Viticultural agroclimatic cartography and zoning at mesoscale level using terrain information, remotely sensed data and weather station measurements.
Case study of Bordeaux winegrowing area.

Cartographie agroclimatique viticole et zonage à méso-échelle basés sur des relevés climatiques, des informations géographiques et des données de télédétection.
Application à la Gironde viticole.

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Abstract

Climate is a key variable for grapevine development and berry ripening processes. At mesoscale level, climate spatial variations are often determined empirically, as weather station networks are generally not dense enough to account for local climate variations.

In this study, climate spatial variations of Bordeaux winegrowing area were assessed by means of solar radiation cartography using satellite sensing and Digital Elevation Model (DEM) information, daily temperature interpolation using weather station and terrain information, spatialized rainfall using rain gauge data and kriging techniques. Temperature and solar radiation data were used to generate evapotranspiration maps at daily time step. Spatialized data was used to characterize the production potential of several zones of Bordeaux winegrowing areas, according to their agroclimatic characteristics.

Temperature differences within Bordeaux vineyards induce considerable discrepancies in vine phenology, as is shown by means of a degree.day model. Solar radiation data and potential evapotranspiration are mostly governed by terrain characteristics (slope and aspect). Rainfall data spatial patterns indicate that the north-western part of Bordeaux vineyards is recurrently drier and the south-western receives higher rainfall amounts during the grapevine growing season. However, spatial distribution of summer rainfall events changes considerably from one year to another.

The results of this study offer useful information to adapt grapevine cultivars and vineyard management to local climate.

Keywords : Climate, Zoning, Bordeaux, GIS, Grapevine.
Mots-clés : Climat, Zonage, Bordeaux, SIG, Vigne.

Introduction

Amongst the environmental components of terroir, climate plays a major role. Rainfall and evapotranspiration are the main climate components of vineyard water balance, which has a large influence on grape ripening (Matthews and Anderson, 1988 ; Tregoat et al., 2002). Solar radiation drives evapotranspiration process (Bois et al., 2008). It also affects anthocyanin, malate and sugar contents within the berry (Kliewer, 1977). Air temperature governs much of grapevine development and phenology as well as grape ripening kinetics (Huglin, 1978 ; Lebon et al., 2006). Hence, it also modifies berry composition, notably malate, sugar and anthocyanins content at ripeness (Buttrose et al., 1971).

Several studies have been performed in attempt to identify which variables amongst physical components of terroir (i.e. soil and climate) play a major role on grapevine development and berry ripening processes. Some of them focused mainly on soil characteristics (Morlat and Bodin, 2006), landscape (Vaudour et al., 1998) or climate. Others study several factor of the terroir effect. Van Leeuwen et al (2004) show that climate has a greater impact on vine development and grape ripening than soil or cultivar. At mesoscale level, climate studies focus mostly on one climate component such as air temperature used for frost risk assessment (Madelin and Beltrando, 2005) or for ripening potential (Bindi and Maselli, 2001, Jones et al., 2004), global radiation (Failla et al., 2004) or wind circulation patterns (Bonnardot et al., 2002). Only few studies have attempted to account for several climate characteristics (Pythoud, 2004 ; Zufferey and Murisier, 2006).

Recent advances in computer technologies (such as Geographical Information Systems, GIS) and measurement devices (e.g. remote sensing and automatic weather stations) provide useful material for climatological studies. In this paper, several techniques based upon geostatistics, regression models, Digital Elevation Model (DEM), GIS and remotely sensed data are evaluated and applied to perform an agroclimatic zoning of Bordeaux winegrowing region (France).

