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Spatial analysis of within-vineyard grapevine sensitivity to solar irradiance patterns. A case study using Pinot noir in a complex terrain

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Abstract

We analyze how the patterns of the solar irradiance affect the growth of Pinot noir grapevines at stand-scale over a hilly terrain bounded by a coniferous forest. Results show that the patterns of irradiance deficit are the primary driving force of the growth. Linear trends display good correlation between the total deficit of irradiance, and the developed growth index (R2 up to 0.96). This result also suggests the impact of low minimum temperature due to cold air drainage and stagnation. Results lead to propose a model able to capture at stand-scale 90% of the whole spatial variability of the growth. The model accounts for the diffuse component of the deficit of irradiance and the squared temperature anomalies. Combining such models through the use of GIS enables to better understand the driving mechanisms of grapevine growth over complex terrain, towards a better management of the "terroir" potential whithin climate change.

Keywords: Irradiance, spatial patterns, grapevine, phenology, growth, temperature, GIS.

* * *

Wine production is a key economic activity in the region of Burgundy. Topography is one of the main environmental factor that influences the grape growing and further the quality of the wine in this area. This has led together with climate and soil factors to the definition of wine labels that range from "communale" appelation to "Grand cru" (top quality). At stand-scale, topography and soils play important roles in grapevine growth and quality, and have an interactive effect with climate elements such as solar irradiance [20]. At larger scale, additional factors such as grape variety and precipitation are of overriding importance [9, 12]. Studies conducted at different spatial scales have provided insights into the complex inter relationships between grapevine growth, wine quality and the local environment. Few studies have been conducted at stand-scale (i.e. toposcale) over this area for which it is assumed that slope, aspect and air drainage exert greatest influence on stand's climate and soil depth and drainage. Hence,

progress is needed to better understand the role of the local climate and soil in determining grapevine growth for a given year. The present study was conducted to determine the spatial relationships at stand-scale between patterns of grapevine growth, and of climate irradiance and temperature variables induced by topography, and the presence of a forest.

It is expected that the shoot development of grapevine is affected by the withinstand climate pattern. We hypothetize that grapevine growth spatial variability is mainly driven by the presence of topography and forest. But experimental analyses for various geometric and radiometric situations are difficult and costly. One alternative is the use of numerical simulations computed from well-established models. We based the work on two models validated over the study area for the complex irradiance geometry of the terrain [5], and the phenology of the "Pinot Noir" [7]. In the present paper a Geographic Information Systems (GIS) was set up to combine multisource data - model simulations and index derived from field measurements - for spatial analysis purpose. The work was carried out in the year 2003 for a top quality vineyard stand locate over the "Côte de Nuits" district which provides a suitable test site for stand-scale grapevine analysis located over a complex terrain.

I. Site and ground data

Figure 1 presents a perspective view of the experimental stand. The stand was planted with "Pinot Noir" plants in 1950 over a surface of slightly less than 1 ha. The altitude varies inside the stand from 310 m to 350 m with a eastward facing slope that reaches 25 degrees to the west. To account for the terrain complexity, a Digital Surface Model (DSM) was derived from a DEMand the height of the forest trees [5]. The neighbouring forest is composed of pure Austrian black pine (Pinus nigra nigricans) plantations of 64 and 50 years old, except for the little grove at the bottom eastern part of the stand (7 to 30 years). Whereas main part of the forest is located at the south and west of the vine stand.

