# ESTIMATING SPATIAL AND TEMPORAL VARIATIONS IN SOLAR RADIATION WITHIN BORDEAUX WINEGROWING REGION USING REMOTELY SENSED DATA

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## Abstract

**Aims**: This paper presents a study of spatial and temporal variations in solar radiation for the Bordeaux winegrowing region, over a 20 year period (1986-2005).

**Methods and results**: Solar radiation data was retrieved from the HelioClim-1 database, elaborated from Meteosat satellite images, using the Heliosat-2 algorithm. Daily data was interpolated using ordinary kriging to produce horizontal solar radiation maps at a 500 m resolution. Then using a digital elevation model, 50 m resolution daily solar radiation maps with terrain integration were produced for the period 2001-2005. The long term (20 year) analysis of solar radiation at low spatial resolution (500 m) showed a west to east decreasing gradient within the Bordeaux winegrowing region. Mean August-to-September daily irradiation values, on horizontal surface, were used to classify the Bordeaux winegrowing region into three zones: low, medium, and high solar radiation areas. This initial zoning was downscaled to 50 m resolution, applying a local correction ratio, based on 2001-2005 solar radiation from the inclined surface analysis. Grapevine development and maturation potential of the different zones of appellation of origin of Bordeaux winegrowing regions are discussed in relation with this zoning.

**Conclusion**: Solar radiation variability within the Bordeaux winegrowing region is mainly governed by terrain slopes and orientations, which induce considerable variations within the eastern part of Bordeaux vineyards.

**Significance and impact of study**: Solar radiation has a major impact on vineyard water balance, grapevine development and berry ripening. However, irradiation data is seldom available in weather stations records. This paper highlights the need for high resolution mapping of solar radiation that uses remote sensing and terrain effect integration for agroclimatic studies in viticulture.

**Key words**: Solar radiation, remote sensing, *Vitis vinifera*, vineyard zoning, Bordeaux

## Résumé

**Objectif** : Cet article présente une étude de la variabilité spatio-temporelle du rayonnement global en Gironde viticole sur une période de 20 ans (1986-2005)

**Méthodes et résultats** : Les données de rayonnement global proviennent de la base de données HelioClim-1, élaborée à partir d'images satellite (Meteosat), analysées par l'algorithme Heliosat-2. Les données quotidiennes ont d'abord été interpolées par krigeage ordinaire, afin de produire des cartes de rayonnement global à une résolution de 500 mètres. Dans un second temps, la résolution des cartes de rayonnement global a été affinée à 50 m, sur la période 2001-2005, en intégrant l'effet du relief sur l'interception du rayonnement indicent à l'aide d'un modèle numérique de terrain. L'analyse cartographique sur une longue période (20 ans), à faible résolution (500 m) a mis en évidence un gradient ouest-est de rayonnement global décroissant au sein de la Gironde viticole. Les données de rayonnement global quotidien sur terrain plat ont été utilisées pour établir un zonage de la Gironde viticole en trois classes de rayonnement : bas, moyen et élevé. Ce zonage initial a été affiné à 50 m en utilisant un facteur de correction locale, basé sur l'analyse du rayonnement incident en zone de relief, sur la période 2001-2005. L'impact du rayonnement global sur le potentiel de développement de la vigne et de maturation du raisin dans les différentes zones d'appellation d'origine du Bordelais est discuté.

**Conclusion** : La variabilité spatiale du rayonnement global en Gironde viticole est essentiellement influencée par le relief, ce qui induit d'importantes variations dans la partie orientale du vignoble.

**Signification et impact de l'étude** : Le rayonnement global a un impact majeur sur le bilan hydrique de la vigne, sur son développement et sur la maturation du raisin. Cependant, cette variable climatique est rarement enregistrée. Cet article souligne les intérêts de la cartographie du rayonnement global à haute résolution en s'appuyant sur la télédétection et l'effet du relief pour mener des études en agroclimatologie viticole.

**Mots-clés** : Rayonnement global, télédétection, *Vitis vinifera*, zonage viticole, Bordeaux

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## INTRODUCTION

Solar radiation has a large influence on vine growth, berry ripening, and disease development in vineyards. Its direct effects are numerous and it affects most other climate variables. Hence, vineyard microclimate depends strongly on this variable. Most of the radiative balance is determined by incoming solar radiation. It induces variations in surface and air temperature, and it has a major role in evapotranspiration processes (Priestley and Taylor, 1972; Bois *et al.*, 2005). Solar radiation determines incoming light and photosynthetically active radiation (PAR). For grapevine (*Vitis vinifera* L.), as for most plants, light availability increases dry mass production (Buttrose, 1969; Grechi *et al.*, 2007), however in hot and dry conditions, photosynthesis can be reduced despite non-limiting light conditions (Zufferey *et al.*, 2000). Several researchers have shown the difficulties in separating temperature from light effects on photosynthesis activity and berry maturation in natural conditions as incoming solar radiation determines both of these climatic variables (Crippen and Morrison, 1986; Schultz *et al.*, 1996; Bergqvist *et al.*, 2001). Results concerning the influence of sun exposition on berries differ according to locations and experimental conditions. Overexposure to sunlight may decrease anthocyanin contents of berries (Bergqvist *et al.*, 2001) and sugar concentration (Kliewer and Lider, 1968). However, sugar concentration level may increase in sun exposed berries due to water loss (Crippen and Morrison, 1986). In all experiments, sunlight-exposed fruits are lower in malate concentration and total titrable acidity (Kliewer and Lider, 1968; Kliewer, 1977; Crippen and Morrison, 1986; Dokoozlian and Kliewer, 1996; Spayd *et al.*, 2002). These results, which are sometimes contradictory, highlight the fact that management of incoming solar radiation *via* vineyard architecture has to be adapted to local conditions (i.e. local climate and soil characteristics). In order to estimate grapevine transpiration and vineyard soil water balance, models have been developed to integrate the quantity of solar irradiation intercepted by leaf area according to vineyard architecture (Riou *et al.*, 1989; Riou *et al.*, 1994; Lebon *et al.*, 2003; Oyarzun *et al.*, 2007).

Solar radiation data is seldom available in weather records, for its precise measurement requires steadily maintained fragile devices such as pyranometers. However, with recent advances in remote sensing and image analysis, it is now possible to retrieve daily solar radiation from satellite data (Solanki *et al.*, 2005). The HelioClim-1 database, elaborated from Meteosat images analysis provides solar radiation data for Europe and Africa (Lefèvre *et al.*, 2007). This database was used to establish the European Solar Radiation Atlas (ESRA, Rigollier *et al.*, 2000), and was coupled to a 2 km resolution Digital Elevation Model (DEM) to include the effects of relief on solar radiation interception for the photovoltaic potential mapping of Africa (Huld *et al.*, 2005).