Material and methods

The study area

The study area is the Bordeaux winegrowing region, located in the southwest of France (figure 1A). Bordeaux appellations of origin cover 2500 km^2 (figure 1B), with about half of the area actually planted to grapevines. The most common cultivars are Merlot, Cabernet-Sauvignon and Cabernet franc (red varieties) and Sauvignon Blanc and Semillon (white varieties). The climate is characterized by moderately warm and dry summers, and mild and wet autumn and winter seasons. The annual rainfall is 930 mm and the mean annual temperature is 13.8°C (1976-2005 normals).
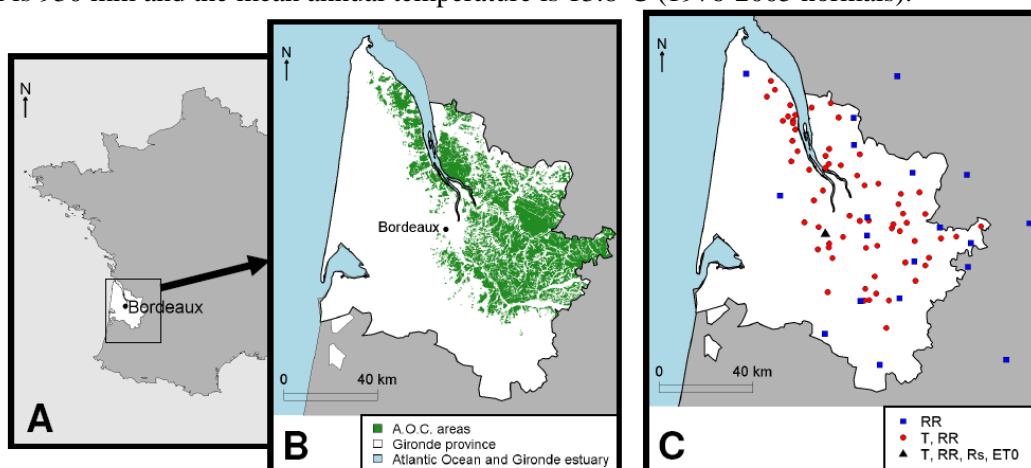

Figure 1 The study area and the weather station locations. A: Location of the Gironde province in France. B: Appellations of Controlled Origin (A.O.C.) of the Bordeaux winegrowing region. C: Weather stations. The symbols indicate which variable each station monitors (*RR*: rainfall ; *T*: air temperature ; *R_S*: solar radiation ; *ET0*: reference evapotranspiration)

Climate data

Weather station data

A database was elaborated by gathering daily weather records of 91 stations (figure 1C). Automatic Cimel® weather stations provided daily rainfall and minimum and maximum air temperature records. Rainfall measurements were completed by manual rain gauges data administrated by Météo-France. One automatic weather station, located in Villenave d'Ornon (44.79 N, 0.58 W), equipped with a class 2 pyranometer, a humidity sensor and a cup anemometer at 2 meters high, was used for solar radiation and reference evapotranspiration validation.

Data was checked and 601 aberrant data series were eliminated. As weather station networks are currently developing, the number of recording sites increases during the study period: weather station number varied from 36 (temperature in 2001) to 85 (rainfall in 2005). For rainfall, interpolations were performed on the 1994-2005 period. For temperature, solar radiation and reference evapotranspiration, the 2001-2005 period was used.

Satellite sensed data

Solar radiation data was retrieved from the HelioClim-1 data base, available at www.soda-is.org. The HelioClim-1 data base has been obtained by the application of the Heliosat-2 method to Météosat satellite images (Gschwind et al., 2006). The Heliosat-2 method is based on the construction of *cloud* and *clearness* indices (Rigollier et al., 2004). Daily solar irradiation data was downloaded at 418 points each sampled at an approximate distance of 20 kilometres inside and at neighbouring sites of Bordeaux winegrowing region.

Geographical information

In order to account for local topography effects on air temperature, geographical information was collected and computed using the GRASS open source Geographical Information System (GIS). Ten geographical co-variables were extracted from a 50 m resolution Digital Elevation Model (DEM) and from the CORINE Land Cover database: elevation, slope, aspect, terrain rugosity, distances to the Atlantic Ocean and to the Gironde estuary, urban proximity index, vegetation index, forest proximity and potential solar radiation. Slope and aspect were also used to account terrain effects on solar irradiation.

