# New methods and technologies to describe the environment in terroir studies

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**Abstract**
The concept of terroir in viticulture deals with the influence of environmental factors on vine behaviour and grape ripening. Recent advances in technology, in particular computer technology, allow a more in-depth study of the environment. Geomorphology can be studied with digital Elevation Models (DEM). Soils can be surveyed with geophysics. The development of automatic weather stations allows more dense registration of climatic parameters like temperature and rainfall. Solar radiation can be remotely sensed with satellites and rainfall with radar. Geographic Information Systems (GIS) allow combining various sources of spatialized environmental factors. The development of high throughput indicators of grapevine development, vine water status and vine nitrogen status allows spatialized validation of vine responses to environmental factors.

**Key words**
Terroir, vine, Digital Elevation Model (DEM), Geophysics, Ground Penetrating Radar (GPM), Geographic Information System (GIS), Global Positioning System (GPS), remote sensing

## Introduction

It is widely admitted that the quality of a wine, and consequently its value, is largely dependent on the terroir in which it is produced. Numerous authors have offered definitions of the concept of terroir in viticulture (Seguin 1986; Vaudour 2003). It involves the vine and its physical environment (soil and climate) as well as their interactions. Terroir varies in space and therefore possesses a geographical dimension. Scale issues are critical (Vaudour 2003). Because many factors are involved in terroir expression, the study of viticultural terroirs requires a pluri-disciplinairy approach. Many scientific disciplines can contribute to the study of terroir, among them geology, geomorphology, pedology, climatology and vine physiology. New powerful tools have been developed over the past years in these disciplines, mainly due to the progress of computer technology. These tools open new perspectives in terroir studies.

## The purpose of terroir studies

Before starting a terroir study, it is important to define the objective pursued. This can be the demarcation of territories according to their potential to produce wine of a certain quality or wine of a certain typicity (demarcation of controlled production areas such as "*Appellations d'Origine Contrôlée*"). Terroir studies can also be implemented to enhance the technical management of vineyards. A deeper knowledge of the spatial variability of certain terroir factors has enabled to choose of the best adapted plant material in each of the zones studied. The same goes for numerous aspects of the vineyard management practices (soil management, fertilisation, drainage, harvesting dates and so on). Viticultural zoning is also useful for sustainable viticultural purposes; for each type of terroir defined, the appropriate viticultural techniques can be chosen that will have the lowest environmental impact. Zoning can also be useful in demarcating terroirs and viticultural landscapes which merit protection, particularly from the effects of urbanisation.

**Scale**

Terroir studies can be carried out at various scales, depending on the objective pursued. The zoning of a large region with little differentiation can be done at a small scale (1:100 000 or 1:250 000). The demarcating of *crus* (wine growths), in a region where the quality potential is well differentiated, requires work at a larger scale (1:25 000 or 1:10 000). Adapting technical management to the environmental, site-specific factors requires an even more refined approach (scale 1:5 000 or even 1:1 000). The soil often has a great spatial variability, which is not necessarily the case for other terroir factors, such as climate. Consequently, a small-scale mapping will have difficulties in taking into account this soil variability. The larger the scale (i.e. the more precise the map), the more costly the zoning will be. In practice, the scale of the zoning is often a compromise between the desired precision and the available budget. Precision viticulture can be considered as the integration of very large scale variations in terroir (1:500 to 1:1000) in viticultural management

**Environmental factors involved in terroir expression**

*Soil related factors*

Soil influences vine development and grape ripening through its impact on microclimate, mineral supply to the vine and water supply to the vine. The soil derives from a given parent-rock (geology) that has evolved over time under the influence of vegetation and climatic factors (in particular rainfall and temperature). Soil distribution in a given area is related to geomorphology, itself related to variability in erodability of parent rock. Hence, soil mapping should take into account the local geology and the geomorphology.

