# IS IT POSSIBLE TO ASSESS THE SPATIAL VARIABILITY OF VINE WATER STATUS?

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## Abstract

**Aims**: Plant water status monitoring during the vineyard growth cycle constitutes a basic parameter for both harvest quality and vineyard management. Unfortunately, the plant water status measurement requires skills and heavy devices which drastically limit the number of repetitions either in space or in time. Moreover, due to the significant spatial variability in viticulture, extrapolation of one local measurement to a larger scale, vine field or vineyard, is difficult. Therefore, the design of tools and methods to characterize and to assess the spatial variability of plant water status constitutes a big challenge. The aim of this paper is to propose an approach allowing the spatial variability of the plant water status to be assessed.

**Methods and results**: This work proposes a complete literature review of previous works using different approaches to assess the vine water status. Based on this review, it leads to a conceptual approach considering the Spatial (S) and Temporal (T) variability of the plant water status assessment at a whole vineyard scale. This paper is divided into three sections: (i) description of plant water status reference methods based on direct measurements on the plant, (ii) plant water status assessment methods based on auxiliary information (i.e. weather, soil and plant vegetative expression), and finally (iii) a proposal for combining local reference measurement and auxiliary information to characterize the spatial variability of the vine water status at the vineyard scale.

**Conclusion**:Taking into account restrictive assumptions, this paper points out the possibility to provide relevant spatial assessment of the vine water status. This possibility is illustrated with a simple example.

**Significance and impact of the results**: This work gives an answer to the significant problem of vine water status assessment over space. It proposes an approach based on high spatial resolution auxiliary information to extrapolate a measurement (PLWP or SWP) made at a given time on a reference site. This proposal determines the different steps for further investigations aiming at proposing a spatial model of vine water status.

**Key words**: grapevine, vine water status, spatial and temporal variability, water restriction zones.

## Résumé

**Objectif** : L'évolution de l'état hydrique de la plante au cours du cycle végétatif est un paramètre important pour la gestion du vignoble et de la qualité de la vendange. Malheureusement, cette mesure fait appel à des dispositifs spécifiques particulièrement contraignants, ce qui limite fortement le nombre de mesures réalisables. La résolution spatiale et temporelle des mesures d'état hydrique est donc généralement faible. Compte tenu de la forte variabilité spatiale observée en viticulture, l'extrapolation de quelques mesures ponctuelles à une zone plus large peut s'avérer délicate. La conception d'outils et de méthodes qui permettent de caractériser cette variabilité constitue à la fois un enjeu et un défi. L'objectif de ce travail est de proposer une approche permettant d'estimer la variabilité spatiale de l'état hydrique des plantes.

**Méthodes et résultats** : Cette proposition s'appuie sur un état de l'art exhaustif des principes de mesures et envisage une approche de modélisation. L'article est divisé en trois parties : (i) une description des méthodes de référence, mesures directes effectuées sur la plante, (ii) une revue des méthodes d'évaluation indirecte, basées sur des informations auxiliaires (climat, sol, expression végétative) et finalement, (iii) une proposition de combinaison des deux approches en vue de caractériser la variabilité de l'état hydrique des plantes à l'échelle du vignoble.

**Conclusion** : Ce travail ouvre des perspectives relatives à l'utilisation de données auxiliaires à haute résolution spatiale pour estimer la variabilité spatiale de l'état hydrique des plantes. Cette perspective est illustrée à travers un exemple simple. Ce travail met également en évidence les limites et les hypothèses de base à formuler pour mettre en œuvre l'approche proposée.

**Signification et impact de l'étude**: Ce travail propose une réponse au problème de l'estimation de l'état hydrique des plantes à l'échelle d'un domaine. Il envisage une approche basée sur l'utilisation de données à haute résolution pour extrapoler une mesure de référence (potentiel hydrique de base ou potentiel hydrique de tige) réalisée à un moment donné sur un site particulier. Cette proposition permet de mettre en évidence toutes les étapes de recherche nécessaires afin d'arriver à un véritable modèle spatial d'estimation de l'état hydrique des plantes.

**Mots clés**: vigne, état hydrique de la vigne, variabilité spatiale et temporelle, zones de restriction hydrique.

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## INTRODUCTION

Several researchers have shown that changes in grapevine water status have a direct effect on grape composition and quality through its influence on vegetative growth, fruit growth, yield, canopy microclimate, and fruit metabolism (van Leeuwen and Seguin, 1994; Dry and Loveys, 1998; Ojeda *et al.*, 2002; Trégoal *et al.*, 2002). Therefore, spatial and temporal knowledge of changes in vine water status is important for deciding several managements inside the vineyard (i.e. harvest from different section of a vineyard block, leaf area, crop load, root stocks selection, etc). However, from an irrigation point of view, the vine water status is of critical importance for deciding whether or not irrigation practice is required at a given time. Adequate irrigation management can be performed using vine water status monitoring over time. Depending on the accuracy of the method used, vine water status monitoring can lead to the development of a relevant decision support tool, which could enable grape growers to optimally manage vineyards for vegetative and fruit growth.

As well, many authors have shown that the majority of vineyards present a great spatial variability in the following factors: yield (number and size of bunches), vegetative growth (canopy density), sugar and grape quality components (Ortega *et al.*, 2003; Bramley and Hamilton, 2004; Taylor *et al.*, 2005). It has also been shown that vine water status presents a significant magnitude of variation even in a single field (Tisseyre *et al.*, 2005; van Leeuwen *et al.*, 2006). This vine water status variability is especially evident at the end of summer when significant water restriction is found under non-irrigated conditions (Ojeda *et al.*, 2005a). Ojeda *et al. (*2005a) showed that, in a single field, the magnitude of variation of the predawn leaf water potential was of -1.6 Mpa over the time and more than -1.2 Mpa at the within field level. Therefore, in addition to temporal water status monitoring, spatial variability of vine water status also needs to be considered.

Spatial variability of vine water status can occur on very different scales depending on the driving factor. Climate variability may mainly explain differences on large scales. Soil and meso-climate variability may explain differences between blocks, even within a given field. The variation in soil components can sometimes be discerned within a-meter-scale (Hellebrand and Umeda, 2004). Since soils are the main substrate for plants, their variations in water holding capacity, induced by variations in texture and soil depth, within a whole field may induce high variability in vine water status (Tisseyre *et al.*, 2005; Ojeda *et al.*, 2005a).

The most appropriate method for monitoring vine water status would then require taking into consideration both sources of variability: (i) the evolution of vine water status over time (T) (growing period) and (ii) spatial variability (S). Therefore, an efficient decision support tool must be based on a Spatio-Temporal (S-T) vine water status monitoring system. This means a system which is able to provide maps or snapshots of plant water status variability in the whole vineyard during the entire growing season.

Most past research on vine water status monitoring have focused on temporal variability (T). Mainly with the practical goal to define the opportune moment for irrigation, maximizing water use efficiency and improve the wine grape quality. These studies aimed at providing efficient and accurate tools to assess plant water status. Thus, different sensing systems and methods have been developed to offer the best estimation of vine water status. This research has supplied sensors that allow the plant water status to be measured very accurately at the leaf level or at the plant level. It has also considered different approaches which take into consideration weather and/or soil data to generate empirical models to estimate the indirect effect of plant water restriction over time (Goodwin and Macrae, 1990; Jensen *et al.*, 1990; Allen *et al.*, 1998; Ortega *et al.*, 2000; Lebon *et al.*, 2003).

Very few authors have focused on spatial variability. Therefore, more relevant tools for growers need to be considered for the large amount of variability in water status within a vineyard and its effect on grape quality and yield (Ortega *et al.*, 2003; Bramley and Hamilton, 2004; Taylor *et al.*, 2005).

It is fundamental to explain that two spatial scales are simultaneously and independently considered in this study. The first spatial scale to be considered deals with the area over which the data provided by a sensor or a measurement is valid. Most of the methods dedicated to the assessment of plant water status are punctual. That means, they provide information only about the specific site where the assessment is carried out. However, depending on the sensing systems and the type of measurement, a large variability can occur even at the site of measurement. That means a method based on leaf measurement necessarily presents a larger variability than a method based on the stem or the whole canopy.