Spatialization methods

For each climate variable a different spatialization procedure was used (figure 2). Rainfall and temperature data were interpolated using weather station records. Rainfall data was interpolated using ordinary kriging. Co-variance models were fitted automatically using the Gstat package (Pebesma, 2004) of R open source statistical software (R Development Core Team, 2007). Rainfall daily data was used to calculate rainfall amount cumulated during relevant periods (i.e. year, grapevine vegetative period and grape development and ripening, see next section 2.5 for details) prior to interpolation.Daily temperature was interpolated using a multiple regression process: each day, the co-variables significantly correlated (at 1% of significance level) to temperature were selected and a linear multiple regression model was constructed using a forward stepwise regression algorithm. The model residuals, calculated for each station location, were then interpolated using ordinary kriging, and added to regression model prediction, in order to provide unbiased estimates at each weather station location. This procedure was used to spatialize daily miminum (T_{min}) and maximum (T_{max}) temperatures. The mean daily temperature was calculated as the average of minimum and maximum temperature.
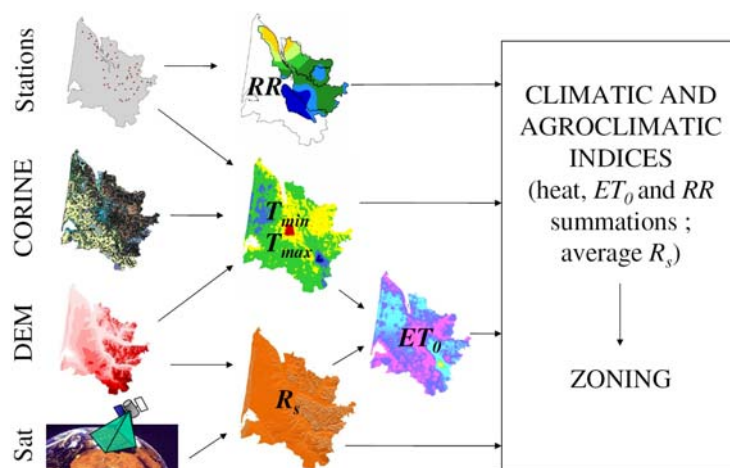
Figure 2 The global spatialization procedure for climatic and agroclimatic variables, and zoning (Sat: Satellite data ; DEM : Digital Elevation Model ; *RR*: rainfall ; T_{min} and T_{max}: minimuim and maximum temperature ; R_S: solar radiation ; ET_0: reference evapotranspiration)

Solar radiation daily data collected from the HelioClim-1 database was interpolated at 1 km resolution using ordinary kriging. For each 1 km pixel, the *r.sun* geometrical model (Hofierka and Suri, 2002) was used to account for terrain effect on solar radiation interception: using elevation, slope and aspect derived from the DEM, 50 m resolution maps of solar radiation were produced.

Climatic and agroclimatic indices

Daily spatialized data was used to calculate, for each pixel, several indices in order to account for climate potential consequences on grapevine development and grape ripening. Average daily temperature was used to calculate heat summation (in growing degree.days, GDD) with a base temperature of 10°C, from January 1st to September 30th.It is hereafter referred as ST_{10}.

Reference evapotranspiration (ET_0, given in mm) was calculated using daily average air temperature and daily solar radiation, using the Turc method (Turc, 1961), re-adjusted to Bordeaux weather conditions:

$$ET_0 = 0,014 \left(23,88\,R_s + 70\right)\left(\frac{T}{T+15}\right) \tag{1}$$

where R_s is the daily solar radiation (MJ m^{-2}), and T is the daily average temperature (°C).

Rainfall height, solar radiation and evapotranspiration daily average were calculated on the following periods: the whole year, the "vegetative" period (from April 1st to September 30th) and the "summer" period (from July 1st to September 30th, which approximately corresponds to the grape growing and ripening period).

Evaluation of spatialization procedures

Rainfall and air temperature daily interpolation errors were calculated at each weather station using a cross-validation process.

