SPIDER : SPATIAL EXTRAPOLATION OF THE VINE WATER STATUS AT THE WHOLE DENOMINATION SCALE FROM A REFERENCE SITE

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Abstract

Aim : The objective of this work was to test an approach to extrapolate the vine water status (Ψ) over a whole denomination. The method has already been tested at the field level, but it has never been validated on a spatial scale that large.

Methods and results : The extrapolation model is based on an empirical approach that relies on a reference measurement and a spatial model of Ψ. Experiments were carried out over the 2946 ha of the denomination of Tavel (Gard, France). This site exhibits significant spatial variability in soil composition (three different soil units) and elevation, it is not irrigated and has a Mediterranean climate. This context leads to strong spatial variability in Ψ. Focusing on the most common grape variety used in the denomination, Grenache, a data base of predawn leaf water potential (PLWP) was built over three consecutive years (2008, 2009 and 2010). Respectively 10, 24 and 24 sites located throughout the denomination have been monitored for PLWP. The monitoring consisted respectively in 7, 10 and 9 measurement dates throughout the growing season. The spatial model was calibrated from 2009 and 2010 data and the prediction was tested on 2008 data. The results showed that the approach was completely transferable to a large territory like Tavel. The model significantly improved the quality of the prediction (R^2 = 0.9) compared to a conventional non-spatial method based on the mean values (R^2 = 0.61).

Conclusion : On the basis of a single measurement taken at time "t" on a reference site, the model makes it possible to estimate Ψ on any site of the study area. The results, therefore, demonstrated the ability to extrapolate a PLWP measurement made on a reference site over the whole denomination constituted of three different soil units.

Significance and impact of the study : This study represents a significant step since it demonstrates the existence of a spatial model of Ψ at a scale larger than the single field. It provides critical knowledge to consider the use of an empirical spatial model across a relatively large territory. This step opens up the possibility to provide spatial extrapolation model of Ψ based on data assimilation or existing data base.

Key words : predawn leaf water potential, spatial variability, spatial extrapolation, vine water status

Résumé

Objectif : L'objectif de ce travail est de tester une approche permettant d'extrapoler l'état hydrique de la vigne à l'échelle de toute une appellation. Le modèle d'extrapolation se base sur une approche empirique qui fait collaborer une mesure de référence et un modèle spatial de l'état hydrique de la vigne. La méthode a déjà été testée au niveau parcellaire, mais n'a jamais été validée à une échelle aussi importante.

Méthodes et résultats : Les expérimentations ont été conduites sur les 2946 ha de l'appellation Tavel (Gard, France). Le site d'étude présente une variabilité importante au niveau du sol (trois unités pédologiques différentes) et en termes d'altitude. Le vignoble n'est pas irrigué et est soumis à un climat méditerranéen. Ce contexte conduit à une variabilité spatiale importante de l'état hydrique de la vigne. L'étude s'est concentrée sur le cépage dominant de l'appellation, le Grenache. Une base de données de potentiel hydrique foliaire de base (PHFB) a été construite sur trois années consécutives (2008, 2009 et 2010). Respectivement 10, 24 et 24 sites repartis sur toute l'appellation ont été suivis en PHFB. Le suivi s'étalant respectivement sur 7, 10 et 9 dates de mesures au cours de la saison végétative. Le modèle spatial a été étalonné grâce aux données de 2009 et 2010 et la qualité de la prédiction a été testée sur les données de 2008. Les résultats montrent que l'approche est complètement transférable à l'échelle d'une appellation comme Tavel. Le modèle d'extrapolation améliore significativement la prédiction (R^2 = 0,9) comparée à une méthode conventionnelle basée sur la moyenne (R^2 = 0,61).

Conclusion : Sur la base d'une seule mesure prise à un temps « t » sur un site de référence, le modèle rend possible l'estimation de l'état hydrique de la vigne sur tous les sites de la zone d'étude. Ainsi, l'étude démontre la possibilité d'extrapoler la mesure d'un PHFB faite sur un site de référence à toute l'appellation constituée de trois unités pédologiques différentes.