The second spatial scale to be considered deals with the management scale. It has a much more complex definition, since it refers to an area over which climate, soil characteristics and the resulting vine response imply similar types of management practices (training systems, fertilization, irrigation, etc.). These areas (or zones) are sometimes defined by soil units based on expert analysis of auxiliary information (i.e. elevation, soil depth, soil colour, or other knowledge). Figure 1 shows an example of such a definition. It considers a whole vineyard (D)

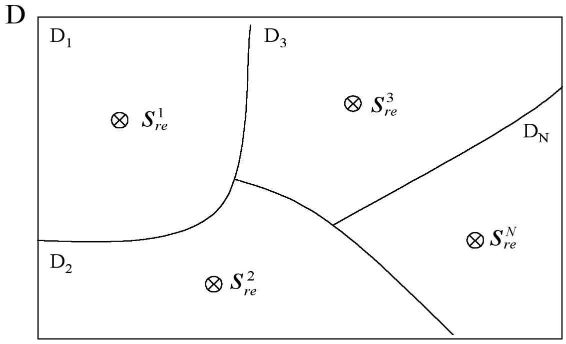


**Figure 1 - Illustration of a sub-zones $D_n$ at a vineyard spatial scale.**

D constitutes the study area (the vineyard) and $(D_n)_{n = 1...N}$ are the sub-zones belonging to D. $S_{re}^n$ is considered as a reference site for $D_n$ ($S_{re}^n \in D_n$). Definition of a reference site is introduced latter in the paper.

which constitutes the study area. It assumes homogeneous weather conditions over D. Conversely, different types of soil were observed; for example, deep sandy soils on $D_1$, limestone on $D_2$,..., etc. $(D_n)_{n = 1...N}$ can be considered as sub-areas or sub-zones of D. Characteristics of each sub-zones determine management practices (choice of variety and rootstock, density, training systems, etc.). A sub-zone may present very similar characteristics, but this does not mean it is homogeneous. For example, differences in soil depth can be found in $D_1$ even if the soil is mainly sandy, regular changes in limestone layers can be observed in $D_2$ inducing a large variability of vine response within D.

The aim of this paper is to propose a complete literature review of previous methods to assess the vine water status. For each method, this paper focuses mainly on (i) a brief description of the principle, (ii) the meaning of the measurement and its relevance towards plant water status estimation, (iii) the practical implementation of the method and its ability to provide measurements either over S or T and, (iv) the underlying assumptions which are considered either in the S or in the T data collection. Based on this review, this paper presents a relevant approach to take into account the spatial and the temporal variability in vine water status assessment at a within vineyard scale. Table 1 provides a summary of the information presented in the following sections.

## PLANT LEVEL MEASUREMENT

In recent years, plant-based measurements have been proposed to assess and quantify the level of water restriction affecting the plants. Consequently, due to their accuracy, some growers are currently using plant-level measurement techniques practically as the unique method to monitor plant water status. These methods provide a direct measurement of plant physical and physiological parameters to assess water status.

An accurate method of vine water status measurement should be one which responds quickly to change in vine water restriction, soil water availability, soil hydraulic conductivity and the ability of the vine to transport water from the soil to the atmosphere (Choné *et al.,* 2000; Choné *et al.,* 2001). A subdivision of these methods based on data collection techniques can be presented as: reference measurements, used to measure the effect of a determined level of water restriction on the vine (usually manual methods), and the plant water status monitoring systems which can collect a large number of measurements over a short period of time.

### Reference measurements

1.1.1 Stomatal conductance ($g_s$)

Stomatal conductance ($g_s$) consists in measuring the water vapour pressure gradient (air flow) between the vine leaf and the atmosphere (water diffusion through vine leaf stoma). $g_s$ is the first factor to be affected by either water stress or high atmospheric demand due to the effect of plant stomatal regulation (Cifre *et al.*, 2005). A high correlation between $g_s$ and plant water potential and/or relative water content has been observed in some grapevines under specific conditions (Bravdo and Naor, 1996; Cifre *et al.*, 2005). According to Flexas *et al.* (2002) and Cifre *et al.* (2005), $g_s$ can be considered as an integrative parameter reflecting the severity of water restriction on different grapevine cultivars. Thus, as plant water restriction increases due to high atmospheric demand and/or soil water deficit, it results in reduced $g_s$ and leaf transpiration rates (Loveys *et al.*, 2001).

Frequently, stomatal conductance and transpiration rate measurements are made at the leaf scale using porometer and gas exchange instrumentation. However, $g_s$ monitoring data are characterized by a high degree of variability between measurements. Therefore, this method requires a great number of single point measurements to be able to accurately characterize variability in the whole canopy of the grapevine. Sampling becomes even more critical when it deals with the assessment of a whole field. For example, in their particular conditions, Loveys *et al.* (2005) defined an optimum sampling strategy to obtain a relative standard error of 5 % at the field scale. This strategy required the sample of 32 vines with four measurements per vine which lasts three hours per field (Loveys *et al.*, 2005).

1.1.2 Plant water potential

Many authors have proposed the use of the pressure chamber method (Scholander *et al.,* 1965) as an excellent tool to measure vine water status under irrigated and non-irrigated conditions (McCutchan and Shackel 1992; van Leeuwen and Seguin, 1994; Naor *et al.*, 2001; Ojeda *et al.*, 2002). Vine water status can be assessed using different pressure chamber approaches such as: (i) leaf water potential (LWP), (ii) stem water potential (SWP) and (iii) predawn leaf water potential (PLWP) (Schultz, 1996; Choné *et al.*, 2000; Choné *et al.*, 2001; Ojeda *et al.*, 2002; Carbonneau *et al.*, 2004; Girona *et al.*, 2006; Sibille *et al.*, 2007).

a) Leaf water potential (LWP)

LWP is commonly used as an auxiliary tool in irrigation scheduling (Loveys *et al.*, 2001). It is made on leaves that are extracted and measured *in-situ* (without waiting for any process of plant stabilization). It is commonly done at the time of the day when the evaporative demand by the atmosphere is maximum. However, the main disadvantage of this method is that the values of water potential are highly variable between leaves and between plants due to differences in the transpiration rate of the canopy (which depends on stomatal behaviour) (van Leeuwen *et al.*, 2007). Thus, LWP represents only the leaf water potential without any kind of plant integration.

b) Stem water potential (SWP)

A pressure chamber can be used to measure SWP and the procedure involves covering a leaf with an aluminium foil bag coated with plastic to stop leaf transpiration (Begg and Turner, 1970). With the transpiration close to zero, leaf water status equilibrates with the stem of the vine. Therefore, the values of water potential measured in the chamber represent SWP (McCutchan and Shackel, 1992). Unlike the LWP, the SWP represents the water potential of the whole vine plant. The midday SWP corresponds to measurements of this parameter at the time of day when the evaporative demand by the atmosphere is maximum (Prichard and Verdegaal, 2001). Various authors have proposed midday SWP as a sensitive physiological indicator of the water status for fruit trees under irrigated conditions (McCutchan and Shackel, 1992; Naor *et al.*, 2001; Choné *et al.*, 2001).

c) Predawn leaf water potential (PLWP)

PLWP assesses the plant water potential measured with a pressure chamber between 3:00 and 5:00 a.m. Thus, PLWP measures the plant water status with zero water flux through the plant and provides information about soil water status close to the root-zone (Katerji and Hallaire, 1984). Indeed, PLWP is considered to be a surrogate for soil matrix potential since during the night, when stomata are closed and transpiration pressure is low, leaf water potential becomes equilibrated with the water potential in the soil. However, PLWP represents the soil water potential in the most humid soil layer and might thus not be representative of average soil water potential when soil water is heterogeneous (Ameglio *et al.*, 1999).

d) Which plant water potential to use ?