Solar radiation spatialization procedure (using remotely sensed data and a terrain integration model) was assessed by comparing spatialized ("predicted") data at the 50 by 50 m pixel where the weather station of Villenave d'Ornon is located, to the weather station records (pyranometer solar radiation, the "observed" value). For reference evapotranspiration, estimated values at Villenave d'Ornon weather station were obtained by calculating ET_0 with predicted daily average temperature values (interpolated using cross validation process, i.e. without Villenave d'Ornon temperature records), and spatialized solar radiation. These estimates were compared to reference evapotranspiration computed with Penman-Monteith FAO-56 method (Allen et al., 1998) using relative humidity, solar radiation, air temperature and 2 m wind speed records.

Statistical indicators of spatialization error were calculated for each weather variable: the root mean squared error (hereafter referred as RMSE) and the mean error (bias).

Results and discussion

Climate variable spatialization accuracy

The statistics relative to spatialization of each climate variable is shown on table 1. Rainfall interpolation was slightly over-estimated (+2.6 mm). Interpolation errors were higher during the whole year (in absolute value) than for summer and vegetation periods. However, when considering the relative error (in percent), rainfall interpolation was more accurate for the whole year and during the vegetative period (9% and 11% of the mean value, respectively), than during summer (15% of the mean value). This could be the consequence of a higher frequency of spatially concentrated rain storms, which induce strong variations of rainfall amounts even over small distances (Ciach and Krajewski, 2006).

	Rainfall (mm)			Temperature (°C or GDD)			Daily solar radiation (MJ m^2)			Daily ET_0 (mm)		
	Year	Veg.	Sum.	T_{min}	T_{max}	ST_{10}	Year	Veg.	Sum.	Year	Veg.	Sum.
Mean	807	363	178	8.7	18.9	1644	13.4	19.6	19.1	2.6	4.0	4.0
Bias	2.6	0.6	0.5	0.1	0.0	4.4	-1.5	-2.0	-1.8	-0.1	-0.2	0.0
RMSE	75.5	39.1	26.1	0.9	0.6	56.3	2.7	3.3	3.2	0.6	0.6	0.6
(%)	9%	11%	15%	-	-	-	20%	17%	17%	21%	16%	16%
N	691	691	691	89238	89032	226	1818	909	454	1818	909	454

Table 1 Statistical indices of spatialization procedures. Veg. : vegetative period ; Sum.: summer period ; N : number of observations (number of situations by number of available stations). See text for further details.

Temperature interpolation using environmental co-variables and residual kriging was more accurate for maximum temperature than for minimum temperature. The difficulties in interpolating minimum temperature are well known from climatologists, as this variable provides strong spatial variations, governed by local topography. Temperature error propagation within heat summation model provided an RMSE of 56.3 GDD, from April to September.

Daily solar radiation and ET_0 errors are considerable (RMSE ranging from 16 to 21% of the mean value). The lowest relative RMSE were found during the July to September period. These errors reduce the relevance of spatial and temporal analyses of these variables, within Bordeaux winegrowing region. However, strong differences were noticed due to terrain local variations (Bois, 2007), suggesting that solar radiation and reference evapotranspiration are mostly governed by slope and aspect in Bordeaux vineyards.

Bordeaux winegrowing area agroclimatic zoning

Due to the lack of accuracy concerning ET_0 and R_S spatialization, it seemed reasonable to focus on the rainfall and temperature spatial and temporal variations.

Thermal characteristics were investigated by means of ST_{10}, during 5 years (2001-2005). Maps were constructed at a 50 m resolution (i.e. pixels of 50 m by 50 m), in order to account for local temperature patterns due to local environmental variations. Maps of rainfall heights were constructed for each year of the 1994 to 2005 period (12 years), at a 250 m resolution.

As climate characteristics strongly vary from one year to another, the redundancy of spatial climate relative differences from were explored.

