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Sensitivity to training system parameters and soil surface albedo of solar radiation intercepted by vine rows

P. Pieri and J. P. Gaudillère

INRA, Ecophysiologie et Agronomie de la Vigne, Villenave d'Ornon, France

Summary

A geometrical model for solar radiation interception has already been developed and validated for application in vine training systems where each row is composed of only one vertical foliage plane. This model has been successfully used for simplified estimation of daily transpiration of non-stressed vines (Riou *et al.* 1994) and in models of photosynthesis. It may therefore also be used for long-term estimation of the soil water balance and growth, which considerably influence grape quality.

In this paper, using simulations based on the model, we studied changes of the solar radiation interception ratio and the vineyard albedo with row distance, row azimuth, shape of rows, and soil surface albedo.

The model was applied to different training systems with a single vertical plane of foliage, in conjunction with 10-day means of incoming global solar radiation for an average year in Bordeaux. From mid-April through end of September values of the ratio of intercepted radiation and of the absolute value of solar radiation interception by the rows were highly sensitive to the view factor of a row with its neighbour. Simplified expressions were established in order to summarize a large number of simulations by the model. These expressions allow an easy assessment of the sensitivity to training system parameters at that latitude. Within a realistic range of variation and ranked in a hierarchical order, most significant parameters for the solar radiation interception ratio and the absolute value of solar radiation interception by the rows were relative spacing of the rows, shape of the rows, soil surface albedo and row azimuth.

Key words: training system, light, albedo, canopy, model, vine spacing.

Introduction

Like many perennial crops, vines are often planted in rows, enabling mechanical or manual operation. The open space between the rows encompass relatively more volume than in orchards and its geometry is often maintained by mechanical pruning. One of the main consequences of this canopy structure is the key role of soil surface in energy balance, thermal microclimate and water status.

Experimental analyses of different vineyard training systems in interaction with soil and climate are difficult and costly, although these experiments are indispensable for understanding and modelling plant behaviour (Katerji *et al.* 1994) or whole canopy performance by taking into account major effects, such as soil surface management. The only alternative is the use of numerical simulations, at least to outline the main trends and to show the relative importance of various parameters upon a well-chosen key variable. Simulations performed on the basis of well-established models are the easiest way to evaluate the consequences of variations of chosen parameters. Results largely depend on the quality and universality of the considered model. Therefore, only models based on an accurate physical or biological description of the processes, rather than mere statistical relations between variables, should be used for these simulations.

This paper gives an example of such simulations within the frame of previously demonstrated interactions between grape quality and soil water balance (Riou 1994). The latter was calculated for the whole growing season, based on climatic data, soil characteristics and the solar radiation partition ratio between vines and soil surface.

A model of solar radiation interception by a vineyard was used here (Riou *et al.* 1989), which can be linked to vine transpiration (Riou *et al.* 1994) and soil water content (Lebon *et al.* 1995). Ten-day means of incoming solar radiation throughout the growing season in a normal year in Bordeaux (latitude 44°40') were used as model input. This paper investigates the variation of both, the solar radiation interception ratio and the absolute value of solar radiation interception by the rows, which are useful for evaluating vine transpiration and water balance as well as photosynthetic active radiation (PAR) interception, photosynthesis and biomass increase.

Model and simulation assumptions

A model of solar radiation interception for a row-crop canopy has been previously established (Riou *et al.* 1989). It is based on simple assumptions about geometry, periodicity and symmetry of the rows and can be adequately compared with direct measurements in traditional vineyards in Bordeaux (one single vertical plane of foliage of nearly rec-

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Correspondence to: Dr. P. Pieri, INRA, Ecophysiologie et Agronomie de la Vigne, BP 81, F-33883 Villenave d'Ornon Cedex, France. Fax: +33-5-5712-2515 E-mail: pieri@bordeaux.inra.fr

tangular shape). Input variables are incoming global (*Rg*) and diffuse (*Rd*) solar radiation. Output variables are solar radiation intercepted by vine leaves (*Rgv*), integrated over the whole rows and relative to the vineyard soil surface, and vineyard albedo (*a*). Most critical parameters are latitude, soil (*as*) and leaf albedos (*al*), row optical porosity, row azimuth (θ) and training system dimensions: row spacing (*D*), height of the foliated part of the rows (*Hf*) and width of the rows (*w*). As solar radiation interception by the trunks is negligible, all parameters describe the row volume filled with leaves.

