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Temporal stability of within-field variability of total soluble solids of grapevine under semi-arid conditions: a first step towards a spatial model

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Abstract

Aims: This work focuses on the study of the intra- and inter-annual Temporal Stability of Within-Field Variability (TSWFV) of Total Soluble Solids (TSS) as an estimate of grape maturity.

Methods and results: The experiment was carried out between 2009 and 2015 in four fields located in the Maule Valley, Chile, under irrigated conditions. Each field corresponded to a different cultivar (namely Cabernet-Sauvignon, Chardonnay, Sauvignon blanc and Carménère), and data collection ranged over two to four years depending on the field. A regular sampling grid was designed within each field, and TSS was measured at each site of the grid on different dates (from veraison to harvest). A Kendall test (W) was used to analyse the TSWFV of TSS between all dates for each cultivar and season. A Spearman's rank correlation coefficient (r_s) was used to analyse the relationships between each sampling date and the date of harvest considered as the reference. Results of the study highlighted high within-field variability in TSS. The W test showed significant intra- and inter-annual TSWFV, and r_s values showed a high and significant correlation between sampling dates.

Conclusion: These results are of interest for precision viticulture since, under the conditions of the experiment, the spatial patterns of the TSS maps obtained 40 days before harvest remain the same until harvest. Therefore, early target sampling of TSS may provide a good estimate of the spatial variability of grape maturity at harvest.

Significance and impact of the study: The inter-annual stability of the TSS spatial patterns makes it possible to propose a simple empirical spatial model that allows estimation of TSS values for the whole field using only one reference measurement, provided that historical data are available.

Keywords: berry maturity, ripening, early zoning, *Vitis vinifera*, differential harvest, spatial model

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Introduction

One of the main goals of precision viticulture is to manage grape and wine quality at the within-field level. One strategy, among others, is to delineate within-vineyard zones of maturity and quality for differential harvest in order to produce wines with different characteristics and properties (Baluja *et al.*, 2013; Trought and Bramley, 2011; Urretavizcaya *et al.*, 2014). Defining quality zones is therefore of paramount importance for differential harvest. Grape characteristics are commonly estimated by repeated sampling during the maturity process (Sadras and Petrie, 2012). Among berry parameters, Total Soluble Solids (TSS) is commonly measured to monitor berry maturity and composition and to determine the optimal harvest date (Baluja *et al.*, 2013; Hall *et al.*, 2011; Sadras and Petrie, 2012; Santos *et al.*, 2012). TSS is a parameter that varies both spatially and temporally at the within-field scale (Irimia *et al.*, 2015; Trought and Bramley, 2011). For logistical issues, the wine industry needs to know the potential quality zones as early as possible. To fulfill this expectation, several strategies have been proposed in the literature, including the use of auxiliary information. It has been proposed to use remote sensing images and derived vegetative indices (i.e. Normalised Difference Vegetation Index, NDVI) to delineate within-vineyard zones of vigour assuming they correspond to quality zones at harvest (Hall *et al.*, 2011). However, the correlation between NDVI maps and grape composition (TSS among other parameters) is not systematic in non-irrigated (Acevedo-Opazo *et al.*, 2008; Santesteban *et al.*, 2013) or irrigated conditions (Tagarakis *et al.*, 2013). Under rainfed vineyard conditions, González-Flor *et al.* (2014) showed that the opportunity to use NDVI zones to delineate TSS zones depends on the phenological stage at which a significant water deficit occurred (before or after veraison).

Another approach to delineate within-vineyard quality zones was proposed by Urretavizcaya *et al.* (2014). It is based on the early sampling of grape composition in the vineyard. This approach assumes that, during maturation, there is temporal stability in the spatial variability of berry composition at the within-field scale. However, literature concerning such an assumption is scarce. Considering the intra-annual level, the stability of quality zones has been reported under drip irrigated (Trought and Bramley, 2011) and non-irrigated conditions (Urretavizcaya *et al.*, 2014). In inter-annual data, a low stability of quality patterns was observed both in non-irrigated conditions in France (Tisseyre *et al.*, 2008) and in irrigated conditions in Australia (Bramley, 2005), while a high stability was observed by Baluja *et al.* (2013) in a cool-climate irrigated vineyard in Spain. The diversity of these results shows that different factors are likely to drive the stability or the instability of quality zones, including farming practices (irrigation, fertilization, canopy management, training system, etc.), genetics (rootstock, cultivars), soil and climate characteristics. These factors, altogether, can lead to stability or instability of quality zones, whether at an intra- and/or inter-annual scale. This complexity justifies performing specific studies in different soil and climatic conditions to produce guidelines for local growers as well as for the scientific community.