The redundancy of spatial patterns observed for each year within Bordeaux winegrowing region was assessed by a classification method, which consists in the following steps: (a) for each year, the whole set of spatialized data (i.e. pixels of the map) was partitioned in 5 classes, using a regular interval clustering. A value from 1 to 5 was given to each pixel, according to its rank within the data set (rank 1 corresponds to the highest amount of rainfall or to the highest ST_{10} value, and rank 5 corresponds to the lowest rainfall amount or to the lowest ST_{10} value). An annual map of relative classification is thus obtained. (b) For each pixel, the mean rank is calculated on the whole period, as well as the standard deviation of the rank. (c) If the standard deviation is larger or equal to 1, which suggest a strong year-

to-year variability, the pixel is classified as "variable". If the standard deviation is lower than 1, the pixel rank is obtained by rounding its average yearly rank. Six classes are thus obtained.
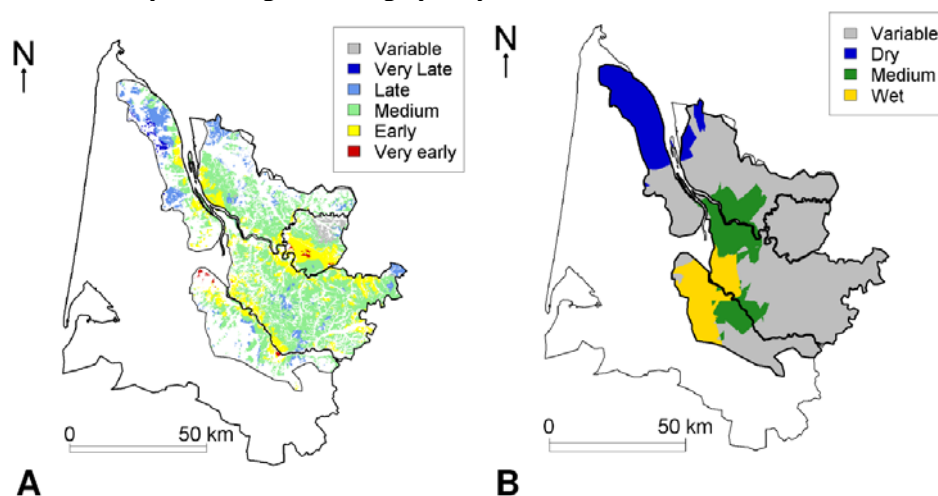

Figure 3 Maps of thermal (GDD) and rainfall zoning. A: zoning based upon ST_{10}, period 2001-2005. B: zoning based upon rainfall height from April to September, period 1994-2005

Maps of ST_{10} and rainfall amounts from April to September are shown on figure 3. For GDD, only a small area in north-eastern part of Bordeaux vineyards is classified as "variable". This indicates a high redundancy concerning temperature spatial patterns. Most of the Bordeaux winegrowing region is classified as "medium" (class 3, 64% of the total area). 21% of the total appellation area is classified as "early" (class 2). It corresponds to areas located on the hillsides of Dorgogne and Garonne valleys, and close to the Gironde estuary. 12% of the total area is classified as "late" (class 4). Most of this surface is located on the north-western part of the Bordeaux winegrowing region, close to the Atlantic Ocean. Small areas exhibit very low temperature sums. These vineyards are located in the northwest, and are classified as "very late" (class 5, 1% of the total area). Three zones benefits of high ST_{10} values: a small part of Saint-Emilion vineyards, located in the eastern part of Bordeaux winegrowing region, the vineyards of the appellation of origin Pessac-Leognan, located within the suburbs of Bordeaux city, in the west, and some vineyards located near Sauternes, in the south. The difference in GDD between each class varies from a year to another, from 42 to 79 GDD. As the grape ripening kinetics strongly depends on GDD (Huglin, 1978), maturity differences from 6 to 11 days are expected between each class (considering that the mean daily temperature is about 17°C at the end of September). Thus, a maximum difference of 30 to 55 days in maturity date may occur in Bordeaux winegrowing region, between the coolest and the warmest areas. However, such differences may not be observed in reality, because several other variables govern grape ripening (cultivar, soil or agricultural practices).