To properly evaluate the energy available for both intervening soil surface and vine rows, the above model was successfully merged with a balance of thermal radiation exchanges into a model of net radiation partition (Riou *et al.* 1994). Then, thermal radiation emissions were assumed to be hemispherical and the interaction of one row with its neighbours was quantified by a shape factor *f*, which was assumed to be the shape factor between two parallel plates of infinite length (Ozisik 1981):

$$f = \tan(^1/_2 \operatorname{atan}(\frac{Hf}{D - w})) \qquad (1)$$

From daily experimental data, the global and net radiation partition ratios, *Rgv/(1-a)Rg* and *Rnv/Rn*, were shown to remain very close to each other (where *Rgv* and *Rnv* are the solar and net radiation absorbed by vines, respectively, *a* the albedo of the whole vineyard, *Rg* the incident global solar radiation and *Rn* the net radiation, or the balance of radiative energy available to the whole vineyard). From sap flow measurements, a simple method for estimating vine water consumption in the absence of water stress was established (Riou *et al.* 1994):

$$\text{Transpiration} = \frac{Rgv}{(1 - a) \cdot Rg} \cdot \text{PET} \qquad (2)$$

where PET, the potential evapotranspiration is calculated according to the Penman formula, from meteorological network data. While the use of the *Rnv/Rn* ratio would require some knowledge about leaf and soil surface temperature, eq. 2 is a simplification since the *Rgv/(1-a)Rg* coefficient can be calculated from the geographic position, date and simple dimensions only. This model was successfully linked with an evaporation model for the bare soil surface to calculate the soil water balance (Lebon *et al.* 1995). By disregarding water stress conditions and interactions between the soil surface and the leaves (Lascano *et al.* 1987; Shuttleworth and Gurney 1990; Ham *et al.* 1991; Heilman *et al.* 1994; Sene 1994) which may be enhanced by specific air flow patterns between rows (Weiss and Allen 1976), the solar radiation interception fraction *Rgv/(1-a)Rg* was supposed to accurately measure differences between trellis systems, with regard to transpiration, on a daily as well as seasonal basis. Since PAR represents a nearly constant fraction of incoming solar radiation, this partition ratio is also relevant for PAR absorption by leaves and photosynthesis and therefore was linked to the observed differences in photosynthesis and accumulated carbon production (Lebon *et al.* 1995).

The previously presented solar radiation interception model was thus used to simulate variations in *Rgv* and *a* resulting from different trellis systems, all belonging to the same family, consisting of a single vertical foliage plane, with a rectangular shape. The relative spacing of the rows (*D*/*Hf*), the row azimuth (*θ*), the row shape and albedo contrast between leaves and the soil surface were the only parameters considered here, *i.e.* we investigated the sensitivity of outputs calculated by the model to realistic variations of these parameters.

The vineyard area was supposed to be horizontal in all simulations. Results were derived from applying the radiation interception model to the same meteorological set of data (sums over 10 d from mid-April to the end of September) of the incoming global radiation (*Rg*), representing an average year in Bordeaux (latitude 44°40'; means of 30 years from 1961 to 1990) (Fig. 1). The vegetation period considered here is actually determined by degree day accumulation (starting on January 1st; temperature ≥10 °C), from about 100 °C days at budburst to about 1500 °C days at maturity of grapes and harvest.