*Climate related factors*

Climate influences vine phenology, vine development, grape ripening and disease pressure mainly through temperatures, rainfall, potential evapotranspiration ($ET_0$) and solar radiation. Timing of phenology is temperature driven. Vine development (shoot growth) and grape ripening are greatly impacted by temperature, but also by vine water status, itself dependant on soil water holding capacity, rainfall, $ET_0$ and leaf area. Solar radiation drives photosynthesis and interferes with grape phenolic and aromatic metabolism. Disease pressure is related to temperature profile, rainfall and Vapour Pressure Deficit (VPD).

**The use of new technologies to describe soils**

The development of new technologies has opened up interesting prospects for the study of viticultural soils. These new technologies use computer technology and measurements taken by sensors. These can be mounted on machines (proxidetection) whose geographical position is known with precision at each moment thanks to differential Global Positioning System (dGPS). They can also be mounted on aircrafts or satellites (remote sensing).

*Digital Elevation Model (DEM)*

The Digital Elevation Model (DEM) divides a given region into a raster (regular grid of squares) or irregular triangular network with sufficient resolution so as to properly capture the altitude variability. Each element of the network is allotted an average altitude. The network enables the slope and exposure of each element to be determined with precision. The DEM enables geomorphological maps to be produced and calculations to be made about the percentage of the surface with a slope superior to X degrees, the percentage of the surface with an altitude superior to Y metres etc. The precision of the maps depends on the sampling density of the network (resolution), often 25m or 50m.

*Geophysics*

Geophysical techniques that are relevant to vineyard imaging and characterization include mainly Ground Penetrating Radar (GPR), electromagnetic induction (EMI) and electrical resistivity. They are effective instruments for high-resolution, real-time and non-invasive determination of the shallow subsurface hydrogeophysical properties at the field scale through the measurement of soil dielectric permittivity and electrical conductivity (Huisman *et al.,* 2003; Lambot *et al.,* 2008; McNeil 1980). Soil dielectric permittivity mainly depends on soil water content (Topp *et al.,* 1980), while soil electrical resistivity is essentially affected by soil water content, soil clay content, soil salinity and soil temperature (Corwin and Lesch 2003, Corwin and Lesch 2005; Friedman 2005). GPR can be combined with EMI or soil electrical resistivity measurements in a data fusion framework, which allows to merge complementary information, thereby leading to more accurate quantitative characterization of soils.

GPR, EMI or soil electrical resistivity devices can be drawn behind a farm machine (quad, tractor, over-the-row-tractor). In vineyards, the presence of iron wires and/or metallic posts may interfere with EMI, which may lead to estimation errors if not properly accounted for. On the other hand, electrical resistivity has also some limitations as it strongly relies on the quality of the contact between the electrodes and the soil. Especially, when the soil surface is relatively dry, the intensity of the current that is injected into the soil is low, which results in a poor signal-to-noise ratio. Measurements can be performed up to various depths (generally at 50cm, 1m and 2m). Several thousand of measurements per hectare can be acquired, typically with a one-meter resolution, and positioned with precision by dGPS. Resistivity (or conductivity) and GPR maps are therefore very useful for precise delineation of relatively homogeneous areas. These techniques do not replace pedological work (soil sampling, study of soil profiles) in determining the type of soil in each of the zones with a homogeneous resistivity, but they enable determining with precision the borders of these zones. The measurement of the resistivity is especially useful for very refined mappings of soils, at scales between 1:1 000 and 1:5 000 (the scale of the parcel or the estate). The 2-D or 3-D GPR images are particularly useful to determine soil layering (e.g., clay layers, water table, etc.).

*Remote sensing*

Remote sensing enables measurements of objects to be made at distance. This technique is based on measurements of wavelength, or ratios of wavelength, of reflected radiation. Remote sensing can be performed using sensors mounted on farm machines (proxidetection) or using airborne sensors (balloon, helicopter, plane or satellite). Remote sensing over bare earth enables us to determine its colour, the presence of coarse elements and its temperature.

