Journal of Agricultural Science; Vol. 14, No. 9; 2022
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Spatial Prediction Model of Plant Water Status of an Olive Orchard (*Olea europaea* L.) cv. Arbequina Under Semiarid Conditions in the Central Valley of Chile

Paulo Cañete-Salinas[1], Héctor Valdés-Gomez[2], Daniel de la Fuente-Sáiz[3], Francisco Maldonado[3], Cristian Espinosa[1], Nicolás Verdugo-Vásquez[4] & César Acevedo-Opazo[3]

[1] ERDE Technology and Applied Engineering SPA, Talca, Chile

[2] Departamento de Fruticultura y Enología, Pontificia Universidad Católica de Chile, Santiago, Chile

[3] Departamento de Producción Agrícola, Facultad de Ciencias Agrarias, Universidad de Talca, Talca, Chile

[4] Instituto de Investigaciones Agropecuarias, Centro de Investigación Intihuasi, La Serena, Chile

Correspondence: César Acevedo-Opazo, Departamento de Producción Agrícola, Facultad de Ciencias Agrarias, Universidad de Talca, Avenida Lircay s/n, Talca, Chile. E-mail: cacevedo@utalca.cl

Received: January 13, 2022 Accepted: August 1, 2022 Online Published: August 15, 2022

doi:10.5539/jas.v14n9p15 URL: https://doi.org/10.5539/jas.v14n9p15

Abstract

The Olive (*Olea europaea* L.) is a typical fruit tree of Mediterranean areas characterized by high-quality oil production and high tolerance to water deficit. Due to worldwide water scarcity in Mediterranean regions, it becomes indispensable to monitor plant water status, in example, through xylem water potential (Ψ_x). Unfortunately, measurement is difficult to perform with high spatial resolution at field scale (> 50 measurements per hectare), due to the large amount of manpower required in the prosses which turned this technique into a high-cost solution. This situation drastically hinders its applicability in large production areas. Thus, the objective of this research is implementing a spatial prediction model of plant water status in an olive orchard, using a single Ψ_x measurement performed in a reference site over the orchard. The experimental site was established in 2.2 hectares of commercial olive trees in the Pencahue valley located in the Maule region (Chile) during the 2013/14 growing season. Measurements of Ψ_x were performed at key phenological stages of olive trees. The proposed methodology allowed to estimate the behavior of Ψ_x in unsampled olive trees from reference site measurements, with an average spatial error less than ±0.6 MPa and correlation of 0.8 (R^2) ratifying the high spatial dependence between different sites sampled at field scale. Therefore, distribution of spatial variability would be adequate for the application of irrigation in homogeneous management zones, facilitating water management practices in clearly identified zones within the olive orchard under study.

Keywords: precision agriculture, spatial variability, midday stem water potential, spatial prediction model

1. Introduction

The severe lack of precipitation is one of the most critical issues in agriculture these days, especially in Mediterranean climate where significant water deficit areas were emerged worldwide. Chile is no free from this issue where annual mean precipitation has been reduced by 45 to 105 mm in the last 31 years (IPCC, 2021), affecting on water availability for agricultural ecosystems (Del Pozo et al., 2019). Also, high variability in annual climatic conditions, due to the ENSO fluctuations occur lasts years directly affecting on precipitations. ENSO consists of the alternation of two seasonal ocean currents, “Niño” and “Niña” cycles which modifying the climate of a year, especially during the “Niña” significantly reducing the precipitation. Thus, proper water management and implementation of methodologies to optimize irrigation during agricultural growing season is increasingly necessary to consider also on olive trees (Ahumada et al., 2018).

Olives (*Olea europaea* L.) has become an important and profitable crop in Mediterranean climates (Tognetti et al., 2006). Chile maintained a stable cultivated surface until 1997 (Ben-Gal et al., 2009), and then it has faced an exponential growth in cultivated hectares due to the high-quality olive oil production and crop ability to tolerate strong water deficits (Ahumada et al., 2017). This issue push growers to plant it on areas with low water availability, where other species could not thrive (Dichio et al., 2003; Moriana et al., 2003; García-González et al., 2010). This high tolerance to lack of water of this specie is due to the strong stomatal control in conjunction with osmoregulation mechanisms to regulates transpiration rate (Fernández et al., 1997; Moriana et al., 2003; Tognetti et al., 2006) allowing olive trees to tolerate long periods with strong soil water deficit during season (Dichio et al., 2003; Ahumada et al., 2017, 2018). Thus, it has been observed in some investigations, that this species can reach xylem water potential values (Ψ_x) of up to -2.0 MPa while maintaining mild stress, and even reach values of -6.0 MPa, for severe stress values with a significant reduction in photosynthetic capacity (Ahumada et al., 2019).

Knowing the water behavior of olive trees by monitoring Ψ_x is fundamental to made decision on irrigation management (Tognetti et al., 2006; Ahumada et al., 2018) (irrigation timing and frequency) to save water, especially considering the current climatic context. However, identifying which sector or plants in the orchard monitor and how many measurements perform in the process is difficult to define, especially in orchards with high soil spatial variability. This variability is present in all agricultural orchards, which is related to some agronomic interest variables (AIV) (López-Granados et al., 2003; Acevedo-Opazo et al., 2010). Thus, the spatialized study of AIV such as Ψ_x (among others), would allow as to know and understand how spatial variability of water status is distributed over the field during the season to propose a site-specific irrigation management (López-Granados et al., 2003; Acevedo-Opazo et al., 2008, 2010, 2013). Similarly, the water behavior can be predicted from a measurement of water potential at a reference site, thus implementing a spatial prediction model of AIV such as water status (Acevedo-Opazo et al., 2009).