Concerning April-to-September rainfall, two thirds of the Bordeaux winegrowing region is classified as "variable". The north-western part of the region (Médoc and most of the Haut-Médoc appellations) exhibits repetitive low rainfall height, whereas the west-middle part (mostly the Pessac-Léognan appellation) is redundantly wetter than the rest of the winegrowing region.

However, these patterns were not observed during the summer period, during which water availability strongly determines grape development and ripening, especially for red grape cultivars: a zoning applied to the July to September rainfall indicates that spatial rainfall patterns are strongly modified from a year to another (i.e. the entire winegrowing region is classified as "variable").

Conclusion

In this paper, an approach to characterize climate variations at mesoscale level is proposed. Using remotely sensed data, weather stations records and geographical information, several methods of climate spatialization are assessed. Rainfall and temperature interpolations provide reasonable accuracy, whereas errors are large for solar radiation and reference evapotranspiration spatialization processes.

The Bordeaux winegrowing region exhibits a large diversity of type of wine. This is the result of spatial variations of cultural practices, cultivar, soil and climatic diversity. In this study it has been shown that rainfall, the only source of water for Bordeaux vineyards, is probably not a factor which can explain the redundant typical characteristics and differences that can be observed for a same type of product (i.e. red, white, dry or sweet wines). As a matter of fact, even if rainfall spatial distribution within the same year may induce strong spatial variations of grapevine water status, grape ripening, and thus grape quality, this particular pattern changes from a year to another.

In contrast, temperature spatial variations are highly redundant, although the maximum differences observed within Bordeaux winegrowing region may be small or large, depending on the vintage. The zoning performed on the 2001-2005 period has shown differences of heat summation (from January to September) from 42 to 79 GDD between each of the 5 classes obtained. These differences might induce considerable lags of harvest date, for a given cultivar. Theses results provide useful information for cultivar adaptation to local climate condition. Using this zoning, it would certainly be of great interest to compare the behaviour of a given cultivar in two contrasted GDD zones as a tool for climate change anticipation.

Acknowledgements

References

ALLEN, R.G., PEREIRA, L.S., RAES, D. and SMITH, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper. Food and Agriculture Organization (FAO), Rome Italy, 300 pp.

BINDI, M. and MASELLI, F., 2001. Extension of crop model outputs over the land surface by the application of statistical and neural network techniques to topographical and satellite data. Climate Research, **16**: 237-246.

BOIS, B., 2007. Cartographie agroclimatique à méso-échelle : méthodologie et application à la variabilité spatiale du climat en Gironde viticole. Conséquences pour le développement de la vigne et la maturation du raisin., Université Bordeaux 2, Bordeaux, 211 pp.

BOIS, B., PIERI, P., VAN LEEUWEN, C., WALD, L., HUARD, F., GAUDILLERE, J.P. and SAUR, E., 2008. Using remotely sensed solar radiation data for reference evapotranspiration estimation at a daily time step. Agricultural and Forest Meteorology, In Press.

BONNARDOT, V., PLANCHON, O., CAREY, V. and CAUTENET, S., 2002. Diurnal wind, relative humidity and temperature variation in the Stellenbosch-Groot Drakenstein wine-growing area. *South African Journal of Enology and Viticulture*, **23(2)**: 62-71.

BUTTROSE, M.S., HALE, C.R. and KLIEWER, W.M., 1971. Effect of the temperature on the composition of Cabernet-Sauvignon berries. *American Journal of Enology and Viticulture*, **22(2)**: 71-75.

CIACH, G.J. and KRAJEWSKI, W.F., 2006. Analysis and modeling of spatial correlation structure in small-scale rainfall in Central Oklahoma. *Advances in Water Resources*, **29(10)**: 1450-1463.

FAILLA, O., MARIANI, L., BRANCADORO, L., MINELLI, R., SCIENZA, A., MURADA, G. and MANCINI, S., 2004. Spatial distribution of solar radiation and its effects on vine phenology and grape ripening in an alpine environment. *American Journal of Enology and Viticulture*, **55(2)**: 128-138.

