The distribution of solar radiation in the viticultural areas of Aosta Valley
La distribution du rayonnement solaire dans les zones viticoles de la Vallée d'Aoste
Distribución de la radiación solar en las zonas vitícolas del Valle de Aosta

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Abstract

The estimation of solar radiation resources available to grapevine is essential in order to evaluate its physiological response to the environment. Topographical features of mountain areas produce a strong variability of these resources, both in space and in time. The aim of this work is to acquire a better understanding of how topography affect the variability of solar radiation in Aosta Valley, as a first step towards the estimation of the real amount of solar radiation reaching the plant canopy (which should also take into account the possible filtering effect of clouds). Estimates were carried out using the model developed for the European Solar Radiation Atlas, available in the gis environment GRASS GIS. The three components of radiation (direct, diffuse and reflected) under clear-sky conditions were computed for each day of the year, with time steps of 15 minutes on a 75m x 75m DTM. Daily raster maps of PAR (photosynthetically active radiation) and insolation time (IT) were obtained. Monthly means of daily PAR and IT were calculated, as well as PAR and IT total amounts during the whole year and specific time intervals relevant for grapevine phenology. The correlations among accumulated PAR and corresponding IT are lower than expected; thus both variables could be employed in modelling the vegetative and productive response of grapevine to the environment. The correlations among PAR accumulated during the considered time intervals are very high. However, some of the residuals of the corresponding regression models aren't negligible; hence, the choice of the time interval may affect the results obtained when modelling the grapevine response to environmental factors. Real solar radiation directly measured or estimated on the base of temperatures show that peak values during the growing season in well exposed locations could significantly exceed saturation, suggesting that the accumulated PAR actually usable in these areas may be overestimated. This phenomenon should be considered in order to correctly evaluate climatic resources in mountain territories where radiation excess is frequently associated with thermal and/or water limitation.

Résumé

L'estimation de la radiation solaire à disposition de la vigne est essentielle afin d'évaluer sa réaction physiologique à l'environnement.

Les caractéristiques topographiques des zones de montagne produisent une forte variabilité de cette ressource, à la fois dans l'espace et dans le temps. Le but de ce travail est d'acquérir une meilleure compréhension de la manière dont la topographie affecte la variabilité du rayonnement solaire en Vallée d'Aoste, comme un premier pas vers l'estimation de la quantité réelle de rayonnement solaire atteignant le couvert végétal (qui devrait aussi évaluer les effets des nuages). Les estimations ont été

effectuées en utilisant le modèle mis au point dans le cadre de l'Atlas européen de la radiation et disponible dans l'environnement SIG GRASS.
Les trois composantes du rayonnement (direct, diffus et réfléchi), sous conditions de ciel clair, ont été calculées pour chaque jour de l'année par des simulations réalisées chaque 15 minutes sur un DTM avec un pixel de 75m. Des cartes de la PAR (rayonnement photosynthétiquement actif) et du temps d'insolation (TI) ont été obtenues. Les moyennes mensuelles de la quantité journalière de PAR et du TI ont été calculées, ainsi que PAR et TI totaux pendant toute l'année et dans des intervalles de temps spécifiques pertinents à la phénologie de la vigne.
Les corrélations entre PAR accumulé et TI correspondant ont été plus faibles que prévu, et donc les deux variables pourraient être utilisées dans la modélisation de la réponse végétative et productive de la vigne à l'environnement. Les corrélations entre PAR accumulé au cours des intervalles de temps considérés sont très élevées. Toutefois, les résidus des modèles de régression correspondants ne sont pas négligeables, d'où l'on derive que le choix de l'intervalle de temps peut avoir une incidence sur les résultats obtenus en terms de réponse de la vigne à l'environnement. Les valeurs du rayonnement solaire réel directement mesurées ou estimées sur la base des températures montrent que les valeurs de pointe pendant la saison de croissance dans les endroits bien exposés pourraient sensiblement dépasser la saturation, ce qui suggère que l'accumulation de PAR réellement utilisable dans ces domaines pourrait être surestimée. Ce phénomène devrait être envisagé afin d'évaluer correctement les ressources climatiques dans les territoires de montagne où un excès de rayonnement pourrait être associé à des excès thermiques et / ou à la limitation d'eau.
Resumen
El cálculo de la radiación solar recibida por la parra resulta esencial para evaluar su respuesta fisiológica al entorno. Las características topográficas de las zonas de montaña producen una fuerte variabilidad de este recurso, tanto en el espacio como en el tiempo. El objeto de este trabajo es el de entender mejor cómo afecta la topografía a la variabilidad de la radiación solar en el Valle de Aosta, como primer paso para calcular la cantidad real de radiación solar que recibe la cubierta vegetal (para lo cual también debe tenerse en cuenta el posible efecto de filtrado de las nubes).
Los cálculos se realizaron empleando el modelo elaborado para el Atlas Europeo de Radiación Solar, disponible en el entorno sig denominado grass gis. Para cada día del año se calcularon los tres componentes de la radiación (directa, difusa y reflejada) en condiciones de cielo despejado, mediante simulaciones realizadas cada 15 minutos en un mdt de 75 x 75 m. Se obtuvieron planos de rejilla diarios de la rfa (radiación fotosintéticamente activa) y del tiempo de insolación (rfa), y se calcularon las medias mensuales de la cantidad diaria de rfa y ti, así como las cantidades totales de rfa y ti durante todo el año y en intervalos específicos relevantes para la fenología de la parra.
Las correlaciones existentes entre la rfa acumulada y el correspondiente ti son menores de lo esperado, por lo cual ambas variables podrían usarse en la modelización de las respuestas vegetativas y productivas de la parra ante el entorno. Las correlaciones observadas entre la rfa acumulada en el transcurso de los intervalos considerados son muy altas. Sin embargo, no resultan desdeñables los residuos de los modelos de regresión correspondientes, de lo cual se deriva que la elección del intervalo temporal puede incidir en los resultados obtenidos al realizar la modelización de la respuesta de la parra a los factores medioambientales. Los valores de la radiación solar real, medidos directamente o calculados en función de las temperaturas, muestran que los valores máximos registrados durante la estación de crecimiento en lugares donde la exposición es alta podrían sobrepasar la saturación de manera significativa, lo que sugiere que