The selection of the appropriate method (LWP, SWP or PLWP) depends on the conditions in which the measurements are made. These conditions can be described by the irrigation method used and the water restriction level. Thus, Sibille *et al.* (2007) showed that in the case of vine water status under high-water restriction conditions to extreme water restriction conditions (PLWP $< -1.0$ MPa), the PLWP was a better option than SWP. To the contrary, LWP and SWP present a higher sensitivity in the low water restriction level ($-0.4 <$ PLWP) (irrigated conditions) compared to PLWP (Sibille *et al.*, 2007). Furthermore, PLWP gives a good estimation of vine water status in the case of homogeneous distribution of water in the soil (flood irrigation or rain feed crops). However, it does not behave in the same way for heterogeneous soil water conditions (partial root-zone drying irrigation and more generally all sorts of drip irrigation) where the use of this indicator is questionable (Améglio and Archer, 1996). PLWP is not a good indicator for irrigation when drip irrigation is implemented (Ameglio *et al.*, 1999).

It is important to consider that depending on the method used, it is possible to make different physiological interpretations from the values obtained. For example, in the case of LWP and SWP, the stomatal behaviour has a strong effect on measurement results. This is mainly due to the direct dependency of LWP and SWP on the stomatal behaviour and water vapour transport processes through the leaf. For this reason, it is more complex to compare values of SWP or LWP between near-isohydric and anisohydric behaviour cultivars, especially when a high water restriction condition is reached (PLWP $\leq -0.8$ MPa) (Sibille *et al.*, 2007; Ojeda *et al.*, 2005b; Shultz, 2003). Moreover, in the case of the PLWP, the stomatal behaviour of the variety is less important, since this method directly gives the soil water status. Therefore, the values of PLWP between different varieties would be comparable, especially if the vines are under strong water restrictions and on the condition that soil humidity is homogeneous (Sibille *et al.*, 2007).

1.1.3 Carbon isotope composition measurement ($\delta^{13}C$)

The carbon 13 isotopic discrimination method is another physiological indicator that is able to integrate the water regime applied to grapevines from veraison to harvest. This method is based on the following known facts: (i) the $^{13}C$ represents 1.1 % of carbon in the $CO_2$ atmospheric concentration and (ii) the $^{12}C$ (lighter than $^{13}C$) is preferentially used during the photosynthesis.

Thus, when soil water availability decreases, leaf water potential also decreases causing partial stomata closure. The later process reduces $CO_2$ exchange between the leaf and the atmosphere (coupled with water diffusion through the stomata), limiting the isotropic discrimination. The ratio $^{13}C/^{12}C$ (denoted $\delta^{13}C$) comes close to the described condition compared to the atmospheric $CO_2$. Therefore, an integrated indicator of water restriction has been based on this isotropic relation. The period that this indicator considers is the synthesis of sugar in berries, which is from veraison to harvest. The $\delta^{13}C$ is expressed in ‰ compared to a standard (Pee Dee Belemnite standard, Farquhar *et al.*, 1989) and values can range from - 20 to -26 ‰, where -20 ‰ indicates a strong water restrictions and -26 ‰ an absence of water restriction (Gaudillère *et al.*, 2002). The interest in assessing plant water stress based on this indicator resides in two main advantages: i) samples for $\delta^{13}C$ measurements are only required during berry maturation (van Leeuwen *et al.*, 2001); ii) a single sampling time allows monitoring a large number of fields, which is not possible using other water-stress assessment methods, such as the pressure chamber.

## 1.2 Plant water status monitoring system

These methods are characterized by continuous monitoring of the physical and physiological parameters of the plant using data loggers. The main advantage of these systems is their ability to take a large number of measurements in a short period of time, making it possible to assess temporal changes in the plant parameters that can occur on a relatively short time scale.

### 1.2.1 Transpiration measurements (Sap flow sensors)

Sap flow sensors measure the rate at which sap ascends the stem using heat as a tracer (Huber, 1932). The main methods to measure sap flow velocity are: (i) heat balance, (ii) heat-pulse velocity and (iii) thermal dispassion (Granier, 1985). These methods allow transpiration rate estimation for the whole plant (Fernández *et al.*, 2001; Giorio and Giorio, 2003).

A decrease in soil water availability induces a reduction in $g_s$ and decreases plant transpiration (Davies *et al.*, 2002). Escalona *et al.* (2002) have demonstrated a very high correlation between single leaf $g_s$ and the instantaneous sap flow in a water-restricted potted grapevine.

Sap flow measurements give reliable, direct estimates of plant water loss without disturbing the leaf environment conditions (Fernandez *et al.*, 2001; Cifre *et al.*, 2005). Therefore, a direct measurement of real vine water use can be obtained without considering water evaporation from the soil (Escalona *et al.*, 2002; Yunusa *et al.*, 2000). Under irrigation conditions, sap flow measurement has proved to be a good tool for estimating canopy transpiration (Yunusa *et al.*, 2000; Cifre *et al.*, 2005). Thus, this method can be used as an auxiliary tool for irrigation scheduling. However, this method is difficult to adapt to adult vine with a thick trunk.

### 1.2.2 Trunk diameter fluctuations monitoring (Dendrometry)

The shrinking and the swelling of the extensible plant tissues provide an indirect measurement of the transpiration streams during daylight periods, and is related to changes in water content and turgor of plants. Therefore, diurnal stem diameter contraction monitoring has been proposed in the past as a mean to monitor plant water status, which can be related to plant growth and water-use (Naor and Cohen, 2003; Cifre *et al.*, 2005). Trunk diameter has been shown to be indirectly related to plant water status, as is LWP (Naor and Cohen, 2003).

Maximum Daily trunk Shrinkage (MDS) was proposed as a plant water stress indicator suitable for irrigation scheduling purposes because it was found to be highly sensitive to changes in soil water availability (Naor and Cohen, 2003). MDS is closely related to plant water status in deficit irrigation treatments due to a strong relationship between the stress imposed and the relative MDS. Weather conditions influence MDS causing greater MDS on hot days characterized by high evaporative demand compared to milder days (Loveys *et al.*, 2001). Nevertheless, in grapevines, MDS is only representative until veraison. After this period, the important production of bark in the trunk makes non-sensible this measurement. Therefore, the sensor must be moved to one of the shoots and then the information generated is difficult to compare with previous data. Furthermore, the shoot may not represent the water status of the whole plant.

### 1.2.3 Leaf and canopy temperature

It has been long recognized that leaf and canopy temperature is highly dependent on the transpiration rate and can therefore be used as a stomatal behaviour indicator (Sinclair *et al.*, 1984). Remote infrared sensing of canopy temperature (as a surrogate for $g_s$) has become an established technique for plant water status assessments (Idso, 1982; Jones, 1999). Infrared Thermography (IRT) has been proposed as an appropriate method for assessing grapevine water status reducing the high variability associated with single point measurements using IRT (Jones *et al.*, 2002).

The increasing availability of infrared imaging analysis tools opens up the possibility of high-resolution studies of stomatal behaviour variations over leaf surfaces. By measuring canopy temperature, using the IRT technique and the index of canopy conductance ($I_g$) proposed by

Jones (1999), it is also possible to integrate a large number of leaves into the measurement, effectively reducing the error associated with leaf to leaf or vine to vine variation.

### 1.3 Technical and spatial consideration

The main advantage of the methods presented in sections 1.1 and 1.2 is to provide a relevant assessment of the plant water status on the plant basis. This means that the real response of the plant to water restriction is taken into account. Nevertheless, each of these methods presents significant drawbacks, which limits the number of field measurements.

In the case of plant water potential (Scholander *et al.*, 1965), the measurement requires an expensive heavy device which has to be brought into the field. Moreover, measurements are manual and time consuming; they sometimes have to be done at dawn (for PLWP), which constitutes a significant constraint for labor management and limits the number of samples measured each day. For $g_s$ estimation, the technical constraints are similar since manual measurements using a porometer or a gas exchange chamber are required in that case. These constraints constitute strong limitations in the use of reference methods. Nevertheless, $g_s$ estimation and plant water potential are supposed to provide the best estimation of plant water status.