For each canopy system, constant geometrical dimensions were applied as model input, from the beginning to the end of the growing season. These dimensions described the canopy structure following the post-bloom first pruning. Solar radiation interception by the rows was therefore overestimated at earlier stages. On the other hand, solar radiation interception was slightly underestimated after the first pruning because growth between repeated pruning operations was not taken into account. Since the initial shoot growth is fast and occurs when global solar radiation is relatively low, we considered results over the whole growing season to be insensitive to this simplistic assumption; *i.e.* a comparison of different training systems should be possible. In the same way, row porosity was assumed to remain constant (0.33) for all simulations because sensitivity of the previous model to this parameter was low.

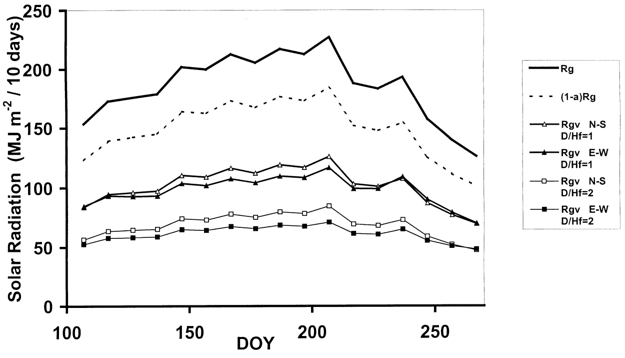

Fig. 1: Values of incoming global radiation, *Rg*, and simulations of whole vineyard intercepted global radiation, *(1-a).Rg*, (with *a* the calculated vineyard albedo) and global radiation intercepted by vines, *Rgv*, for *D*/*Hf* = 1 and 2 and two row directions, N-S and E-W. *w* = 0.35 m and *Hf* = 1.2 m are held constant (*D* is the distance between axes of neighbouring rows, *Hf* the height of foliage within a row and *w* the width of a row). Albedos are also held constant (*al* = 0.25 for leaves, and *as* = 0.18 for the soil surface). DOY stands for day of year. Time courses of *(1-a).Rg* were undistinguishable for all training systems considered.

The second main assumption is part of the calculation method: for each 10-day period, the model was applied to only one day, the daily incoming global radiation, *Rg,* of which a tenth of *Rg* was integrated over that period. This day represented the whole 10-day period, and during that day, the *Rg*/*Rg0* and *Rd*/*Rg* fractions were also assumed to remain constant, where *Rg0* is the theoretical extra-atmospheric global radiation and *Rd* the incoming diffuse radiation. Therefore these fractions were assumed to remain constant all along any given 10-day period, and related to each other by daily measured data in Bordeaux over two different years:

$$Rd/Rg = Min\,(1.\;,\;1.09\text{-}2.69(Rg/Rg0)^2 + 1.28(Rg/Rg0)^3\,)$$

$$(r^2 = 0.93;\ n = 121) \qquad (3)$$

Results

10-day ratios of solar radiation interception: In the considered average year, variations of 10-day integrals of global radiation estimates showed that, even at a rather close spacing of the rows, the radiation interception by the vines, *Rgv*, was significantly lower than that of the whole vineyard *(1-a)Rg* (Fig. 1), which is a direct, well known consequence of the open and discontinuous structure of the canopy. The significant solar radiation interception by the soil surface was estimated by the difference *(1-a)Rg - Rgv*. Changes of row spacing, within a realistic range, led to much larger differences than changes of row azimuth (Fig. 1).

10-day ratios of solar radiation absorption by the rows, *Rgv/(1-a)Rg* (both *Rgv* and *a* calculated by the model), also exhibited strong variation with the relative inter-row distance but showed quite different azimuthal patterns (Fig. 2). N-S rows were quite insensitive to the sun position and therefore to the date. On the other hand, E-W rows were much more sensitive to the sun position on this time scale, whereas they are far less sensitive within a single day (SMART 1973; RIOU *et al.* 1989). Near the equinox (266th day of year), when the sun position changed most rapidly and solar elevation decreased, the solar radiation interception ratio of E-W rows increased steadily for all relative row spacing values. For closely spaced E-W rows, it reached a peak and dropped when mutual shadowing of neighbouring rows became prominent (Fig. 2).