Orography has a major effect on incoming solar radiation, especially between 30° and 60° latitudes when close to the equinox (Oke, 1978). Advances in computer technology and development of GIS software have provided methods to easily determine spatial variations of solar irradiation provided by terrain slope and aspect (Durand and Legros, 1981; Flint and Childs, 1987; Hofierka and Suri, 2002; Kang *et al.*, 2002; Wang *et al.*, 2002).

Therefore, the purpose of this research is to combine remote sensed data and solar irradiation models based upon orography to estimate the spatial and temporal variability of solar radiation interception of the Bordeaux winegrowing region (France). The results provided by the modeling and mapping methods are then used as a tool for viticulture zoning.

## MATERIAL AND METHODS

### 1. Study area

The winegrowing region of Bordeaux is located in southwest France, in the province (département) of Gironde. It is composed of 57 appellations of controlled origin (AOC) covering about 230 000 ha, although only 120 000 ha are actually planted to grapevines. Grapevine cultivars planted in the region are mostly Merlot, Cabernet-Sauvignon, Cabernet franc for red varieties, and Sauvignon blanc and Semillion for white varieties. The vineyards are located 20 to 150 kilometers from the Atlantic Ocean and between 45.5 °N and 44.3 °N (figures 1A and 1B). The Bordeaux vineyards can be divided in 5 sub-regions (contiguous area being separated by the main rivers), as proposed on figure 1B and in table 1.

The climate of the Bordeaux region is temperate, with moderately dry summers (200 mm from July to September) and wet autumn and winter periods. The average annual rainfall is 930 mm (1976-2005 mean) and ranges from 700 to 1300 mm. The mean annual temperature is 13.8 °C and ranges from 22.3 °C in August to 7.8 °C in December. The size of the area of the Bordeaux region provides a considerable diversity of climatic conditions due to several topographic variations. The Medoc region (in the north of region I, figure 1B), lies between the Atlantic Ocean and the Gironde Estuary. In the southeast, the eastern Entre-deux-Mers area is marked by frequent storms during summer. Most of the western side of the Bordeaux winegrowing region is flat, whereas the eastern part is hilly. Some of the vineyards are located within the suburbs of Bordeaux city and benefit


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from higher temperatures due to urban heat island effects (Oke, 1978).

## 2. Solar radiation mapping

a- Solar radiation on horizontal surfaces

Daily solar irradiation data was taken from the HelioClim-1 database, available at the SoDa Web Service (http://www.soda-is.org, Gschwind *et al.*, 2006). This database has been obtained by the application of the Heliosat-2 method to reduced data sets ISCCP-B2 Meteosat satellite images (Lefèvre *et al.*, 2007). The ISCCP-B2 data set was produced by reducing the sampling in time and space of Meteosat images, in order to better exploit the wealth of information that they provide. First, the sampling frequency was reduced to 3-hours intervals. Second, the higher resolution in the visible channel was averaged to match the lower resolution of infrared channel data (i.e. an image of 2500 by 2500 pixels with a resolution of 5 km over Europe). Finally, 1 pixel out of 6 in each direction is sampled, starting with the southernmost pixel.

The Heliosat-2 method is based upon the construction of cloud and clear-sky indices for each pixel of a satellite image (Rigollier *et al.*, 2004). The precision of the method depends mostly on the cloud cover; relative uncertainties are lower during clear-sky days (Rigollier *et al.*, 2004). The HelioClim-1 database provides root mean squared differences of about 20 % from daily pyranometers values for Europe and Africa (Lefèvre *et al.*, 2007). However, the Heliosat-2 method does not account for slope and aspect of the terrain.

Daily solar irradiation data from Heliosat-2 was collected for the period 1986-2005 and downloaded at 418 points, each sampled at an approximate distance of 20 kilometres inside and at neighbouring sites of the Gironde province.

From daily irradiation data, cloud cover temporal patterns were analyzed using a clearness index ($K_T$), calculated as follows:

$$K_T = \frac{G_{dh}}{G_{d0}} \qquad [1]$$

where $G_{dh}$ is the daily irradiation on a horizontal surface (in MJ $m^{-2}$) and $G_{d0}$ is the daily extra-atmospheric irradiation (in MJ $m^{-2}$) calculated from astronomical formulae.

Mean daily irradiation for several periods and mean monthly $K_T$ values were then interpolated on a 500 m resolution grid, using the ordinary kriging technique (for a review on geostatistical techniques see Goovaerts, 1999). Kriging was done using the Gstat package of the R statistical software (Pebesma, 2004; R Development Core

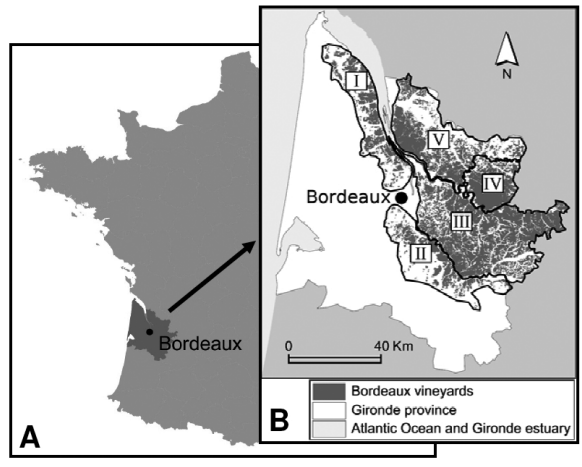



**Figure 1 - Maps of the study area.**
**A) France, with the Gironde province and the city of Bordeaux.**
**B) The Bordeaux winegrowing region, located in Gironde province.**
Figures in roman numbers indicate the number of the five sub-regions of the Bordeaux winegrowing region (see table 1 for the list of the appellations of origin located in each region).

**Table 1 - Classification by region of appellations of origin of the Bordeaux winegrowing region (see figure 1B).**

| Region | Appellations of origin (AOC) |
|---|---|
| **I** | Bordeaux ; Bordeaux Supérieur ; Haut-Médoc ; Listrac ; Margaux ; Médoc ; Moulis ; Pauillac ; Saint-Estèphe ; Saint-Julien |
| **II** | Barsac ; Bordeaux ; Bordeaux Supérieur ; Cerons ; Graves ; Graves Supérieures ; Pessac-Léognan ; Sauternes |
| **III** | Bordeaux ; Bordeaux Supérieur ; Côtes de Bordeaux ; Saint-Macaire ; Entre-Deux-Mers ; Haut-Bénauge ; Graves-de-Vayres ; Loupiac ; Premières Côtes de Bordeaux ; Cadillac ; Sainte-Croix-du-Mont ; Sainte-Foy Bordeaux |
| **IV** | Bordeaux ; Bordeaux Supérieur ; Côtes de Francs ; Côtes de Castillon ; Lalande de Pomerol ; Lussac Saint-Emilion ; Montagne Saint-Emilion ; Pomerol ; Puisseguin Saint-Emilion ; Saint-Emilion ; Saint-Georges Saint-Emilion |
| **V** | Blaye ; Blayais ; Bordeaux ; Bordeaux Supérieur ; Canon Fronsac ; Côtes de Bourg ; Fronsac ; Premières Côtes de Blaye ; Côtes de Blaye |


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Team, 2007). Linear co-variance models were fitted automatically to experimental semi-variograms, by the least squared method.

b- Terrain integration for incoming solar radiation mapping

Effects of terrain on solar irradiation were taken into account by mean of direct geometrical relations. The solar radiation model *r.sun* (Hofierka and Suri, 2002), implemented in GRASS Geographical Information System (GIS) was used. The *r.sun* model estimates beam, diffuse and reflected components of solar incoming radiation on horizontal and inclined surfaces. Daily solar irradiation is calculated at a 15 minute time step and cumulated for each day. Mask effects of surrounding orography are taken into account.

