GRAPEVINE RESPONSES TO TERROIR : A GLOBAL APPROACH

LES RÉPONSES DE LA VIGNE AU TERROIR : UNE APPROCHE GLOBALE

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Abstract: This paper deals with the technical and/or practical treatment of terroir as a study concept, together with related functional aspects. Functioning of the terroir relies on the relation between climate, soil and vine. In addition to this interaction, a comprehensive study concept for terroir requires the consideration of viticultural and enological sciences and techniques necessary to ensure the assurance of wine quality, together with spatial aspects of the grapevine response to environmental factors, as required for vineyard management. In order to comprehend the quality of the harvest, it is necessary to understand the relationship « whole plant - berry ». An easy field and laboratory method to study the relationship between the whole plant and berry and the consequences thereof for wine quality is proposed. Knowledge of grapevine water status and the biochemical evolution within the grape berry from berry set onwards are important issues for the understanding of the role that terroir plays with respect to the quality of the harvest and the wine style or « typicality ».

Résumé : Le terroir est un concept qui nécessite une approche globale permettant une étude combinée du climat, du sol, de la vigne et du rôle de l'homme. Les sciences de la viticulture et de l'œnologie sont alors nécessaires pour comprendre les déterminants de la qualité du vin en relation avec les facteurs de l'environnement. En connexion aux études de terroir qui portent sur le climat et le sol, nous proposons une approche globale qui intègre l'étude des relations «vigne - raisin - vin ». L'état hydrique de la vigne est l'un des éléments clefs du fonctionnement de la vigne et de la qualité du raisin en relation avec le style de vin. Cet article rappelle les méthodes de référence pour la mesure de l'état hydrique de la vigne et les conséquences possibles des déficits hydriques sur le fonctionnement de la plante et de ses fruits.

Key words: terroir, grapevine, global approach, soil, climate, water status, wine, berry.

Mots clefs : terroir, vigne, approche globale, sol, climat, état hydrique, vin, baie.

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INTRODUCTION

Insight into viticultural terroirs has been the subject of several publications over the past number of years (SEGUIN, 1970, 1983, 1986; DUTEAU *et al.*, 1981; MORLAT, 1989; RIOU *et al.*, 1995; SALETTE *et al.*, 1997; BARBEAU *et al.*, 1998; 2001; CHONÉ *et al.*, 2001a; DELOIRE *et al.*, 2002; TRÉGOAT *et al.*, 2002; VAUDOUR, 2003; CAREY and BONNARDOT, 2004; VAN LEEUWEN *et al.*, 2004 ; VAUDOUR *et al.*, 2005). This has, however, not always been the case and terroir as a study concept has, in the past, sometimes even been disparaged. Nonetheless, it has always encompassed great or rich notions that are linked to quality and « typicality » of some agricultural products. This is particularly the case for products of the grapevine.

The terroir concept should be considered from a technical-scientific point of view so that, beyond the mystique and marketing, this concept will be based on least debatable realities, even if it remains slightly quixotic. In this article we will define the concept of terroir and discuss its technical or practical handling as a study concept in the field and in the laboratory for both researchers and professionals. The terroir study needs to be a global approach.

DEFINITIONS OF THE TERM « TERROIR »

Possible connotations of the term « terroir » have been well described by VAUDOUR (2002). The term « terroir » stems from the Vulgar Latin « terratorium », a corruption of « territorium ». Terroir can be defined as a spatial and temporal entity, which is characterized by homogeneous or dominant features that are of significance for grapes and/or wine; i.e. soil, landscape and climate, at a given scale-duration, within a territory that has been founded on social and historical experience and genotype related technical choices (VAUDOUR, 2003). Until recently, despite the diversity of terroir-related scientific works, very little attention has been paid to the spatial modelling and scale issues of terroir. Traditionally, these types of studies were performed uniquely with point measurements, without interpolation and validation of these measurements within larger areas.

At the scale of a vineyard or group of vineyards, it is worthwhile to recall the following terms, which are frequently referred to in the wine industry:

- UTB (MORLAT, 1989; SALETTE *et al.*, 1997): basic terroir unit (Unité Terroir de Base) = « mesoclimate x soil / substratum »for a series of years / vintages. However, as diverse methods exist to characterize vineyard environments (for example UTB relies mainly on geological data), the general term of « environmental terroir unit » (TU) is preferable. It is also important to remember that the various TU delimitations do not necessarily refer to a unique spatial level of analysis and may correspond to different extents and variables.

- According to CARBONNEAU (2001), viticultural and enological technology should also be included in the definition of terroir, leading to the concept of VTU: viticultural terroir unit (Unité de Terroir Viticole) = TU x cultivar x viticultural and oenological technology.

The viticulturist acts on some intrinsic components of the VTU, such as light, temperature or moisture-related microclimate within the canopy in the bunch zone. He influences, therefore, the quality of the harvest and the typicality of the wine in partnership with the winemaker.

The heritage and socio-cultural dimension of the terroir is also important and reinforces its unique character (DION, 1977; LACHIVER, 1988; GARRIER, 1998; CARBONNEAU *et al.*, 2001a).