This research proposes the implementation of a spatial prediction model of water status in an Olive orchard, to study the spatial variability at field scale and optimize the water resources during the growing season. The model is expected to propose homogeneous management zones for xylem water status management within the orchard, generating significant water savings and facilitating irrigation work.

2. Materials and Method

2.1 Study Site

The study was conducted in olive orchard orchard (*Olea Europea* L., cv. Arbequina) during the 2013/2014 growing season in the "Olivares de Quepu" company, located in Pencahue Valley, Chile (35º23′ LS; 71º44′ LW; 96 m.a.s.l.) in an area of 2.2 hectares (ha). The nine years old orchard has planting by a frame of 5.0 × 1.5 m (1332 pl ha^{-1}), with monocone training system, irrigated by two drippers per plant with a discharge of 2.0 L h^{-1}. Pencahue valley is classified as warm temperate Mediterranean climate, with a prolonged dry season during spring to summer (annual rainfall of 700 mm, concentrated in winter), with average minimum temperatures of 4.4 ºC and average maximum temperature of 30 ºC. Regarding the soils, they correspond to the Pencahue series, which are characterized by being shallow, with slopes that surround 2 to 10%, textures that vary between fine sandy loam and sandy clay loam. Regarding the reference evapotranspiration, this is approximately 6 mm day^{-1} for the month of January, 4.5 mm day^{-1} for February and 3 mm day^{-1} for March.

Due to the conditions of water demand described above and the characteristics of the soil, the irrigations are carried out every 15 to 20 days for the same irrigation sector. However, due to the lack of water as of mid-January, the irrigations are extended every 30 days.

2.2 Geolocation of the Experimental Site

The develop and implementation of the model, 38 sampling sites were selected within a 2.2 hectares olive orchard (Figure 1). These sites were distributed in a non-regular grid, according to the nested method (Weitz et al., 1993). This method considers the location of the first points of the grid at smaller distances, to later increase the monitoring distance between them, to minimize the experimental or field error at spatial semi-variance calculating moment. To know the exact localization of each site on grid, a geo-referenced process was made using a DGPS (Trimble, Pathfinder ProXRS, Sunnyvale, California, USA).

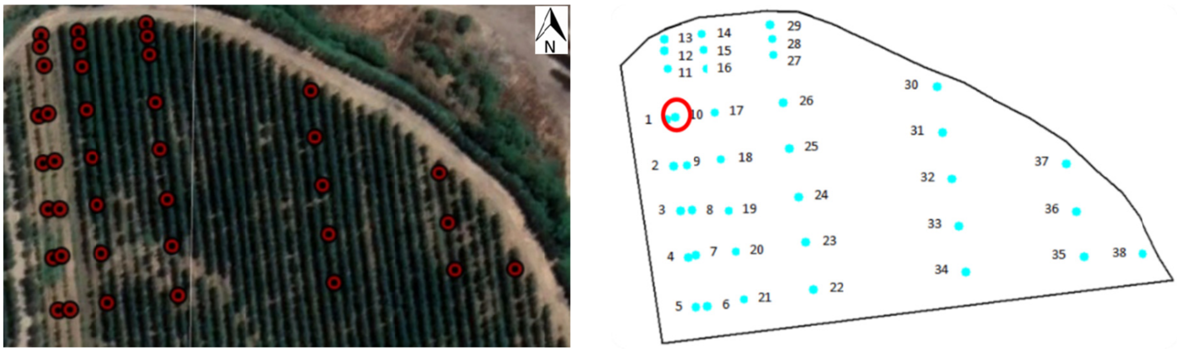

Figure 1. Distribution (irregular grid) of sampling sites in the 2.2 hectares of olive orchard. "10" corresponds to reference site

2.3 Plant Water Status Measurements

To characterize olive water behavior, xylem water potential (Ψ_x) was measured at each of 38 sites at six moments during the season (November to March in the southern hemisphere) using a Scholander-type pressure chamber (PMS Instrument Co., model 1000, Corvallis, Oregon, USA; Sholander et al., 1965). To determine the xylem water status of the plant, two leaves per measurement point (tree) located in the middle third of the plant exposed to direct radiation, were covered with plastic and metal foil to equal the water status of the plant with the leaf at least two hours before measurements, that were made close to local solar noon (between 12:00 and 14:00 h).

2.4 Geo-statistical Spatial Analysis

The data collected in field were analyzed through the calculation of the spatial semi-variance, using the geo-statistical analysis software GS+ v.10 (γ gammadesign software), with which the parameters derived from the semi-variogram were obtained and analyzed: Nugget (C_0), Sill ($C_0 + C_1$) and range (A_0) (Cambardella et al., 1994). From these parameters, the spatial dependence (SD) was determined which allows identifying the magnitude of the spatial variation explained by the location of the points in the orchard by means of the following Equation 1 (Cambardella et al., 1994).

$$\mathrm{SD} = \frac{C_0}{C_0 + C_1} \times 100 \quad (1)$$

For this reason, SD values ≤ 25% the variable is considered with strong spatial dependence; SD values between 25 and 75%, the variable is considered with moderate spatial dependence and SD values ≥ 75%, the variable was considered with weak spatial dependence.