Terrain effects on solar radiation interception are considerable during clear-sky days as most of the incoming radiation is direct and the relationship between irradiation and orography is geometric. During cloudy days most of the incoming radiation is diffuse. In such situations, except the mask effects produced by surrounding relief, terrain effects are minor. For maritime climate conditions, such as experienced in the Bordeaux region, the frequency of cloudy days can be substantial. For this reason, we used the *r.sun* model, which integrates diffuse radiation (standard overcast method).

Input data for *r.sun* are: elevation, slope and aspect (retrieved from a 50 m resolution Digital Elevation Model (DEM)), ground albedo (set to a default value of 0.2), horizontal surface irradiation from HelioClim-1 database, the Linke turbidity coefficient, whose monthly values were provided by the SoDa Web service, the diffuse (kdh) and beam (kbh) proportions (i.e. values from 0 to 1) of daily irradiation on horizontal surfaces, estimated with an empirical relationship established at Bordeaux (Pieri and Valancogne, unpublished results) :

$$k_{dh} = \min\left(1.09 - 2.6896\left(\frac{G_{dh}}{G_{d0}}\right)^2 + 1.2843\left(\frac{G_{dh}}{G_{d0}}\right)^3 ; 1\right) \quad [2]$$

and $k_{dh} = 1 \; if \left(\frac{G_{dh}}{G_{d0}}\right) < 0.2$ [3]

and $k_{bh} = 1 - k_{dh}$ [4]

where $G_{dh}$ and $G_{d0}$ have the same significance and units as in equation [1].

The *r.sun* model produced daily beam, diffuse and reflected solar radiation on inclined surfaces at the DEM resolution (i.e. 50 m by 50 m). These three variables were then summed to obtain the daily irradiation data. The inter-annual differences between horizontal and inclined surfaces were evaluated for a 5 year period from 2001 to 2005.

## RESULTS

### 1. Solar radiation climatology for the Bordeaux region

The annual mean of daily solar irradiation, annual sunshine duration and annual clear-sky frequency data for the Gironde province and the Bordeaux winegrowing region are shown in table 2. Mean daily irradiation ranges from 11.7 to 13.3 MJ m$^{-2}$ (-5 % to 9 % of the mean value) for the Gironde province and from 11.8 to 12.8 MJ m$^{-2}$ in the Bordeaux winegrowing region (-3 % to 7 % of the mean value). The average clearness index is 0.44 for the Gironde province and 0.43 for Bordeaux winegrowing area. Solar irradiation reaches its maximum in June and July (figure 2) and remains low from October to February (mean daily irradiation below 10 MJ m$^{-2}$). The spatial variation of solar irradiation is larger for the Gironde province than for the Bordeaux winegrowing region (figure 2).

**Table 2 - Statistics of solar radiation data for the period 1986-2005 for the Gironde province and the Bordeaux winegrowing region.**

CV = coefficient of variation (standard deviation, σ divided by the mean, given in percent).

| | Gironde Province | | Bordeaux Winegrowing Region | |
|---|---|---|---|---|
| | Daily irradiation (MJ m$^{-2}$) | Clearness index ($K_T$) | Daily irradiation (MJ m$^{-2}$) | Clearness index ($K_T$) |
| **Min.** | 11.7 | 0.42 | 11.7 | 0.43 |
| **1st quartile** | 12.0 | 0.43 | 11.8 | 0.43 |
| **Median** | 12.2 | 0.44 | 11.9 | 0.43 |
| **Mean** | 12.3 | 0.44 | 12.0 | 0.43 |
| **3rd quartile** | 12.5 | 0.45 | 12.0 | 0.44 |
| **Max.** | 13.3 | 0.48 | 12.8 | 0.46 |
| σ | 0.38 | 0.01 | 0.20 | 0.01 |
| **CV** | 3.1% | 2.9% | 1.7% | 1.6% |


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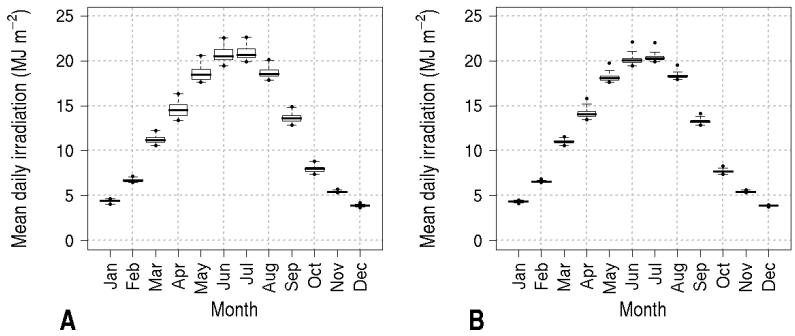



**Figure 2 - Box-plots of monthly means of daily irradiation during the period 1986-2005, for the Gironde province (A) and the Bordeaux winegrowing region (B).**

Data used to create each box are the mean daily irradiation values of each 500 m pixel.
Points outside the boxes represent the minimum and the maximum values observed within each area.