THE SYSTEM « SOIL - CLIMATE - PLANT » AND THE NEED FOR GEOGRAPHIC INFORMATION

Methods to study the association « soil-climate-plant » are numerous. During the last three decades, various terroir-related scientific studies have been carried out, mostly focusing on the relationship between the analytical and sensorial analyses of wine, the monitoring of grape maturation falling intermediate between the plant and the wine, and a few soil and climatic characteristics at the plant or plot level, e. g. in Alsace (LEBON *et al.*, 1993), Bordeaux (SEGUIN, 1970; DUTEAU *et al.*, 1981; VAN LEEUWEN and SEGUIN, 1994; TREGOAT *et al.*, 2002), the Loire Valley (MORLAT, 1989), Champagne (DOLÉDEC, 1995), the Rhone Valley (MARTIN, 1995; VAUDOUR, 2001), California (NOBLE, 1979); Australia (RANKINE *et al.*, 1971); Trentino (FALCETTI and SCIENZA, 1991); Rheingau (FISCHER *et al.*, 1999) and South Africa (HUNTER and BONNARDOT, 2002; CAREY *et al.*, 2003a, b; CAREY and BONNARDOT, 2004). These terroir-related scientific studies can be separated into two main groups: on the one hand, those insisting on the geographical differentiation of wines or grapes; and, on the other hand, those focusing on the geographical differentiation of land capability or vineyard suitability. The latter, which are the most frequent, lead to either local approaches directed towards understanding the plant ecophysiological functioning (NOBLE, 1979; LEBON *et al.*, 1993; VAN LEEUWEN and SEGUIN, 1994; RIOU *et al.*, 1995; CARBONNEAU, 1997; MORLAT, 1996, CHONE *et al.*, 2001a; TREGOAT *et al.*, 2002; DELOIRE *et al.*, 2004; VAN LEEUWEN *et al.*, 2004), or global or regional approaches oriented towards the characterization of land geographical patterns (JACQUINET *et al.*,

1989; DOLÉDEC, 1995; MARTIN, 1995; SOTÉS et al, 1997; VAUDOUR, 2001, CAREY, 2001). The so-called « UTB » or « TU » units mainly correspond to local approaches, although the widespread implementation of geomatics, geophysics and precision viticulture leads to questioning of the way such units are spatially characterized. The tools provided by geomatics include Geographic Information Systems (GIS), Global Positioning System (GPS), digital image processing and interpretation of satellite images and aerial photographs. These methods are needed for the analysis of terroir across the earth's biosphere, at scales (or organizational levels) that may range from the field, farm or watershed to the regional, continental or global level. It is important to consider several of these levels concurrently. The field level has to be examined in order to understand some viticultural situations, and this requires entering further into understanding of the relationship between the whole plant and berries. The levels encompassing wider areas are more adapted to professional managerial needs over a viticultural district and the relationship of the broader district to the sample of sites selected at field level must be analyzed.

The above mentioned definition of terroir relies on the following partnership: climate, soil, cultivar and man. We will therefore take a brief look at the different components, emphasizing the plant, main subject of this publication, i.e. the field (and subfield) level. We will not tackle the human factor, which is dealt with in other publications (DUPUY, 1989; LETABLIER and NICOLAS, 1994).

1) Climate

There are three main scales at which climate is referred to in viticultural research and these are related to differences in the scales used to describe surface and time:

The macroclimate describes the climate of a wide area or region, which extends over hundreds of kilometres and is studied over a long time-period (usually 30 years or more) using annual, seasonal and / or monthly data.

The meso-climate describes the climate within smaller areas, which extend from less than a hectometre to several kilometres (e.g. vineyards) and over shorter periods of time using hourly or daily data. It is also known as « topoclimate »as it is influenced by the surrounding topographic factors of elevation or altitude, slope inclination and aspect and proximity to bodies of water (VAUDOUR, 2003).

The microclimate is the climate immediately within or surrounding the plant canopy and differences occur within a few centimetres / meters and seconds / minutes. It is influenced by the vigour of the grapevine and cultural practices (inter alia canopy management, row orientation and spacing), but also by the soil surface characteristics.

These levels may, however, to some extent be ambiguous as their scales are not strictly defined (VAUDOUR, 2003).

Climatic data are particularly important for the choice of grapevine varieties. Each variety needs a minimum temperature summation to reach maturity. The thermal-time value varies considerably from one cultivar to another and is related to the growth cycle of the cultivar (HUGLIN and SCHNEIDER, 1998). When a late ripening variety is planted in a cool climate, grapes will not reach complete maturity and quality wines cannot be produced. On the other hand, when an early ripening variety is planted in a warm climate, aromatic expression and wine « finesse »is reduced due to too rapid ripening (RIBÉREAU-GAYON and PEYNAUD, 1960). This explains why the best terroir expression is obtained with varieties that reach complete ripeness at the end of the season under the local climatic conditions.

Another important feature of climate with respect to vine growing is water balance, which depends on rainfall and potential evapo-transpiration (TONIETTO and CARBONNEAU, 2004). The style of wine will depend on the plant water content and evolution during the growing season, with or without irrigation. In very dry climates, quality wine production is also possible, either by maintaining the yields and the total leaf area at a low level or by providing controlled irrigation to the grapes.

Climatic indices for viticulture, combining various components (mainly temperature, be it minimum, maximum or mean, but also rainfall, relative humidity, sunshine duration and water balance) have been developed to describe the viticultural potential of a region on a macroscale. Some use monthly data or daily data only, while others are a combination of different scales (daily with monthly data e.g. HUGLIN, 1978). They are usually summated over a period of time (growth season or whole year), but may also use mean data of a single month. They are established for a specific country or region, but may be adapted to other regions or used for a systematic global classification of the climate (TONIETTO, 1999, TONIETTO and CARBONNEAU, 2004). The growing degree-day index (WINKLER *et al.*, 1974), the heliothermal index (HUGLIN, 1978); the cool night index (TONIETTO, 1999) and the dryness index or potential soil water balance (CARBONNEAU *et al.*, 1992; RIOU, 1998; TONIETTO and CARBONNEAU, 2004) are examples of some commonly used indices.