Calculated 10-day ratios of solar radiation interception by the rows (Fig. 2), were combined with PET values to estimate accumulated transpiration (eq. 2), assuming the effect of stomatal conductance to be negligible. With a total PET of 640 mm over the period (mean of the years 1986-1999 in the Bordeaux area), N-S row transpiration was 437 mm and 286 mm for relative inter-row spacing *D*/*Hf* of 1 and 2, respectively. E-W row transpiration was reduced by 5 and 12 %, respectively.

Along with forecasting stomatal conductance effects and analysis of risks associated with local soil water balance conditions, these findings provide a rationale about row orientation, although other effects like grape microclimate during the maturation period must be considered as well. Similarly, differences in solar radiation interception by different training systems are closely related to differences in PAR absorption, photosynthesis and growth.

Whole growing season ratio of solar radiation interception: On the basis of seasonal integrals of *Rgv* and *(1-a)Rg*, the results were summarized by an overall ratio of intercepted global radiation, which is an essential and unique characteristic of each training system. As expected, it was very sensitive to the relative spacing of rows *D*/*Hf* whereas the influence of the azimuth of the rows was comparatively much lower but still not negligible (Fig. 3). The strongest effect of row azimuth was observed for intermediate row spacings. For large inter-row distances, the maximum row azimuth influence was nearly constant (a stable fraction of 14 % of the N-S rows interception ratio) whereas it was limited by shadowing for closely spaced rows, the theoretical limit being *D* = *w* where the canopy is continuous and therefore an influence of row orientation can be excluded. Hence, maximum azimuthal influence was 0.055, in absolute value of the interception ratio, when *D*/*Hf* = 2.

Effects of view factor and azimuth: The whole growing season ratio of solar radiation intercep-

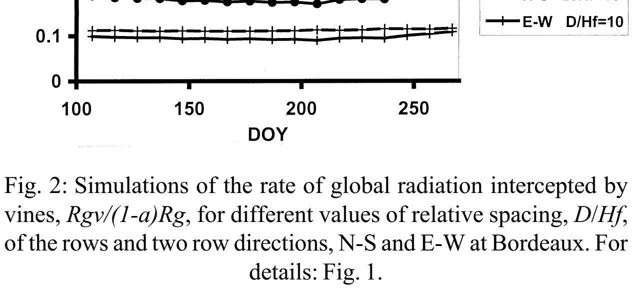

Fig. 2: Simulations of the rate of global radiation intercepted by vines, *Rgv/(1-a)Rg*, for different values of relative spacing, *D*/*Hf*, of the rows and two row directions, N-S and E-W at Bordeaux. For details: Fig. 1.

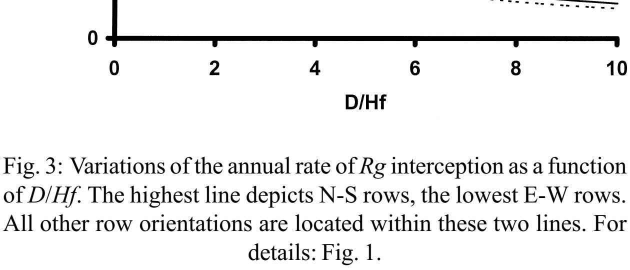

Fig. 3: Variations of the annual rate of *Rg* interception as a function of *D*/*Hf*. The highest line depicts N-S rows, the lowest E-W rows. All other row orientations are located within these two lines. For details: Fig. 1.

tion by the vines described previously was considered a satisfactory means to quantify differences between various canopy geometries. The influence of training system parameters was summarized from (1) considering realistic but exhaustive ranges of variations in main training system parameters, (2) applying to each combination of parameters, and therefore to each training system considered, the complete model operating on a 30 min time scale, (3) linearly correlating results of integrated solar radiation interception with the explaining parameters.