2.5 Spatial Prediction Model of Plant Water Status

The conceptual model proposed by Acevedo-Opazo et al. (2008) was used to implement the spatial prediction model of plant water status. This model (Equation 2) aims to estimate xylem water potential of an entire orchard using the measurement of plant water status performed at a reference site $z_{re}(s_{re}, t_j)$ using the coefficients of determination "a_{si}" related to $z_{re}(s_{re}, t_j)$ for each of the estimation sites s_i within the olive orchard (D) at any time of the season (t_j).

$$z(s_i, t_j) = a_{si} \times [z_{re}(s_{re}, t_j)];\ s_{re} \in \mathrm{D},\ \forall\ s_i \in \mathrm{D},\ a_{si} \in \mathrm{R} \quad (2)$$

The Matlab® v7.0 Software package (Mathworks, Inc.) was used for data analysis and model programming. All Ψ_x values measured in the orchard were subjected to linear correlation (r) and co-variance (cov) analysis between all the sampled sites (s_i and s_k) during all the measurement dates of the season (Equation 3).

$$r = \frac{cov\,[z(s_i), z(s_k)]}{\sigma_{S_i} \cdot \sigma_{S_k}} \quad (3)$$

Where, σ_{S_i} (respectively σ_{S_k}) correspond to the standard deviations of the Ψ_x values observed for each s_i site (respectively σ_{S_k}) in time (Equation 4):

$$cov[z(s_i), z(s_k)] = \frac{1}{m} \sum_{j=1}^{m} \left[(z(s_i, t_i) - z(s_i)\right] \cdot [z(s_k, t_j) - z(s_k)] \quad (4)$$

Where, $z(s_i)$ [respectively $z(s_k)$] corresponds to the average of the values measured at sites s_i (respectively s_k) for all available dates (n = 6).

Within the implementation stages of the plant water status prediction model proposed by Acevedo-Opazo et al. (2008), the reference site (s_{re}) was determined, which turned out to be S10, with an average correlation of 0.8 with the rest of the sites sampled in the study.

2.6 Spatial Distribution Maps

For Ψ_x mapping of the olive orchard, sectors with different ranges of plant water status were identified. For this, the range proposed by Ahumada et al. (2019) was used, who determined that for Ψ_x from -2.2 MPa a slight stress begins to be observed in the water status of the Olives, and above -3.6 MPa, this stress passes to be moderate. Due to the stress levels reached in this study, the step from zero to slight stress was used to differentiate two different management sectors, considering that the entire orchard was subjected to the same type of irrigation. Thus, thematic cartographies of midday stem water potential were performed using the 3D Field software (Version 2.9.0.0, 2007 Vladimir Galouchko, Rusia).

2.7 Model Validation

To statistically corroborate the errors associated with the model, root mean square error (RMSE; Equation 5) and correlation coefficient (R^2) was used. With this statistic, cartographies were constructed to observe the spatial distribution of the error of the proposed model.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(y_{obs}t - y_{est}\right)^2}{n}} \tag{5}$$

3. Results

3.1 Semi-variogram Analysis

The semi-variogram models evaluated at different monitoring dates during the season, in most cases, showed a good degree of correlation with the values of Ψ_x, being the Exponential model the one that presented the best results. In this sense, the R^2 values ranged between 0.44 and 0.99 (Table 1). The lowest R^2 value was recorded during the first monitoring date (January 1), with a value of 0.44. This result was due to the irrigation criteria used by the grower. An irrigation frequency of around 20 days was considered (at the beginning of the season), which would have generated a condition of null to slight water restriction. The above is shown in Figure 2, where Ψ_x showed values below -1.6 MPa. This situation changed from the second monitoring date (January 31), where the irrigation frequency was extended to 30 days, increasing the water potential level above -1.9 MPa (Figure 2).

Table 1. Parameters of the adjusted semi-variogram for each xylematic water potential measurement (MPa) evaluated

Components Semi-variogram of Olive Orchard—Summer Season 2014							
Date	**Unit**	**Model**	**R2**	**C_0**	**$C_0 + C$**	**A_0**	**SD (%)**
03-01-14	MPa	Ex	0.44	0.006	0.04	33.90	14.7
31-01-14	MPa	Ex	0.91	0.000	0.18	150.60	0.1
07-02-14	MPa	G	0.97	0.069	1.79	279.03	3.8
28-02-14	MPa	Ex	0.90	0.003	0.39	94.20	0.8
07-03-14	MPa	Ex	0.99	0.012	0.19	195.00	6.8
14-03-14	MPa	G	0.98	0.049	0.34	217.54	14.2

Note. C_0: Nugget. $C_0 + C$: Sill. A_0: Range. SD: Spatial Dependence (%). G: Gaussian, Ex: Exponential.

On the other hand, for different values of A_0 calculated on different sampling dates, an important variability was observed, which ranged between 33 and 280 meters (Table 1), being these values always higher than the sampling distances used in the field (nest method, with actual sampling distances that varied between 1.5 and 23 meters).