Signification et impact de l'étude : Cette étude représente une avancée importante puisqu'elle démontre l'existence d'un modèle spatial de l'état hydrique de la vigne à une échelle plus grande que celle de la simple parcelle. Cette étude fournit des connaissances cruciales pour envisager l'utilisation d'un modèle spatial empirique sur une aire relativement grande. Cette avancée ouvre la porte au développement d'un modèle d'extrapolation spatial de l'état hydrique de la vigne basé sur l'acquisition d'une base de données ou sur une base de données existante.

Mots clés : potentiel hydrique foliaire de base, variabilité spatiale, extrapolation spatiale, état hydrique de la vigne

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INTRODUCTION

Several researchers have shown that changes in grapevine water status (Ψ) have a direct effect on grape composition and quality by influencing vegetative growth, fruit growth, yield, canopy microclimate, and fruit metabolism (see among others, Tregoat *et al.*, 2002, Dry and Loveys 1998, Van Leeuwen and Seguin 1994, Ojeda *et al.*, 2002). Characterizing the spatial variability of Ψ is then a key issue for terroir study (Seguin 1983, Van Leeuwen *et al.*, 2009). The spatial monitoring of Ψ therefore provides important information to manage and/or assess grape quality (Van Leeuwen *et al.*, 2009, Hakimi Rezaei and Reynolds 2010). In a review paper, Acevedo-Opazo *et al.* (2008) discussed the importance of methods for spatially monitoring Ψ. Furthermore, they proposed a conceptual spatial model to predict Ψ across a given domain (vineyard block, vineyard, region, etc.). The proposed model predicts Ψ by combining local reference measurements (to take into account the temporal variability) and a spatial model determined from a data base of previous Ψ measurements. This spatial model enables to characterize the spatial variability of Ψ. Acevedo-Opazo *et al.* (2008) showed that at the within-field level the spatial model takes into account the relative difference in Ψ between a reference point and all other sites across the vine field. In a subsequent paper, they demonstrated that this relative difference is linear in nature and temporally stable (Acevedo-Opazo *et al.*, 2010a).

The proposed conceptual model, as defined by Acevedo-Opazo *et al.* (2010a), is shown in Equation 1.

$$\hat{z}(s_i, t_j) = a_{si}.\, z(s_{re}, t_j)) \;\forall\; s_i \in D \text{ with } s_{re} \in D \quad \text{[eq. 1]}$$

The model requires the measurement of a Ψ reference value $z_{re}(s_{re},t_j)$ at site s_{re} and time t_j. The goal is to extrapolate the reference value $z_{re}(s_{re},t_j)$ at the same time (t_j), using a collection of coefficients a_{si} that relates $z_{re}(s_{re},t_j)$ to each location s_i over a domain scale (D). At the within-field level, Acevedo-Opazo *et al.* (2010b) demonstrated the possibility to estimate the coefficients a_{si} with some ancillary information sources (AIS) that are easily obtained with a high spatial resolution. A spatial model of Ψ using AIS may be of interest for commercial vineyards since it can be easily calibrated (as it is not dependent on a full descriptive model of the vineyard environment) and can easily generate spatial predictions from singular reference points. By coupling high quality, high cost punctual vine measurements with low cost medium-high density AIS, the model would provide quick estimations of Ψ at spatial resolutions that would be cost prohibitive and cumbersome to generate with classical punctual measurements.

Acevedo-Opazo *et al.* (2008) demonstrated the relevance of the approach at the within-field level on two case studies. In a more recent paper, Taylor *et al.* (2011) tested this approach at vineyard scale over a small number of fields. At this scale, these authors proposed a spatial model based on the extrapolation of the mean field. Given several authors, it was shown that the spatial variability of Ψ might be significant at the within-field or inter-field level (Acevedo-Opazo *et al.*, 2010a; Van Leeuwen *et al.*, 2006; Taylor *et al.*, 2010), they hypothesized a two-step approach : i) the spatial extrapolation of the mean field which takes into account the meso-scale variability and ii) the spatial extrapolation of the mean field for each field, which takes into account the micro-scale spatial variability (Acevedo-Opazo *et al.*, 2008). Taylor *et al.* (2011) showed that the model presented in Equation 1 remained relevant at the meso-scale. They showed that extrapolation appeared to be feasible between fields on different soil types if the general soil moisture regimes were similar. Indeed, the linear relationships considered in the model did break down when the soil moisture regimes were variable. The promising results presented by Taylor *et al.* (2011) on a small number of fields justified its testing on a larger scale like a whole vineyard, a production area, a denomination or a cooperative. At such large scales, the monitoring of Ψ and its spatial variability also provides important information either for field selection (Reynard *et al.*, 2011), to define priority zones for irrigation or simply to produce a decision support for irrigation scheduling (Ortega-Farías *et al.*, 2004). The objective of this study was to test the relevance of the model presented in Equation 1 over a large scale (entire denomination). At this scale, the study aims at verifying the existence of a spatial model to see if it is possible to extrapolate a reference measurement to the whole area. As proposed by Taylor *et al.* (2011), this study focuses on the meso-scale variability. It constitutes a first validation step aiming at verifying the linearity as well as the temporal stability of the spatial coefficients over a domain D that encompasses a whole denomination and several pedological units.