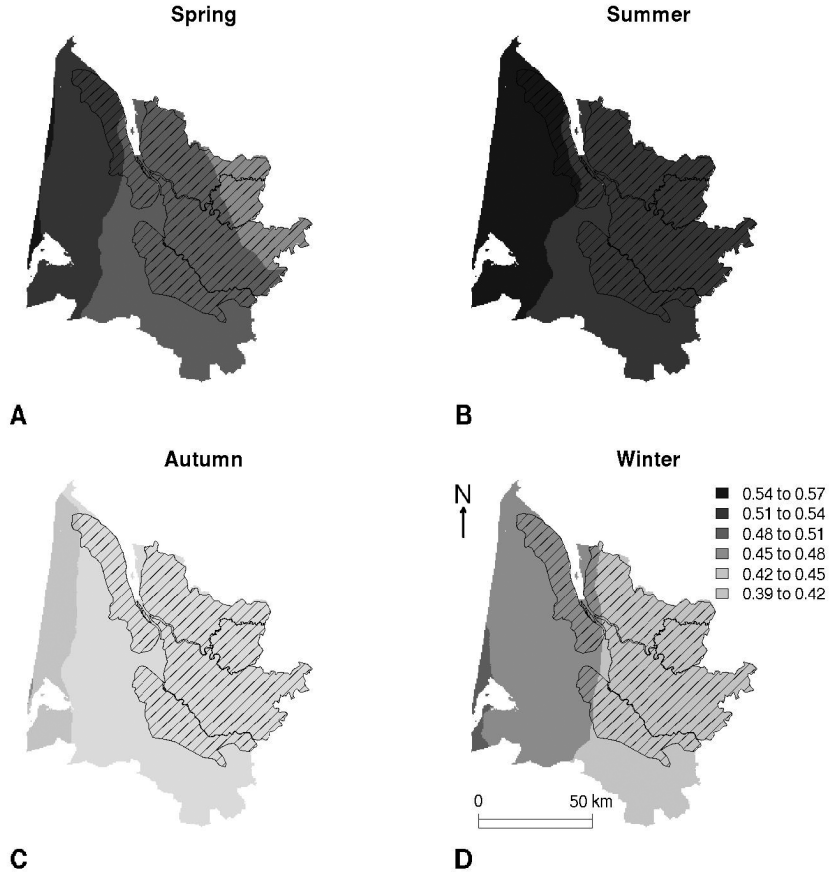



**Figure 3 - Seasonal maps of the clearness index for the Gironde province (period 1986-2005).**

The dashed areas represent the five sub-regions of the Bordeaux winegrowing region (see figure 1B). A: « spring », from April to June ; B: « Summer », from July to September ; C: « Autumn », from October to December ; D: « Winter », from January to March.

The growing season, spanning a period from April to September, benefits from clearness indices from 0.46 to 0.58 (figures 3A and 3B) in the Gironde province. During the autumn period, the proportion of extra-atmospheric global radiation that reaches the ground is lower than during other seasons (figure 3C). This could be explained both by the cloud climatology (weather is globally cloudier from October to February in the Gironde province) and the increasing length of solar radiation path throughout the atmosphere, due to sun inclination. The spatial pattern of the clearness index remains similar throughout the rest of the year with the Atlantic Ocean coast receiving the highest amount of solar radiation. The clearness index decreases from west to east, during spring, summer and winter. During autumn, it decreases from west to east until the center of the Gironde province, and then increases


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again toward east (figure 3C). This particular spatial pattern might be related to the greater diversity of synoptic situations during this period (Jones and Davis, 2000). The largest spatial variability is observed during winter, where the western part of the Bordeaux winegrowing region receives the highest amount of solar radiation.

In the Medoc, located in the northwest of the Gironde (region I, see figure 1), the clearness index is 4 to 8 % higher than in the easternmost vineyard areas from April to September (figures 3A and 3B).

**Table 3 - Statistics of mean solar irradiation (MJ m$^{-2}$) in the Bordeaux winegrowing region from August to September for the three classes obtained by regular interval clustering.**

CV = coefficient of variation (standard deviation, σ divided by the mean x 100).

| | Horizontal surface classes | | | Inclined surface classes | | |
|---|---|---|---|---|---|---|
| | **Low** | **Medium** | **High** | **Low** | **Medium** | **High** |
| **Mean** | 15.7 | 16.0 | 16.5 | 15.6 | 16.1 | 16.5 |
| **σ** | 0.10 | 0.15 | 0.14 | 0.22 | 0.14 | 0.18 |
| **CV** | 0.6% | 0.9% | 0.8% | 1.4% | 0.9% | 1.1% |
| **Min.** | 15.4 | 15.9 | 16.3 | 12.4 | 15.9 | 16.3 |
| **Max.** | 15.8 | 16.3 | 16.8 | 15.9 | 16.3 | 17.8 |
| **Area (ha.)** | 156106 | 77065 | 3889 | 127819 | 92962 | 16279 |

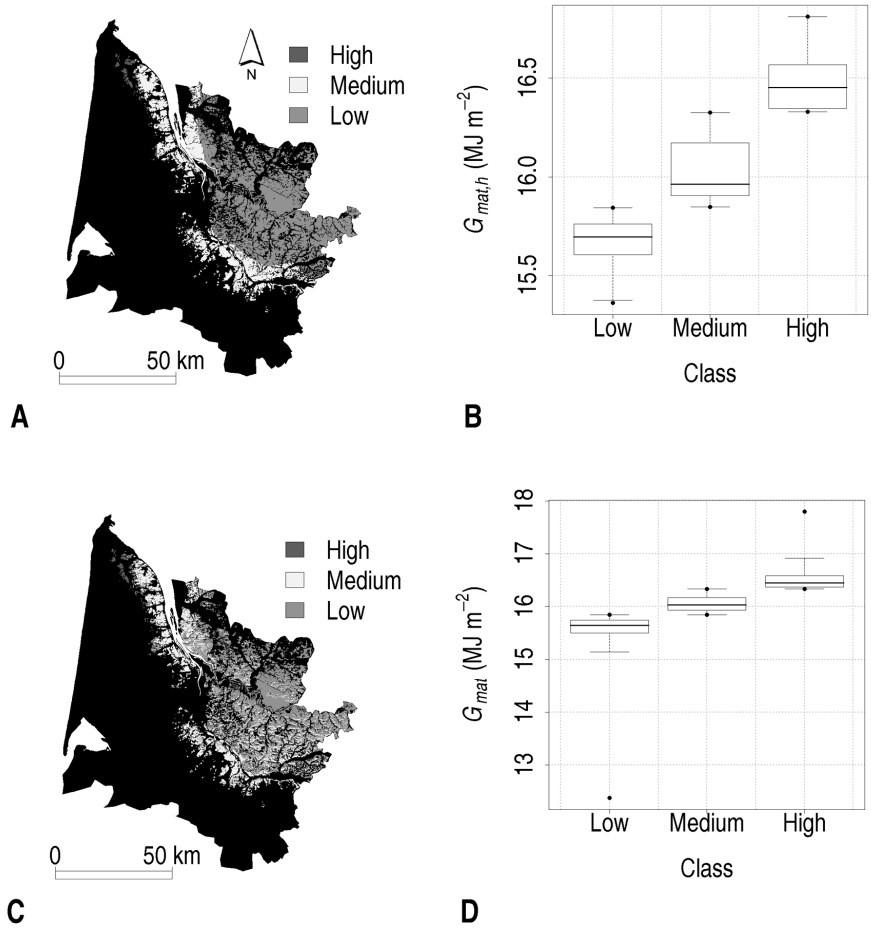



**Figure 4 - Zoning of the Bordeaux winegrowing region based on the mean daily solar irradiation value from August to September ($G_{mat,h}$) for the period 1986-2005.**
**A: map of $G_{mat,h}$ classes (horizontal surface zoning);**
**B: box-plot of $G_{mat,h}$ values of the three classes; C: map of $G_{mat}$ classes (inclined surface zoning) ;**
**D: box-plot of $G_{mat}$ values of the three classes.**

Points on the box-plots figures correspond to the extremes values of each class.