3.2 Water Status of Olive Tree

For each of the sampling dates (six in total) the mean Ψ_x of the 38 sampling sites was calculated (Figure 2). In this regard, it is observed that as the season elapses the Ψ_x measurement of the orchard becomes more negative until 59 Julian day with a mean value of -2.4 MPa, date from which the water stress was reduced, reaching values of -1.9 MPa on the last measurement date of the season (73 Julian day). A similar behavior was observed for the standard deviation (SDD), which was higher during the dates with greater water stress (Figure 2).

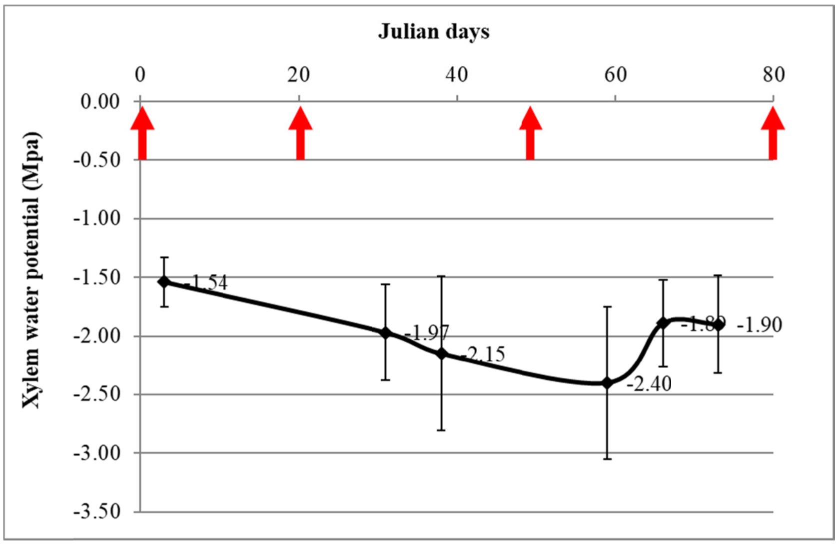

Figure 2. Evolution of the average measurement of xylem water potential (Ψ_x) for the olive orchard under study. Black vertical lines represent the standard deviation (SDD) for each sampling date in MPa. Red arrows represent the moments in which the irrigations were carried out

3.3 Model Development and Validation

Within the model implementation stages, the choice of the reference site s_{re} was determined, which provides the prediction of the Ψ_x of the rest of the sites within the orchard for each of the measurement dates. As mentioned earlier site S_{10} was selected as the reference site as it had an average correlation of 0.8 (R^2) with the rest of the measurement sites within the orchard. In this regard, the model evaluated using the S_{10} reference site presented its best prediction of spatial variability during the last measurement date (73 Julian day), that is, when the $RMSE_t$ was the lowest (0.25 MPa), and on the other hand it obtained the worst prediction during February 7, that is, when the $RMSE_t$ value was the highest (0.44 MPa) (Table 2).

Table 2. Average values of xylematic water potential measurement (Ψx)

	Xylematic Water Potential (Ψ_X)					
Date	**03-01-14**	**31-01-14**	**07-02-14**	**28-02-14**	**07-03-14**	**14-03-14**
SDD	0.2	0.41	0.64	0.62	0.37	0.42
Ψ_X (MPA)	-1.54	-1.97	-2.15	-2.40	-1.89	-1.90
CV (%)	13.0	20.8	29.8	25.8	19.6	22.1
R^2	0.396	0.411	0.397	0.425	0.385	0.373
$RMSE_t$	0.31	0.32	0.44	0.33	0.26	0.25

Note. Standard deviation (SDD); Percentage of variation explained by the model (R^2); Coefficient of Variation (CV); and Root mean square error in time (RMSEt) for each of the date measurement.

The reference site (S_{10}) was correlated with three different sites within the orchard, for which the best, worst, and intermediate correlation values were selected, using the coefficients of determination (R^2) obtained (Figure 3), respectively. Thus, the worst linear correlation showed a coefficient of determination $R^2 = 0.53$ (with site 15), the best linear determination (site 38) an $R^2 = 0.96$ and the intermediate value a coefficient of determination with an $R^2 = 0.82$ (site 7). In this sense, the results (Figure 3), show that the shape of the Ψ_x model of the orchard is linear, which corroborates the possibility of using a linear model to predict the water state of an olive orchard, using a single Ψ_x measurement performed at a reference site.