The aim of this work is to study the Temporal Stability of Within-Field Variability (TSWFV) of TSS as an estimate of grape maturity in semi-arid irrigated vineyards. The study of TSWFV is justified by practical standpoints. Indeed, the presence of TSWFV for TSS may permit the delineation of relevant quality zones for differential harvest very early in the season from TSS measurements previously obtained either in the same season (intra-annual TSWFV of TSS) or in prior years (inter-annual TSWFV of TSS). Finally, when a high TSWFV is observed, the possibility of using ancillary data (e.g. historical TSS data) to propose a local empirical spatial model at the within-field scale may be considered.

Materials and methods

1. Experimental fields

The experiment was carried out on four fields (one cultivar each) of cvs Cabernet-Sauvignon (CS), Chardonnay (CH), Sauvignon blanc (SB) and Carménère (CA) located in the Maule Valley, Chile, under irrigated conditions (Figure 1). The cvs CS, CH and SB are located at the University of Talca's experimental vineyard, while the cv CA is located in a commercial vineyard in Pencahue, 18 km from the other fields. All vineyards were managed according to conventional viticultural practices in central Chile in terms of canopy management, fertilization, pest and disease control, pruning and irrigation. The characteristics of each field are summarized in Table 1.

A regular sampling grid of 20×20 m was designed within each vineyard (Figure 2). This sampling grid considered 18 sampling sites for cv CS, 19 sites for cv CH, 30 sites for cv SB and 20 sites for cv CA. Each sampling site was represented by four consecutive plants in a row. Sampling grid characteristics were mainly conditioned by the

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Table 1. Field characteristics of the four experimental vineyards.

Vineyard	Area (ha)	Date of plantation	Trellis/Pruning system	Spacing (m x m)	Rootstock	Irrigation system
Cabernet-Sauvignon (CS)	1.56	1998	VSP/Two-bilateral spur-cordon	3.0 x 1.5	Own-rooted	Furrow irrigation
Chardonnay (CH)	1.66	1994	VSP/Guyot	3.0 x 1.25		
Sauvignon blanc (SB)	2.73	1997	VSP/Two-bilateral spur-cordon	3.0 x 1.5		
Carménère (CA)	1.60	1998	VSP/Guyot	2.5 x 1.25		

operational constraints related to the time required to make the measurements over the fields. Note, however, that in absence of other spatial information, given the average spatial variability of yield on a large number of vineyard plots (Taylor *et al.*, 2005), this distance was sufficient to account for a large part of the within-field variability. The borders of the fields and sampling sites within each field were geo-referenced with a differential global positioning system receiver (Trimble, Pathfinder Pro XRS, Sunnyvale, California, USA) and stored as East and North coordinates (Datum WGS84, UTM projection, Zone 19S).

2. Climatic data

An automatic weather station (Adcon Telemetric, A730, Klosterneuburg, Austria) installed under reference conditions was used to characterize the weather conditions (air temperature and precipitation) of the seasons. Data were collected at 15-min intervals from September to April every year. The automatic weather station was located at 0.3 km from the CS, CH and SB vineyards, and at 18 km from the CA vineyard.

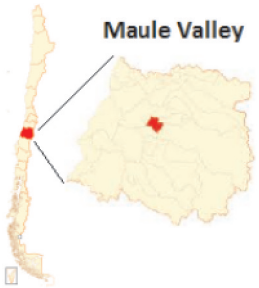


Figure 1. Location of the Maule Valley in Chile.