*Geographical Information System (GIS)*

GIS enables geo-referenced information to be managed with the help of a computer. The first application in viticultural zoning is its utilisation in the publishing of maps. Thanks to GIS, maps can easily be updated. Databases can be associated with the map –e.g. the analytical data for each soil profile. GIS also enables different layers of spatialised information to be cross referenced. For example, information on soil-type, climatic zone, altitude, slope and exposure can be cross referenced in order to identify the viticultural potential of a vast geographical zone. This approach is of particular interest for the identification of zones with high quality potential in new regions of production. It has been applied successfully in Oregon by Jones *et al.,* 2004. The limitation of this approach is in the quality and the reliability of the different layers of information used. Furthermore, the cross-referencing of the information supposes the attribution of classes to each layer and allotting them a value. It is not always easy to determine the optimal class for each layer of information.

*Geostatistics*

Geostatistics enables us to transform punctual data (measured in a given point) into spatial data (quantified in any point of space, i.e. maps). Different techniques exist, of which the most often used is kriging. The production of good quality maps requires a large amount of punctual data, generally more than 50 points.

**The use of new technologies to describe climate**

Advances in technology, computer sciences and spatial statistics have increased the accuracy and the relevance of climate time and space variability analysis. The spatial coverage of climate observations has been enlarged thanks to satellite images and the use of automatic weather stations. Weather models offer prospective climate analysis, and provide complementary information for places where climate records are scarce. Continuous climate data can be established from point observations using interpolation methods, which performances are globally improved when environmental information is used through guiding covariates.
Amongst theses methods and devices, many consist in relevant tools for the analysis of climate variability within grapegrowing regions and terroir characterization. A better understanding of climate/grapevine relationship is achieved with the use of agroclimatic indices calculated from original climate data using crop models of various levels of complexity.

*Automatic weather stations*

Weather stations coverage has been increasing since the end of the 20th century by means of automatic weather station, as they considerably reduce the time cost of climate recording. The automated monitoring and storage allows faster collecting and analysing of climate data. Information can be transmitted to the operator via remote communication systems such as GSM. Consequently, large climate networks can be developed and managed at reduced human costs. The major drawback of this consistent improvement for climate studies is data quality management. Site and device maintenance, as well as erroneous data detection, have to be considered when a weather station network is developed or during the analysis of data of an existing network, as some crop models can be dramatically sensitive to small variations of climate input data (Courault and Ruget 2001).

*Remotely sensed data*

Remote sensing provides contiguous spatial climate information. Surface temperature and solar radiation can be derived from satellite or airborne observations. The first is useful for frost risk analysis (François *et al.,* 1999) or evapotranspiration studies (Gomez *et al.,* 2005).

Solar radiation estimates are performed by cloud detection analysis within satellite images. Operational solar radiation data can provide relevant information for grapegrowing region climate zoning (Bois *et al.,* 2008c) and reference evapotranspiration estimation (Bois *et al.,* 2008a). Radar images may improve spatial monitoring of rainfall, especially during local convective events (storms), that an insufficiently dense rainfall gauge network fail to capture (Bois 2007). However, ground located radars are expensive and their spatial coverage is limited in mountainous areas.

*Weather models*

Atmospheric (or Ocean-Vegetation-Atmosphere models) classically used for weather prediction are now commonly used for climate prospective analysis. Whereas their manipulation requires specific skills and powerful computer resources, numerous outputs are available. The so-called regional models simulations are useful tools for future climate analysis. Prospective studies concerning the evolution of grapevine production potentials are being driven on the bases of weather research models at different scales (White *et al.,* 2006 ; Webb *et al.,* 2007).