Climate is monitored by means of automatic and mechanical weather stations. The inadequate number of standardized weather stations within a zone often limits

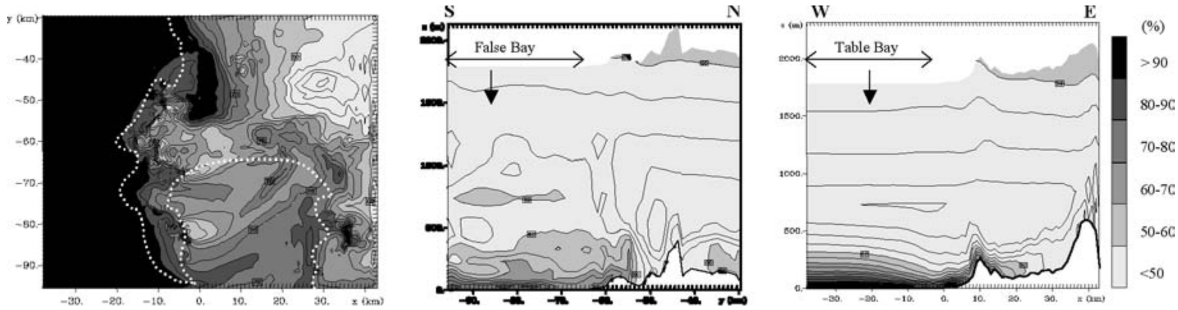

Figure 1 - Study domain for simulations in the Western Cape of South Africa
(coastline in white on horizontal cross section). Horizontal and vertical cross-sections of relative humidity (1 km resolution) at 17:00 on 18 February 2000 (from BONNARDOT, 2002; BONNARDOT *et al.*, 2005).

Simulation de l'évolution du climat à l'Est du Cap en Afrique du Sud

studies at a mesoscale. The greater the number of weather stations, the more accurate the research. In Champagne, for instance, the Comité Interprofessionnel du Vin de Champagne (CIVC) has installed a network of automatic weather stations in order to develop an early warning system for frost (BELTRANDO, 1998; DE SAINTIGNON, 1998). In South Africa, where the Wine Industry fosters research on terroir, the Institute for Soil, Climate and Water (ISCW) of the Agricultural Research Council (ARC) has developed a countrywide network of weather stations aimed at monitoring the climate and satisfying the climatic requirements of agriculture. In the Western Cape Province itself, where vineyards are traditionally situated, there are 84 automatic weather stations available and mostly situated in a vine row or on open ground next to a vineyard (BONNARDOT *et al.*, 2004b). For example, a network of 10 automatic weather stations over a study domain of 25 000 ha was used for terroir studies in the Stellenbosch district (CAREY, 2001) and seven automatic weather stations were used for a study of the genotype x terroir interaction of Sauvignon blanc in Stellenbosch and Durbanville districts (CONRADIE *et al.*, 2002).

New tools, such as atmospheric models, can also be used to study the influence of the mesoclimate in a specific region. The Regional Atmospheric Modelling System has been used in the Stellenbosch wine-producing region (figure 1) to investigate the penetration of the sea breeze (BONNARDOT *et al.*, 2002, 2005). It was shown, for example, for a specific day during the maturation eriod (18/02/2000), that the sea breeze was responsible for a temperature decrease of 6°C in 3 hours, reducing the thermal stress (figure 2). The concomitant increase in wind velocity and relative humidity in the afternoon is also a factor that has significant implications for viticulture in this area (CAREY and BONNARDOT, 2004). The sea breeze in the Stellenbosch wine-producing region may be a restrictive factor for optimal photosynthesis as far as wind is concerned, but the moderate temperature would appear to be positive with respect to colour development and aroma retention (HUNTER and BONNARDOT, 2002).

2) Soil

Soil studies are an important aspect of terroir assessment, especially when leading to the development of soil maps and the understanding of the soil-grapevine relationship through soil water profiles and grapevine root profiles (SEGUIN, 1970; DUTEAU *et al.*, 1981; TRAMBOUZE and VOLTZ, 1997; HUNTER, 1998; VAUDOUR *et al.*, 2005). Spatial modelling of soil is needed to evaluate whether each individual site is representative of the whole managed viticultural area and to assess spatial units that represent potential similar functioning for the vine (VAUDOUR, 2003).

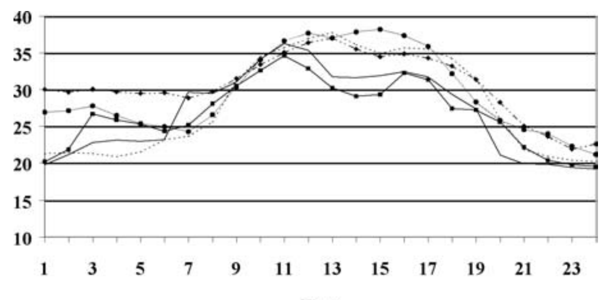

Figure 2 - Observed temperature (°C) in the Stellenbosch vineyards at different distances from the sea (T07, 12 km; T10, 12 km; T01, 20 km; T16, 30 km; T28, 55km) on 18/02/2000 (from BONNARDOT, 2002).