Considering the $\delta^{13}C$ method, it requires a high initial and running investment (associated instrumentation and laboratory analysis). This drawback could drastically limit the spatial resolution of the measurements since an important number of samplings and analyses within the vineyard is required to highlight the spatial variability of the vine water restriction. Another significant drawback of the method, in the frame of this work, is due to the characteristics of the $\delta^{13}C$ technique which gives an information of the water restriction experienced by the vines after harvest (berry collection during harvest). Obviously, this information is to late for irrigation scheduling management during the season. However, we will see later in this paper, that the $\delta^{13}C$ could provide relevant information of the plant water status spatial variability. Assuming spatial patterns highlighted by this technique are time stable, the $\delta^{13}C$ could constitute a relevant auxiliary information to model the spatial variability of the plant water status in association with other measurements.

The development of plant water status monitoring systems allows this problem to be partly addressed. These methods can provide an estimate of this measurement with a high temporal resolution since a data logger is used to monitor plant water status. Nevertheless, these methods also present significant limitations:

- The measurements provided by trunk diameter sensors or sap flow sensors have to be carried out on the same plant. The relevance of such information is mainly due to its dynamic variation over the season; different plants can show different responses at different times of the season complicating data interpretation.

- The cost and the maintenance of the system limits the number of devices that it is possible to use at the vineyard scale. The amount of available information in terms of space is consequently small, limiting the knowledge of the spatial variability of plant water status.

- For each system (trunk diameter sensors, sap flow sensors or infra-red thermography), the measurement does not provide any direct estimation of the plant water status. For irrigation scheduling, these monitoring systems can constitute a relevant decision support system. Nevertheless, for other purposes, if a reference measurement is required, a calibration model provided by previous experiments performed on the same location has to be defined. Such models developed on specific locations have already been proposed in the literature for sap flow (Escalona *et al.*, 2002), trunk diameter (Naor and Cohen, 2003) or canopy temperature measurements (Jones, 1999; Möller *et al.*, 2006). These studies show that a relation between monitoring systems and reference measurement is possible locally. However, they require extensive experimentation.

## PLANT WATER STATUS ASSESSMENT BASED ON AUXILIARY INFORMATION

There are indirect methods based on mathematical models that can be used to estimate plant water status. These models use auxiliary information like weather and/or soil variables to provide an indirect plant water status assessment. Therefore, these methods are widely used for irrigation scheduling design. Depending on the auxiliary information used, such methods can provide estimation on very different spatial scales. Thus, the study of water transport through the soil - plant - atmosphere continuum provides the standardization of critical parameters to represent plant water status. After identifying these critical parameters, a validation process is made comparing them with physiological reference measurement (see section 1).

Over the last years, many new technologies have been developed and adopted in agriculture such as: Global Positioning Systems (GPS), on-board crop and soil measurement systems and reliable devices to store and exchange/share information, among others. These new technologies applied to viticulture produce a large amount of auxiliary information easily available at a high-spatial resolution (i.e. remote sensing and soil electrical property maps), which can be used to define different water restriction zones at the vineyard scale (Acevedo-Opazo *et al.*, 2007).

**1. Climate**

A large number of more or less empirical methods have been developed over the last 50 years by numerous scientists and specialists worldwide to estimate evaporation from an open water surface from different climatic variables. These methods classically combine the energy balance with the mass transfer method and derive an equation to compute the evaporation from standard climate records of sunshine, temperature, humidity and wind speed. They are used to provide an assessment of the water consumption of the plants which, in addition with soil average characteristics (water holding capacity), are widely used for irrigation scheduling design.

Available methods and indices used to estimate vine water consumption based on weather variables can be summarized as: (i) methods to estimate the crop evapotranspiration like the Penman-Monteith method recommended by the FAO (Food and Agriculture Organization of the United Nations) (Allen *et al.*, 1998; Bois *et al.*, 2008a; Bois *et al.*, 2008b), (ii) methodologies to estimate the plant water status (crop and soil water stress indices).

Crop evapotranspiration (ETc), or water consumption of the plants, is determined using empirical models (Penman-Monteith, Blanney-Criddle, Radiation and Class A evaporation pan). Accurate results can be obtained using the Penman-Monteith method for non-stressed plants due to the incorporation of the canopy resistance parameter (rc). Various models have been proposed to estimate rc using weather variables (Allen *et al.*, 1989; Pereira *et al.*, 1999).

Others approaches have been developed to assess and quantify the stress level in vines at different phenological stages to maximize crop water use efficiency in order to control vigour harvest quality and yield. The most common one implies the use of the Crop Water Stress Indices (CWSI). This approach is based on the crop evapotranspiration estimations corrected by infrared thermometry and Vapour Pressure Deficit (VPD) to construct a plant water stress index which was related to the plant water potential (Idso *et al.*, 1981; Sammis *et al.*, 1988; Goodwin and Macrae, 1990; McCarthy, 1997).

For all these methods, weather information is the key parameter to estimate the vine water consumption derived from evaporation models. The advantage of these approaches relies on the ability to record the information with a high temporal resolution by means of automatic weather stations. Such systems have been available for a long time and as a result have a wide adoption by growers. Moreover climatological records are assumed reliable over a large area (at least the vineyard). However, depending on the topographic conditions, the area over which climatological data are relevant may vary drastically, this last point is still under research (Stahl *et al.*, 2006, Martinez-Cob *et al.*, 1996). In the rest of this review, the study area (D) will be considered small enough to assume homogeneous climate.

**2. Soil**

The soil is the main substrate for the plants; its variation in water holding capacity, induced by variations in texture and soil depth at the field scale may induce a high variability in plant water status (Tisseyre *et al.*, 2005; Ojeda *et al.*, 2005a; van Leeuwen *et al.*, 2006; van Leeuwen *et al.*, 2007). Thus, soil variability may explain differences at the within field level as well as between fields. There are different approaches which take into consideration the soil data to estimating the effect of water restriction on plants over time. One of the most studied approaches is based on evaluation of the soil water resource and its influence on plant water status (McCarthy, 1997; Peregrino *et al.*, 2004; Loveys *et al.*, 2005).

There are many methods available for soil moisture monitoring, nevertheless, they are quite expensive and tend to be used at only a few points. Some methods like tensiometers are based on soil water potential measurement other methods are based soil water content assessement, this is the case of neutron moisture probes, TDR probes and capacitance sensor, among others). Both methods are commonly used in vine irrigation scheduling. The tensiometers are mainly used to control the size and the depth of humid soil in drip irrigation, The other methods measure the punctual Soil Water Content (SWC) with relatively little disruption (Topp *et al.*, 1980; Ortega-Farías and Acevedo, 2004). These sensors assess SWC indirectly by different principles such as: pressure indicator, soil electrical resistance assessment, and measuring the travel time through the soil of a short pulse of electromagnetic energy, among others.

Plant water restriction can be monitored using soil moisture measurements during the season. Locally, soil moisture can be correlated to evapotranspiration (Stevens *et al.*, 1995; McCarthy, 1997). This allows the creation of Soil Water Stress Indices (SWSI), which are based on soil water content measurements close to the root-zone (McCarthy, 1997; Colaizzi *et al.*, 2003). The use of these SWSI in irrigation scheduling programs has allowed, for example, the grape and wine quality to be improved for the cv. Cabernet-Sauvignon (Ortega-Farías *et al.*, 2004b).

Soil water status and the relationship with the plant water status are commonly evaluated to obtain plant water stress diagnosis. This method uses the fractions of Transpirable Soil Water (FTSW) to characterize the soil water deficit experienced by the plant (Lebon *et al.*, 2003; Pellegrino *et al.*, 2004). Lebon *et al.*, (2003) showed that FTSW is linked to several variables describing vegetative growth in vines growing in pots. These results show that FTSW is sensitive to quantify the soil water deficit experienced by a crop. However, the positioning of soil moisture probes is critical to get representative information about soil water status for crops using trickle irrigation (Li *et al.*, 2002; Fuentes *et al.*, 2004). A probe located in a dry spot in the soil will give underestimated soil moisture values while another located in a non-representative wet soil will generate an overestimated one.