puede haberse sobreestimado la rfa acumulada que es realmente utilizable en estas zonas. Se debe considerar este fenómeno a fin de evaluar correctamente los recursos climáticos de los territorios de montaña, donde un exceso de radiación suele asociarse con temperaturas extremas y/o limitaciones hídricas.

1Introduction

Solar radiation is a fundamental driving variable for agro-ecosystems, representing the primary source of energy and a fundamental source of information for any research involving plants. This means that in whatever experimental study aiming to investigate physiological responses of the grapevine (or any other plant) to environmental factors, a quantitative evaluation of the solar radiation which can be used by the plant during the growing season is essential. Only a fraction of the global radiation reaching the upper limit of the atmosphere will eventually be converted to chemical energy by the photosynthesizing cells of the grapevine leaves (Fig. 1); an important part will be filtered out or, even if it reaches the leaves, will not be exploited by the plants because of the light saturation effect or physiological stress (a severe thermal and water stress, for instance, will greatly reduce the light saturation point) (van Keulen and Wolf, 1986). A number of methods for direct measurement or estimation or remote sensing of variables associated with solar radiation are available today. These methods are generally referred to values of (i) clear-sky solar radiation (referred to a sky free of clouds and other obscurations as observed from the point of observation - American meteorological Society – Meteorological Glossary - http://amsglossary.allen press.com/glossary.) or (ii) real solar radiation. These variables can be measured/simulated/remote sensed using different methods like those listed in Table 1. A complementary variable, the Insolation Time (IT), can be measured by means of specific instruments (the Campbell-Stockes's sunshine recorder or electronic gauges) or can be computationally estimated. Depending on the goal of a specific investigation, the most suitable variable could be the Solar Radiation dropping at the top of the canopy as Visible & Near Infrared (Global Solar Radiation - GSR), or only a fraction of it (PAR, Photosynthetically Active Radiation) or Ultraviolet A and/or B. The real interception of solar radiation by canopy is the function of training systems, row orientation, crop phenology, LAI, etc. Direct measurement (or simulated / remote sensed values) can be expressed as instantaneous density of flux or as values integrated on particular periods like hours, days, months, other physiologically relevant periods (Monteith, 1973). PAR should be evaluated by applying a multiplicative coefficient to GSR or adopting specific instruments (PAR meters). The evaluation of UV resources can be carried out by adopting specific UV meters, which are generally quite expensive. A coarse evaluation of UV resources can be carried out by applying multiplicative coefficients to GSR data but in this case a local calibration is needed.

The topography of mountain areas affects the radiation availability due to a wide range of effects (shadowing, aspect, effects on clear sky turbidity and cloud distribution and thickness) (Barry, 1992). The first aim of this work is to better understand the role played by the topography on the distribution of solar radiation in a mountain area (Aosta Valley, situated in the North-Western corner of Italy); the second aim is the selection and characterization of a few variables or indexes which could be used in statistical modeling when radiation resources must be taken into account. The viticultural area of Aosta Valley has various prevailing expositions: in the higher part, where the valley follows a NW to SE direction, vineyards are mostly exposed towards S or SW; the wider, central part goes from West to East, and has most of vineyards on S-facing slopes, though an important viticultural area lies on the opposite N-facing side; in the lower part the valley turns N-S, then NW-SE; here the vineyards are located mainly on the valley bottom, on the W and SW-facing slopes and on alluvial fans on both sides.