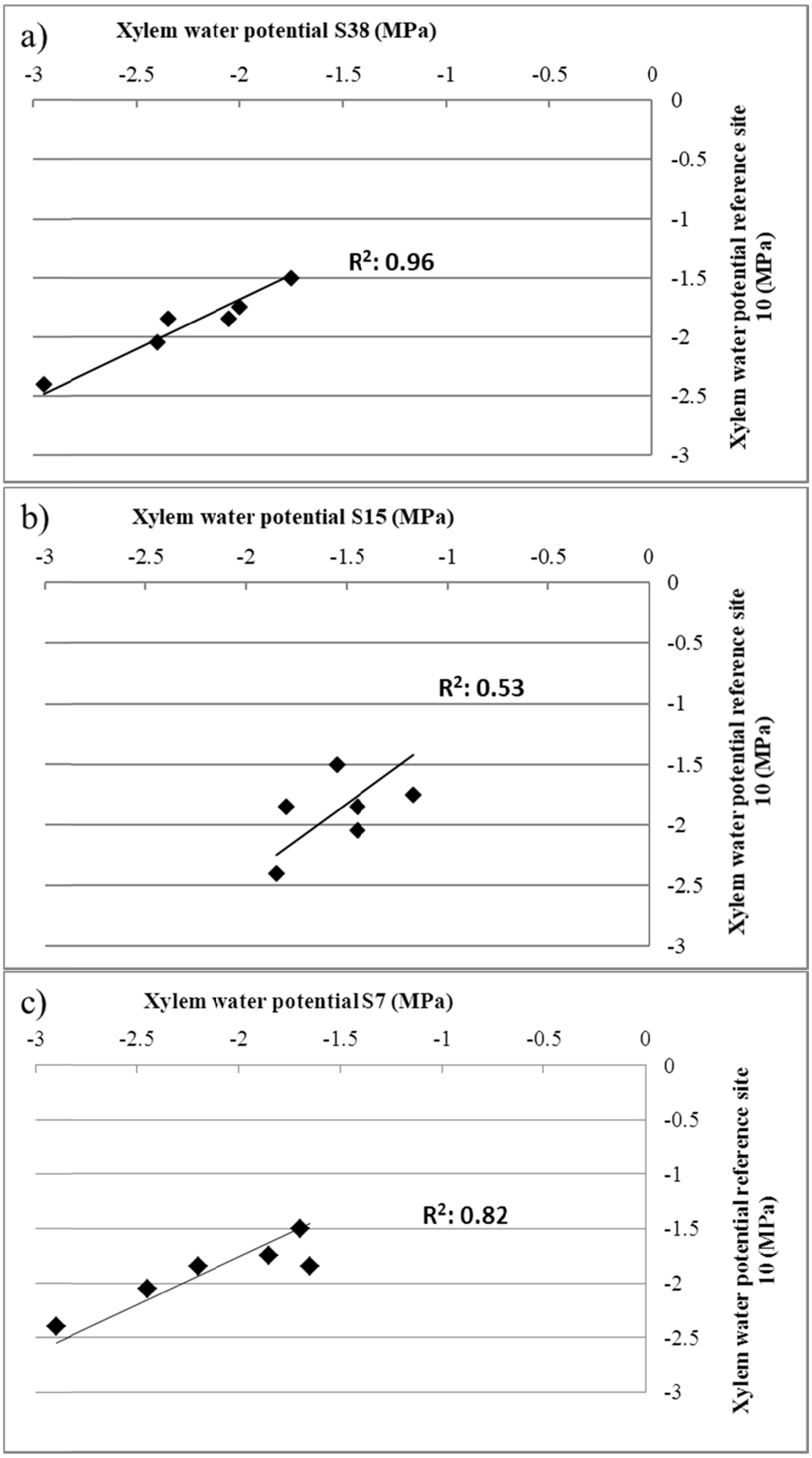

Figure 3. Example of linear correlations between xylem water potential measured at the reference site (s_{re}) and three other sites within the olive orchard. (a) The best correlation between s_{re} and site 38; (b) the intermediate correlation between s_{re} and site 7; and (c) the worst correlation between s_{re} and site 15

Using the reference site (S_{10}) and the vector "a_{si}" previously established through the spatial prediction model proposed by Acevedo-Opazo et al. (2008), each information was used to estimate the water status of an olive orchard. This estimation was used for the elaboration of thematic cartographies to perform a visual analysis between the real values and those predicted by the model. The best (Figures 4a and 4b) and worst (Figures 5a and 5b) prediction dates were March 14 and February 7, respectively.

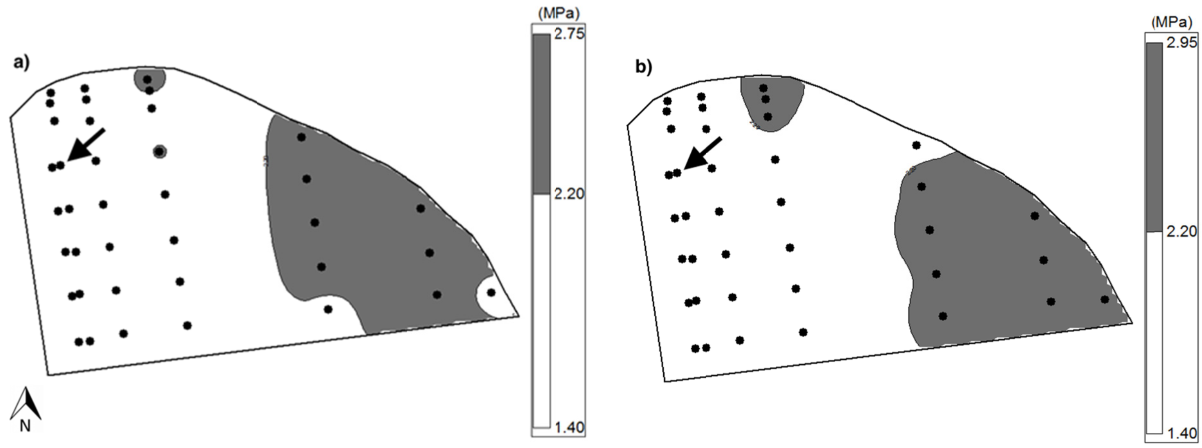

Figure 4. Cartography of xylem water potential (MPa) in absolute value. Actual measurement (a) vs the model's best estimate of water potential for the same date (b) (March 14).
The reference site (S_{10}) is indicated with an arrow