## 3. High-spatial resolution information

No sensor providing a direct assessment of the plant water status with a high spatial resolution is currently commercially available. The most promising technology is infra-red thermography to derive plant water status and stomatal conductance from the canopy temperature. Many authors investigated this way at the leaf and the plant level (Jackson *et al.*, 1981; Sepaskhah and kashefipour, 1994). It was more recently applied with infra red camera at the vine level (Jones, 1999; Jones *et al.*, 2002; Möller *et al.*, 2006). This approach is interesting, however, (i) it requires temperature calibration with field measurements during image acquisition, (ii) in the field, (proximal) sensors are still very expensive which reduces the potential number of measurement sites, (iii) and finally resolution of thermal images provided by satellites is still too low for vine applications.

Therefore, an alternative approach to characterize spatial variability would be based on low cost complementary information that is easy to get at a high-spatial resolution (for example multispectral images from airborne or satellites, soil electrical conductivity maps) to define time stable zones with different water restriction (Taylor *et al.*, 2004; Tisseyre *et al.*, 2007; Acevedo-Opazo *et al.*, 2007, 2008). The following sections provide a brief description of possible high resolution information sources and then detail their potential and limits to characterize spatial variability of plant water status. Table 1 summarizes the information presented in the following sections.

1- Plant variability

a) Airborne imagery

Optical remote sensors detect and record sunlight reflected from the surface of objects on the ground. The ability of a sensor to detect object reflectance is quantified in terms of the spatial and spectral resolution of the sensor (Hall *et al.*, 2002). Airborne imagery is currently dominated by multi-spectral sensors due to their low cost and easy operability (Blue, Green, Red and Near Infra-Red wavelengths). For viticulture purposes, the required spatial resolution of an image is generally about 1-3 $m^2$ per pixel. This resolution is applicable to the inter-row width (densities between 3,000 and 4,000 vines $ha^{-1}$) (Tisseyre *et al.*, 2007). However airborne imagery may also be used at larger scale to provide information at the regional scale; for example Montero *et al.* (1999) used satellite images to provide an assessment of vine development according to available water resources at a regional scale corresponding to La Mancha in Spain.

Since the collected information contains mixed pixels, which includes reflectance from the vines and the soil, images are generally processed to produce indices, such as NDVI (Normalised Difference Vegetative Index) or Plant Cell Density (PCD) for every pixel (Tisseyre *et al.*, 2007). These indices are generally used as a vigour assessment. In viticulture, vigour generally refers to the vine growth rate (of shoots). Whereas, in remote sensing, vigour refers to a combination of plant biomass (vine size) and photosynthetic activity, termed the « photosynthetically active biomass » (PAB) (Bramley, 2001). The computed index (either PCD or NDVI) can be related to vigour, since vigorous vines are characterised by larger and denser canopies than vines of lower vigour. Many authors have shown relationships between NDVI and Leaf Area Index (LAI) (Johnson *et al.*, 2003), annual pruning weight (Dobrowski *et al.*, 2003) and other vine parameters (Lamb *et al.*, 2004) at the vineyard scale. Therefore, the use of remote sensing data often constitutes a relevant and low cost information source to perform vigour zoning at the field scale (Hall *et al.*, 2002; Bramley *et al.*, 2005).

In conditions where water is the limiting parameters, vigour is strongly related to soil water availability, therefore NDVI maps may provide relevant information to zone the vineyard according to water restriction (Tisseyre *et al.*, 2007; Acevedo-Opazo *et al.*, 2007).

Despite its relevancy, this information presents some analytical challenges for the considered application. Canopies are highly discontinuous in viticulture, especially in the case of vertical shoot positioning systems where large areas of soil appear between vine rows. To cope with this problem, a moving averaged window of NDVI calculation can be used. This solution leads to mixed pixels where soil, cover grass along the inter-row, training systems and summer trimming operations may affect the NDVI values. Most of these problems are overcome with an image acquired in the late summer (after veraison), when growth has stopped and the canopy has achieved its maximum size. Under non-irrigated Mediterranean conditions this solution is also convenient to overcome the problem of cover crop since grass is dry, thus minimizing the effect on NDVI values. Under other conditions (irrigated or humid areas), inter-row cover crop may remain a significant problem, leading to more sophisticated image processing. In that case, image resolution has to be high enough (less than 30 cm pixel 1) to segment vine rows from inter-rows to analyze NDVI information from vines (Da Costa *et al.*, 2006; Hall *et al.*, 2003; Homayouni *et al.*, 2008).

b) Ground-based sensors

In order to cope with the issues of remote sensing problems due vertical shoot positioning, ground-based monitoring systems have been developed to assess and map canopy properties (plant biomass, vine size and photosynthetic activity). These systems avoid background noise problems due to mixed pixels containing soil, grass and vine canopy, which is an advantage over remote sensing technologies. Some of these systems are based on digital imaging, which provides the measurement of several parameters such as canopy height and canopy porosity (Praat *et al.*, 2004; Tisseyre *et al.*, 1999). Others systems are based on ground-based NDVI measurement (GreenSeeker™). It has been shown that the information provided is strongly related to VLAI (Vertical Leaf Area Index) and canopy porosity (Goutouly *et al.*, 2006).

These ground-based systems are designed to be mounted on existing machinery, allowing the acquisition of spatial information during the daily management of the vineyard (trimming and spraying, among others). They allow the spatial variability of the vigour to be characterized with a resolution never before achieved. Again, in areas where water availability constitutes the main constraint, these systems could be useful to characterize spatial variability due to different levels of water restriction at the vineyard scale.

2- Soil variability

Section 2.2 showed the main punctual methods for soil water content assessment, which is a fundamental information for water management at the vine field scale. In complement, this section introduces new technologies that allow the soil physical properties to be characterized with a high spatial resolution. These sensors are based on the soil di-electric or electro-magnetic properties. The soil Apparent Electrical Conductivity ($EC_a$) is a quick, reliable measurement for the spatial characterization of edaphic (i.e. salinity, water content and texture, among others) and anthropogenic properties (Corwin and Lesch, 2005; Samouëlian *et al.*, 2005). Spatial $EC_a$ measurements have become a common method used for field and landscape-scale studies related to soil properties. This method offers a very attractive tool for describing the soil properties with a small number of soil observations. There are two types of $EC_a$ sensors available: (i) Electrical Resistivity (ER) sensors that use invasive electrodes and (ii) non-invasive Electromagnetic Induction (EMI or EM) sensors (Tisseyre *et al.*, 2007). Invasive ER and non-invasive EM are the most frequently used sensors as they have been widely commercialized.

Both technologies (ER and EM) have been widely implemented in viticulture. Barbeau *et al.* (2005) used ER to compare the effect of rows with and without grass cover on soil water distribution. Bramley (2005) used such soil information to determine different soil zones within fields. High resolution $EC_a$ was used to delineate zones with different water availability (Taylor, 2004). Taylor (2004) also proposed an estimation of soil water holding capacity based on $EC_a$ measurement over a whole vineyard. This estimation required the calibration of a transfer function allowing the soil water holding capacity to be derived from $EC_a$ values. This work required a large data base of known points to calibrate the model. Obviously, this approach is hardly tractable for commercial vineyards, however, it shows the relevance of $EC_a$ information to delineate zones where water restriction experienced by the plants may be significantly different. We (Acevedo-Opazo *et al.*, 2007, 2008) showed that extreme care must be taken in using this information to highlight zones with difference in plant water status. An expert delineation of the main soil types should better be considered before using $EC_a$ information directly. We mainly focused on electrical parameters since they are used for a long time, however, depending on the location, many others technology like ground penetrating radar or gamma radiometre may be helpful to provide relevant soil variability maps.