Exemple d'évolution journalière des températures (°C) dans les vignobles de Stellenbosch à différentes distances de l'océan

Effective study systems using digital processing of satellite images and GIS, are increasingly developed and adapted to spatial modelling or zoning of viticultural terroirs, by means of characterisation of viticultural soils within soil-landscape units. They are able to integrate multiple layers of information, notably related to soil cover, climate or the plant, which are structured and managed through a GIS.

The acquisition and manipulation of these data has proved to be an interesting approach to understand spatial variability of soil-landscape units, but is subject to data availability according to three types of situation:

a) The soil and climatic data have been obtained at the level of the plot (vineyard) and/or groups of plots (vineyards).

b) The data has not been obtained and the obtaining thereof is not conceivable due to limited means, in particular the absence of a weather station for climatic data.

c) It is possible to obtain the soil and climatic data, even partially, in parallel with the studies performed on the plant.

Generally, it is easier to obtain spatial soil and landscape data than spatial climate or plant data. The use of high or very high resolution satellite images is very promising for both detailed precision viticulture studies and synthetic regional zonings and is being developed in several countries.

As renowned wines are produced on varied soils types, it is not always possible to establish a direct relationship between soil types and wine quality (SEGUIN, 1983), but some soils are more likely to favour it (VAUDOUR *et al.*, 2005). Soil depth and soil water holding capacity are important soil characteristics related to wine quality, as is soil nitrogen supply to the vines (CHONE *et al.*, 2001a). No direct relationship can be established between soil minerals (except for nitrogen) and wine quality, as long as severe deficiencies do not interact with normal plant functioning (VAN LEEUWEN *et al.*, 2004). Therefore, soil science related studies, though necessary, cannot, by themselves, enable to describe and understand the functioning of the plant and biochemical evolution of the berry. A global approach which takes into account the whole plant and berry levels in relation with the environmental context is necessary to understand the quality of the harvest and of the wines. We are going to describe this apsect in the following part.

3) Plant

Many studies have been performed on the grapevine and its functioning over many years (MAY *et al.*, 1976; CARBONNEAU *et al.*, 1978; SCHULTZ, 1993; SMART, 1995; CARBONNEAU, 1996; NAOR *et al.*, 1997; DÜRING, 1998; HUNTER and RUFFNER, 2001; HUNTER, 1998; ZUFFEREY *et al.*, 2000, WANG *et al.*, 2003b), and have been continued in recent years within the domain of molecular physiology (ROUBELAKIS-ANGELAKIS, 2001). Many of the numerous existing studies on this subject show the interest of studies at the level of the whole plant and the pertinence of a multidisciplinary approach. Such studies are of significance in the determination of the hierarchy of influence of the environmental parameters within a specific region. For such studies, it is necessary to use multivariate statistical methods such as principal component, discriminant or cluster analyses (BERTAMINI *et al.*, 1996; REYNOLDS *et al.*, 1996; BARBEAU *et al.*, 1998; CAREY *et al.*, 2003a, b; CAREY AND BONNARDOT, 2004), multifactor ANOVA (VAN LEEUWEN *et al.*, 2004), methods investigating the dependence of data such as forward or backward step-wise regression (CAREY *et al.*, 2003b) or logically flexible models such as Classification and Regression Trees (SCHWARZ, 1997). A study within the Stellenbosch wine-producing region (CAREY and BONNARDOT, 2004), investigated the importance of sea breeze related parameters within the terroir x genotype interaction using inter alia principal component analyses. It was shown that temperature, relative humidity and exposure to wind, as well as soil-related factors, had consequences for grapevine growth and wine quality for the three cultivars studied (Sauvignon blanc, Chardonnay, Cabernet-Sauvignon), although the three cultivars reacted very differently.

THE « WHOLE PLANT-BERRY » APPROACH

With respect to the plant, compilation of some of the technical and scientific knowledge and / or experience that have been acquired provides insight into the « whole plant-berry » interaction within the context of the viticultural terroir study field. This approach may be easily performed and can provide pertinent information on the behaviour of the grapevine and the biochemistry of the berry in relation to the environment (figure 3).

Data obtained on the whole plant and berry levels, which integrate the environmental context of the grapevine, are in direct relationship with the quality of the harvest and the quality of the wines. Previous studies have shown the highly important role of the water status of the plant and the bunch microclimate in relation to the biochemistry of the berry from berry set onwards (SEGUIN, 1970; DUTEAU *et al.*, 1981, SEGUIN, 1986; VAN LEEUWEN and SEGUIN, 1994; CARBONNEAU, 1987; TREGOAT *et al.*, 2002; OJEDA *et al.*, 2002; VAN LEEUWEN *et al.*, 2004). Grape potential for wine making