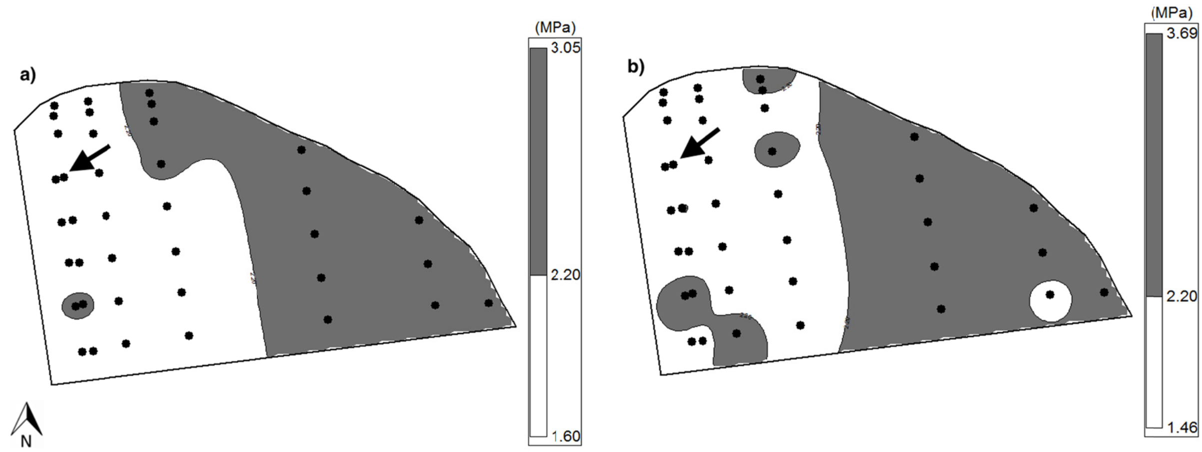

Figure 5. Cartography of xylem water potential (MPa) in absolute value. Actual measurement (a) vs the model's worst estimate of water potential for the same date (b) (February 28).
The reference site (S_{10}) is indicated with an arrow

Figure 6 shows the RMSE mapping, which represents the spatial evaluation of the error of the proposed model. This figure shows an error lower than 0.4 MPa in at least 80% of the sampled sites, where only 18% of the evaluated sites show a spatial error higher than 0.4 MPa. Therefore, the model presents a low error, being the eastern sector the one that presents most of the spatial error.

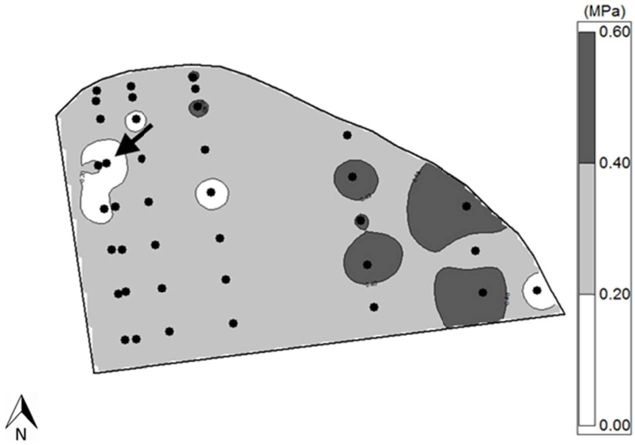

Figure 6. Cartography of the Root Mean Square Error (RMSE).
The reference site (S_{10}) is indicated with an arrow

4. Discussion

The change in irrigation frequency implemented from the second measurement date, that is, an increase in irrigation frequency, improved the correlation of the experimental semi-variogram (Table 1), since the higher the water restriction condition, the clearer the differences in plant water status values recorded between the different sampling sites at the field level, generating two well differentiated water management zones. If the irrigation criterion had been maintained, the plants would not have presented hydric stress, hiding these differences.

The trial measurements for Ψ_x were adequate to detect the total spatial variability of the orchard under study. Regarding the SD of the sampled sites, the results obtained from the semi-variogram analysis suggest that the Ψ_x measurements would present a high spatial structure with Cambardella index values below 25% (Table 1) (Cambardella et al., 1994). This would indicate that most of the variability observed in the field would be explained mainly by the spatial variability of the Olive orchards or Structural Variance C (Cambardella et al., 1994), that is, the effect of factors such as soil, climate, and/or water management (irrigation), as observed by Acevedo-Opazo et al. (2008), would be main sources of variability detected by growers at the field level. Thus, the management of these factors would allow site-specific orchard management. Another important factor was the use of the nest method for the monitoring network determined at the field level. In a geostatistical study by Borgelt et al. (1997), on different soil chemical properties, the nest method was the most appropriate to detect the spatial dependence of the variables. This may be due to the high variability observed in the soil chemical information, in relation to the measurement of Ψ_x which are more stable. As explained, in a scenario of water deficit such as the one Chile has been going through in recent years, it makes it easier for this type of model to be implemented, since the required modifications in the irrigation criteria and the reduction in the water applied favor the differentiation of homogeneous management sectors.

Although, stress was higher for this date, according to the study by Ahumada et al. (2017, 2019), carried out in an orchard adjacent to this experiment, only slight stress values (around -2.5 MPa) would have been reached. Regardless of this, it can be observed that there is an important spatial and temporal variability within the olive orchard under study, since from January 31, the same irrigation strategy was maintained using the same irrigation frequency (every 30 days).