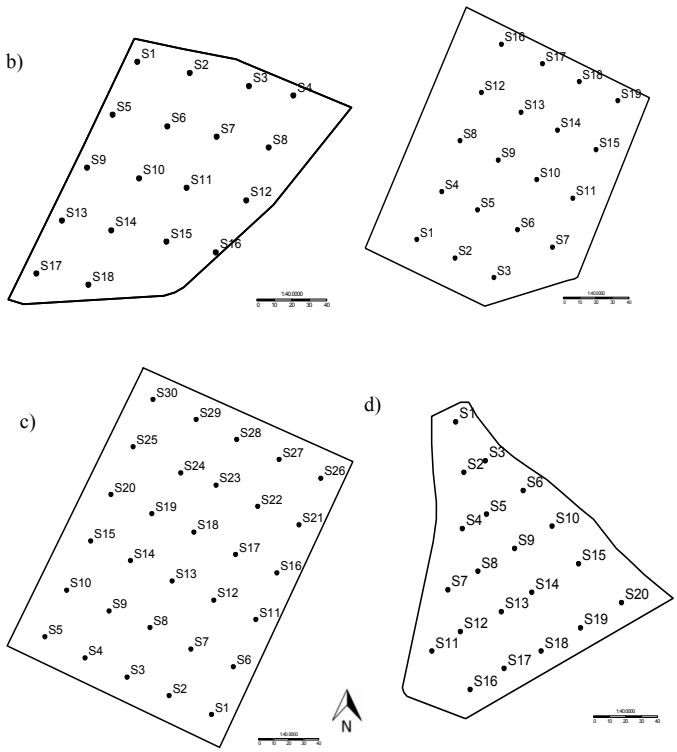


Figure 2. Measurement grids used in the experiments: a) 18 sites for the Cabernet-Sauvignon vineyard, b) 19 sites for the Chardonnay vineyard, c) 30 sites for the Sauvignon Blanc vineyard and d) 20 sites for the Carménère vineyard. S_i represents the sampling site number i.

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3. TSS measurements

TSS was measured on 48-berry samples from each site of the grids (Figure 2) using a thermo-compensated refractometer (BRIX30 model, Leica, USA). Berries were selected following the same methodology for each site as proposed by Trought and Bramley (2011): two clusters were randomly chosen from each of the four plants per site, and two berries were sampled at the top, middle and bottom of each cluster (total of 6 berries per cluster and 48 berries per site). The 48 berries were hand-crushed in a plastic bag, and TSS was measured in the resulting juice. For each site, measurements were made from veraison to harvest at intervals ranging from 2 to 15 days. Phenological dates for budburst and veraison were estimated using the Eichhorn and Lorenz phenological scale as modified by Coombe (Coombe, 1995). In the following sections, the term precocity will be used to define the time of occurrence of phenological stages (Tesic *et al.*, 2002). The number of sampling dates (ranging between 4 and 8) was related to the precocity of each cultivar. This experiment lasted four years for the CS and CH vineyards, three years for the SB vineyard, and two years for the CA vineyard.

4. Analysis method

a. Descriptive analysis

Descriptive statistics, such as mean, standard deviation (SD) and coefficient of variation (CV) were calculated for each dataset (date×cultivars). For the classical statistical analysis, Statgraphics Plus 5.1 (StatPoint Inc., Virginia, USA) software was used.

b. Intra-annual TSWFV

Two statistics were used to quantify the intra-annual TSWFV: (i) the Kendall's coefficient of concordance (W) and (ii) the Spearman's rank correlation coefficient (r_s). Both statistics (W and r_s) have been used in similar studies (Kazmierski *et al.*, 2011; Tisseyre *et al.*, 2008). W was used to analyse the intra-annual TSWFV between all dates for each vineyard and season. W focuses on the rank of the values and provides an assessment of how the rank given by several judges fits between the different *n* objects (Saporta, 1990). In this work, the *n* objects were the sampling sites of each vineyard (Figure 2), and the "judges" were the different sampling dates measured in each season and vineyard. The analysis was then conducted on a matrix where the lines referred to the sampling sites and the columns to the TSS values measured at different dates for each season and vineyard. W varies from 0 (total disagreement or no temporal stability) to 1 (total agreement or high temporal stability) and was computed according to Eq. 1 (Saporta, 1990) :

