the use of predawn leaf water potential for tree irrigation. *Plant and Soil*, **207**, 155-167.

BECKER N. and ZIMMERMANN H., 1984. Influence de divers apports d'eau sur des vignes en pots, sur la maturation des sarments, le développement des baies et la qualité des vins. *Bull. O.I.V.*, **641-642**, 584-596.

BEGG J. and TURNER N., 1970. Water potential gradients in field tobacco. *Plant Physiology*, **46**, 343-346.

CHONÉ X., TRÉGOAT O., VAN LEEUWEN C. and DUBOURDIEU D., 2000. Déficit hydrique modéré de la vigne : parmi les trois applications de la chambre à pression, le potentiel tige est l'indicateur le plus précis. *J. Int. Sci. Vigne Vin*, **34**, 169-176.

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

CHONÉ X., TRÉGOAT O. and VAN LEEUWEN C., 2001b. Fonctionnement hydrique des terroirs, base de l'irrigation raisonnée de la vigne. *J. Int. Sci. Vigne Vin, N° hors série* : « Un raisin de qualité : de la vigne à la cuve », 47-51.

CIFRE J., BOTA J., ESCALONA J., MEDRANO H. and FLEXAS J., 2005. Physiological tools for irrigation scheduling in grapevine (*Vitis vinifera* L.): an open gate to improve water use efficiency? *Agric., Ecosystems Environment*, **106**, 159-170.

COIPEL J., RODRIGUEZ-LOVELLE B., SIPP C. and VAN LEEUWEN C., 2006. « Terroir » effect, as a result of environmental stress, depends more on soil depth than on soil type (*Vitis vinifera* L. cv. Grenache noir, Côtes du Rhône, France, 2000). *J. Int. Sci. Vigne Vin*, **40**, 177-185.

DUTEAU J., 1990. Relations entre l'état de maturité des raisins (Merlot noir) et un indice climatique. Utilisation pour fixer la date des vendanges en année faiblement humide dans les crus de Bordelais. *In Actualités œnologiques 89*, pp. 7-12. Paris : Dunod.

DUTEAU J., GUILLOUX M. and SEGUIN G., 1981. Influence des facteurs naturels sur la maturation du raisin, en 1979, à Pomerol et Saint-Émilion. *Connaissance Vigne Vin*, **15**, 1-27.

DUTEAU J., 1987. Contribution des réserves hydriques profondes du calcaire à Astéries compact à l'alimentation en eau de la vigne dans le Bordelais. *Agronomie*, **7**, 589-865.

DRY P., LOVEYS B., MCCARTHY M. and STOLL M., 2001. Strategic irrigation management in Australian vineyards. *J. Int. Sci. Vigne Vin*, **35**, 129-139.

ESCALONA J., FLEXAS J. and MEDRANO H., 2002. Drought effects on water flow, photosynthesis and growth of potted grapevines. *Vitis*, **41**, 57-62.

FARQUHAR G., EHLERINGER J. and HUBICK K., 1989. Carbon isotope discrimination and photosynthesis. *Annual Rev.Plant Physiol. Plant Molecular Biol.*, **40**, 503-537.

FERERES E. and SORIANO M., 2007. Deficit irrigation for reducing agricultural water use. *J. Exp. Botany*, **58**, 147-159.

GARNIER E. and BERGER A., 1986. Effects of water stress on stem diameter changes of peach trees growing in the field. *J. Applied Ecology*, **23**, 193-209.

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. Botany*, **53**, 757-763.

GREENSPAN M., SHACKEL K. and MATTHEWS M., 1994. Developmental changes in the diurnal water budget of the grape berry exposed to water deficits. *Plant, Cell Environment*, **17**, 811-820.

JONES G., 1999. Use of infrared thermometry for estimation of stomatal conductance as a possible aid for irrigation scheduling. *Agric. For. Meteorol.*, **95**, 139-149.

HANSON B., DOUGLAS P. and ORLOFF S., 2000. Effectiveness of tensiometers and electrical resistance sensors varies with soil conditions. *California Agriculture*, **54**, 47-50.

HARDIE W. and CONSIDINE J., 1976. Response of grapes to water-deficit stress in particular stages of development. *Am. J. Enol. Vitic.*, **27**, 55-61.