GSCHWIND, B., MENARD, L., ALBUISSON, M. and WALD, L., 2006. Converting a successful research project into a sustainable service: The case of the SoDa Web service. *Environmental Modelling & Software*, **21(11)**: 1555-1561.

HOFIERKA, J. and SURI, M., 2002. The solar radiation model for Open source GIS: implementation and applications., Open source GIS - GRASS users conference 2002, Trento, Italy.

HUGLIN, P., 1978. Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. Comptes Rendus de l'Académie de l'Agriculture de France, **64**: 1117-1126.

JONES, G.V., NELSON, P. and SNEAD, N., 2004. Modeling Viticultural Landscapes: A GIS Analysis of the Terroir Potential in the Umpqua Valley of Oregon. *Geoscience Canada*, **31(4)**: 167-178.

KLIEWER, W.M., 1977. Influence of temperature, solar radiation and nitrogen on coloration and composition of Emperor grapes. *American Journal of Enology and Viticulture*, **28(2)**: 96-103.

LEBON, E., PELLEGRINO, A., LOUARN, G. and LECOEUR, J., 2006. Branch development controls leaf area dynamics in grapevine (Vitis vinifera) growing in drying soil. *Annals of Botany*, **98(1)**: 175-185.

MADELIN, M. and BELTRANDO, G., 2005. Spatial interpolation-based mapping of the spring frost hazard in the Champagne vineyards. *Meteorological Applications*, **12(1)**: 51-56.

MATTHEWS, M.A. and ANDERSON, M.M., 1988. Fruit ripening in Vitis vinifera L.: Responses to seasonal water deficits. *American Journal of Enology and Viticulture*, **39(4):** 313-320.

MORLAT, R. and BODIN, F., 2006. Characterization of viticultural terroirs using a simple field model based on soil depth - II. Validation of the grape yield and berry quality in the Anjou vineyard (France). *Plant and Soil*, 2**81(1-2)**: 55-69.

PEBESMA, E.J., 2004. Multivariable geostatistics in S: the gstat package. *Computers & Geosciences,* **30(7)**: 683-691.

PYTHOUD, K., 2004. Etude des terroirs viticoles vaudois. 3. Modélisation des paramètres climatiques. *Revue Suisse de Viticulture, Arboriculture et Horticulture*, **36(4)**: 10-14.

R Development Core Team, 2007. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

RIGOLLIER, C., LEFEVRE, M. and WALD, L., 2004. The method Heliosat-2 for deriving shortwave solar radiation from satellite images. *Solar Energy*, **77(2)**: 159-169.

TREGOAT, O., VAN LEEUWEN, C., CHONE, X. and GAUDILLERE, J.P., 2002. Etude du régime hydrique et de la nutrition azotée de la vigne par des indicateurs physiologiques. Influence sur le comportement de la vigne et la maturation du raisin (Vitis vinifera L. cv. Merlot, 2000, Bordeaux). *Journal International des Sciences de la Vigne et du Vin*, **36(3)**: 133-142.

TURC, L., 1961. Evaluation des besoins en eau d'irrigation, évapotranspiration potentielle. *Annales Agronomiques*, **12(1)**: 13-49.

VAN LEEUWEN, C., FRIANT, P., CHONE, X., TREGOAT, O., KOUNDOURAS, S. and DUBOURDIEU, D., 2004. Influence of climate, soil, and cultivar on terroir. *American Journal of Enology and Viticulture*, **55(3)**: 207-217.

VAUDOUR, E., GIRARD, M.C., BREMOND, L.M. and LURTON, L., 1998. Caracterisation spatiale des terroirs et constitution des raisins en A.O.C. Cotes-du-Rhone meridionales (Bassin de Nyons-Valreas). *Journal International des Sciences de la Vigne et du Vin*, **32(4)**: 169-182.

ZUFFEREY, V. and MURISIER, F., 2006. Terroirs viticoles vaudois et alimentation hydrique de la vigne. *Revue Suisse de Viticulture, Arboriculture et Horticulture*, **38(5)**: 283-287.