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## 2. Bordeaux region vineyard zoning

In the Bordeaux winegrowing region, the veraison period for red and white grape varieties generally occurs at the end of July or at the beginning of August and the harvest period ranges from mid-September to the beginning of October. As climate conditions from veraison to harvest are crucial for quality, mean daily values of solar irradiation from August to September on horizontal surface were calculated. This index is referred hereafter as $G_{mat,h}$ (where *mat* stands for maturation period, i.e. August to September, and h indicates that $G_{mat}$ is calculated on a horizontal surface). Solar radiation during this period was used to perform a zoning of the Bordeaux winegrowing region as follows: (a) Mean $G_{mat,h}$ for a 20 year period was calculated for each pixel located in the Bordeaux winegrowing region ; (b) all the pixel values were classified into 3 groups based on a regular interval. The classes obtained correspond to low, middle and high $G_{mat,h}$ values (table 3, figure 4B). The first class « low » corresponds to a mean daily irradiation (for August and September) ranging from 15.4 to 15.8 MJ $m^{-2}$, with a mean value of 15.7 MJ $m^{-2}$. For the second class « medium », $G_{mat,h}$ ranges from 15.9 to 16.3 MJ $m^{-2}$, with a mean value of 16 MJ $m^{-2}$. For the third class « high », $G_{mat,h}$ ranges from 16.3 to 16.8 MJ $m^{-2}$, with a mean value of 16.5 MJ $m^{-2}$. Whereas the total amplitude of $G_{mat,h}$ observed within the Bordeaux winegrowing region equals 9 % of the mean horizontal value, the difference between the mean values are small (-2 % between low and medium, and 3 % between medium and high). Class 1 (low $G_{mat,h}$ value) represent 66 % of the total area of Bordeaux vineyards, class 2 (medium) 32 % and class 3 (high) 2 %.

The western and southern portions of the Bordeaux winegrowing region (region I and II, and west of region V) are located in the medium $G_{mat,h}$ value zone and the eastern part of the Bordeaux winegrowing region (region III and IV) is located in the low $G_{mat,h}$ value zone, as well as the eastern part of region V (figure 4A). A small area in the northwestern most portion of the Bordeaux winegrowing region (region I) is located in high $G_{mat,h}$ value zone.

## 3. Terrain integration of solar radiation zoning

Daily solar irradiation data with integrated terrain effects were calculated for the period 2001-2005 using the *r.sun* algorithm at the DEM cell resolution (i.e., a 50 m by 50 m pixel). However, mapping at this resolution has a high computational cost: it is both time and hard-disk-space consuming, and the calculation on a 20 year period would have taken several weeks of computer calculations. To reduce computational cost, $G_{mat}$ (i.e., mean daily irradiation from August to September with integrated terrain effects) for the 20 year period was obtained using an empirical correction factor calculated for the period 2001-2005: $G_{mat}$ for the 20 year period was assessed by multiplying $G_{mat,h}$ (1986-2005) by the 5 year average (2001-2005) of the ratio $G_{mat,h}/G_{mat}$ calculated for each 50 m pixel. We assumed for each 50 m pixel, with its own terrain characteristics (i.e., slope inclination and aspect), that the ratio between $G_{mat}$ (computed using daily irradiation data with terrain integration at high resolution) and $G_{mat,h}$ (horizontal irradiation data at 500 m resolution) remained constant. This was verified with the 2001-2005 high resolution data set where the relative difference for each pixel (i.e., $(G_{mat} - G_{mat,h})/ G_{mat,h}$) is almost the same from 2001 to 2005 (figure 5). In other words, the effect of terrain on solar radiation interception during August and September is nearly the same from one year to another.

A new zoning was achieved, using the high resolution $G_{mat}$ for the period 1986-2005 to classify the Bordeaux winegrowing region into the 3 classes « low », « medium » and « high ») previously obtained with $G_{mat,h}$. The repartition of Bordeaux's appellations of origin before and after the integration of terrain effects on solar radiation interception is shown in table 4. In region I, the zoning changes for three appellations of origin areas include 16 to 34 % of the total area in the Listrac, Médoc and Moulis appellations are situated in high $G_{mat}$ class after terrain integration, whereas they were located in the medium class in the horizontal zoning. The $G_{mat,h}$ values of these areas are close to the threshold values of medium-high classes, which explains that a

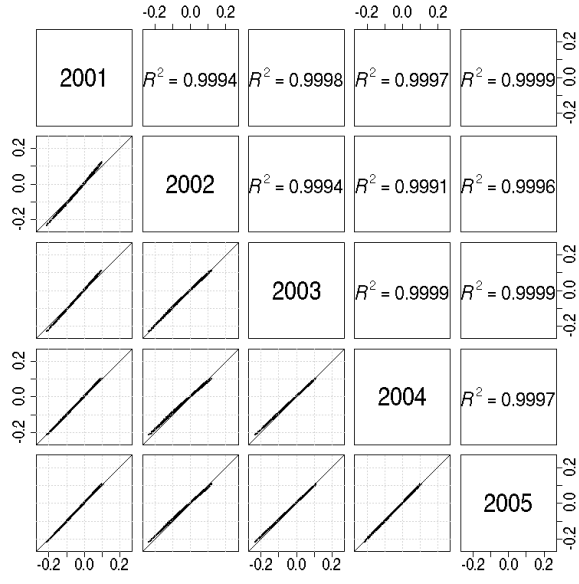



**Figure 5 - Scatter plot comparing, for different years, the values of the relative differences between $G_{mat}$ on horizontal and inclined solar radiation data, of each pixel located in the Bordeaux winegrowing area (N = 948239).**


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small variation in incoming solar radiation induced by terrain strongly modified the zoning. For regions II, III, IV and V, the classification was considerably modified. For example, 93 % of the Entre-deux-Mers appellation of origin was classified in the low *Gmat,h* zone but after integrating the terrain, 63 % of the area remains in the low *Gmat* zone, one third is classified in the medium *Gmat* zone, and 4 % of the area is classified in the high *Gmat* zone. In addition, the well-known area of Saint-Émilion receives relatively little solar radiation during August and September when compared to the whole Bordeaux winegrowing region with 100 % of the total surface area of this appellation located in low *Gmat,h* area. After integrating the terrain, 8 % of the appellation changes class with 6 % of the appellation medium Gmat area and 2 % high *Gmat* area. Figure 6B shows that the south-