*Interpolation of climate data*

Point weather data may not represent relevantly the range of climatic conditions within a grapegrowing region. Spatial interpolation is an objective approach to produce spatialized climate information. Numerous researches concerning climate data spatial interpolation has been driven lately, and several interpolation strategies are now available. Amongst those geostatistics and thin plate splines interpolation methods are often the most successful at limiting spatial interpolation errors (Price *et al.,* 2000 ; Jarvis and Stuart 2001). Besides, additional environmental information benefits to the relevance of the interpolation process, as landscape, vegetation or water bodies generally affect the spatial distribution of climate fields (Joly *et al.,* 2003 ; Bois *et al.,* 2008b). Operational softwares have been developed to perform interpolation of climate data (e.g. PRISM, http://www.prism.oregonstate.edu or ANLUSPLIN, http://fennerschool.anu.edu.au/publications/software/anusplin.php). Based upon these methods, operational gridded interpolated data has been produced (New *et al.,* 2002 ; Hijmans *et al.,* 2005), and can be used for climate analysis of grapegrowing regions (Jones *et al.,* 2009).

**New methods in validation of terroir studies**

In order to validate terroir zoning, the behaviour of the vine in relation to the physical environment has to be taken into account. The interaction between the vine, the soil and the climate is the domain of so-called "eco-physiology". These studies take into account interactions between the vine, the climate and the soil. Hence, they can explain differences in quality potential and typicity among various terroirs, which a study of the physical environment alone cannot. Eco-physiological studies historically rely most often on a network of plots. In each plot, the soil and climate are studied, and measurements are taken on the vines and detailed analyses are made on the grapes. Numerous eco-physiological studies have been made in highly varied environments (Seguin 1975 ; Duteau *et al.,* 1981; van Leeuwen and Seguin 1994; Choné *et al*., 2001; Trégoat *et al.,* 2002; Tesic *et al.,* 2002a and 2002b; Bodin and Morlat 2006; Koundouras *et al.,* 2006; Coipel *et al.,* 2006). They have enabled us to improve considerably our understanding of the functioning of viticultural terroirs. All these studies highlighted the important role played by the vine's water supply regime on the expression of viticultural terroirs. Vine water deficit reduces vine vigour and yield, limits the size of the berries and increases the grape's sugar content and phenolic components. Some studies show a similar effect on the quality potential of red wines when the nitrogen supply is limited (Choné *et al.,* 2001; Trégoat *et al.,* 2002), but a low supply of nitrogen is not desirable for the production of dry, white wines, particularly for the Sauvignon blanc grape variety (Peyrot des Gachons *et al.,* 2005; Choné *et al.,* 2006).

Despite eco-physiological studies being of interest for advances in viticultural terroir knowledge, their main disadvantage is the extremely time-consuming nature of these studies. The great number of measurements performed (several dozens per site and per year) result in very high costs and limits the number of sites that can be studied simultaneously. Furthermore, these studies remain difficult to spatialise: the functioning of a vine can be known with precision at a given place, but the domain of validity of this type of response is not known. It can be very limited in space and concern an area of less than one hectare.

Thanks to the development of new tools, three very important elements of the eco-physiological approach can be routinely measured and therefore spatialised: the nitrogen status of the vine, its water status and its vigour. Vine nitrogen status can be evaluated by the measure of nitrogen in grape juice (e.g. Yeast Avaialable Nitrogen) at ripeness (van Leeuwen *et al.,* 2000). Through taking numerous measurements on a wine estate, maps of the vines' nitrogen status on the estate can be produced (figure 1). The vines' water status can be determined through the measurement of carbon isotope discrimination ($^{13}C/^{12}C$ ratio) on the must sugars at ripeness (van Leeuwen *et al.,* 2001; Gaudillère *et al.,* 2002). This measuring is offered by specialised laboratories at a reasonable price. Carrying out numerous measurements enables the water supply regime to be spatialised at the scale of the plot or of the estate (figure 2). Vine vigour can be mapped by means by deriving Normalized Differential Vegetation Index (NDVI) from remotely sensed images (Costa-Ferreira *et al.,* 2007; figure 3). It is conceivable that one day the crossing of maps of vines' nitrogen status and water supply regime with those of the response of the vines to the effects of the environment (maps of the vine canopy, maps of the grape sugar content, maps of the grapes' anthocyanins) will enable a precise zoning of the terroir's potentialities to be carried out at an intra-plot level.