The maximum stress achieved in this test was -2.4 MPa, a value that according to Ahumada et al. (2017, 2019), in a test carried out in an orchard adjacent to this experiment, it is only slight stress values (around -2.5 MPa). Regardless of this, it can be observed that there is an important spatial and temporal variability within the olive orchard under study, since from January 31, the same irrigation strategy was maintained using the same irrigation frequency (every 30 days). Although this stress is low for the olive tree, it is high for other fruit species that are managed in the area, such as cherry, vines and hazelnut, for which reason it is enough to mark the differences between the sites.

From the results obtained (Figures 4a and 4b; 5a and 5b), it is possible to differentiate two zone of differentiate management in relation to the water management of the orchard under study, where zone 1 (in gray color), shows the values of Ψ_x with higher water restriction and zone 2 (in white color), a sector with lower water restriction for both dates evaluated (Ahumada et al., 2019). The cartographies show the predictive results of the model performance, which show a good degree of spatial coincidence between the proposed zones (spatial motifs) in terms of their spatial distribution and the identification of irrigation management zones, even for the worst performing date (February 7).

When observing the results of the cartographies obtained by the proposed model for the worst estimation date (February 7) (Figure 5), it is observed that there is an 86% coincidence between the actual values measured in the field compared to the values estimated by the model for the same sampling sites. On the other hand, for the best estimation date (March 14), there is a 95% coincidence between the actual measured values compared to the values estimated by the model for the same sites of the sampling grid. The results obtained are interesting, since when comparing the results obtained in the proposed cartographies, a good degree of coincidence is observed between both plant water status cartographies proposed by the spatial model, allowing to clearly identify two different irrigation management zones within the orchard, facilitating the producer's decision making.

In the Figure 6, the areas of black color represent the sites where the spatial prediction of the model is less reliable. Regarding the spatial distribution of these sectors (black color), they are mainly located in the "eastern" sector of the orchard under study, a sector that coincides with the zone of highest water restriction in the orchard, observed throughout the season. Therefore, as indicated in the research proposed by Acevedo-Opazo et al. (2008) there is an important coincidence between the sectors of highest spatial variability with the zones of highest water restriction and highest spatial error measured within the orchard. This tool represents an important contribution for farmers, since it generates a significant reduction in the labor used for monitoring the water status.

The methodology used in this article was proposed to spatially model the phenology and maturity of the vine with interesting results (Verdugo-Vásquez et al., 2016, 2018, 2019). This first validation approach in olives orchards opens the opportunity to continue exploring different models of interest in this species, such as phenology, yield, and maturity, among others. There is also space to evaluate its use in other species affected by climate change, such as the cherry tree.

5. Conclusion

The evaluated orchard presents an important spatial structure, corroborating that most of the semi-variance observed for the plant water status variable, would be explained mainly by the high spatial variability of the field or structural variance "C". Thus, it is possible to propose a site-specific management for the intra-predial irrigation operation. Based on this, it is possible to propose a linear model for spatial prediction of xylem water potential in olive trees with a spatial error of less than 0.4 MPa in more than 80% of the orchard area. This measurement is relevant in conditions of high spatial variability and in a semi-arid climate. Therefore, it is possible to propose two well-defined and structured site-specific management zones within the orchard under study, in which two different irrigation criteria are observed for each of the sectors identified in the study, where the threshold identified between both zones was -2.2 MPa.

References

Acevedo-Opazo, C., Tisseyre, B., Ojeda, H., Ortega-Farias, S., & Guillaume, S. (2008). Is it possible to assess the spatial variability of vine water status? *Journal International des Sciences de la Vigne et du Vin, 42*, 203-220. https://doi.org/10.20870/oeno-one.2008.42.4.811

Acevedo-Opazo, C., Tisseyre, B., Taylor, J. A., Ojeda, H., & Guillaume, S. (2010). A model for the spatial prediction of water status in vines (*Vitis vinífera* L.) using high resolution ancillary information. *Precision Agriculture, 11*, 358-378. https://doi.org/10.1007/s11119-010-9164-7

Acevedo-Opazo, C., Tisseyre, B., Taylor, J.A., Ojeda, H., & Guillaume, S. (2009). Spatial extrapolation of the vine (*Vitis vinífera* L.) water status: a first step towards a spatial prediction model. *Irrigation Science, 28*, 143-155. https://doi.org/10.1007/s00271-009-0170-3

Acevedo-Opazo, C., Valdés-Gómez, H., Taylor J., Avalo, A. Verduo-Vásquez, N., Araya, M., ... Tisseyre, B. (2013). Assessment of an empirical spatial prediction model of vine water status for irrigation management in a gravepine field. *Agricultural Water Management, 124*, 58-68. https://doi.org/10.1016/j.agwat.2013.03.018

Ahumada-Orellana, L., Ortega-Farías, S., & Searles, P. (2018). Olive oil quality response to irrigation cut-off strategies in a super-high-density orchard. *Agricultural Water Management, 202*, 81-88. https://doi.org/10.1016/j.agwat.2018.02.008

Ahumada-Orellana, L., Ortega-Farías, S., Echeverría, P., & Searles, P. (2019). Estimation of stomatal conductance and stem water potential threshold values for water stress in olive trees (cv. Arbequina). *Irrig Sci, 37*, 461-467. https://doi.org/10.1007/s00271-019-00623-9