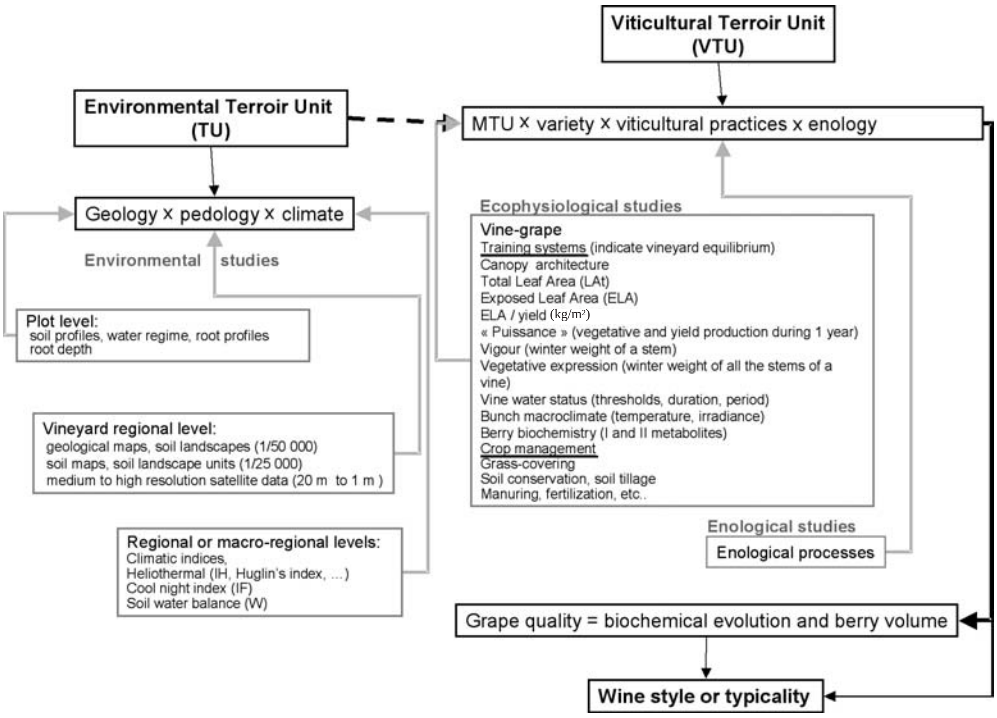

Figure 3 - Global approach towards viticulture terroirs.
Choice of methods and related scientific domains will depend study objectives and available means.

Une approche globale des terroirs viticoles. Le choix des méthodes et des disciplines scientifiques va dépendre des objectifs de l'étude et des moyens disponibles.

is the result of numerous factors, which makes it difficult to establish pertinent correlations.

EXPLANATIONS OF SOME ASPECTS OF THE « VINE - BERRY - WINE » GLOBAL APPROACH

I - THE PLANT WATER STATUS

a) Pre-dawn leaf water potential (LWP_{pd})

This data is obtained by measuring the leaf water potential by means of a pressure chamber (SCHOLANDER *et al.*, 1965). It estimates the capacity of the plant to retain water by pressurising a leaf with a neutral gas. The less free water there is in the plant, the greater the pressure required to cause it to exude. The result is expressed in bar or MPa, always as a negative value. The reference method used today is the measurement of predawn leaf water potential (LWP_{pd}; ψpd), which is performed before sunrise, when the stomata of the plant are closed and when the grapevine has been able to equilibrate its water potential with the most humid layer of the soil. Threshold values for LWP_{pd} have been proposed by CARBONNEAU (1998), which makes it possible to evaluate the degree of water deficit experienced by the plant (table I). The approximate values are the result of 20 or more years of observations in many vineyards of different cultivars. A comparison of the Syrah LWP_{pd} evolution during three years shows the possible vine water status variability, on the same type of soil (figure 4).

Table I - Predawn leaf water potential and grapevine water status (according to CARBONNEAU, 1998).

Potentiel foliaire de base et état hydrique de la vigne (selon Carbonneau)

classes	Predawn leaf water potential (ψ_{pd}, MPa)	Level of stress
0	0 MPa ≥ ψ_{pd} ≥ -0.2 MPa	no water deficit
1	-0.2 MPa > ψ_{pd}≥ -0.4 MPa	mild to moderate water deficit
2	-0.4 MPa > ψ_{pd} ≥ -0.6 MPa	moderate to severe water deficit
3	-0.6 MPa > ψ_{pd}≥ -0.8 MPa	Severe to high water deficit

Some suggestions are made regarding the use of LWP measurements:

LWPpd is a very reliable technique of determining vine water status that can be used in many situations. However, LWPpd can underestimate vine water deficits experienced by the vines during the day when soil water content is heterogeneous.

The LWPpd depends on rain or irrigation events and this must be taken into account in the kinetic monitoring. It is a method which enables the measurement of a short term hydric response (a few hours) of the plant in reaction to a change in the soil water status. After a small amount of rainfall on a dry soil, LWPpd underestimates water deficit experienced by the vines during the following days, because water potential in the vine balances during the night with the most humid soil layer.

In situations where the available soil water is not easily measured by neutron moisture or TDR probes due to the depth of the soil, LWPpd can still be used to determine plant water status.

LWPpd measurements are preferably made at regular intervals between either flowering and maturity or veraison and maturity. It is the evolution of the water status of the plant during the vegetative growth cycle which provides the most information on the impact of water on the growth of the plant and on the biochemistry/maturation of the berry (table II).

These measurements, realised at the scale of the whole plant, enable the characterisation of the homogeneity or the heterogeneity of a plot (vineyard) or a group of plots (vineyards) with respect to water relations. It allows replications and statistical analysis of the data.

The assessment of LWPpd across a plot (vineyard) enables us to confirm the importance of soil and root profile examinations in order to understand the eventual heterogeneity in observed vine reaction. This is notably linked to the root profile of the plant, which in turn is in relation to soil depth or texture.

The central role of vine water status concerns as much the soil (supply) as the sunlight interception in relation to the plant architecture and climate (rainfall, evaporative demand).

2) Leaf water potential (LWPf)

The leaf water potential (LWPf) is frequently used to determine the daily dynamic of plant water use (CARBONNEAU *et al.*, 2004).