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Table 1 - Summary of predawn leaf water potential (PLWP) measurements for each year and each soil unit.

Soil Unit	Number of PLWP measurements					
	Year					
	2008		2009		2010	
	site	date	site	date	site	date
Sand/Alluvions	2	7	5	10	5	9
Lauzes	6	7	13	10	13	9
Galets	2	7	6	10	6	9
Total	70		240		216	

MATERIALS AND METHODS

1. Experimental site

The study was carried out on the Tavel denomination (44°0'46.34"N, 4°41'52.84"E, Gard, France). The study site has an area of 2946 ha with 2441 different fields (Figure 1) and exhibits significant variability in soil composition, elevation (80 to 200 m), field area and production systems (age of planting, density, trellising, soil tillage, etc.). It has a Mediterranean climate characterized by high summer evapotranspiration rates and its pedo-climatic context leads to a strong spatial variability in Ψ. The Tavel denomination has three main grape varieties, of which Grenache is dominant and accounts for ~60 % of the planted area. Since the objective was to focus on the spatial model over the whole denomination, the analysis was simplified to take into account only the Grenache variety. This choice removed any potential varietal effect from the analysis. Further, it allowed taking into account a significant proportion of the spatial variability due to environmental factors since areas planted to Grenache remained large enough and were spread over the whole study site. The Tavel denomination is divided in three main soil types (Figure 1): i) Lauzes (stony soil on marly calcareous soil with argillaceous seams), ii) Galets (upper terraces with rounded quartzite galets and red clay) and iii) Sand/alluvions (dry light soil on Pliocene sands).

2. Measurements

Ψ was measured as predawn leaf water potential (PLWP). Measurements were carried out over three consecutive years (2008, 2009 and 2010). During these three years, respectively 10, 24 and 24 sites located throughout the denomination have been monitored for PLWP (Figure 1). AIS like elevation, slope and aspects were used to define the locations of the sites in order to encompass a large diversity of situations at the denomination scale. At the within-field level, the sites were chosen after a survey performed by two viticulturists and local growers. The objective was to provide sites as representative as possible of the field they were located on, avoiding too low or too high vigorous zones and diseased vines. Note that the goal of the study was not to provide an exhaustive map of Ψ but to test the relevance of the approach presented in Equation 1 with a large diversity of situations. We acknowledge that the use of 24 sites is far from being sufficient to provide a decision map at the denomination scale; this point will be part of the discussion.

The monitoring consisted respectively of 7, 10 and 9 measurement dates for the years 2008, 2009 and 2010 (Table 1). PLWP measurements were done between 4:00 and 6:00 a.m. using a pressure chamber (Scholander *et al.*, 1965). Five consecutive vines were measured at each site (s_i) and averaged to obtain a site value ($z(s_i)$). As shown by Taylor *et al.* (2011), the within-site variance was always lower than the inter-site variance except for early dates when water restriction is low.

The sampling scheme is indicated in Figure 1. The sites were geo-referenced with a stand-alone GPS receiver (Garmin Etrex, Olathe, Kansas).