Ahumada-Orellana, L., Ortega-Farías, S., Searles, P., & Retamales, J. (2017). Yield and Water Productivity Responses to Irrigation Cut-off Strategies after Fruit Set Using Stem Water Potential Thresholds in a Super-High Density Olive Orchard. *Frontiers in Plant Science, 8*, 1280. https://doi.org/10.3389/fpls.2017.01280

Ben-Gal, A., Agam, N., Alchanatis, V., Cohen, Y., Yermiyahu, U., Zipori, I., … Dag, A. (2009). Evaluating water stress in irrigated olives: correlation of soil water status, tree water status, and thermal imagery. *Irrig Sci., 27*, 367-376. https://doi.org/10.1007/s00271-009-0150-7

Borgelt, S., Wieda, R., & Sudduth, A. (1997). Geostatistical analysis of soil chemical properties from nested grids. *Applied Engineering in Agriculture, 13*(4), 477-483. https://doi.org/10.13031/2013.21631

Cambardella, C., Moorman, T., Novak, J., Parkin, T., Karlen, D., Turco, R., & Konopka, A. (1994). Field-Scale Variability of Soil Properties in Central Iowa Soils. *Soil Sci. Soc. Am. J., 58*, 1501-1511. https://doi.org/10.2136/sssaj1994.03615995005800050033x

Del Pozo, A., Brunel-Saldias, N., Engler, A., Ortega-Farías, S., Acevedo-Opazo, C., Lobos, G., … Molina-Montenegro, M., (2019). Climate change impacts and adaptation strategies of agriculture in Mediterranean-climate regions (MCRs). *Sustainability, 11*, 2769. https://doi.org/10.3390/su11102769

Dichio, B., Xiloyannis, C., Angelopoulos, K., Nuzzo, V., Bufo, S., & Celano, G. (2003). Drought-induced variations of water relations parameters in Olea europaea. *Plant and Soil, 257*, 381-389. https://doi.org/10.1023/A:1027392831483

Fernández, J., Moreno, F., Girón, I., & Blázquez, O. (1997). Stomatal control of water use in olive tree leaves. *Plant and Soil, 190*, 179-192. https://doi.org/10.1023/A:1004293026973

Garcia-González, D., Romero, N., & Aparicio, R. (2010). Comparative Study of Virgin Olive Oil Quality Form Single Varietes Cultivated in Chile and Spain. *Journal of Agriculture and Food Chemistry, 58*, 12899-12905. https://doi.org/10.1021/jf1031313

IPCC (Intergovernmental Panel on Climate Change). (2021). *Ginebra*. Swiss. Retrieved from http://www.ipcc.ch

López-Granados, F., Jurado-Expósito, M., Álamo, S., & García-Torres, L. (2004). Leaf nutrient spatial variability and site-specific fertilization maps within olive (*Olea europea* L.) orchards. *European Journal of Agronomy, 21*, 209-222. https://doi.org/10.1016/j.eja.2003.08.005

Moriana, A., Orgaz, F., Pastor, M., & Fereres, E. (2003). Yield responses of a mature olive orchard to water deficits. *J. Amer. Soc. Hort. Sci., 128*(3), 425-43. https://doi.org/10.21273/JASHS.128.3.0425

Sholander, P., Hammel, H., Bradstreet, E., & Hemmingsen, E. (1965). Sap pressure in vascular plants. *Science, 148*, 339-346. https://doi.org/10.1126/science.148.3668.339

Tognetti, R., d'Andria, R., Sacchi, R., Lavini, A., Morelli, G., & Alvino, A. (2007). Deficit irrigation affects seasonal changes in leaf physiology and oil quality of Olea europaea (cultivars Frantoio and Leccino). *Annals of Applied Biology, 150*, 169-186. http://doi.org/10.1111/j.1744-7348.2007.00117.x

Verdugo-Vásquez, N., Acevedo-Opazo, C., Valdés-Gómez, H., Araya-Alman, M., Ingram, B., & García de Cortázar-Atauri, I. (2016). Spatial variability of phenology in two irrigated grapevine cultivar growing under semi-arid conditions. *Precision Agric, 17*, 218-245. https://doi.org/10.1007/s11119-015-9418-5

Verdugo-Vásquez, N., Acevedo-Opazo, C., Valdes-Gomez, H., Ingram, B., García de Cortázar-Atauri, I., & Tisseyre, B. (2018). Temporal stability of within-field variability of total soluble solids of grapevine under semi-arid conditions: A first step towards a spatial model. *Oeno One, 52*(1), 15-30. https://doi.org/10.20870/oeno-one.2018.52.1.1782

Verdugo-Vásquez, N., Acevedo-Opazo, C., Valdés-Gómez, H., Ingram, B., García de Cortázar-Atauri, I., & Tisseyre, B. (2019). Towards an empirical model to estimate the spatial variability of grapevine phenology at the within field scale. *Precision Agric, 21*, 107-130. https://doi.org/10.1007/s11119-019-09657-7

Weitz, A., Bunte, D., & Hersemann, H. (1993). Application of nested sampling technique to determine the scale of variation in soil physical and chemical properties. *CATENA, 20*, 207-214. https://doi.org/10.1016/0341-8162(93)90040-V