2 Materials and methods

The clear-sky radiation was estimated using the model proposed by the new digital European Solar Radiation Atlas (ESRA, http://www.helioclim.net/esra/), as implemented in the r.sun module of the open source gis environment GRASS GIS (Neteler, 2007; Hofierka and Suri, 2002, http://grass.itc.it). The three radiation components (beam, diffuse and reflected) were computed under clear-sky conditions for each day of the year with the following parameterization: (i) time step of 15 minutes (ii) a ground albedo value of 0.2 (default value for r.sun model) and (iii) the monthly Linke turbidity factors suggested by r.sun documentation for mountain conditions. The shadowing effect of the relief was taken into account by three raster maps: a DTM with a 75 m x 75 m pixel and the derived slope and aspect maps. Daily raster maps of clear-sky PAR (estimated as 50% of the GSR - van Keulen and Wolf, 1986) and insolation time (IT) were obtained. Both (i) monthly means of daily clear-sky PAR and IT and (ii) accumulated values for the whole year (YEAR) as well as for specific time intervals relevant for grapevine phenology where calculated from these maps. Three time intervals were considered: beginning-APril to end-October (APOC), Mid-August to end-OCtober (MAOC) and Mid-August to end-SEptember (MASE), respectively considered as the whole grapevine vegetative and reproductive season, the ripening season for late varieties and the ripening season for early varieties. Hourly irradiances for each first day of the month were also calculated.

The R system was used for graphical data exploration, statistical analysis and final graphics. R is an open source software for statistical computation and graphics with a programming language almost 100% compatible with S (R Development Core Team, 2007, http://www.r-project.org). All the maps were created with Generic Mapping Tools, an open source collection of tools for producing high quality, press-ready maps (Wessel and Smith, 1998, http://www.soest.hawaii.edu/gmt/).

3 Results and discussion

3.1 Seasonal changes in daily irradiation intensity and duration

The monthly averages of the daily PAR (MJ m^{-2} day^{-1}) for March, June, September and December respectively, and the corresponding hours of daily irradiation times (IT) are shown in Figure 2. The effect of the topography on the spatio-temporal distribution of solar radiation is quite evident. The steep slopes facing South are greatly advantaged during the whole year. However, from May to mid-August (the period corresponding to the vegetative development, until the veraison) almost the whole viticultural area, including most of the North-facing sites as well as the lower and higher parts (where the Valley changes direction from E-W to NE-SW or even N-S) show high levels of clear-sky PAR, with daily values between 13 and 16 MJ m^{-2} day^{-1}. While the South-facing slopes greatly benefit of their best exposure both for an earlier bud burst and for a better and longer ripening period, for half of the growing season their advantage is less evident at least from the point of view of the *total amount* of energy received each day.

The comparison between the less favored viticultural areas is even more interesting. During most of the year, from spring to autumn, the lower part and the North-facing central part of the valley receive about the same amount of radiation. But the *temporal distribution* of this radiation is quite different, being concentrated in a much shorter

daily insolation time on the area with N-S direction in the lower part of the valley. This phenomenon gives rise to important differences between the two areas, due to the changes in light characteristic (not only quantity but also quality), with significant effects on anthocyanines synthesis, perhaps modulated by the phytochrome activity (Hummell and Ferree, 1997). In the coldest months of the year, the situation is reversed, with North-facing slopes almost completely shadowed. This should not have significant impacts on the grapevines, as they are in their rest period.
The raster map of IT daily means of June shows another interesting feature: on the central part of the valley, the daily duration of direct solar radiation on the North-facing side is even longer than on the opposite Southward-facing slope due to the ENE and WNW position of the sun at sunrise and sunset, probably compensating for the slightly lower daily accumulated irradiation.

Another way of visualizing the seasonal variation of the clear-sky PAR and IT in different sites can be the plotting of the daily means of some particular sites. In Fig. 4 this has been done for 48 vineyards used as sample sites in a viticultural zoning study. These sites, placed on the two opposite slopes of the W-E oriented segment of the valley, show very different patterns for both the variables considered.

3.2 Accumulated PAR and IT

The raster maps of the accumulated clear-sky PAR and IT for the four considered time intervals (Fig. 3) confirm what already emerged from the analysis of the annual behavior of the daily means: while the summations of PAR in the North-facing slopes don't differ very much from those of the lower area (with the notable exception of the small, well known area of Donnas on the south-eastern corner), the accumulated IT are much higher on the former. We therefore suggest that, when the clear-sky radiation is used for a preliminary evaluation of the available radiation resources, the summations of IT (Jones and Davis, 2000) and clear-sky PAR for physiologically relevant time intervals should be used, and both should be considered in an initial statistical model. An analogous rule should be adopted for analysis of data directly measured or remote sensed.