In addition to different soil units, the sampling sites encompass a large diversity of situations. For the 24 sampling sites of years 2009-2010, the elevation ranged from 79 to 202 m, the planting density varied from 3000 to 4500 vines per hectare and different training systems were taken into account (no trellising and 1, 2 or 3 levels of wires for trellising system). Note, however, that for the three years of the study all the sites presented north oriented rows and their inter-rows were subjected

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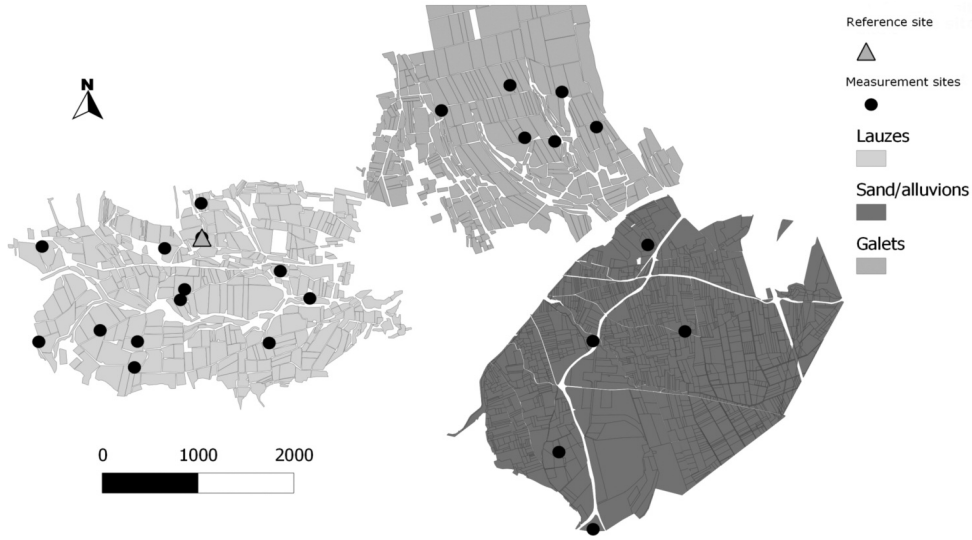


Figure 1. Location of the measurement sites in the years 2009 and 2010 over the Tavel denomination and its three soil units.

to weed control performed either chemically or mechanically.

3. Model computation

Model computation involves several steps.

a. Choice of a reference site (s_{re}) for the domain D

The choice of the reference site can affect the accuracy of prediction from the proposed model, particularly in high water restriction conditions (non-irrigated) when there is a wide range of variation in PLWP over the whole denomination. In a previous analysis, Acevedo-Opazo *et al.* (2010a) showed that at the within-field level the random selection of reference sites did not affect the model output adversely. The reference site was therefore chosen randomly.

Still, a sensitivity analysis was performed to confirm the validity of the method at the denomination scale. This sensitivity analysis aimed to test the quality of the model generated after calibration. It was carried out on the 2009 and 2010 measurements, using each of the 24 measurement sites available (Table 1) as reference site. This procedure generated 24 different extrapolation models. For each of them, the standard error of calibration (SEC) (see next section) was used to assess its ability to predict the Ψ on all the 23 remaining sites.

b. Model calibration

The calibration of the model was done across the 2009 and 2010 measurement dates. For these two years, the accuracy of the calibration was estimated across all sites and dates using the SEC and the proportion of variance (r^2) explained by the model. The SEC was computed as follows:

$$SEC = \sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{m}\left(E(s_i,t_j)\right)^2}{(n\times m)-1}} \text{ , with } E(s_i,t_j) = \left(\hat{z}(s_i,t_j) - z(s_i,t_j)\right)$$

[eq. 2]

Where n is the number of sites and m is the number of available dates.

c. Model prediction

The ability of the model to predict PLWP values was assessed using the 2008 data set. As the 2008 data set was not used to calibrate the model, it allowed to test the prediction of the model on an independent data set. Two standard errors of prediction (SEP) were then computed:

$$SEPt_j = \sqrt{\frac{\sum_{i=1}^{n}\left(E(s_i,t_j)\right)^2}{n-1}} \quad \text{and} \quad SEPs_i = \sqrt{\frac{\sum_{j=1}^{m}\left(E(s_i,t_j)\right)^2}{m-1}}$$

[Eq. 3]

The temporal error of prediction ($SEPt_j$) indicated how well, on average, the model predicts across the domain at a given date for a given reference measurement, while the spatial error of prediction ($SEPs_i$) indicated how well each point was predicted and identified areas in the domain that were correctly or poorly predicted. Thus, the first indicated whether the model was valid temporally and the second indicated the spatial pattern of

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prediction in the domain and areas where larger prediction errors occurred.