$$W = \frac{\sum_{i=1}^{n}(R_i - \bar{R})^2}{\frac{1}{12}k^2(n^3 - n)} \quad \text{(Eq. 1)} \quad \text{with}$$

$$R_i = \sum_{t=1}^{k} R(X_{i,t})$$

and

$$\bar{R} = \frac{\sum_{i=1}^{n} R_i}{n}$$

Where:

n: is the number of sampling sites of each vineyard,

k: is the number of sampling dates considered,

$X_{i,t}$: is the rank of TSS value on site *i* and date *t* on each field, and

$\bar{R}$: is the average rank of the sampling site over all the considered dates.

When the W value is significant, it means that at least one of the judges (in this case sampling dates) is concordant with one, or some of the others (Legendre, 2005). In addition to the Kendall's W statistic, a more detailed analysis was performed with the Spearman's rank correlation coefficient (r_s) to determine which dates are similar to harvest. To this end, r_s was used to analyse the relationship between sampling dates, using TSS measured at harvest as reference. The aim of this analysis was to determine whether the same part of the vineyard systematically presents high, medium or low TSS values, compared to TSS observed at harvest. The Spearman's rank method does not require any assumptions either on the linearity of the relationship or on data distribution. r_s was computed according to Eq. 2 (Saporta, 1990):

$$r_s = 1 - \frac{6\,x\,\sum_{i=1}^{n}(R(X_{k,t_1}) - R(X_{k,t_2}))^2}{n\,x\,(n^2-1)} \quad \text{(Eq. 2)}$$

Where:

n: is the number of sampling sites on each vineyard,

X_{k,t_1}: is the TSS value on site *k* and date t_1 on each vineyard,

X_{k,t_2}: is the TSS value on site *k* and date t_2 (date of harvest) on each vineyard,

$R(X_{k,t_1})$: is the rank of among all the values of date t_1, and

$\bar{R}$: is the rank of among all the values of date t_2 (date of harvest).

r_s varies from -1 to 1, where a r_s value of 1 implies that all the values present exactly the same rank in both dates under comparison and therefore a strong temporal stability of the TSS patterns. The level of significance considered for both statistics (W and r_s) was $p<0.05$.

c. Inter-annual TSWFV

The number of TSS measurements varied from 4 to 8 measurement dates depending on the vineyard and the year (Table 2). In order to be able to analyse the inter-annual TSWFV, only four of the main stages of maturity were considered: "veraison" (TSS measured at veraison), "post-veraison" (TSS measured 20 days after veraison), "pre-harvest" (TSS measured 20 days before harvest) and "harvest" (TSS measured at harvest). W was computed (Eq. 1) considering these stages of maturity throughout all the seasons (four for the CS and CH vineyards, three for the SB vineyard and two for the CA vineyard). In this case, the *n* objects were the sampling sites of each vineyard (Figure 2) and the "judges" were the different sampling dates measured according to each stage of maturity and vineyard. Similarly to the intra-annual TSWFV study, the W value was used to summarize the main trend of temporal stability. r_s was used to verify the results obtained through W. To this end, r_s was used to identify the number of pairs of judges (sampling dates of different years) that are concordant when W is significant. This analysis was performed for all vineyards and stages of maturity.

d. Data mapping

Mapping was only used to visualize the results. To this end, the interpolation method used in this study was based on a deterministic function (inverse distance weighting) with a power coefficient value p=0.5. Data mapping was performed with 3Dfield software (version 2.9.0.0., Copyright 1998–2007, Vladimir Galouchko, Russia). For each season and vineyard, only three dates were considered for mapping: 35 days before harvest, 20 days before harvest and date of harvest. Data were mapped in 33% quantiles for each date. Three TSS classes were therefore considered for each map: low (0-33%