Previous results (Figs 1 and 2) showed that the view factor *f* between neighbouring rows (eq. 1) gave the most simple and most accurate relations with the overall ratio of intercepted global radiation. Since this parameter represents hemispherical radiation interactions between adjacent rows, it is also well suited to represent diffuse radiation interception and integrated direct radiation interception for various sun positions, for single days and for the whole growing season. The view factor *f* was therefore more relevant for explaining the overall ratio of intercepted global radiation than the more classical relative spacing ratio *D/Hf*.

For instance, with a given row direction, the annual ratio $Rgv/(1-a)Rg$ was found to be linearly related to $\sqrt{f}$. On the other hand, for a given *f* or relative spacing *D/Hf*, the same ratio followed a sinusoidal law of azimuth, whose amplitude α was very close to a Rayleigh function A(*f*) of *f* (Fig. 4). As previously stated, azimuthal influence never exceeded 0.055 in absolute value, or 14 % of the growing season ratio $Rgv/(1-a)Rg$, and was maximum for intermediate (around *D/Hf* = 2) inter-row distances. Mutual shadowing effects of neighbouring rows were prominent in reducing azimuthal influence for most common training systems (the A(*f*) function separates by 10 % and more from its 0.0246 f/b″ linear asymptote as soon as $f \geq 0.126$, or $D/Hf \leq 4.20$). These variations were therefore well summarized by the equation:

$$\frac{Rgv}{(1-a)\,Rg} = \mathrm{C}\,[(-0.16 + 1.17\sqrt{f}\,) - A(f)\,(1 - \sin\theta)] \qquad (4)$$

($r^2 = 0.999$; n = 200; *D/Hf* = 0.5 to 10 by 0.5;
$\theta = 0°$ to 90° by 10°)

where θ is the azimuthal direction (0° for E-W rows and 90° for N-S rows), and *A*(*f*) the amplitude previously defined (Fig. 4). C is a constant when only *f* and θ vary. Its value is 1 for the reference row shape (*w/Hf* = 0.29) and albedos (*al* = 0.25 and *as* = 0.18).

Effects of row shape and soil surface albedo: Within a realistic range of parameters describing row shape and surface albedos, results showed that the same simplified relation (eq. 4) was still valid with different values of C. These values depended from the albedo contrast between the leaves and the soil surface and from the row shape (Fig. 5), as measured by the internal row shape factor *fs*, directly linked to the row aspect ratio *w/Hf* by:

$$fs = \tan\left(\tfrac{1}{2}\,\mathrm{atan}\left(\frac{w}{Hf}\right)\right) \qquad (5)/$$

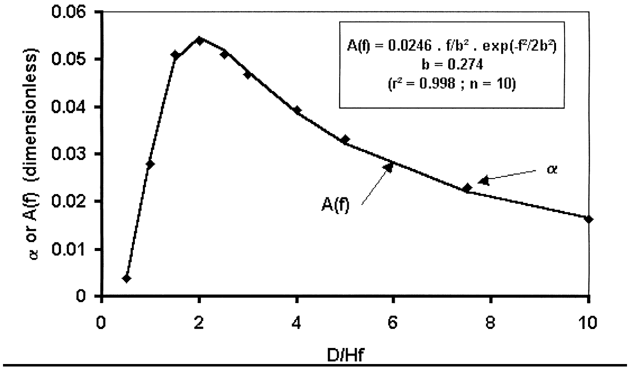

Fig. 4: Variations of the estimated amplitude α (of sinusoidal variation with row azimuth) of the annual rate of *Rg* interception as a function of *D/H*. Comparison with a Rayleigh function *A* of the shape factor *f*. For details: Fig. 1.