4. Data analysis and data mapping

Mapping was done with the 3Dfield software (version 2.9.0.0, Copyright 1998-2007, Vladimir Galouchko, Russia) and the Quantum GIS software (version Copiapo 1.6.0, under General Public Licence). Model computation and evaluation was done with Matlab (MathWorks, Natick, Massachusetts).

RESULTS

1. Results of the non-spatial (basic) model

In absence of a spatial model, the reference measurement was considered as the mean PLWP of the whole denomination. Therefore, at each date and each location, the predicted PLWP was the mean PLWP. From Figure 2 it can be interpreted that the range (and variance) of measured PLWP increased as water restriction increased. This observation is important as it indicates that an irrigation decision late in the season (when the timing of irrigation is more critical) based on a single measurement or the mean of the area under consideration may be inappropriate for a significant part of the domain. The fit of the non-spatial model is $R^2 = 0.61$. However, a difference between conditions where water is non-limiting (> -0.4 MPa) and limiting (< -0.4 MPa) is observed. In non-limiting conditions the R^2 remains rather high ($R^2 = 0.7$), while in limiting conditions the non-spatial model results in a poorer fit ($R^2 = 0.3$).

2. Results of calibration of the spatial model

Results were obtained with a randomly chosen reference site that happens to be located on the Lauzes pedological unit (Figure 1). The plot of model predictions against observed values is shown in Figure 3 (this figure should be compared with Figure 2). Considering the calibration on all the available measurements in year 2009 and 2010, the model R^2 value is 0.87 (0.70 if only limiting conditions corresponding to PLWP < -0.4 MPa are considered). The addition of spatial information into the model has considerably reduced the dispersion of the predicted values, particularly during periods of higher water restriction. However, note that for very high water restriction (PLWP < -1.1 MPa) the dispersion of the points is increasing, thus showing that the spatial model does not catch all the spatial variability.

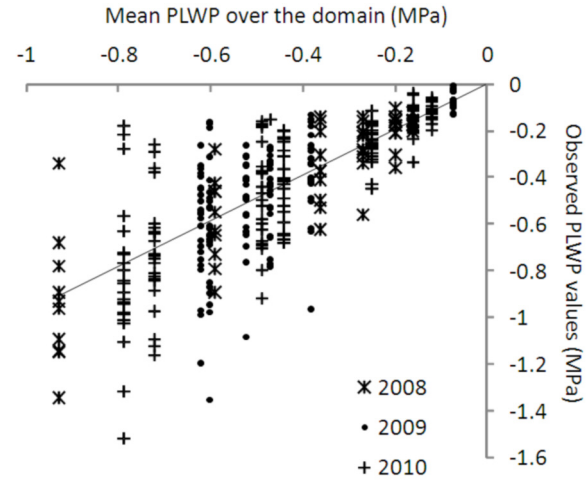


Figure 2. Prediction results of PLWP values from the non-spatial model (mean PLWP values) at each measurement date for the years 2008, 2009 and 2010.

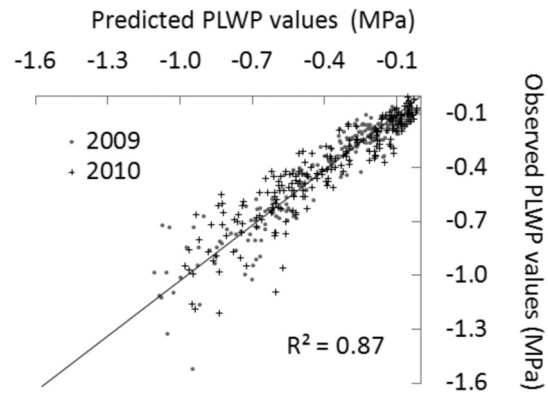


Figure 3. Prediction results of PLWP values from the spatial model for the years 2009 and 2010 (data set used to calibrate the model).

Note that Figure 3 does not show any patterns related to either years or pedological units. Table 2 confirms this result. It shows the SEC for both years (2009 and 2010) and the three soil units. The SEC remains low (≤ 0.11 MPa) for all the years and all the soil units, showing that the prediction from a reference site located on the Lauzes soil unit may be relevant for the other soil units at all the dates.