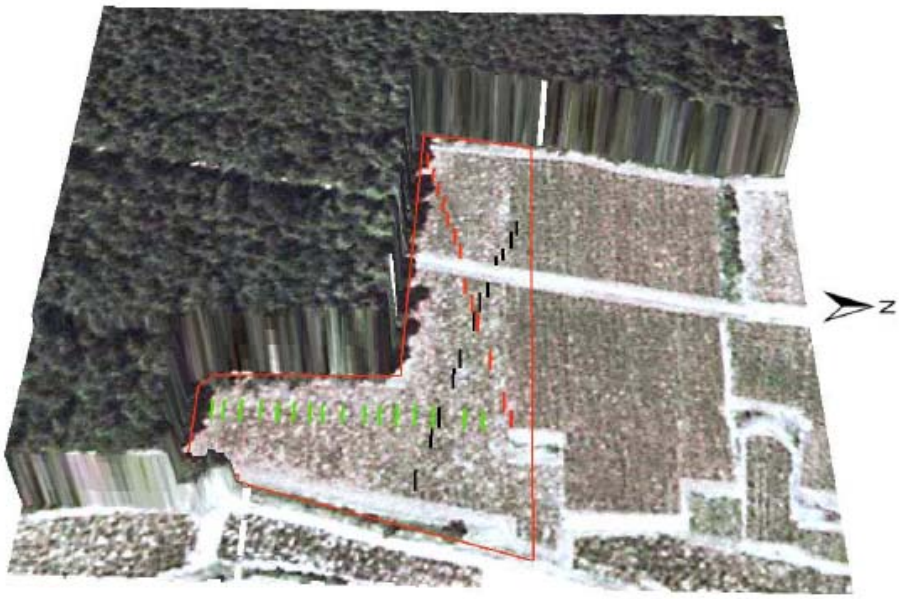

Figure 1: 3D perspective view of the stand (red line) with a vertical exaggeration of 1.5. upper-slope transect (red), middle-slope transect (black) and lower-slope transect (green) present the measurements locations. A Digital Surface Model (DSM) is drapped with an aerial orthophoto cIGN.

Three main transects were designed for the field measurements of the phenology. Each transect is composed of 13, 12 and 16 sub-transects for upper-, middleand lower-slope transects, respectively (Fig. 1). Each sub-transect includes 5 to 7 vine plants. The sampling strategy performed during year 2003 includes the monitoring of the phenological stage every 7 to 12 days. Measurements were realized for nearly a growing season (May-August) for each sub-transect following the Eichorn-Lorenz growth stages descriptive system [10]. All branches of each sampled vine plant were referenced. Reference temperature data used to determine temperature anomalies were obtained from the meteorological station of Dijon-Longvic. The data were collected on a daily timescale, and consist of average temperature from April to August computed for the period 1991-2000. The temperature data were provided by Météo France.

II. Four steps methodology

II.1. Computation of irradiance patterns

The model fully describe in Castel [5] aims to compute irradiance patterns that are robust radiometrically and accurate geometrically. Conceptually, the model is based on the radiation equations of the clear-sky ESRA model [23] for which the Linke turbidity factor is one of the key point. The transmission through the forest canopy is described by the classical Beer's equation [1] and further improved by integrating 1) the vertical structure [26], and 2) the local path length for sloping terrain [6]. For complex terrain, scientific challenges involve viewshed algorithms. The algorithm has to compute the horizon for all point of the surface with the presence of both topography and forest canopy. Indeed, horizon is a key parameter for shading and visibility applications for which a fast and accurate approach is needed [8]. The modelling scheme uses efficient algorithms developed by Stewart [25] and by Reda and Andreas [22] for horizon and solar position computation respectively. The irradiance maps are calculated via Digital Surface Models (DSMs) derived from a Digital Elevation Model (DEM) and the height of the tree. From there we define a simple climate index as the cumulative deficit of irradiance, also called irradiance, computed for the whole vegetative period that may be seen as a climatic index. The deficit of irradiance is defined as the difference between received irradiance at any location with and without the presence of the forest. Due to the high level and large range of the values, it is expressed in kilowatts per square meter (kW/m2).

II.2. Index of development : Smax

To analyse the characteristics of the vinegrape growing, a time-integrative index was defined as the maximum phenological stage - i.e. Smax (eq. 1) - that may be reached by the vine. The estimation of Smax is based on fitting phenological data derived from field measurements of the stages by a four-parameter logistic function given as [13]:

$$S = S_{\max} + \frac{S_{\max} - s_{\min}}{1 + \exp((t - t_{\mathrm{I}})/\alpha)} \tag{1}$$

with S the phenological stage, Smax the maximum potential stage i.e. the left asymptote, smin the starting stage i.e. the right asymptote, tI the halfway time between asymptotes and a a constant that determines the rapidity of ascent. The values of S refer to the phenological stages according to the Eichorn-Lorenz systems of shoot development in the grapevine. The values range from 1

that correspond to winter dormancy (winter buds scales more or less closed) to 37 that state the end of the berry ripening (véraison). The method is based on the reconstruction of a finer growth curve on which equation (1) is fitted using a non-linear least-squares algorithm based on the quasi-Newton method [16]. Note that the statistical processing is carried out using tools available under R environment [21].

II.3 GIS-based analysis of zonal statistics

To analyse the relationships between the growth stage and the climatic variables, a multi-stage GIS analysis was set up to incorporate factors related to topography, soils and sub-transect position. The stand was surveyed during 2003 using a Global Positioning System (GPS) to geographically locate field measurements. A post-processing differential technic was performed to obtain accurate positionning, and to derive a high resolution DEM (1 m resolution). Besides stand attributes, the GIS-database includes a georeferenced map of cumulative irradiance deficit derived from the model presented by Castel [5]. The validation of irradiance patterns was carried out for both radiometry and geometry. The values of irradiance computed by the model were compared to the values of irradiance measured by the weather station at Dijon. While for the geometry (i.e. the extension of the shadow) the values were compared to in situ GPS measurements. In both cases very good agreements are obtained (rmse of irradiance = 40 – 50W/m2/day, position error < 0.5m). From there, the spatial analysis has consisted on:

1. creating buffer zones around each sub-transect;
2. computing zonal statistics of the irradiance deficit;
3. relating the growth index to the local mean of irradiance deficit.