3.3 Correlation between Accumulated PAR and IT during the whole year and April-October

The comparison between the four time intervals suggest that values accumulated for the whole year are linearly correlated very well with MAOC, less with MASE and APOC. The scatterplots of YEAR vs APOC accumulated PAR and IT, show two different patterns, especially evident for IT summations (Fig. 4): some points are placed along a linear correlation line, while others follow a quadratic curve. This is not surprising, because sites with wider yearly variations (e.g. placed on the North-facing slope) will tend to reduce the differences between the two considered interval periods. A geostatistical exploration tool available for the R system (package GeoXp) confirmed that most of the points that lie out of an hypothetical regression line (shown in magenta) represent sites situated on the North-facing slope or in very similar aspect conditions (slopes facing Northwards, with a W-E valley direction).
The June/December monthly mean of daily PAR and IT ratio (or the ratio of the extreme values within a relevant time interval) could be used as an index of the seasonal variability of radiation resources. While it does not give any information about the absolute values of these resources (note that very well exposed South-facing slopes have the same index as some of the worst exposed in the lower areas, where the valley turns N to S), it could help, for instance, in selecting areas with a shorter growing season (late bud burst and shorter ripening period) but excellent conditions during the

late spring to late summer period, therefore perfectly fit to successfully grow earlier varieties (Fig. 5).

4 Conclusions

The main goal of this study was to investigate the effect of topography on spatio-temporal distribution of clear sky radiation and to select and characterize variables which successfully summarize these resources and could therefore be employed in statistical modeling. Obviously the distribution of solar energy is strongly influenced by topography, whose effect is not constant during the whole year. While some sites can be very highly penalized in one season, they could receive more than adequate amounts of useful radiation in another (both in terms of cumulated solar irradiance and insolation time). On the other hand, other sites apparently less penalized during the worst period of the year (winter months), could remain heavily shadowed during the critical periods of vegetative and reproductive development. The same phenomenon can be observed on a daily scale: the same amount of clear-sky PAR could be distributed in substantially different insolation times, hence the amount of irradiation alone often does not allow to understand the potential physiological response.

As a consequence, it may be more effective to use the clear-sky PAR and IT accumulations at the same time. These summations should encompass time periods relevant for the studied physiological processes. A third, additional variable which may help the interpretation of the clear-sky radiation resource could be the June/December monthly mean of daily PAR and IT ratio. These three variables together should give a good insight about the total amount of radiation resources, their daily distribution and their variability over time. In our case, three different conditions, each prevailing in different zones of the Aosta Valley viticultural area have been determined:

1.high availability of solar radiation and relatively high presence of sun above the orographic horizon throughout year;

2.low availability of solar radiation and relatively very short presence of sun above the orographic horizon throughout year;

3.high variability of solar radiation and presence of sun above the orographic horizon throughout year;.

A further step could be the adoption of variables which represent the real-sky conditions taking into account real effects of cloud coverage and air mass turbidity; this should be obtained by direct measures with solarimeters installed in each experimental site, or by estimation with models founded on daily thermal range (Bechini et al., 2000; Allen et al., 1998). To adopt these models it is necessary a preliminary calibration with filed measurements with pyranometers.

An alternative estimate of real-sky daily radiation should be based on cloud type and coverage data. In the last decades there is an increasing lack of subjective observations of clouds in mountain areas; due to the importance of these data for climatology of mountain areas (Barry, 1992) maybe in the future subjective observations of cloud amount and cloud type will be substituted with instrumental observations.

The availability of real-sky radiation data and the realistic description of the light interception by canopies make possible the further step of taking into account the light saturation effects and other physiological responses. This approach would represent a considerable improvement in modeling studies, since light saturation is without any doubt a common situation in mountain areas and some specific analysis show that only about a half of the PAR reaching the leaves on a bright summer day can actually be captured by the photosynthetic activity (Huglin and Schneider, 1998; Cartechini and Palliotti, 1995; Pena and Tarara,

2004).
Finally, it should be noted that the evaluation of advantages and disadvantages of different methods of radiation analysis (Table 1) can be interesting in order to (i) promote integrated approaches to single point and territorial analysis of radiation which overcome existing limitations (i) carry out a quality check of data produced with different methods. Table 2 summarizes the characteristics of some variables or indexes which could be adopted for the evaluation of radiation resources.

5 References

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Table 1: Advantages and disadvantages of some methods for direct measurement / simulation / remote sensing of solar radiation resources. Methods are referred to Insolation Time (IT) or Solar Radiation (SR) in specific spectral regions (UV, VIS, IR).

Avantages et désavantages de quelques méthodes pour obtenir des mésures directes ou des estimations par simulation / télédétection des ressources radiatives. Cettes méthodes sont referées au Temps d'Insolation (IT) ou à la Radiation Solaire (SR) dans des régions spectrales spécifiques.