3) Stem water potential (LWPs)

The stem water potential (LWPS) is measured on leaves which are bagged with both a plastic sheet and an aluminium foil at least one hour before measurement. The bagging of the leaves prevents transpiration and their water potential reaches equilibrium with water potential in the stems. Stem water potential measurement is a way of obtaining whole vine water status during the day. Stem water potential values are highly correlated with transpiration (CHONÉ *et al.*, 2001b). They are particularly accurate for revealing small water deficits, or water deficits on soils with heterogeneous soil humidity. Stem water potential is generally measured early in the afternoon (between 1300 h and 1600 h) when values reach a minimum.

4) Carbon isotope discrimination ($\delta^{13}C$)

Atmospheric CO_2 contains 98.9 % of ^{12}C and 1.1 % of ^{13}C. Plants incorporate ^{12}C more easily into their biomass during photosynthesis, which results in carbon isotope discrimination. When stomata are closed, due to water deficit, carbon isotope discrimination is reduced. As a result, the $^{13}C/^{12}C$ ratio (or $\delta^{13}C$) in primary products of photosynthesis (for grapevines being sugar) bears the signature of the intensity of the water deficit during the ripening period. $\delta^{13}C$ can be easily measured by mass spectrometry in specialized laboratories. This method

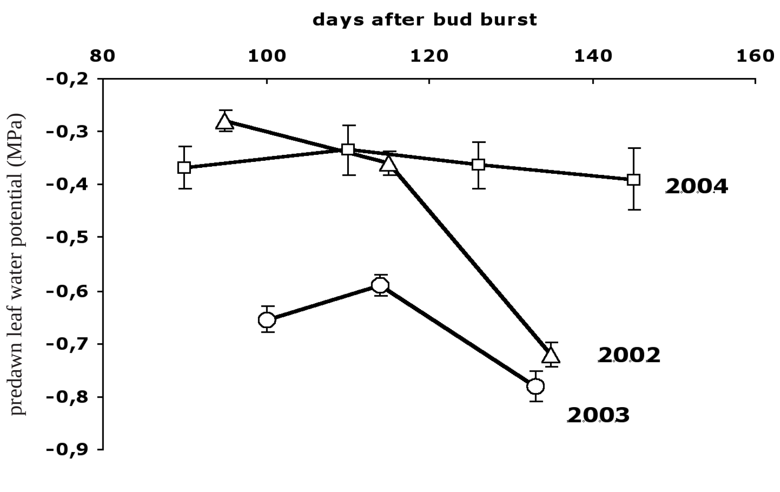

Figure 4 - Evolution of the predawn leaf water potential (LWPpd) of the variety Syrah during 3 years, in the Hérault région (South of France).

The figure shows the plant water status evolution for one year and the difference between 3 years. This is a clear illustration of the possible inter annual change, in the same plot, of the soil water reserve in interaction with the rain (i.e. « terroir » x vintage).

Évolution des potentiels hydriques foliaires de base du cépage Syrah au cours du cycle annuel de développement et sur 3 ans (région de l'Hérault, Sud de la France)

Table II - Relationships between pre-dawn leaf water potential, vegetative and fruit growth and berry physiology and biochemistry of *Vitis vinifera* L.

The budburst-flowering stage is not taken into account as a water deficit does not generally exist during this period under field conditions. The water deficit threshold values indicated and the resulting effects on the vine refer to the 'flowering - veraison' and 'veraison - maturity' stages. In order to fully appreciate the effect of water deficit, its duration must also be taken into account.

Relations possibles entre le potentiel hydrique foliaire de base, la croissance végétative et fructifère, la physiologie de la plante et la biochimie du fruit chez *Vitis vinifera* L.

LWPpd (Mpa)	Vegetative growth	Berry growth	photosynthesis	Berry maturation
0 to -0.3 Mpa	normal	normal	normal	normal
-0.3 to -0.5 Mpa	reduced	reduced	normal or slightly reduced	higher than normal*
-0.6 Mpa to -0.9 Mpa	inhibited	reduced or inhibited	reduced or inhibited	reduced or inhibited
< -0.9 Mpa	inhibited	inhibited	inhibited	inhibited

* i.e. stimulation of the biosynthesis or/and concentration of some compounds

has the advantage that it integrates the water deficit over a longer period and that it does not require measurements in the field. A great number of plots can be sampled, which makes a spatial representation of the results possible (VAN LEEUWEN *et al.*, 2001; GAUDILLÈRE *et al.*, 2002). Values range from -20 p. 1 000 (severely water stressed vines) to -27 p.1 000 (no water deficit).