4- Technical and spatial considerations of auxiliary information

Focusing first on methods based on weather information, it has been shown that they are widely used. They are usually used on large scale studies, such as the whole vineyard, or a complete region. It is important to consider that these methods do not take into account the spatial variability which is usually encountered at the field scale. Moreover, these methods need to be calibrated on field conditions by comparing their estimates with physiological reference measurements (i.e. plant water potential or stomatal conductance).

Soil moisture monitoring systems require the consideration of a series of technical details, such as: (i) the choice of the appropriate method among all the available ones for soil moisture monitoring, (ii) they are all quite expensive leading to use them on a few selected sites. This last point is critical since spatial variability in soil depth, texture and other properties might not be taken into account properly. Although pedological maps or elevation information might constitute a relevant support to help in deciding the sensor locations, soil water holding capacity may vary over small spatial range (even within a same pedological unit) leading to weak spatial relevance of the soil moisture measurements. Thus, soil water monitoring does not allow flexibility in measurement sites once the access tubes or probes are put in place.

The main advantage of airborne imagery and soil electrical survey is that they can bring high resolution information that can reach more than 2000 measurements per hectare. Both information are able to provide information on plant and soil variability with a resolution achieved never before. In addition to spatial resolution, a significant advantage of remote sensing technology remains the spatial support of the information since one acquisition (or one fly) may cover several hundred hectares of vines. Soil conductivity remains a punctual information which requires an exhaustive soil survey. Depending on the required resolution and the field distribution, 40 hectares to more than 100 hectares might be analysed in a day. Data need also to be processed (krigging) to provide the information on a regular grid. Apart from these spatial considerations, the use of multispectral imagery or soil apparent conductivity in zoning vineyard according to plant water status raises several problems.

Considering multispectral airborne imagery:

- The canopy architecture and the resulting information can vary drastically between fields due to different training system (Johnson *et al.*, 2003). This means that indices derived from remote sensing images like NDVI can be helpful in analyzing variability when homogeneous training systems are encountered (at field level). However, care must be taken when assessing vigour variability between areas where different training systems may be encountered.

- NDVI is presented as a possible way to map variations in vine water status. This might be true in un-irrigated vineyards in dry climates, where the main factor inducing differences in NDVI is vine water status. However, in many cases NDVI varies rather with the nitrogen offer of the soil. When soil is moved during soil preparation before plantation, zones with low organic matter content are easily created. Vigour is generally low in these zones because of low nitrogen status of the vines. On the other hand, Johnson *et al.* (1996) shown that canopy diseases/pests problems or nutritional deficiencies also induce great changes in NDVI values. Obviously, missing vines also bias this information.

Considering soil apparent conductivity (or resistivity):

- This method integrates many soil parameters (i.e. salinity, water content, texture, among others), which makes its interpretation difficult (Corwin and Lesch,

**Table 1 - Summary of plant water status measurement methods and their spatial and temporal characteristics.**

| Method | Type measurement | Record | Time resolution | Spatial resolution of the measure | Spatial validity of the measure | Area covered by day |
|---|---|---|---|---|---|---|
| Plant based methods | | | | | | |
| Stomatal conductance | direct | manual | low | within leaf (~cm²) | leaf (cm²) | < 50 plants |
| Leaf Water Potential | direct | manual | low | leaf (~dm²) | leaf (dm²) | < 50 plants |
| Stem Water Potential | direct | manual | low | stem (~dm²) | plant (dm²) | < 50 plants |
| Carbon isotope composition | indirect | manual | low (at harvest) | cluster (~cm²) | plant (m²) | < 100 plants |
| Predawn leaf Water Potential | direct | manual | low | plant (~m²) | depend on soil variability | < 50 plants |
| Sap flow | indirect | automatic | high (every day or more) | plant (~m²) | plant (m²) | 1 plant |
| Dendrometry | indirect | automatic | high (every day or more) | plant (~m²) | plant (m²) | 1 plant |
| Canopy temperature | indirect | automatic<br>manual | high (every day or more)<br>low | plant (~m²) | plant (m²) or several plants | < 100 plants |
| Auxiliary methods | | | | | | |
| Crop Evapotranspiration | indirect | automatic<br>manual | high (every day or more) | punctual (soil and weather station) | soil and climate unit | several ha |
| Soil moisture sensors | indirect | automatic<br>manual | high (every day or more)<br>low | punctual (~m²) | soil unit | punctual |
| Airborne imagery | indirect | automatic | low | (0 cm²-3m²) | (0 cm²-3m²) | several ha |
| Apparent soil conductivity survey ($EC_a$) | indirect | automatic | low | ~ m² | ~ m² | several ha |

2005; Samouëlian *et al.*, 2005). Obviously, the same conductivity value may be observed for two different soil types. To cope with this problem, a rough soil delineation based on expert analysis (i.e. elevation, soil depth, soil color or other knowledge) may be done. The area under study is then divided in simple soil units leading to a more simple analysis of soil apparent conductivity data. Figure 1 shows an example where the study area is divided in different soil units. Soil conductivity remains interesting to characterise soil variability (texture, depth, etc.) within each soil unit.

- As said previously, the investigation depth depends on sensor characteristics. It is limited to 1 to 2 m for most available systems. Depending on the situation, this depth may not fit with vine rooting system. Therefore, information derived from $EC_a$ survey may be weakly linked to the water really available for the plant roots.

Table 1 summarizes main specificities of the different methods presented section 1 and section 2. For each method, table 1 particularly focuses on spatial characteristics and in a less extend on temporal characteristics. Quick analysis of table 1 highlights the lack of ideal system allowing the plant water status to be known with a high spatial resolution. This conclusion leads to consider cooperation between different information sources to provide an assessment of plant water status over large area. Such a cooperation needs to take into account the spatial variability which may be encountered.

## TOWARD THE SPATIAL MODELLING OF VINE WATER STATUS

This section aims at presenting an approach based on reference measurements and other spatial information. Obviously, depending on the location and the available information, many particular methods may be relevant. This is the reason why this section focuses on an approach as general as possible trying to encompass most of particular cases.

Let us remind the reader of the problem under consideration. Let's consider a whole vineyard (D) which constitutes the study area. D is small enough to assume homogeneous weather conditions. This last point means that climate (rainfall, temperature…) can be characterised by only one weather station over D and also that climate variables affect plants and soil homogeneously over D. Spatial modelling of the plant water status aims at providing an estimate $\hat{z}(s_i,t_j)$ of the plant water status $z(s_i,t_j)$ at time $t_j$ and location $s_i$ belonging to the study area D. Depending on the training system, the irrigation system and measurements usually carried out, $z(s_i,t_j)$ can refer either to the PLWP or to the SWP. The rest of the section considers that $z$ is a common reference measurement that management practices or irrigation scheduling can be based on.

### 1. Considering a unique zone

A classical approximation considers that all locations $(s_i)_{i=1...I}$ on D presents approximately the same water status. Plant water status is then measured on an appropriate reference site $s_{re}$ to provide the value $z(s_{re},t_j)$ at time $t_j$. As summarized by equation 1, $z(s_{re},t_j)$ is then considered as the estimate of the plant water status on D at $t_j$. This approach ignores the spatial variability.

$$\hat{z}(s_i,t_j) = z(s_{re},t_j)\ ,\ \forall s_i \in D \qquad \text{(equation 1)}$$

where:

$s_{re}$ is the location (or the set of locations) where the reference measurement of the plant water status (PLWP or SWP) is performed on.