Method	Details	Pros	Cons
Analysis of Clear sky GSR or IT on single days or selected periods	Astronomic algorithms which describe sun trajectory are applied to DTMs	Data produced with a reduced amount of resources. Output is useful to evaluate spatial and temporal variability of radiation resources on given territories. Data can be useful to estimate the presence of cloud coverage matching with radiation data simulated with mathematical models (see below). Clear sky GSR is essential for remote sensing estimations of GSR or IT (see below)	Pixel of DTM is crucial to obtain a realistic description in mountain territories. Cloud effects aren't considered (output of these models can be adopted for viticultural zoning only hypothesising the homogeneity of cloud coverage, which is often unrealistic)
Simulation of Real SR with mathematical models	Models working on the base of maximum and minimum temperatures (e.g.: Hargreaves, Campbell and Donatelli, Campbell and Bristow, etc.)	Accurate measurement of temperature is less expensive that accurate measurements of solar radiation.	Models need a local calibration with reference instruments. Data are referred to single points.
Measurement of Real SR with meteorological instruments	Pyranometers, PAR meters, UV meters, Albedometers (standards for instruments are defined in WMO, 1997. Guide to met. Instruments and methods of observation, Geneva)	Direct evaluation of SR received by single vineyards	WMO second class instruments are needed to obtain accurate measurements. Instruments must be constantly checked and, if necessary, recalibrated. Higher costs (1 instrument in each experimental site).
Measurement of Real IT with meteorological instruments	Campbell Stockes sunshine recorders or electronic instruments (standards for IT meters are defined in WMO, 1997. Guide to met. Instruments and methods of observation, Geneva)	Direct evaluation of IT received by single vineyards.	Data are referred to single points.
Remote sensing estimation of GSR or IT	Processing of radiometric data coming from geostationary satellites	Description over continuous surface data. Data produced with a reduced amount of resources.	Relatively coarse resolution.

Table 2: Example of indexes that can be obtained from data listed in Table 1.

Exemples d'indices qui peuvent être obtenus à partir des données décrits dans le Tableau 1.

Index	Meaning
GSR/UV/PAR/IT on physol-ogically relevant periods (e.g. vegetative period, last month before the harvest)	Can be adopted as reference indexes of radiative resources to evaluate characters of single years or to analyse suitability are specific territories or sites for viticulture.
June/December ratio of potential GSR or IT	Used as index of seasonal variability of the radiative resources (quite sensitive to effects of aspect).
Reference evapotranspiration	Evapotranspiration is driven by solar radiation, wind speed, air temperature and relative humidity; in particular, Penman Monteith and Priesley - Taylor algorithms take into account solar radiation (van Keulen and Wolf, 1986).
Empirical ecological indexes	e.g.: Costantinescu index

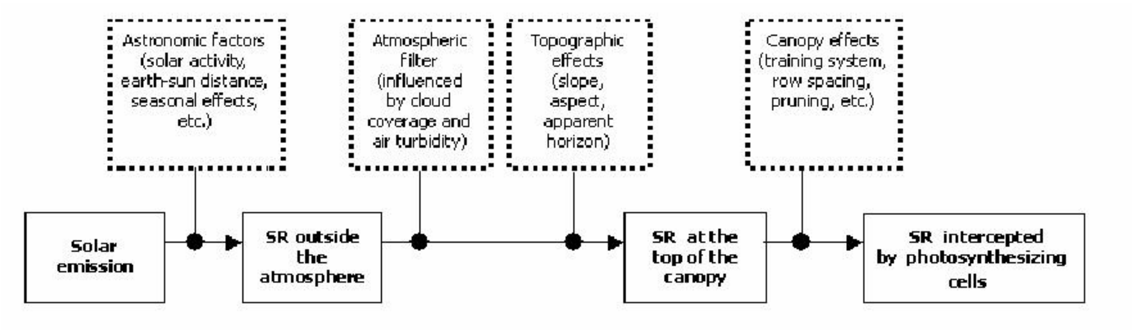

Figure 1: Scheme of Solar Radiation (SR) behavior from Solar emission to plant interception. Boxes with solid lines represent state variables of the system (e.g.: energy flux density); boxes with dotted lines represent the variables which modulate fluxes.

Schéma des modifications de la Radiation Solaire dans son trajet de l'emission solaire jusqu'a l'interception par la canopée. Les boîtes solides représentent les variables d'état du système (par example la densité du flux d'énergie), les boîtes pointillées représentent les variables qui modulent les fluxes.