3. Results of the prediction of the spatial model

The plot of model predictions against observed values is shown in Figure 4. The predictions were performed with the 2008 data set, which has not been used for the calibration. Figure 4 shows the predictions made from the PLWP measured on the reference site, which were extrapolated according to

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Table 2. Standard error of calibration (SEC) and spatial standard error of prediction (SEPs) according to the year and the different pedological unit

	Year		Soil Unit		
	2010	2010	Lauzes	Sand/alluvions	Galets
SEC (MPa)	0.10	0.10	0.11	0.08	0.09
SEPs (MPa)	-	-	0.14	0.08	0.10

Table 3. Temporal error of prediction (SEPt), mean PLWP and standard deviation (Std) observed for each measurement date in year 2008.

	Date						
(MPa)	t_1	t_2	t_3	t_4	t_5	t_6	t_7
Mean	-0.16	-0.2	-0.27	-0.36	-0.57	-0.59	-0.93
Std	0.02	0.07	0.12	0.16	0.25	0.20	0.28
SEPt	0.05	0.05	0.09	0.10	0.10	0.12	0.15

the spatial model determined from the 2009 and 2010 data sets. The model R^2 value is 0.90 for all the soil units together (0.76 if only limiting conditions corresponding to PLWP < -0.4 MPa are considered).

Table 2 shows that spatial standard error of prediction (SEPs) increases only slightly compared to SEC whatever the soil unit. Further, it shows that the model calibrated for the years 2009 and 2010 may well be used on other years. Note that the Lauzes soil unit presents the highest SEPs. A better prediction was expected for this soil unit since it encompasses the reference site. The 2008 data set presents a higher water restriction compared to 2009 and 2010 (Figure 1). The spatial variability of Ψ is consistently larger on the Lauzes soil unit (results not shown). This feature may explain the larger spatial variability in 2008 on this soil unit than in 2009 and 2010, which were used to calibrate the model. In this context, the calibration data base was not variable enough to predict the extreme values of 2008.

Table 3 shows the SEPt over the seven different measurement dates in 2008. It shows the increase of the mean PLWP throughout the summer season from the first date of measurement (t_1) to the last one (t_7). The Std also increases, showing that the spatial variability becomes significant for high water restriction. For low water restriction (PLWP > -0.36), the SEPt remains very similar to the Std, showing that the spatial model does not improve the prediction. For high water restriction, the SEPt remains low compared to the Std, showing the improvement in prediction brought by the spatial model.

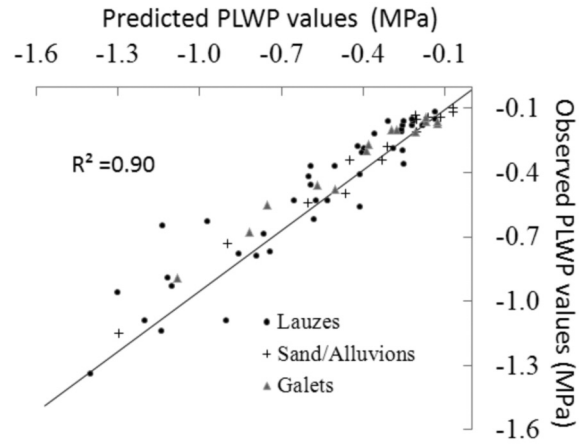


Figure 4. Prediction results of PLWP values from the spatial model for the independent 2008 data set.

4. Results of the sensitivity to the choice of the reference site

The study of the sensitivity to the choice of reference site shows that whatever the site considered, the SEC is between 0.09 and 0.14 MPa (Figure 5). The SEC remains smaller than that observed with a non-spatial model (SEC = 0.19 MPa). Whatever the reference site considered, the estimation is always better with the spatial model. Note, however, that the quality of the estimations may vary slightly depending on the choice of the reference site. This observation will necessarily affect the practical implementation of such an approach. This question will be addressed in the discussion. The SEC observed for each soil

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unit are 0.11, 0.11 and 0.13 MPa respectively for Lauzes, Galets and Sand/alluvions. The highest SEC observed for the Sand/alluvions soil unit is not significantly different from the other values (results not shown).