**Table 4 - Distribution of appellation of origin areas, within the three solar radiation zones (i.e. classes), before and after the integration of terrain effects.**

| Region | Appellation of origin (A.O.C.) | Horizontal surface $G_{mat}$ zones[a] | | | $G_{mat}$ zones with terrain effects integration[a] | | | Total area (ha) |
|---|---|---|---|---|---|---|---|---|
| | | Low | Medium | High | Low | Medium | High | |
| I | **Bordeaux ; Bordeaux supérieur** | - | 99% | 1% | - | 99% | 1% | **1472** |
| | **Haut-Médoc** | - | 97% | 3% | - | 81% | 19% | **9077** |
| | **Listrac** | - | 73% | 27% | - | 48% | 52% | **1393** |
| | **Margaux** | - | 100% | - | - | 94% | 6% | **1856** |
| | **Médoc** | - | 70% | 30% | - | 54% | 46% | **10419** |
| | **Moulis** | - | 94% | 6% | - | 60% | 40% | **1034** |
| | **Pauillac** | - | 100% | - | 2% | 96% | 2% | **1600** |
| | **Saint-Estèphe** | - | 100% | - | - | 92% | 8% | **1552** |
| | **Saint-Julien** | - | 100% | - | - | 94% | 6% | **997** |
| II | **Barsac** | - | 100% | - | 4% | 96% | - | **860** |
| | **Bordeaux ; Bordeaux supérieur** | - | 100% | - | 15% | 83% | 2% | **3131** |
| | **Cerons ; Graves ; Graves supérieures** | - | 100% | - | 10% | 89% | 1% | **2446** |
| | **Graves ; Graves supérieures** | - | 100% | - | 20% | 78% | 2% | **8994** |
| | **Pessac-Léognan** | - | 100% | - | 13% | 85% | 2% | **4514** |
| | **Sauternes** | - | 100% | - | 22% | 75% | 3% | **2154** |
| III | **Bordeaux ; Bordeaux supérieur** | 69% | 31% | - | 69% | 30% | 1% | **4471** |
| | **Côtes de Bordeaux ; Saint-Macaire** | 25% | 75% | - | 39% | 47% | 14% | **4498** |
| | **Entre-Deux-Mers** | 93% | 7% | - | 63% | 33% | 4% | **59325** |
| | **Entre-Deux-Mers ; Bordeaux ; Haut-Benauge** | 99% | 1% | - | 48% | 47% | 5% | **6809** |
| | **Graves de Vayres** | 100% | - | - | 89% | 11% | - | **1370** |
| | **Loupiac** | - | 100% | - | 45% | 40% | 15% | **828** |
| | **Premières Côtes de Bordeaux** | 88% | 12% | - | 60% | 33% | 7% | **4207** |
| | **Premières Côtes de Bordeaux ; Cadillac** | 42% | 58% | - | 40% | 40% | 20% | **8356** |
| | **Sainte-Croix-Du-Mont** | - | 100% | - | 33% | 31% | 36% | **760** |
| | **Sainte-Foy Bordeaux** | 100% | - | - | 79% | 20% | 1% | **16425** |
| IV | **Bordeaux ; Bordeaux supérieur** | 100% | - | - | 97% | 3% | - | **7379** |
| | **Bordeaux ; Côtes de Francs** | 100% | - | - | 86% | 14% | - | **1030** |
| | **Côtes de Castillon** | 100% | - | - | 80% | 17% | 3% | **5608** |
| | **Lalande de Pomerol** | 100% | - | - | 96% | 4% | - | **1378** |
| | **Lussac Saint-Emilion** | 100% | - | - | 90% | 9% | 1% | **1834** |
| | **Montagne Saint-Emilion** | 100% | - | - | 83% | 16% | 1% | **2097** |
| | **Pomerol** | 100% | - | - | 100% | - | - | **978** |
| | **Puisseguin Saint-Emilion** | 100% | - | - | 84% | 14% | 2% | **1041** |
| | **Saint-Emilion** | 100% | - | - | 92% | 6% | 2% | **7153** |
| | **Saint-Georges Saint-Emilion** | 100% | - | - | 61% | 38% | 1% | **274** |
| V | **Blaye ; Blayais** | 66% | 34% | - | 59% | 41% | - | **2426** |
| | **Bordeaux ; Bordeaux supérieur** | 98% | 2% | - | 83% | 16% | 1% | **21498** |
| | **Canon Fronsac** | 100% | - | - | 50% | 35% | 15% | **396** |
| | **Côtes de Bourg** | 48% | 52% | - | 48% | 40% | 12% | **7005** |
| | **Fronsac** | 100% | - | - | 51% | 37% | 12% | **1311** |
| | **Premières Côtes de Blaye ; Côtes de Blaye** | 53% | 47% | - | 51% | 46% | 3% | **17111** |


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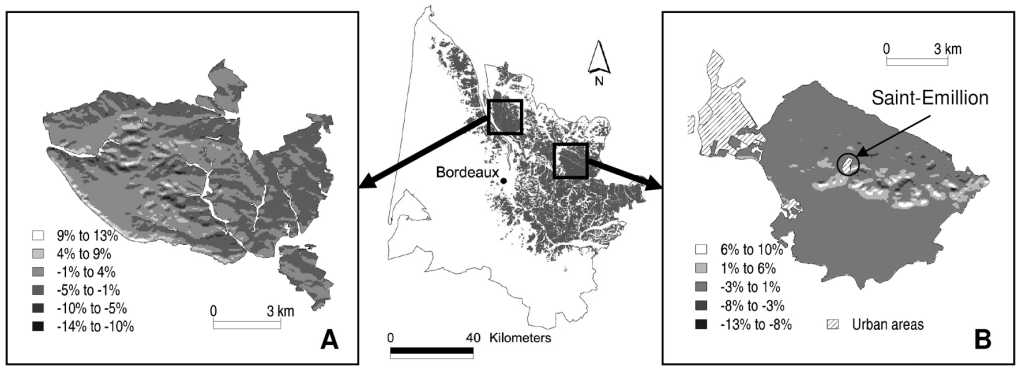



**Figure 6 - Mean daily solar irradiation data from August to September for the period 1986-2005 for two appellations of origin (A.O.C.) areas of Bordeaux.**

The data is expressed in percent of the mean value of each whole area. A) A.O.C. Côtes-de-Bourg, B) A.O.C. Saint-Émilion (the circle indicates the center of the village of Saint-Émilion).

exposed slopes close to Saint-Émilion village receive from 1 to 10 % more solar radiation than the mean value of the area.

Another example is the appellation of origin Côtes-de-Bourg, where 48 % of the area is classified in the low *Gmat,h* area and 52 % of the total area is classified in the medium *Gmat,h* area. After integrating the terrain, 12 % of the total area is situated in the high *Gmat* class. *Gmat* within the appellation of origin Côtes de Bourg varies from -14 % to +13 % of the mean appellation value (figure 6A).