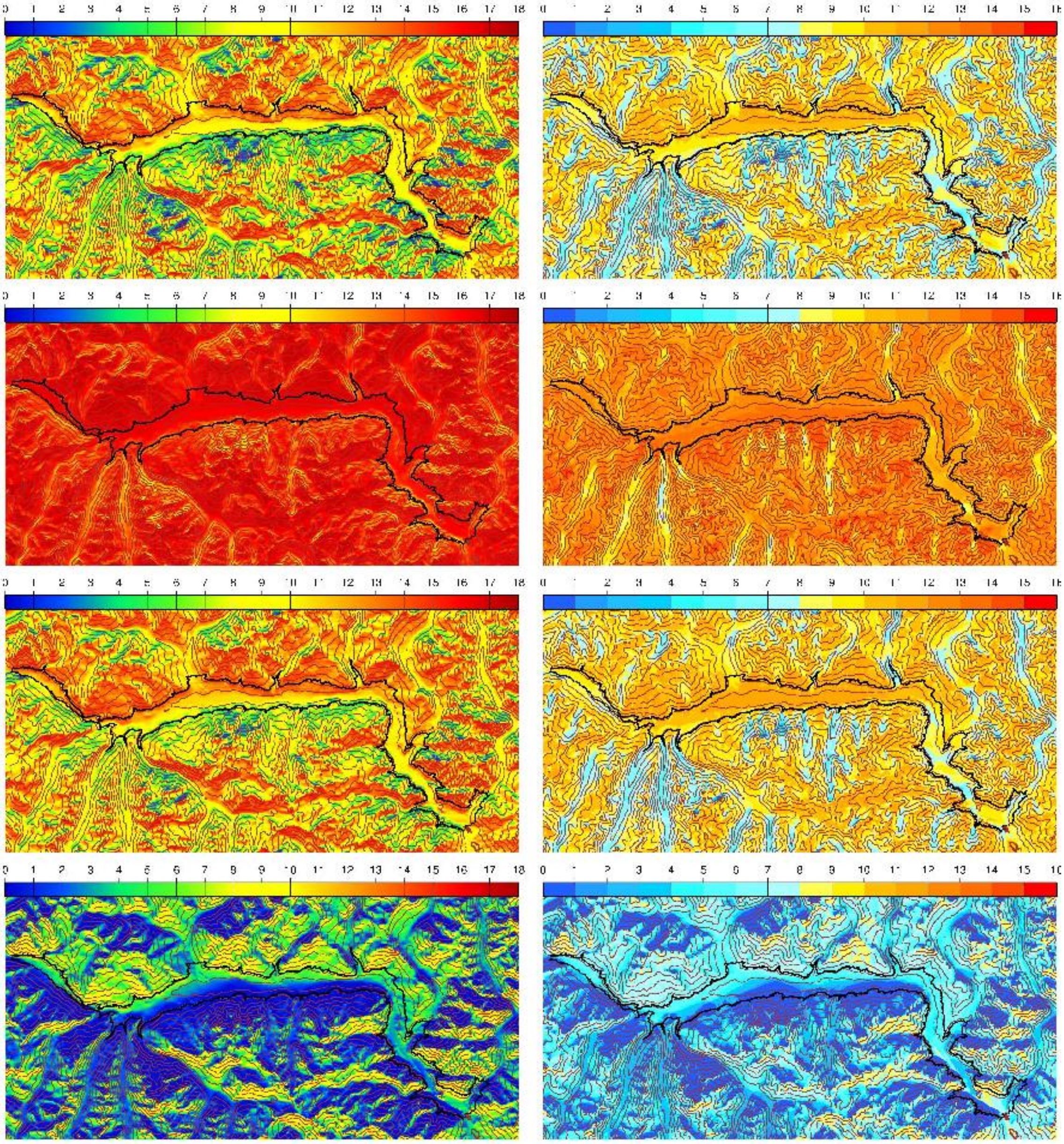

Figure 2: Monthly averages of the daily PAR (MJ m^{-2} day^{-1}, on the left) and insolation times in hours (IT, on the right) in March, June, September and December (from top to bottom).

Moyennes mensuelles de la PAR journalière (MJ m^{-2} jour^{-1}, à gauche) et des heures d'insolation (IT, à droite) aux mois de Mars, Juin, Septembre, et Décembre (à partir du haut).