An error map shown in Figure 6 was made to highlight any potential spatial patterns. Figure 6 shows the spatial distribution of SEC in relation with the choice of the reference site. The reference sites leading to high quality models (SEC < 0.11 MPa) can be located either in the center or in the periphery of the domain and can be found on all of the soil units. The same observation can be made for reference sites providing models with a higher error (SEC > 0.13 MPa). As before, the Sand/alluvions soil unit has a higher proportion of sites that lead to significant SEC. Despite this observation, the SEC related to the choice of the reference site can be considered randomly distributed.

Note that the reference site randomly chosen to conduct this study (Figure 1) results in SEC between 0.10 and 0.11 MPa. This reference site is among the good sites but is not the best.

DISCUSSION

The results clearly show that it is possible to apply the approach proposed by Acevedo-Opazo *et al.* (2008) at a scale larger than the single field. This study demonstrates the ability of the SPIDER approach to extrapolate a PLWP measurement made on a reference site over the whole denomination constituted of three different soil units. At this scale the model remains linear and temporally stable. It significantly improves the quality of the predictions compared to a conventional approach like the mean value. At denomination scale, our results confirm the value of using a reference measurement (reference field). The PLWP value of the reference field can be extrapolated over the whole domain, provided the spatial model is previously determined.

Note, however, that these results remain specific to the studied area. Although it encompasses three very different soil units, it seems each of them presents similar water regimes. This feature can explain why a reference site located on a soil unit is

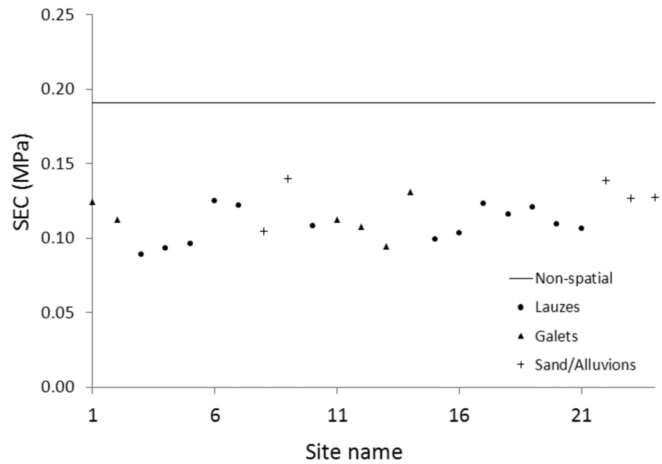


Figure 5. Standard error of calibration (SEC) obtained on years 2009 and 2010 for each of the 24 available sites when each of them is considered as a reference site and the non-spatial model.

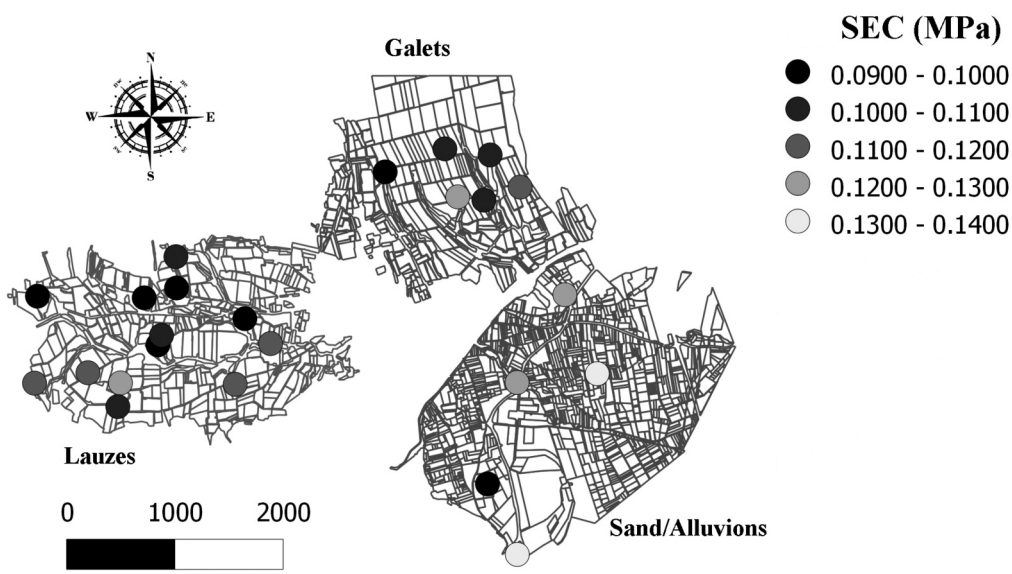


Figure 6. Map of the standard error of calibration (SEC) affected to each of the 24 available sites when each of them is considered as a reference site.