## DISCUSSION AND CONCLUSIONS

Satellite derived solar radiation data from the HelioClim-1 database, combined with terrain information was used to calculate solar irradiation for the Bordeaux winegrowing region at a high resolution (50 m). The period studied (1985-2005) is sufficiently long to provide a robust analysis of the solar radiation climatology of the Bordeaux winegrowing region. A study such as this would not have been possible using ground measurement devices such as pyranometers. First, pyranometer devices are quite recent and the technology has been improved, so data would have required several recalibration algorithms. Second, only a small number of weather stations located close to or within the Bordeaux region provide solar radiation records for such a long period (less than 5 stations). However, our high resolution spatially derived solar irradiation daily values (50 m) underestimate solar radiation. Comparing these records to the pyranometer records from the weather station in Villenave d'Ornon

**Table 5 - Comparison of pyranometer and high-resolution mean daily spatial irradiation data at the weather station of Villenave d'Ornon (44.789°N ; 0.577°E).**

$G_{dh}$ = pyranometers mean daily values ; Bias = mean error (spatial - pyranometer), RMSD = Root Mean Squared Difference ; Min. = the minimum daily difference, Max = the maximum daily difference ; N = the number of observations. The values between brackets indicate the statistical indicator in fractions of the pyranometer values ($G_{dh}$). Except for N, the values are given in MJ $m^{-2}$.

| Period | $G_{dh}$ | Bias | | RMSD | | Min. | Max. | N |
|---|---|---|---|---|---|---|---|---|
| **January** | 4.6 | -0.5 | (-9.9%) | 1.0 | (22.5%) | -3.3 | 1.8 | 155 |
| **February** | 7.7 | -1.4 | (-18.0%) | 2.0 | (25.8%) | -5.2 | 3.0 | 141 |
| **March** | 12.4 | -1.8 | (-14.2%) | 2.4 | (19.7%) | -7.4 | 1.3 | 155 |
| **April** | 16.4 | -1.9 | (-11.6%) | 3.0 | (18.3%) | -8.7 | 8.6 | 150 |
| **May** | 20.5 | -2.7 | (-13.0%) | 4.0 | (19.5%) | -10.8 | 9.3 | 155 |
| **June** | 23.3 | -1.8 | (-7.7%) | 3.1 | (13.1%) | -11.0 | 5.2 | 150 |
| **July** | 22.2 | -2.2 | (-9.9%) | 3.7 | (16.6%) | -10.8 | 5.3 | 155 |
| **August** | 19.6 | -1.7 | (-8.8%) | 3.1 | (16.0%) | -10.4 | 4.5 | 155 |
| **September** | 15.3 | -1.7 | (-11.2%) | 2.7 | (17.3%) | -10.4 | 6.1 | 150 |
| **October** | 9.3 | -1.9 | (-20.9%) | 2.5 | (27.4%) | -9.4 | 2.1 | 155 |
| **November** | 5.6 | -0.3 | (-5.8%) | 1.3 | (22.5%) | -3.4 | 3.5 | 150 |
| **December** | 4.1 | -0.1 | (-1.8%) | 1.0 | (25.0%) | -3.7 | 2.6 | 155 |
| **Year** | 13.4 | -1.5 | (-11.1%) | 2.7 | (19.8%) | -11.0 | 9.3 | 1826 |
| **Aug. – Sept.** | 17.5 | -1.7 | (-9.8%) | 2.9 | (16.6%) | -10.4 | 6.1 | 305 |


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(located between regions I and II) for the period 2001-2005, they showed a mean difference (bias) of -1.5 MJ $m^{-2}$ indicating a underestimation of 11.1 % of the annual mean (table 5). The root mean square difference was 2.7 MJ $m^{-2}$ (19.8 % of the mean annual pyranometer value). For *Gmat*, the bias and root mean square differences are -9.8 % and 16.6 % of the annual mean, respectively. However, these errors are in the range of uncertainties provided by the use of pyranometer measurements (Llasat and Snyder, 1998; Droogers and Allen, 2002). Although the relative spatial differences presented in this study have not been affected by this underestimation, the absolute values may be slightly higher.

It has been shown that the western portion of the Bordeaux winegrowing region receives more solar radiation throughout the year than the eastern portion. As the ripening of grapevine varieties of Bordeaux area occurs during August and September, a zoning based on the mean daily irradiation during this period (referred as *Gmat,h*) was proposed. The Bordeaux winegrowing region was partitioned into three classes: low, medium and high *Gmat,h* values. The southern and the eastern portions of the Bordeaux winegrowing region receive the highest amount of solar radiation during the berry ripening period. When increasing the resolution of the zoning, using the *r.sun* model, it was shown that terrain effects on solar radiation are substantial, although the Bordeaux winegrowing region is not considered a mountainous region. Well exposed (south) slopes of the eastern portion of the Bordeaux region receive as much solar radiation as flat surfaces in the western areas. Failla *et al.* (2004) found that slopes that receive a higher amount of solar radiation were associated with earlier phenology, higher sugar content, lower titrable acidity and lower phenolic content in berries, in red cv. Nebbiolo vineyards, within Valtellina winegrowing region.

The attempt of the present work was to evaluate the solar radiation climatology of the Bordeaux winegrowing region, and to propose a new zoning approach for estimating the ripening potential of vineyards. Multiple assumptions made prior to such zoning include: 1) solar irradiation affects berry ripening (Dokoozlian and Kliewer, 1996; Bergqvist *et al.*, 2001); 2) solar irradiation has a major effect on surface and air temperature, which affect grapevine phenology, malate degradation within berries, polyphenolic, sugar and aromatic contents of berries (Buttrose *et al.*, 1971; Reynolds and Wardle, 1989; Bergqvist *et al.*, 2001; Spayd *et al.*, 2002); 3) as the spatial variation of cumulated incoming solar radiation during the berry maturation period depends mainly on vineyard slopes and aspects, it is also associated with different water runoff patterns where steep slopes will be associated with higher runoff, and 4); solar radiation plays a major role in vineyard transpiration and it is a key parameter of water balance models (Trambouze and Voltz, 2001; Lebon *et al.*, 2003), therefore, south-exposed vineyards would certainly be subject to higher evaporative demands. An increasing *Gmat* index may thus be associated with higher water deficits.

Row orientations and spacing, as well as canopy structure dramatically affect the incoming solar radiation distribution between grapevine rows and bare or grass-covered surfaces (Smart, 1973; Pieri and Gaudillère, 2003, 2005). Oyarzun *et al.* (2007) recently proposed a solar radiation interception model for horizontal and inclined surfaces in orchards and vineyards. Coupling this kind of model to remotely sensed solar radiation, water runoff and water balance models would certainly improve the general knowledge about inclined surface effects on grapevine development and berry maturation.

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## REFERENCES

Bergqvist J., Dokoozlian N. and Ebisuda N., 2001. Sunlight exposure and temperature effects on berry growth and composition of Cabernet-Sauvignon and Grenache in the Central San Joaquin Valley of California. *Am. J. Enol. Vitic.*, **52**, n°1, 1-7.

Bois B., Pieri P., van Leeuwen C. and Gaudillère, J.P., 2005. Sensitivity analysis of the Penman-Monteith evapotranspiration formula and comparison of empirical methods used in viticulture soil water balance, *XIV International GESCO Viticulture Congress*, Geisenheim, Germany, 23-27 August, 2005.

Buttrose M.S., 1969. Vegetative growth of grapevine varieties under controlled temperature and light intensity. *Vitis*, **8**, 280-285.