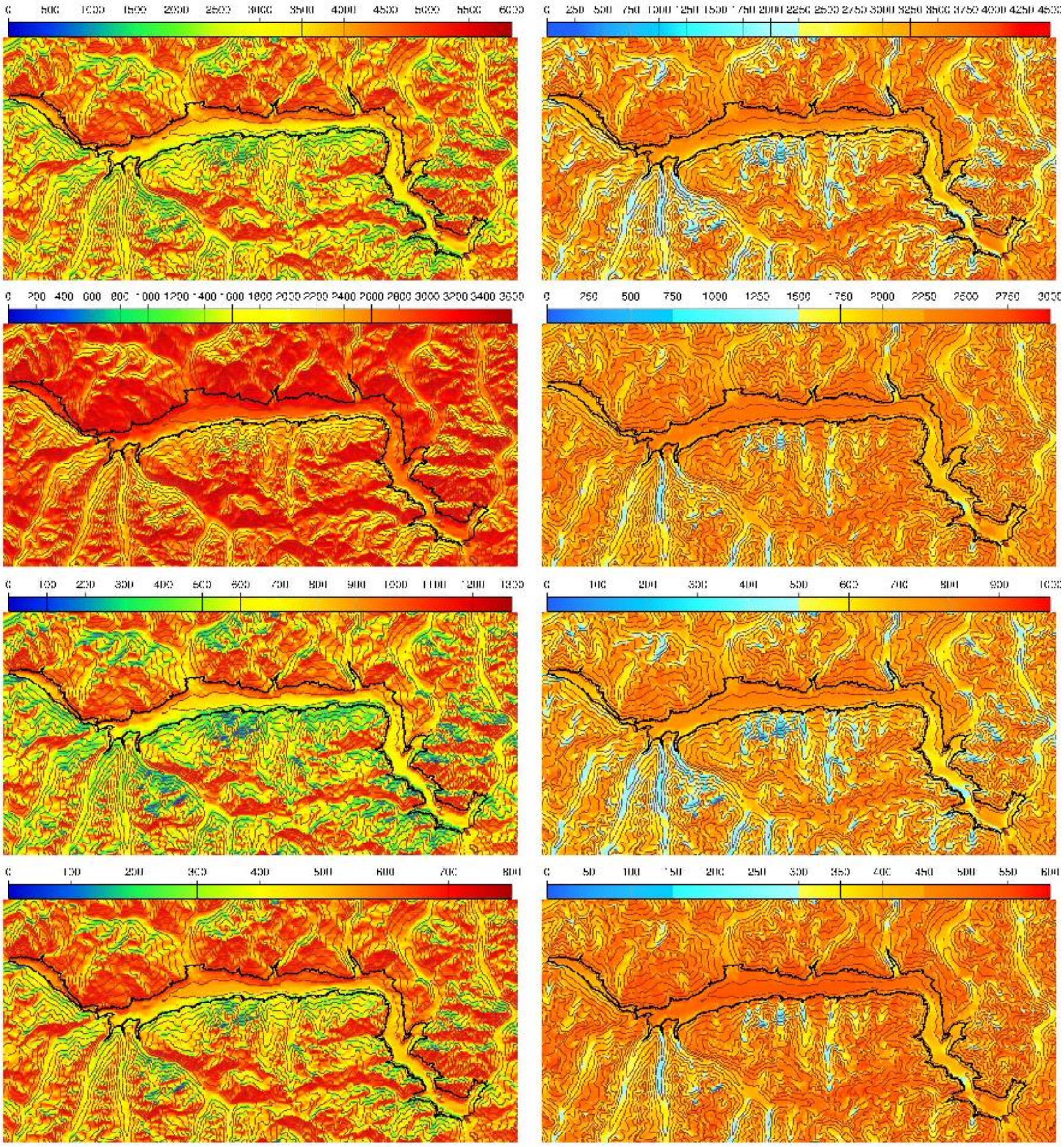

Figure 3: Accumulated clear-sky PAR (MJ m^{-2} day^{-1}, on the left) and insolation times in hours (IT, on the right) of the four considered time intervals (YEAR, APOC, INOC, INSE, from top to bottom).

Clear-sky PAR (MJ m^{-2} day^{-1}, à gauche) et temps d'insolation (IT, à droite) accumulés pendent les quatre intervalles de temps considérés (YEAR, APOC, INOC, INSE, à partir du haut).