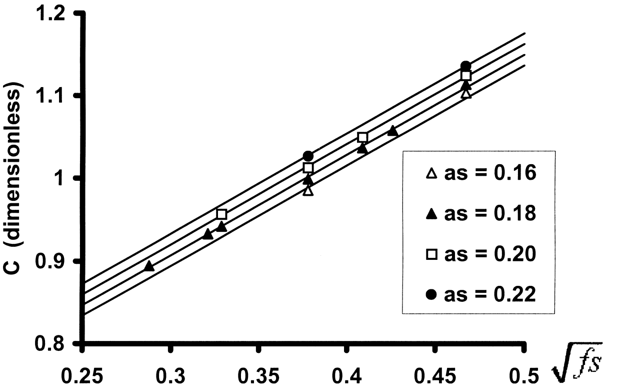

Fig. 5: Variations of C (of equation 4) for different row shapes, as measured by the within-row shape factor *fs*, and different albedos of the soil surface *as*. Leaf albedo *al* = 0.25 is held constant. C = 1 for the reference system (*w* = 0.35 m, *Hf* = 1.2 m, *al* = 0.25 and *as* = 0.18).

It became evident that, for most common training systems ($\sqrt{f}$ = 0.22 and 0.49 for *w/Hf* = 0.1 and 0.5, respectively), C varied linearly with $\sqrt{f}$, and was displaced by a simple offset when the soil surface albedo *as* was changed (Fig. 5). Variations of C were therefore assumed to be linear, of slope 1.209 and intercept 0.544 for the reference soil albedo (C=1 for reference values $\sqrt{f}$ = 0.378 and *as* = 0.18). Parallel lines, with an offset uniformly shifted by 0.0104 for each as variation of 0.01, accurately represented variations of C with the soil surface albedo (Fig. 5). Sensitivities of the overall ratio of intercepted global radiation to row shape and soil surface albedo were nearly identical, at least when large variations of *as* were considered (Fig. 5). Both exceeded the sensitivity to row azimuth.

Summarizing, for the latitude of Bordeaux a simple way to quantify effects of main training system parameters coupled with soil surface albedo values, upon seasonal ratio of radiation interception, was given by:

$$\frac{Rgv}{(1-a)\,Rg} = [0.544+1.04\,(as-0.18)+1.209\sqrt{fs}\,]\,[(-0.16+0.17\sqrt{f}) - A(f)\,(1-\sin\theta)]$$

($r^2 > 0.98$ for all systems investigated in this paper) (6)

This simplified expression allows a straightforward quantification of the influence of training system parameters on the whole growing season ratio of solar radiation interception, and hence on vine transpiration in the absence of water stress. Ranked in a hierarchical order, driving parameters are relative spacing of rows, aspect ratio of rows, soil surface albedo and row azimuth.

Variations of accumulated solar radiation interception in absolute values: Absolute values of accumulated solar radiation interception by the rows, useful for accumulated PAR interception, photosynthesis and biomass growth estimations, may be derived from previous simplified relations (eq. 6) only if the overall value of the vineyard albedo *a* is known.

The overall value of the albedo *a* of a vineyard over the whole period depended on values of the albedos of leaves (*al*) and of soil surface (*as*), along with the same trellis system parameters already examined. A higher albedo contrast *al-as* led to higher trellis system-related variations. Results showed that variations of *a* were similar to those of the interception rate (Fig. 6). However, estimates of absolute values of *Rgv* were rather insensitive to variations of *a* alone, at least with realistic values of parameters. For different values of relative spacing *D*/*Hf*, time courses of *(*1-*a).Rg* would be undistinguishable in Fig. 1. Therefore, direct sensitivity of *Rgv*, rather than *a*, to training system parameters and albedo contrast was investigated.

Results were summarized by a single approximation, similar to eq. 4, which allowed a fast and easy quantification of the influence of different training systems on radiation interception in absolute values ($r^2 > 0.98$ for each system considered):

$$Rgv = Rg\,[0.54 - 0.6\,(al - as) + 0.8\,\sqrt{f}\,]\,[(-\,0.16 + 1.17\,\sqrt{f}\,) - A(f)\,(1 - \sin\theta)] \qquad (7)$$