Buttrose M.S., Hale C.R. and Kliewer W.M., 1971. Effect of the temperature on the composition of Cabernet-Sauvignon berries. *Am. J. Enol. Vitic.*, **22**, 2, 71-75.

Crippen D.D., Jr. and Morrison J.C., 1986. The effects of sun exposure on the compositional development of Cabernet Sauvignon berries. *Am. J. Enol. Vitic.*, **37**, 4, 235-242.

Dokoozlian N.K. and Kliewer W.M., 1996. Influence of light on grape berry growth and composition varies during fruit development. *J. Amer. Soc. Hortic. Sci.*, **121**, 5, 869-874.

Droogers P. and Allen R.G., 2002. Estimating reference evapotranspiration under inaccurate data conditions. Irrigation and Drainage Systems, **16**, 1, 33-45.

Durand R. and Legros J.P., 1981. Cartographie automatique de l'énergie solaire en fonction du relief. *Agronomie*, **1**, 1, 31-39.

Failla O., Mariani L., Brancadoro L., Minelli R., Scienza A., Murada G., Mancini S., 2004. Spatial distribution of solar radiation and its effects on vine phenology and grape ripening in an alpine environment. *Am. J. Enol. Vitic.*, **55**, 2, 128-138.


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Flint A.L. and Childs S.W., 1987. Calculation of solar radiation in mountainous terrain. Agric. Forest Meteorol., **40**, 3, 233-249.

Goovaerts P., 1999. Geostatistics in soil science: state-of-the-art and perspectives. *Geoderma*, **89**, 1-2, 1-45.

Grechi I., Vivin P., Hilbert G., Milin S., Robert T., Gaudillère J.-P., 2007. Effect of light and nitrogen supply on internal C:N balance and control of root-to-shoot biomass allocation in grapevine. *Environmental and Experimental Botany*, **59,** 2, 139-149.

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.

Huld T., Suri M., Dunlop E. and Wald L., 2005. Integration of Helioclim-1 database into PV-GIS to estimate solar electricity potential in Africa. *20th European Photovoltaic Solar Energy Conference and Exhibition*, Bacelona, Spain.

Jones G.V. and Davis R.E., 2000. Using a synoptic climatological approach to understand climate-viticulture relationships. *Int. J. Clim.*, **20,** 8, 813-837.

Kang S., Kim S. and Lee D., 2002. Spatial and temporal patterns of solar radiation based on topography and air temperature. *Canadian J. Forest Res.*, **32**, 3, 487-497.

Kliewer W.M., 1977. Influence of temperature, solar radiation and nitrogen on coloration and composition of Emperor grapes. *Am. J. Enol. Vitic.*, **28**, 2, 96-103.

Kliewer W.M. and Lider L.A. (1968). Influence of cluster exposure to the sun on the composition of Thompson seedless fruit. *Am. J. Enol. Vitic.*, **19**, 3, 175-184.

Lebon E., Dumas V., Pieri P. and Schultz H.R., 2003. Modelling the seasonal dynamics of the soil water balance of vineyards. *Functional Plant Biology*, **30**, 6, 699-710.

Lefèvre M., Wald L. and Diabate L., 2007. Using reduced data sets ISCCP-B2 from the Meteosat satellites to assess surface solar irradiance. *Solar Energy*, **81**, 2, 240-253.

Llasat M.C. and Snyder R.L., 1998. Data error effects on net radiation and evapotranspiration estimation. *Agric. Forest Meteorology*, **91**, 3/4, 209-221.

Oyarzun R.A., Stockle C.O. and Whiting M.D., 2007. A simple approach to modeling radiation interception by fruit-tree orchards. *Agric. Forest Meteorology*, **142**, 1, 12-24.

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

Pieri P. and Gaudillère J.P., 2003. Sensitivity to training system parameters and soil surface albedo of solar radiation intercepted by vine rows. *Vitis*, **42**, 2, 77-82.

Pieri P. and Gaudillère J.P., 2005. Vines water stress derived from a soil water balance model - sensitivity to soil and training system parameters, *XIV International GESCO Viticulture Congress*, Geisenheim, Germany, 23-27 August, 2005, 457-463.

Priestley C.H.B. and Taylor R.J., 1972. On assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review*, **100**, 2, 81-92.

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

Reynolds A.G. and Wardle D.A., 1989. Influence of fruit microclimate on monoterpene levels of Gewurztraminer. *Am. J. Enol. Vitic.*, **40**, 3, 149-154.

Rigollier C., Bauer O. and Wald L., 2000. On the clear-sky model of the ESRA - European Solar Radiation Atlas - with respect to the Heliosat method. *Solar Energy*, **68**, 1, 33-48.

Rigollier C., Lefèvre M. and Wald L., 2004. The method Heliosat-2 for deriving shortwave solar radiation from satellite images. *Solar Energy*, **77**, 2, 159-169.

Riou C., Pieri P. and Clech B.l., 1994. Water use of grapevines well supplied with water. Simplified expression of transpiration. *Vitis*, **33**, 3, 109-115.

Riou C., Valancogne C. and Pieri P., 1989. Un modèle simple d'interception du rayonnement solaire par la vigne. Vérification expérimentale. *Agronomie*, **9**, 5, 441-450.

Schultz H.R. Kiefer W. and Gruppe W., 1996. Photosynthetic duration, carboxylation efficiency and stomatal limitation of sun and shade leaves of different ages in field-grown grapevine (*Vitis vinifera* L.). *Vitis*, **35**, 4, 169-176.

Smart R.E., 1973. Sunlight interception by vineyards. Am.J. Enol. Vitic., **24**, 4, 141-147.

Solanki S.K., Krivova, N.A. and Wenzler, T., 2005. Irradiance models. *Advances in Space Research*, **35**, 376-383.

Spayd S.E., Tarara J.M., Mee D.L. and Ferguson J.C., 2002. Separation of sunlight and temperature effects on the composition of *Vitis vinifera* cv. Merlot berries. *Am. J. Enol. Vitic.*, **53**, 3, 171-182.

Trambouze, W. and Voltz M., 2001. Measurement and modelling of the transpiration of a Mediterranean vineyard. *Agric. Forest Meteorology*, **107**, 2, 153-166.

Turc L., 1961. Évaluation des besoins en eau d'irrigation, évapotranspiration potentielle. *Annales Agronomiques*, **12**, 1, 13-49.

Wang S., Chen W. and Cihlar J., 2002. New calculation methods of diurnal distribution of solar radiation and its interception by canopy over complex terrain. *Ecological Modelling*, **155** (2/3), 191-204.

Wei C.-P., Lee Y.-H. and Hsu C.-M., 2003. Empirical comparison of fast partitioning-based clustering algorithms for large data sets. *Expert Systems with Applications*, 24, 4, 351-363.

Zufferey V., Murisier F. and Schultz H.R., 2000. A model analysis of the photosynthetic response of *Vitis vinifera* L. cvs Riesling and Chasselas leaves in the field: I. Interaction of age, light and temperature. *Vitis*, **39**, 1, 19-26.


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