When plant monitoring systems (sap flow, trunk diameter or canopy temperature) or soil monitoring systems are available on D, a similar reasoning is possible. In that case, a calibration function $f_{(D,K)}$ determined on D, may be used to derive reference plant water status from $x_K$, the measurement provided by the monitoring system. The site of reference $s_{re}$ is then the location (or the set of locations) of the monitoring system. Considering that all locations $(s_i)_{i=1...I}$ on D presents approximately the same water status leads to provide an estimate over D as presented by equation 2.

$$\hat{z}(s_{re},t_j) = f_{(D,K)}(x_K(s_{re},t_j)) \iff \hat{z}(s_i,t_j) = f_{(D,K)}(x_K(s_{re},t_j)),\ \forall s_i \in D \qquad \text{(equation 2)}$$

where:

$x_K(s_{re},t_j)$ is the value provided by the monitoring systems at time $tj$ on the location $s_{re}$.

$f_{(D,K)}$ models the relation between z and $x_k$ on D. Several authors proposed such a relation in the literature either with plant monitoring systems (Bravdo and Naor, 1996; Cifre *et al.*, 2005) or weather data (Allen *et al.*, 1989; Pereira *et al.*, 1999). $K$ refers to the type of measurement performed on the reference site (stomatal conductance, sap flow, trunk diameter or canopy temperature).

Equations 1 and 2 highlight several problems in spatial estimation of the plant water status. The choice of $s_{re}$ (or set of $s_{re}$) is critical since it determines the plant water status over the whole vineyard. Although, variability which happens from leaf to leaf or vine to vine may be smoothed by considering average values over a small area around $s_{re}$, meso-scale variability (mainly due to soil and elevation) may not be taken into account. For plant monitoring systems the problem of the choice of $s_{re}$ may be of greater importance since the value comes from


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the vine located at $s_{re}$ during the whole season. This means that the estimation over D can be systematically over estimated or under estimated. In summary, plant based measurements certainly provide the best assessment of the plant water status. They provide an assessment of the real response of the plant. Nevertheless, for each method the values always come from a small sampling area which is extrapolated to the whole vineyard. Depending on the spatial variability, the measurement should be considered as relevant only on a defined area centered around the measurement site ($s_{re}$). In practice, end users do no have a reliable picture of the spatial variability. The information measured at the reference site has then to be used with extreme care.

## 2. A set of zones

In order to cope with limitations detailed in the previous section, a simple approach may consist in zoning the study area D in sub-areas with more or less homogeneous characteristics (figure 1). Let's call this sub-areas $(D_n)_{n=1...N}$. The N sub-areas (or zones) may be defined according to soil units based on expert analysis of auxiliary information (i.e. elevation, soil depth, soil colour, soil sample among others). The reasoning presented in the previous section is then applied to each sub-areas. All locations $(s_i)_{i=1...I}$ on $D_n$ are assumed to presents approximately the same water status. Plant water status is then measured on an appropriate site considered as a reference site $s_{re}^n$ for $D_n$ ($s_{re}^n \in D_n$).

The measurement provides the value $z(s_{re}^n, t_j)$ at time $t_j$. which is then used to assess the plant water status over $D_n$. When reference measurement is used, this leads to a very similar case as the one presented in equation 1. Equation 3 summarizes the principle of this approach in the case with plant monitoring system.

$$\hat{z}\,(s_i, t_j) = f_{(D_n,K)}(x_K(s_{re}^n, t_j)) \qquad \text{(equation 3)}$$

$\forall s_i \in D_n, n = 1...N$, with $s_{re}^n \in D_n$ and $D_n \subset D$,

where:

$s_{re}^n$ belonging to sub-area $D_n$ of D.

$f_{(D_n,K)}$ models the relation between z and $x_k$ specifically on $D_n$.

The approach presented in this section is interesting since it takes into account the macro-scale variability due to soil for example. It may be applied at various scale, however, it is commonly used on large areas to provide advice on irrigation management. An approach based on remote imagery like the one proposed by Montero *et al.* (1999) could be used to design such large zones. $D_n$ are usually large zones and depending on the method used to their delineation, some locations may be attributed to two or more zones. As a result, a significant spatial variability may remain in each zones. This means that at the within zone level, all the problems presented section 3.1. may remain significant. Obviously, this approach leads to increasing number of reference sites since a minimum of one measurement site is required for each zone. Therefore it increases the number of measurements or the number of plant and soil monitoring systems. Obviously, for practical considerations, this approach cannot be extended to characterize small scale spatial patterns.

## 3. Maps of spatial variability

The next step is to design an approach that integrates reference measurements and high resolution information sources (HRIS) to maximise quality of information for management. Equation 4 summarizes the principle of such an approach.

$$\hat{z}\,(s_i, t_j) = f_{D_n}(q_1(s_i), q_2(s_i), \ldots, q_M(s_i), z(s_{re}^n, t_j)) \qquad \text{(equation 4)}$$

$\forall s_i \in D_n, n = 1...N$, with $s_{re}^n \in D_n$ and $D_n \subset D$,

In equation 4, $f_{D_n}$ can be seen as a function that allows the extrapolation of the measurement of reference ($z(s_{re}^n, t_j)$) over $D_n$ according to spatial variability characterised by the different HRIS ($(q_m(s_i))_{m=1...M}$).

HRIS might then improve significantly the spatial prediction of the plant water status. Each location $(s_i)_{i=1...I}$ of $D_n$ will then be characterised by additional information $(q_m(s_i))_{m=1...M}$. Depending on the available HRIS or depending on the local specificities, the number M of variables may be more or less important. Note that the date of acquisition is not taken into account. This means that HRIS only provide information on the spatial structure which drives the plant water status. This spatial structure is then assumed to be time-stable. Obviously, to be able to provide an estimate $\hat{z}\,(s_i, t_j)$ of the plant water status at time $t_j$, HRIS require additional information to take into account the level of water restriction at $t_j$. As shown equation 4, interaction between HRIS and plant water status measurements is then necessary to provide $\hat{z}\,(s_i, t_j)$. In order to simplify the formulation, equation 4 only considers the case where $z(s_{re}^n, t_j)$ is the reference measurement. Regarding equation 3, it is easy to modify equation 4 so that to consider the case with a plant monitoring system.

As seen in previous sections, it is possible to use information which provides knowledge on plant water status spatial variability like:

(i) plant vigour and canopy size (multispectral imagery) which are affected by plant water restriction,

(ii) soil depth, soil water content, texture (soil conductivity) and elevation that the spatial variability induces difference in plant water restriction.

(iii) water regime applied to grapevines during the whole season, the $\delta^{13}C$ technique also can be used as complementary information. However, despite its relevance, note that δ13C method is based on sampling. Obviously this drawback strongly limits the spatial resolution of this information.

Therefore, under assumptions which will be detailed further, these high resolution information sources (HRIS) may be useful to:

(i) delineate the $D_n$ zones more accurately,

(ii) improve the spatial prediction of the plant water status within each zone.

Obviously, equation 4 makes reasonable assumptions:

(i) the approach assumes that HRIS are available at each location $s_i$.

(ii) the study area ($D_n$) is small enough to assume homogeneous weather conditions. Temporal variability of the plant water status is only taken into account with the measurement of reference $z(s_{re}^n, t_j)$.

(iii) training system, disease infestation and other similar parameters that can affect plant response are assumed to have the same effect over $D_n$.

## 4. Example of a very simple spatial model

In order to illustrate the approach, figures 2 and 3 provide an example from real data at the within field level. The goal is only to show an example for a better understanding of the proposed approach. The case study is just a first attempt; therefore the model is very simple. Calibration step and coefficients are not thoroughly detailed and the results will only be analysed qualitatively. A more precise presentation of this case study will be presented in a next paper.