HSIAO T., 1973. Plant responses to water stress. *Annual Rev. Plant Physiol.*, **24**, 519-570.

JONES H., 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods. *J. Exp. Botany*, **55**, 2427-2436.

KOUNDOURAS S., VAN LEEUWEN C., SEGUIN G. and GLORIES Y., 1999. Influence de l'alimentation en eau sur la croissance de la vigne, la maturation des raisins et les caractéristiques des vins en zone méditerranéenne (exemple de Némée, Grèce, cépage Saint-Georges, 1997). *J. Int. Sci. Vigne Vin*, **33**, 149-160.

KOUNDOURAS S., MARINOS V., GKOULIOTI A., KOTSERIDIS Y. and VAN LEEUWEN C., 2006. Influence of vineyard location and vine water status on fruit maturation of non-irrigated cv Agiorgitiko (*Vitis vinifera* L.). Effects on wine phenolic and aroma components. *J. Agric. Food Chem.*, **54,** 5077-5086.

LEBON E., DUMAS V., PIERI P. and SCHULTZ H., 2003. Modelling the seasonal dynamics of the soil water balance of vineyards. *Funct. Plant Biol.*, **30**, 699-710.

LEBON E., PELLEGRINO A., LOUARN G. and LECOEUR J., 2006. Branch development controls leaf area dynamics in grapevine (*Vitis vinifera*) growing in drying soil. *Annals Botany*, **98**, 175-185.

LOVISOLO C. and SCHUBERT A., 1998. Effects of water stress on vessel size and xylem hydraulic conductivity in *Vitis vinifera* L. *J. Exp. Botany*, **49**, 693-700.

MABROUK H. et CARBONNEAU A., 1996. Une méthode simple de détermination de la surface foliaire de la vigne (*Vitis vinifera* L.). *Progrès Agric. Vitic*., **18**, 392-398.

MATTHEWS M. and ANDERSON M., 1988. Fruit ripening in *Vitis vinifera* L.: responses to seasonal water deficits. *Am. J. Enol. Vitic.*, **39**, 313-320.

MATTHEWS M. and ANDERSON M., 1989. Reproductive development in grape (*Vitis vinifera* L.): responses to seasonal water deficit. *Am. J. Enol. Vitic.*, **40**, 52-60.

MCCARTHY M.,1997. The effect of transient water deficit on berry development of cv. Shiraz (*Vitis vinifera* L.). *Aust. J. Grape Wine Res.*, **3**, 40-45.

MCCUTCHAN H. and SHACKEL K., 1992. Stem water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv French). *J. Am. Soc. Hortic. Sci.*, **117**, 607-611.

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 de doctorat d'État*, 289 p. + annexes, Université Bordeaux II.

NADAL M. and AROLA L., 1995. Effects of limited irrigation on the composition of must and wine of Cabernet-Sauvignon under semi-arid conditions. *Vitis*, **34**, 151-154.

OJEDA H., ANDARY C., KRAEVA E., CARBONNEAU A. and DELOIRE A., 2002. Influence of pre- and postvéraison water deficit on synthesis and concentration of skin phenolic compounds during berry growth of *Vitis vinifera* cv. Shiraz. *Am. J. Enol. Vitic.*, **53**, 261-267.

PELLEGRINO A., LEBON E., SIMONNEAU T. and WERY J., 2005. Toward a simple indicator of water stress in grapevine (*Vitis vinifera* L.) based on the differential sensitivities of vegetative growth components. *Aust. J. Grape Wine Res.*, **11**, 306-315.

PELLEGRINO A., GOZÉ E., LEBON E. and WERY J., 2006. A model-based diagnosis tool to evaluate the water stress experienced by grapevine in field sites. *Europ. J. Agronomy*, **25**, 49-59.

PIERI P. and GAUDILLÈRE J.-P., 2005. Vines water stress derived from a soil water balance model – sensitivity to soil and training parameters. *In SCHULTZ H. (ed) Proceedings of the XIVth Int. Conf.GESCO*, 23 – 27 August 2005, Geisenheim (Germany), 457-463.

RIBÉREAU-GAYON P., DUBOURDIEU D., DONÈCHE B. and LONVAUD A., 1998. *Traité d'œnologie : Tome 1, microbiologie et vinification*. Dunod, Paris, 560 pp.