The buffer distance was taken equal to 1.5 m, and the deficit of irradiance was calculated for a whole growing season. The spatial analysis was performed within the Arc/Info GIS [11].

II.4. Temperature anomalies (Δt) retrieving

Chuine *et al.* [7] have developed a model able to reproduce the timing of "Pinot Noir" development as a function of daily mean temperature. The inversion of the model was used to estimate the temperature anomaly that would provides the observed flowering date for each sub-transect retrieve the temperature as followed:

$$\Delta_t = \frac{\sum_{t_0}^{t_f} R_f(x_t) - F}{t_0 - t_f} \; with: \qquad (2)$$

t_f	observed flowering date
x_t	day mean temperature (1999-2000)
R_f	degree-day function
T_b, F, t_0	fitted parameters: 8.63, 412.97, 92

Note that up to 82 percent of the temperature variance is explained by the model. The reference temperature was filtered in order to eliminate shortest (i.e. below few days) fluctuations. To this aim, a low pass butterworth filter which does not change the temporal phase has been applied [17]. Computed temperature anomalies were entered into the GIS-database for analysis purposes.

III. Results and discussion

The relationships between the growth index (Smax) and the climate index (D irradiance) show strong linear trends especially for the upper-slope transect and to a lesser extent for the lower-slope transect (Fig. 2). A decrease of Smax is found with increasing irradiance deficit. Middle-slope transect has no clear relationship between both indexes. The relationships also differ substantially between upper- and lower-slope transects. Indeed, the linearity is higher for upper-slope transect (R2 = 0.95) than lower-slope transect (R2 = 0.66), which indicates that the deficit of irradiance is a better explanatory variable for the upper-slope transect. It also appears that the slope of the trend - indicating the rate at which grapevine growth increases as deficit of irradiance falls - is steeper for lower-slope (
= −0.051) than for upperslope transect (
= −0.027). Note that using a linear fit for lower-slope transect implies an under-estimate of the slope.

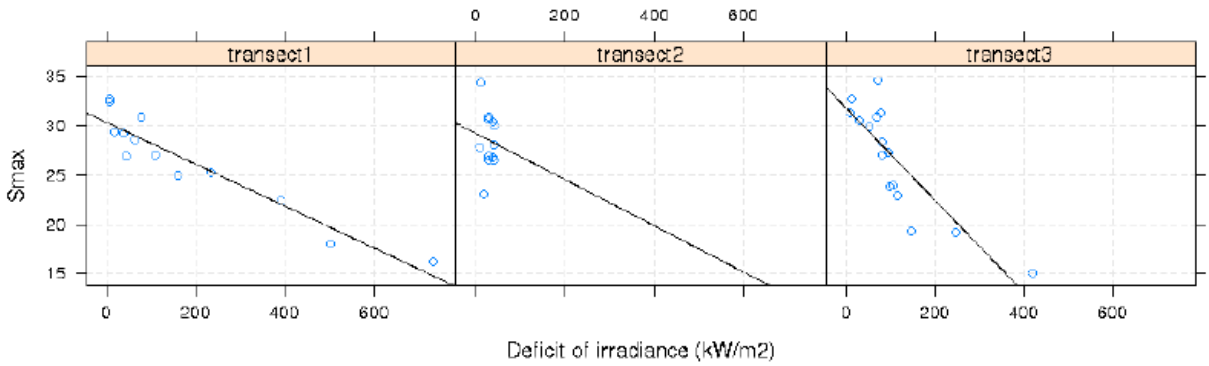

Figure 2: Smax vs. deficit of irradiance for the three transects. Line indicates the fitted linear trend.

For lower-slope transect the results suggest that an extra process strongly impacts, in combination with irradiance patterns, the mean temperature level, and consequently the grapevine growth. This is supported by the relationship between Smax and temperature anomalies (Fig. 3). Data are best fitted (R2 = 0.92) by a quadratic rather than a linear regression, which points for the curvature of the Smax response to temperature anomalies. By contrast there is less significative improvement by fitting data of upper- and middle-slope transects by quadratic regressions. The summary of the regression statistics indicates that the quadratic term improves significatively (p = 0.0026) the fit. This may be interpreted when it is compared to a linear increasing rate as a supplementary delay in the growth of grapevine. Such a behaviour is probably due to lower minimum air temperature over this area of the stand.