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relevant to provide an estimation on the other soil units. This result is in contradiction with the results of Taylor *et al.* (2011) obtained on a smaller area and with a smaller number of fields. The application of this method to another area necessarily requires knowledge on the soil units. At least the first year, one reference site per soil unit should be considered.

Mediterranean climate results in particularly high water restriction. In this context, the spatial variability is mainly determined by stable environmental factors like the soil. The effect of these factors prevail when water restriction is particularly important. Such an approach remains to be validated in conditions with moderate water restriction (> -0.4 MPa). In such context, our results suggest that the spatial variability explained by the SPIDER approach will be low and similar compared to a non-spatial approach. Note, however, that even for low water restriction (> -0.3 MPa), the SPIDER approach presents the advantage to produce an estimate with equivalent or better quality than a conventional approach with only one single measuring site (the site of reference).

The SPIDER approach presents limitations on irrigated vineyards since the linear relationship with the reference site may be altered by irrigation. On non-irrigated vineyard, the spatial model is of interest as a decision support for i) field selection according to water restriction experienced by the vines (Reynard *et al.*, 2011) or ii) identifying zones where irrigation is most needed.

In this context and at the spatial scale investigated here, the SPIDER approach may present several practical advantages : i) it relies solely on direct PLWP measurements, which can be performed by wine growers. Therefore, the calibration of the model can be implemented within a conventional monitoring of Ψ. The method does not require spatial estimates of other variables related to soil or other environmental factors that may be difficult and expensive to measure ; ii) the model can also be calibrated from measurements already made. Therefore, it makes it possible to use existing data bases of Ψ (historical data bases), provided that the data are geo-located ; and iii) the principle of the method allows to consider asynchronous measurements when labor is the limiting factor. Indeed, provided that the measurement of the PLWP is systematically done on the reference site, the method shows that it is possible to cover a large area in several nights.

The method still needs some improvements. Several points have to be investigated : i) the quality of the prediction is slightly affected by the choice of the reference site. It will be necessary to propose a procedure aiming at identifying the best possible reference site during the measurement campaign. A simple practical recommendation would be to choose several potential reference sites in the first year of the study and select the best one afterward ; ii) the historical data base used to calibrate the model must necessarily include data with a large magnitude of water restriction. This necessarily requires the integration of several years of monitoring in the data base to include years with extreme water restriction ; iii) improving the spatial resolution of the model necessarily requires an increasing number of field measurements. As successfully proposed by Acevedo-Opazo *et al.* (2010b), AIS like exposed leaf area or normalized difference vegetation index (NDVI) (Rouse *et al.*, 1973) could constitute surrogate information to improve the spatial resolution of the model. However, at the considered spatial scale, these AIS are not straightforward to use since it is affected by field factors like plantation density, trellising, etc. (Tisseyre *et al.*, 2011). Other AIS should be considered like the δC13 (Gaudillère *et al.*, 2002) ; iv) to limit the number of factors affecting the spatial model, this study focused on a single grape variety. In the future, it will be necessary to consider other varieties to study how the linearity of the spatial model is affected ; and finally v) the area of the domain (D) within which the spatial model remains valid is unknown. The approach assumes that the climate has to remain approximately the same over D ; otherwise, the linear relationship with the reference site could be affected. The D area will certainly have to fit with local environmental characteristics, which may lead to very different climatic conditions (topography, the distance to the sea, etc.). High resolution climatic information should be a good decision support to determine D over which such an approach may remain relevant.

CONCLUSION

This study represents a significant step since it demonstrates the existence of a spatial model of Ψ at a scale larger than the single field. It has been demonstrated that at this scale the relationship between the Ψ of a reference site and another site of the domain remains linear and temporally stable. This study provides critical knowledge to consider the use of an empirical spatial model across a relatively large territory. This step opens up the

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possibility to provide spatial extrapolation model of the Ψ based on data assimilation.

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