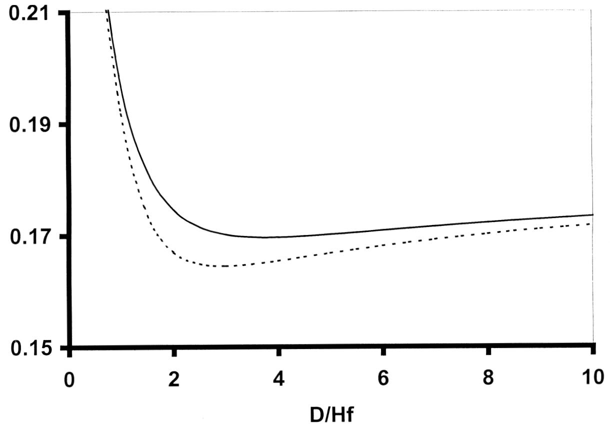

Fig. 6: Simulated variations of the whole vineyard albedo *a* as a function of relative spacing, *D*/*Hf*, and azimuth of the rows. The highest line depicts N-S rows, the lowest E-W rows. All other row orientations are located within these two lines. *w* = 0.35 m, *Hf* = 1.2 m, *al* = 0.25 and *as* = 0.18 are all held constant.

The constants in equations (4), (6) and (7) are obviously location dependent (latitude effect) and/or year-dependent (effect of the climatic value and variations of the input variable *Rg* with time). Following the previously described method, it would be easy to repeat it for different locations or different meteorological data sets.

Discussion and Conclusion

A 30 min time-scale model of solar radiation interception by rows of a vineyard was used to simulate the behaviour of different types of training systems and soil surface albedo conditions throughout an average growing season in Bordeaux. Main driving parameters were identified for both, the integrated solar radiation interception ratio and the absolute value of intercepted solar radiation. An adequate way to describe the overall effects of these parameters was to use view factors, especially the view factor *f* of a row with its neighbour.

The results of these simulations allowed a quantitative evaluation, at least as a reasonable approximation, of the influence of the training system on solar radiation absorption, and therefore on transpiration at non-limiting water availability, as well as on vineyard albedo. It may be possible to approximate photosynthesis, biomass growth and radiation use efficiency (Sinclair and Muchow 1999) with this approach. The orders of magnitude of relative variations with the row direction matched the few data available from direct, short-term measurements of evapotranspiration (20 %, according to Hicks 1973). Application of this approach will also greatly improve the estimation of grapevine crop coefficients (Riou *et al.* 1994; Stevens and Harvey 1996).

Simplified equations (4) to (7) summarize the results for an average year (or vintage) in Bordeaux. Similar relations can easily be derived for other places and other time intervals. They allow a fast estimation of the differences introduced by different types of trellis systems all made up of a single vertical plane of foliage. In a hierarchical order, and within realistic ranges of variation, the most significant parameters were relative spacing, shape of the rows, soil surface albedo and row azimuth. The mean soil surface albedo is both, an intrinsic soil characteristic and a soil surface management parameter.

Therefore these simulations are useful for easily evaluating any training system with regard to the general trend of harvest quality *versus* soil water balance and/or vegetative growth. However, corrections must be made in the case of a drying soil, which may slightly increase vine transpiration through energy transport from the soil surface towards the leaves (Lascano *et al.* 1987; Shuttleworth and Gurney 1990; Ham *et al.* 1991; Heilman *et al.* 1994; Sene 1994) before decreasing it by stomatal closure (Tardieu and Simonneau 1998; Schultz *et al.* 1999). Similarly, these results could be relevant even in the case of a moderate nitrogen deficiency since integrated solar radiation interception is far less sensitive to leaf area density and row porosity than to other parameters. However when vegetative growth is strongly reduced, results clearly demonstrate that reductions in row dimensions must be taken into account.

The conditions of mutual shadowing of neighbouring rows were discussed. Although demonstrated for the overall solar radiation interception rate only, the same conditions affect photosynthesis of individual leaves as well as the microclimate of grapes, which are usually situated in the lower part of the canopy. Since grape quality also strongly depends upon leaf carbon conversion efficiency and berry microclimate, models and results of simulations like those exhibited here will help to optimise training systems.

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