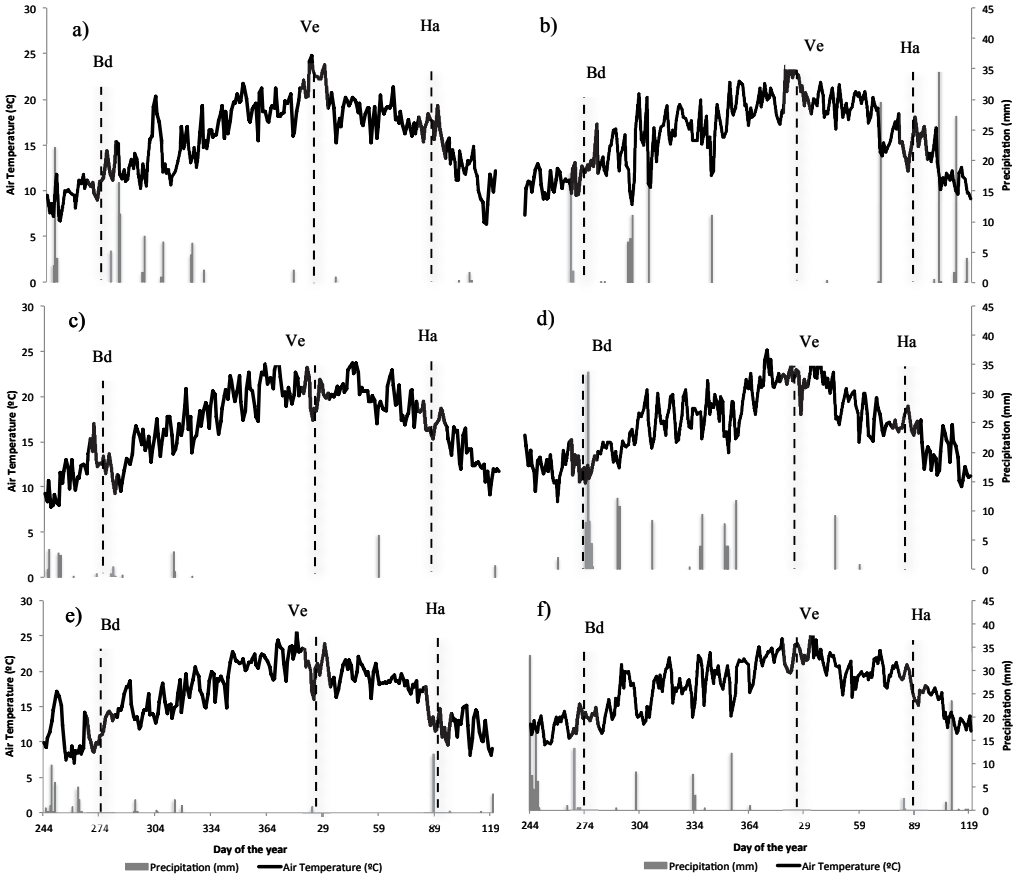


Figure 3. Air temperature and precipitation throughout the seasons: a) 2009-2010 season, b) 2010-2011 season, c) 2011-2012 season, d) 2012-2013 season, e) 2013-2014 season and f) 2014-2015 season.

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quantile), medium (34-67% quantile) and high (68-100% quantile).

Results

1. Climate conditions

Climatic characteristics (mean air temperature and precipitation) from September (beginning of the season) to April (end of the season) for each of the six study seasons are shown in Fig. 3. Air temperature shows a similar pattern over the six seasons of the experiment. The highest temperatures were recorded near veraison for all seasons (around 25°C), while the lowest ones were observed at the beginning of the season. The rainfall pattern changed depending on the season. Thus, the seasons 2011-12 and 2013-14 were dry between budburst and harvest, while 2010-11 and 2012-13 were wetter during the same period. Accumulated rainfall in the veraison-harvest period was low (<12 mm) for all the seasons except 2010-11 (30 mm) (Fig. 3b). These high temperatures and the absence of significant rainfall during the veraison-harvest period are representative of the environmental conditions of the Maule region.

Vertical dashed lines represent the average dates of phenological stages considering all cultivars together: budburst (Bd), veraison (Ve) and harvest (Ha).