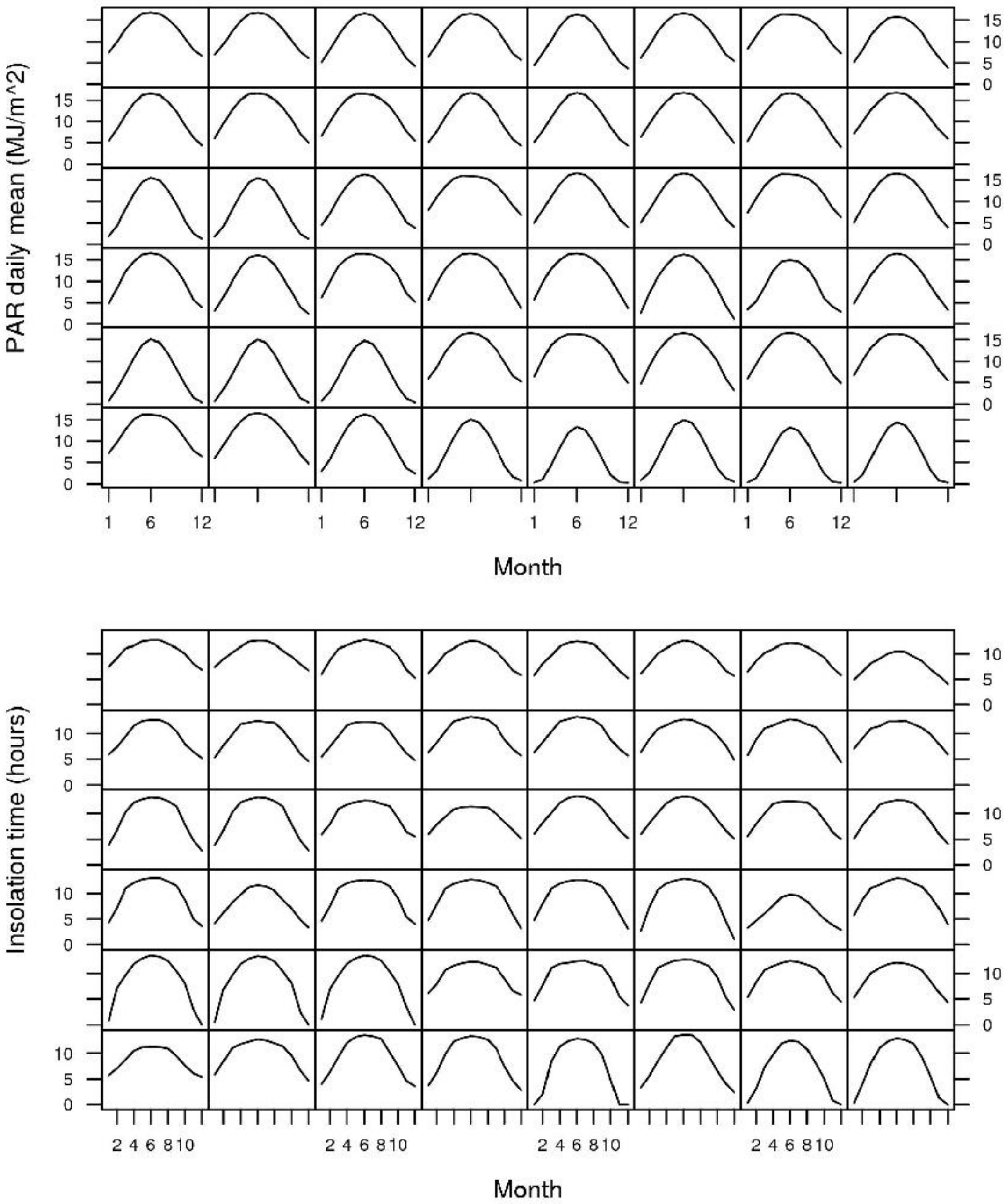

Figure 4: Plots of monthly means of daily clear-sky PAR and insolation times (IT) in 48 vineyards used as sampling sites in a viticultural zoning study.

Moyennes mensuelles de la PAR journalière (MJ m^{-2} $jour^{-1}$, en haut) et des temps d'insolation (IT, en bas) dans 48 parcelles de vigne utilisées comme sites d'échantillonnage pour un zonage viticole.

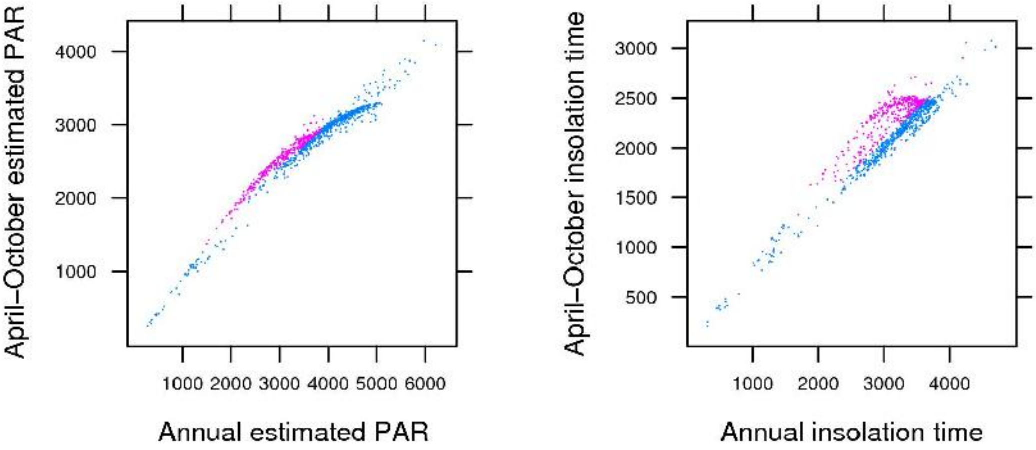

Figure 5: Scatterplots of Yearly vs APOC accumulated PAR and IT of 1000 random sites in the Aosta Valley viticultural area.

Rélation entre PAR et IT accumulés pendent les intervalles de temps YEAR et APOC de 1000 sites aléatoires dans la région viticole de la Vallée d'Aoste.

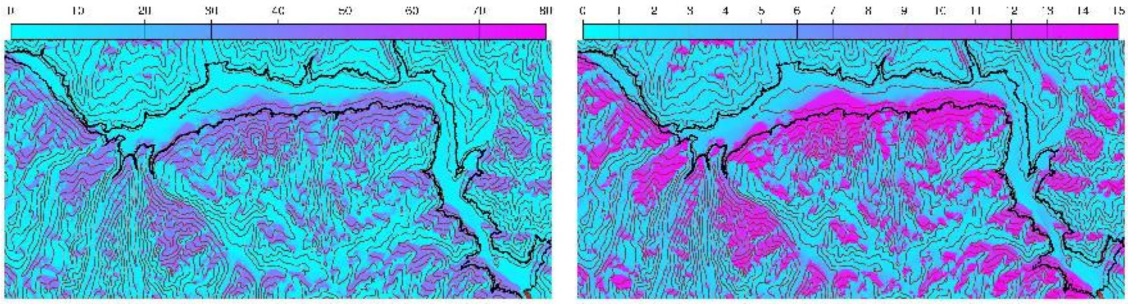

Figure 6: June/December monthly mean of daily clear-sky PAR (left) and IT (right) ratio.

Rapport entre les moyennes mensuelles de Juin et Décembre des PAR journalières (gauche) et des IT (droite).