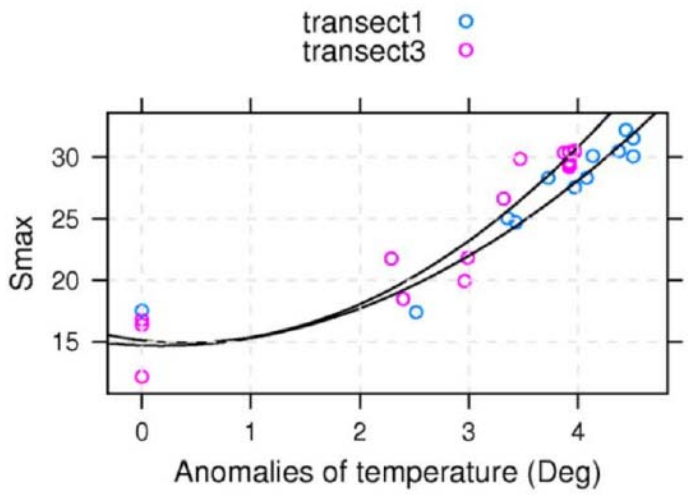

Figure 3: Smax vs. temperature anomalies along the upper (transect 1) and lower (transect 3) slope transects.

The results indicate that the differences of grapevine growth are related to the spatial variability of both i) deficit of irradiance and ii) temperature anomalies. Stand-scale variability - e.g. topography, distance to forest - modify substantially the respective weight of each explanatory variable in the modelling of the growth index. As pointed by Bolstad *et al.* [4], and more recently by Lookingbill and Urban [14], a primary interpretation of the grapevine growth behaviour suggests that temperature maxima may be particularly sensitive to radiation difference (see behaviour of upper-slope transect). Moreover, temperature minima may be more strongly influenced by relative position along the slope and by topographic air currents (see behaviour of lower-slope transect). Hence, a combination of topography and forest can strongly influence the microclimate of the stand that they border [24]. Our results have emphasized two main contrasted behaviours concerning the grapevine growth for the upper- and lower-slope transects. Concerning upper-slope transect, the phenological stage appeared directly correlated to the amount of radiation received, which is mainly driven by the adjacent forest. Furthermore, as upper-slope transect is found on steep slopes there is least risk of frost [2]. This explains the observed strong correlation between maximum phenological stage and deficit of irradiance. This is also supported by the fact that the deficit of irradiance and temperature anomalies are strongly correlated.

For the lower-slope transect, due to the relative slope and forest position, the mechanisms are more complex. As indicated by Blennow [2], such a flat, low-lying part of the stand is most frost prone. In such area, drainage ponding and stagnation of cold air is expected. This is further improved by the forest "protection" against high wind speed. Indeed, Bogren *et al.* [3] show that wind speed above 2 m/s prevents the development of large air temperature differences. High stem density of the forest stress the minimum temperature via cooling effect that may be strong and deeper even for slight slope [15, 27]. The amplitude of temperature differences due to topography and wind may rise up to 4.6oC [2] and 8oC [3], respectively. This range may explain the huge variability observed during year 2003 for the anomalies of temperature within the stand. Such an analysis is supported from a physiological point of view.

IV. Conclusion

The finding of this work revealed that the development is related to both deficit of irradiance and temperature anomalies. Furthermore, the sensitivity of the delopment appears heavely modulated by temperature anomalies. Whereas the pattern of irradiance is mainly related to the presence of a neighbouring forest, the spatial variability of temperature anomalies is driven by a balance between the surface topography (relative elevation and local slope) and the deficit of irradiance. Hence, the impact of both explanatory variables on growth appears strongly location dependent. Morevover, the results support the assumption that growth along upperslope transect is more directly affected by the pattern of irradiance than along lower-slope transect for which growth is mainly driven by lower minimum air temperature. This latter suggests an indirect effect of the irradiance pattern, modulated by cold air drainage, ponding and stagnation.

As recently pointed by Pierce *et al.* [19], an accurate capturing variability in radiation differences is needed for finest patterns vegetation analyses. Wine production on such an area is the result of a subtil balance between light avaibility and cold air stagnation and cooling. This affects shoot development in grapevine as well as wine quality [18]. Moreover, in the context of climate change, the results clearly point the need to account for stand complexity in order to better assess the global warming impacts on wine production. The above-developed methodology can applied to the entire "côte viticole" in order to create thematic maps about climate potential in changing environment. These thematic maps are of primary importance to improve the management of the complex interactions between local climate, soil, and site location (termed the "terroir" in France) which determine the potential of grape development in the "Côte de Nuits" and "Côte de Beaune" districts. Combining irradiance and phenological models through the use of GIS is suitable to soundly understand the development process of grapevine over complex terrain.

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