II - VEGETATIVE GROWTH

Regular measurements of principal shoot length can provide information on the dynamics of plant growth (BESSIS and ECEVIT, 1974; FOURNIOUX, 2001). The growth of the principal and secondary shoots is in direct relation with the water status of the plant (HARDIE and MARTIN, 2000; LEBON *et al.*, 2005) and its nitrogen status (CONRADIE, 1980). The measures of vigour and vegetative expression are of particular importance for comparison of different situations, whether to compare plots (vineyards) with different situations, plots (vineyards) with different water relations and/or different nitrogen status or simply to compare, for a situation with the same vigour, different training systems (CARBONNEAU *et al.*, 2001b). These growth measurements must be linked to phenological stages and in this regard the use of the scale of LORENZ *et al.* (1995) is advised. Assessment of the carbon situation provides worthwhile information on the apportioning between organs (CONRADIE, 1980). Finally, the fact that the plant water status is explained in terms of the water supply (soil) together with the demand (canopy architecture, evaporative demand) must be emphasized. This increases the relevance of total leaf area and exposed leaf area measurements (CARBONNEAU, 1995; MURISIER, 1996; MABROUK and CARBONNEAU, 1996). In this regard, it must be recalled that the ratio Exposed Leaf Area/Yield (ELA/Y) must be interpreted in relation to plant vigour (CARBONNEAU, 1999). The ELA/Y ratio will have a higher value when the sinks competing with bunches are more numerous (the sinks of the primary and secondary shoots; their extent/size is evaluated by measurements of vigour (winter weight of a shoot) and vegetative expression (total pruning weight of a vine)). Extensive research has shown that the training system of the grapevine is an important component in the quality of the harvest and the style or typicality of the wines.

III - BERRY GROWTH

Berry selection as a function of diameter or sugar content enables the visualisation of the stages of berry growth and has confirmed the absence of a systematic relationship between the size of the berry and the sugar content per berry (DELOIRE *et al.*, 2004). The visual assessment of berry growth is uncertain/risky, and the selection method has shown that, for many cultivars and in many situations, there is heterogeneity in size and mass between berries on a bunch, bunches on a vine and bunches of different vines, which should be taken into account. There is equally a diurnal change in berry diameter in relation to the grapevine water status (GREENSPAN *et al.*, 1994). The number of classes and their frequency depends, inter alia, on the plant water status. For some studies (sugar or acid content, secondary metabolites, berry growth) it is of interest to work with berry classes (OJEDA *et al.*, 1999; OJEDA *et al.*, 2001). For some research, it may be necessary to study the mechanical properties of the berry, which reflect their turgidity in relation to the cultivar or the terroir (ROBIN *et al.*, 1997). The berry sampling needs to be very strict.

Recent studies have provided original results indicating that applied water stress between flowering and veraison does not modify cell division, but rather cell enlargement in an irreversible manner, depending on the intensity of the constraint (OJEDA *et al.*, 1999; 2001).

On the other hand any deficits during the period veraison to maturity can be reversed, due to the plasticity of the cell (the softening of the berry that is one of the first characteristics of veraison). The concentration-dilution phenomenon is indirectly dependent on the plant water status, which is in turn related to the available soil water reserve, water supplying incidents (rain, irrigation) and evaporative demand. For the grape berry, the number and size of cells are important aspects that participate in the quality of the harvest, similarly to the ratio skin surface/pulp (CARBONNEAU *et al.*, 1998). For this reason, the result of biochemical analyses of primary and secondary metabolites can be expressed either in concentration (generally expressed as mg/g) or as the result of biosynthesis (expressed as mg/berry).

IV - BERRY BIOCHEMISTRY

Berry volume and sugar accumulation are affected by several factors, such as plant water status, photosynthetic activity and temperature (VAN LEEUWEN *et al.*, 1994; PONI *et al.*, 1994 ; FLEXAS *et al.*,1999; OJEDA *et al.*, 2001; VAN LEEUWEN *et al.*, 2004). Berry growth depends principally on water supply, whereas the accumulation of sugar in berries depends on other factors, such source-sink and sink-sink relationships (CARBONNEAU and DELOIRE, 2001; WANG *et al.*, 2003a, b). The growth of grape berries from veraison to maturity may be divided into three phases that clearly correlate with the water status of the plant. The accumulation of sugar in the berry, in other words, phloem unloading, depends on the photosynthetic activity of the plant, which in turn depends on the water status of the entire plant throughout the day and during the course of ripening.

Numerous studies have been carried out on the effects of water stress on sugar accumulation in the berry. CARBONNEAU and DELOIRE (2001) have shown that moderate water deficits retard shoot growth without notably affecting photosynthetic activity, and that it facilitates the distribution of sugar in the berries and perennial organs during ripening.

Sugar phloem unloading in ripening grape berries via the apoplastic network is a process that requires sugar transporters, the intervention of enzymes and a source of energy (DAVIES and ROBINSON, 1996; FILLON *et al.*, 1999; AGEORGES *et al.*, 2000; WANG *et al.*, 2003a). It is possible that there are many sugar unloading mechanisms in the grape berry: apoplastic, symplastic or co-exited (BOSS and DAVIS, 2001). Water stress could reduce the activity of both the sugar transporters and the enzyme involved in the process thus leading to a reduction in sugar unloading in the ripening berry.

Depending on the severity of water deficit and the point in time at which it occurs (terroir effect) or at which it is applied (irrigated vines), a reduction in vegetative growth (plant vigor) can compensate for the observed reduction in photosynthetic activity without affecting berry sugar unloading (CARBONNEAU and DELOIRE, 2001). When moderate water deficit is regularly and continually applied throughout the ripening period of the berries, the accumulation of sugar at maturity is affected in a manner that is independent of berry volume: when the berry volume decreases at maturity due to water loss, the concomitant increase in sugar levels occurs more by concentration than by accumulation (i.e. sugar unloading).

The availability of water better explains the observed effects on berry volume, whereas photosynthetic activity, which is related to the ratio of exposed leaf area and yield quantity, accounts to a greater extent for the effects on phloem sugar unloading in the ripening grape berry.

Studies that have been undertaken on the evolution of berry phenols as « indicators » of the response of the vine (OJEDA *et al.*, 2002) have resulted in many observations:

The importance of considering the evolution of certain metabolites during the green growth stage of the berry (berry set - véraison). It is worthwhile to take the influence of the viticultural practices during this period into account in order to understand and interpret the growth and biochemistry of the berry in relation to the quality of the harvest.