RIOU C. and LEBON E., 2000. Application d'un modèle de bilan hydrique et de la mesure de la température de couvert au diagnostic du stress hydrique de la vigne à la parcelle. *Bull. O.I.V.*, **837-838**, 755-764

SCHOLANDER P., HAMMEL H., EDDA D., BRADSTREET E. and HEMMINGSEN E., 1965. Sap pressure in vascular plants. *Science*, **148**, 339-346.

SCHULTZ H., 2003. Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown *Vitis vinifera* L. cultivars during drought. *Plant, Cell and Environment*, **26**, 1393-1405.

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

SHACKEL K., 2006. Water relations of woody perennial plant species, in: VAN LEEUWEN C. *et al.* (ed) *Proceedings of the VIth International Terroir Congress*, 2-7 July 2006, Bordeaux: ENITA – Montpellier: Syndicat Viticole des Coteaux du Languedoc (France), 54-63.

SEGUIN G., 1975. Alimentation en eau de la vigne et composition chimique des moûts dans les Grands Crus du Médoc. Phénomènes de régulation. *Connaissance Vigne Vin*, **9**, 23-34.

SEGUIN G., 1986. « Terroirs » and pedology of vinegrowing. *Experientia*, **42**, 861-873.

SOAR C., DRY P. and LOVEYS B., 2006. Scion photosynthesis and leaf gas exchange in *Vitis vinifera* L. cv. Shiraz: mediation of rootstock effects via xylem sap ABA. *Aust. J. Grape Res.,* **12**, 82-96.

STOLL M., LOVEYS B. and DRY P., 2000. Hormonal changes induced by partial rootzone drying of irrigated grapevine. *J. Exp. Botany*, **51**, 1627-1634.

TRÉGOAT O., VAN LEEUWEN C., CHONÉ X. and GAUDILLÈRE J.-P., 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. *J. Int. Sci. Vigne Vin*, **36**, 133-142.

VAN LEEUWEN C., 2001. Choix du cépage en fonction du terroir dans le Bordelais. *J. Int. Sci. Vigne Vin*, *N° hors série : « Un raisin de qualité : de la vigne à la cuve »*, 97-102.

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-Émilion, 1990). *J. Int. Sci. Vigne Vin*, **28**, 81-110.

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. *The Australian Grapegrower Winemaker*, **449**, June 2001, 18-24.

VAN LEEUWEN C., GAUDILLÈRE J.-P. and TRÉGOAT O., 2001b. Évaluation du régime hydrique de la vigne à partir du rapport isotopique $^{13}C/^{12}C$. *J. Int. Sciences Vigne Vin*, **35**, 195-205.

VAN LEEUWEN C., FRIANT Ph., CHONÉ X., TRÉGOAT O., KOUNDOURAS S. and DUBOURDIEU D., 2004. The influence of climate, soil and cultivar on terroir. *Am. J. Enol. Vitic.*, **55**, 207-217.

VAN LEEUWEN C. and SEGUIN G.,2006. The concept of terroir in viticulture. *J. Wine Res.*, **17**, 1-10.

VAN LEEUWEN C., GOUTOULY J.-P., AZAÏS C., COSTA FERREIRA A.-M., MARGUERIT E., ROBY J.-Ph., CHONÉ X. and GAUDILLÈRE J.-P., 2006. Intra-block variations of vine water status in time and space. *In: VAN LEEUWEN C. et al. (ed) Proceedings of the VIth Int. Terroir Congres*s, 2-7 July 2006, Bordeaux: ENITA – Montpellier: Syndicat Viticole des Coteaux du Languedoc (France), 64-69.

VAN LEEUWEN C., TRÉGOAT O., CHONÉ O., GAUDILLÈRE J.-P. and PERNET D., 2007. Different environmental conditions, different results: the role of controlled environmental stress on grape quality and the way to monitor it. *In: Proceedings of the XIIIth Aust. Wine Industry Tech. Conf.*, 28 July – 2 August 2007, Adelaide.

WINKLER A., COOK J., KLIEWER W. and LIDER L., 1974. *General viticulture*. University of California press, Berkeley, 710 p.