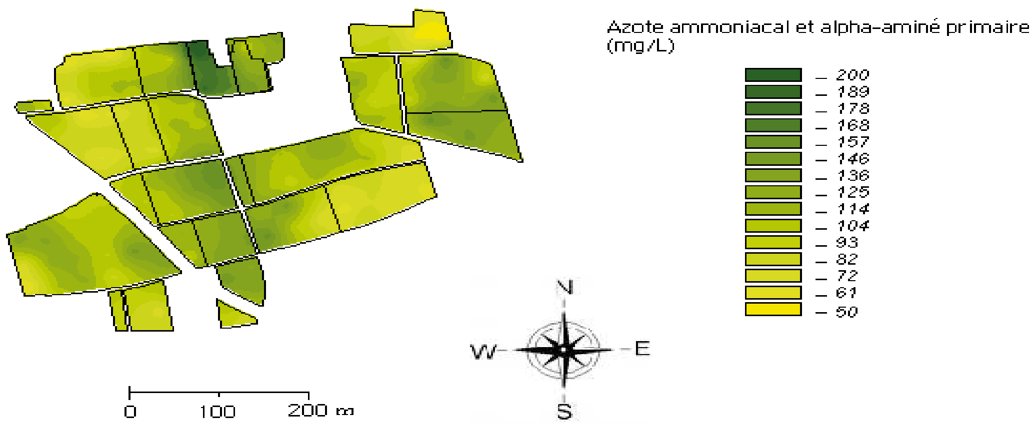


Figure 1 – Spatialisation of the nitrogen status of the vines at the scale of the estate, based on the amount of ammoniacal nitrogen and primary alpha-amine in the grapes (2007 vintage; data: SOVIVINS, F33650 Martillac)

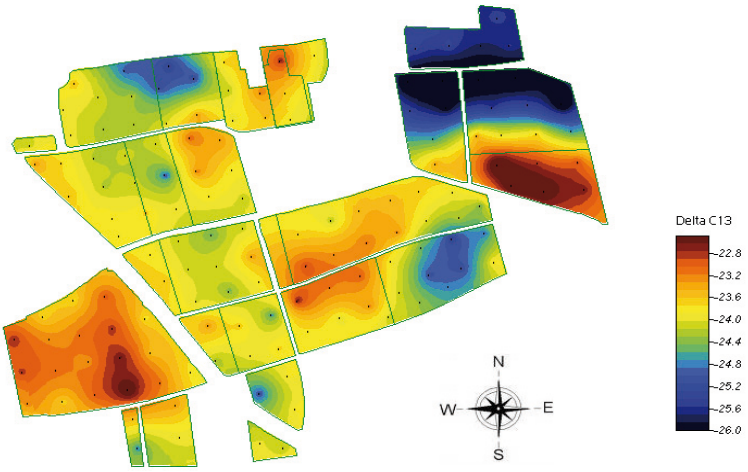


Figure 2 - Spatialisation of vine water status at the scale of the estate based on the measurement carbon isotope discrimination ($^{13}C/^{12}C$ ration) on the grape sugars at ripeness (2007 vintage; data: SOVIVINS, F33650 Martillac).


Figure 3 – Spatialisation of vine vigour at the scale of an estate by means of airborne remote sensing

## Conclusions

Recent development of new sensors and advances in computer technology allow to better characterization the environment of the grapevine. High density observations can be obtained at a reasonable cost. The simultaneous use of the sensors with a GPS device enable to obtain very precise maps of some environment related factors (e.g. soil resistivity). Although still quite expensive, three major responses of the vine to the environment can also be obtained at a high spatial resolution: vine nitrogen status, vine water status and vine vigour. It is likely that terroir studies will greatly benefit from these new tools over the next years.

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