The importance of dissociating results expressing concentration (mg/g or mg/L) from those expressing biosynthetic events (mg/berry).

The importance of taking into account, for a given water deficit situation, its period of occurrence, its duration and its intensity in order to explain the relationship « plant water status - berry biochemistry ». For example, the cultivars Syrah and Grenache noir differ in biosynthesis of anthocyanins or flavonols in relation to water deficits above a certain level (ψpd $\cong$ -0.6 Mpa; OJEDA *et al.*, 2002).

The importance of taking the bunch microclimate into account in the interpretation of the dynamics of berry biochemistry in relation to water stress and grapevine vigour.

To considere the evolution of the berry biochemistry in relation with the plant water content, and in interaction with the « puissance » (vegetative and yield production of the considered year) and the bunch microclimate (for a specific training system and mesoclimate).

Some of the phenolic components that have been studied play a role in the biodefense of grape berries. The relationship between plant water status and its ability to defend against « bioagressors » is, therefore, also a terroir component that should be taken into account together with the bunch microclimate and canopy architecture (DELOIRE *et al.*, 1998).

THE RELATIONSHIP BETWEEN GRAPES AND WINE

This complex subject has been studied by competent teams (*inter alia* FLANZY, 1998; BROSSAUD *et al.*, 1999). It has been shown that water stress could modify the value of tannins polymerisation (OJEDA *et al.*, 2002), information that was not available from the classic monitoring of maturation.

It must be questioned whether the impact of this type of observation on wine quality is in direct relation with the wine making process. In this regard, the sensorial analysis of berries (ROUSSEAU and DELTEIL, 2000) is an interesting technique for the determination of grape maturity, but it should be complemented, due to the desired level of understanding and knowledge of the functioning of « terroir-grapevine-wine » interaction, by more detailed analyses.

Following this, it is necessary to establish potential relationships between biochemical responses of the berry and the quality, the style and the typicality of corresponding wines. In this respect, investment in mini-vinification (0.5 to 1 hl) and in sensorial analyses is useful for comparison of different situations. The development of analytical techniques such as Infra Red spectrometry already allows the rapid, reliable and high turnover analyses of some primary metabolites and should in the future include secondary metabolites contained in must and wines. The relationship between the biochemistry of the berry, terroir and the typicality of the wine should therefore be more readily established.

CONCLUSIONS AND PERSPECTIVES

Studies of the grapevine response to terroir require the implementation of both the « whole plant-berry » approach and spatial modelling of the considered environmental parameters over the whole study area. Tools such as GIS, geophysics and remote sensing are being implemented for this purpose and related to plant data. High resolution remote sensing and soil resistivity measurements (geophysics) can be used for a « precision viticulture » approach (that is to say, at a fine resolution within a limited extent of a single vineyard). For instance, vine vigour may be differenciated using a vegetation index such as the NDVI, vine water status may be characterized through canopy temperature using a thermal InfraRed camera (ROBY *et al.*, 2004; MARGUERIT *et al.*, 2004). In this way, the genotype x terroir interaction can be spatialized.

The proposed « grapevine-terroir-wine » study method is not exhaustive and could be improved. The available methods do, however, allow some industry needs to be met. Current studies can be differentiated based on the duration of the analysis of the responses of the grapevine to the terroir:

- Short term studies (for one cycle), which allow a preliminary zoning of grapevines within a vineyard or group of vineyards (e.g.: zoning of vine water status by means of $\delta^{13}C$ or LWPpd; monitoring of grape ripening).

- Medium length studies (at least 3 years), which allow the integration of the vintage effect.

- Studies of long duration, which, together with spatial and temporal repetitions, allow the complete characterisation of a viticultural zone.

Depending on the study objectives and available means, there must be agreement between the desired duration of the study, the extent of the area and the methods to be used. For example, the measurement of $\Delta^{13}C$ or LWPpd during the developmental cycle of the grapevine already enables a preliminary zoning of the plant water relationship on the studied plots. To investigate the stability of the terroir, the importance of repeating the measurements over different vintages (at least 3 years) must be accepted. A frequency analysis performed for a long period of data pertaining to berry analyses of Grenache noir in central Côtes-du-Rhône (primary metabolites and mass of 200 berries) has shown that a series of 7 years best approaches the results of a series of 17 years (1982 - 1998), but that a poorly chosen series of 3 years (1995 - 1997) does not really represent the maximum period considered (VAUDOUR, 2001).

The proposed kinetic studies, for example the biochemical evolution of berries together with the monitoring of the water status of the grapevine, will enable a more rapid determination of the vintage effect for a specific cultivar on a specific terroir, whereas a series of three to five years of measurements of the relationship « grapevine-berry-wine »will enable a more accurate determination of the terroir effect.

The possible objectives of these studies are notably:

a) on the one hand to provide a better understanding of the relationship « terroir-wine », which can be used for internal communication (for example between members of a cooperative cellar to justify the necessity for vineyard selection and/or the choice of dates of harvest) or external communication to defend the terroir concept with the aid of precise or accurate arguments,

b) and, on the other hand, in the short term, to provide advice on the adaptation of viticultural practices and wine-making techniques to specific terroirs, in relation to the type of product desired by the markets. Furthermore, it is necessary to explain why different styles of wines are obtained from the same grape variety grown on different types of terroirs.

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