Figure 2a presents the 1.2 ha study area ($D_n$) under consideration, it corresponds to a grape field. 49 sites $(s_i)_{i=1\ldots49}$ are defined on $D_n$. Figures 2b and 2c represent the high resolution information sources (HRIS) available on $D_n$. HRIS correspond to canopy area ($q_1$) and soil apparent resistivity ($q_2$) for figures 2b and 2c respectively. Each site $(s_i)_{i=1\ldots49}$ of $D_n$ is then characterized by two types of HRIS $[q_1(s_i); q_2(s_i)]$ which bring additional local information at each site $(s_i)$. The plant water status is measured at time $t_j$, only on one location considered as the reference site ($s_{re}^n$). The approach presented in equation 4 was applied to the set of data with a very simple model presented equation 5.

$$\hat{z}(s_i, t_j) = (a_1 \times q_1(s_i) + a_2 \times q_2(s_i) + a_3) \times z(s_{re}^n, t_j)$$

(equation 5)

with $a_1, a_2$ and $a_3 \in \Re$,

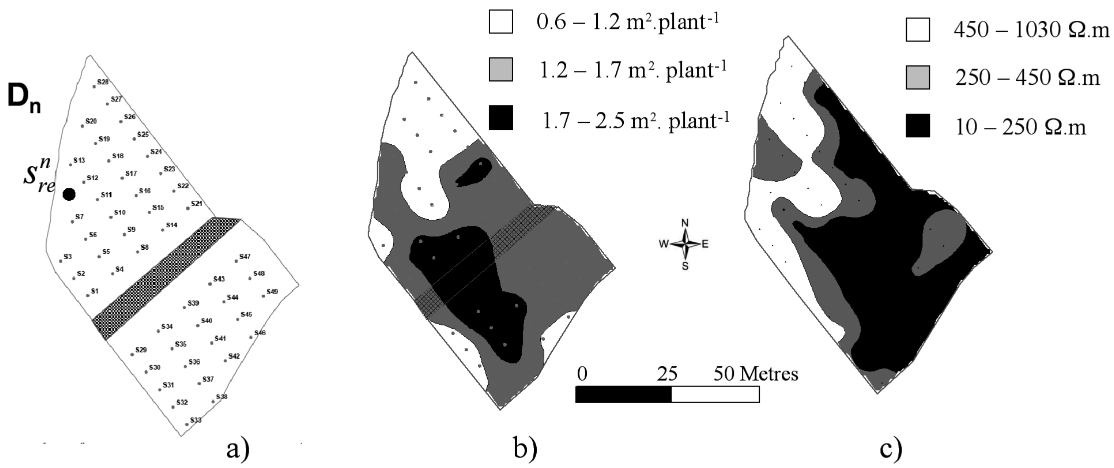


**Figure 2 - (a) example of a zone ($D_n$) corresponding to a grape field with 49 sites $(s_i)_{i=1\ldots49}$ and a reference site ( $s_{re}^n \in D_n$). (b) and (c) represent two High resolution information sources $[q_1(s_i); q_2(s_i)]$ which characterize each site of $D_n$. (b) and (c) correspond to canopy area and soil apparent resistivity respectively.**

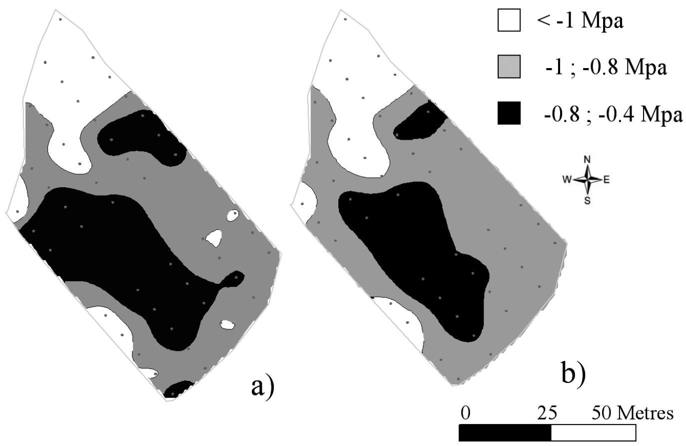


**Figure 3 - Maps of plant water status at the end of the summer (predawn leaf water potential). a) map resulting from measurements on 49 sites with a Scholander pressure chamber. b) Map of estimations of the plant water status (PLWP) resulting from the model presented equation 5.**

Equation 5 models a cooperation between the plant water status on the reference site $S_{re}^{n}$ at time $t_j$ and the HRIS to assess the plant water status on each site of $D_n$.

Figure 3a shows a map of the Predawn leaf water potential realised at the end of the summer on the grape field. Figure 3b shows the PLWP prediction map obtained from the model presented in equation 5. The calibration of the model was realised from a data base of PLWP measured over two different years. Figure 3a highlights the significant variability of the plant water status observed at the within field level. Assessment of the plant water status without any spatial consideration would have lead to affect an average PLWP of -0,9 Mpa to the whole field. Obviously the spatial variability allows the consideration of very different zones with very different vine water status. Comparison of figures 3a and 3b) points out the relevance of the model to provide an assessment of the plant water status variability. Note that this map results from only one measurement at a reference site and the HRIS (once the model has been calibrated).

Obviously this field is small which leads to a very simplistic model. However this example shows that such an approach is possible. Extension to other fields and larger area will probably lead to more advanced models.

## CONCLUSIONS

The majority of vineyards present a great spatial variability in yield (number and size of bunches), vegetative growth (canopy density), sugar and grape quality components and also in vine water status. This vine water status variability is especially evident at the end of summer, when significant water restriction is found under non-irrigated conditions. Therefore, in addition to temporal water status monitoring, spatial variability of vine water status also needs to be considered.

Many approaches are now available to provide a measurement of the plant water status. They are based either on direct or indirect methods. The first methods use plant-based measurements (reference measurements) to provide a relevant and accurate assessment of the plant water status at the plant scale. Nevertheless, each of these methods requires an expensive heavy device, such as a pressure chamber and porometer sensors to be brought to the field for the manual measurements. Moreover, measurements are time consuming, which constitutes a significant constraint for labour management and significantly limits the number of measurements either in time or in space.

Other plant based systems deliver continuous information. The relevance of such information is mainly due to its dynamic variation over the season; different vines can show different responses at different times in the season complicating data interpretation. This means that absolute values provided by these sensors do not bring any direct estimation of plant water status. Indeed, the cost and the maintenance of the system limit the number of devices that it is possible to use at the vineyard scale. The amount of available spatial information is consequently quite small, limiting the knowledge about the spatial variability of plant water status.

Plant water status may also be assessed using indirect methods based on weather and/or soil information. These methods are widely used on large scale studies, the whole vineyard or a complete region. However, they do not take into account the spatial variability which is usually encountered at the vine field scale. Moreover, these methods need to be calibrated for field conditions comparing their estimates with physiological reference measurements (i.e. plant water potential and stomatal conductance).

Finally, information provided by sensing systems developed in the framework of precision viticulture can give useful information, allowing the spatial variability of plant water status to be characterized at a fine scale. However, it does not provide any information on the plant water status itself. It only gives knowledge about the spatial variability of parameters which are affected by differences in water availability (vigour, canopy size), or which induce differences in plant water regimes (soil variability in depth, water content, texture and elevation). These parameters can only be considered as auxiliary information allowing the spatial variability to be modelled. This means that using this information to provide an estimate of the vine water status over space and over time in a study area will necessarily require a reference measurement (PLWP or SWP) made at a given time on one or more reference sites. In such an approach, auxiliary information measured with a high resolution over the study area may be used to extrapolate the reference measurement.

Nevertheless, it is important to say that this approach assumes significant restrictive hypothesis. It refers mainly to the study area over which the model has to be relevant (homogeneous climate conditions, relevancy of auxiliary information, etc.). This work proposes a formalization of a possible approach allowing the spatial variability of plant water status to be characterized. This formalization shows that scientific problems still have to be addressed in order to build up such a spatial model. The first point deals with the selection of the best auxiliary information allowing the vine water status to be spatially estimated for different conditions of training systems and soil types. Obviously best auxiliary information may change from region to another. The second point deals with the model determination. This point aims at testing and proving the relevancy of this approach. It requires a large and complete database aiming at having high spatial and temporal resolution plant water status measurements over several years for a single study area. The third point deals with the introduction of auxiliary information (selected during step 1) within the model in order to compute the model parameters according to the encountered spatial variability.

These points will constitute our further investigations aiming at proposing a spatial model of plant water status.

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