2. Descriptive analysis

Figure 4 shows the mean, standard deviation (SD) and coefficient of variation (CV) of TSS observed for each sampling date and each vineyard over the different seasons. The magnitude of variation changed during the maturity process. For all the vineyards and seasons, a similar trend was observed: SD (like CV) decreased from veraison (~25 Day of the year, DOY) to harvest (DOY ~80-100). The highest CV values occurred when TSS ranged between 8-13°Brix, which corresponds to the veraison and the post-veraison period (Parker *et al.*, 2014), while lower CV values occurred at harvest.

The change in CV was due to both an increase in the mean field value and a decrease in SD (Figure 4). Comparing the variability between vineyards at harvest, the SB vineyard presented the highest variability (CV=8.2%), while the CH vineyard presented the lowest (CV=2.4 to 4.9%). These differences in CV may be explained by the combined effects of the characteristics of the cultivars and the specific environmental conditions of each vineyard. For example, the CS vineyard presented two soil series that induce significant differences both in vine water status and vigour (Acevedo-Opazo *et al.*, 2013), as well as in phenology and fruit maturity (Verdugo-Vásquez *et al.*, 2016).

3. Intra-annual TSWFV

The coefficient W highlighted significant intra-annual stability from veraison to harvest for the four vineyards (Table 2). Observed W values were high (W>0.52) and statistically significant for all fields and seasons. Differences in W values in different

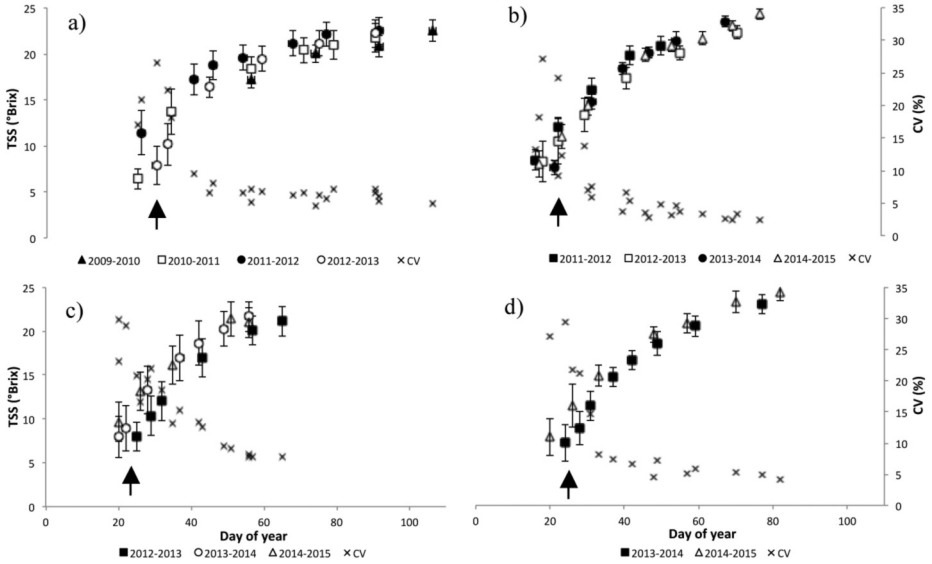


Figure 4. Total Soluble Solids (TSS, °Brix, circles, squares and triangles) measured at different dates and Coefficient of Variation (CV, %) for the four vineyards: a) cv Cabernet-Sauvignon, b) cv Chardonnay, c) cv Sauvignon blanc and d) cv Carménère. Error bars represent the standard deviation (SD). Arrows indicate the mean veraison date for each vineyard.

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Table 2. Kendall's coefficient of concordance (W) of TSS measured within the seasons for each vineyard (intra-annual stability).

Vineyard	No. dates	W Kendall	Significance ($p<0.05$)
Cabernet-Sauvignon			
2009-2010	4	0.78	**
2010-2011	6	0.67	**
2011-2012	7	0.75	**
2012-2013	6	0.56	**
Chardonnay			
2011-2012	5	0.68	**
2012-2013	6	0.71	**
2013-2014	6	0.52	**
2014-2015	8	0.63	**
Sauvignon blanc			
2012-2013	6	0.76	**
2013-2014	7	0.78	**
2014-2015	5	0.76	**
Carménère			
2013-2014	8	0.54	**
2014-2015	7	0.64	**

seasons for each vineyard were related with the magnitude of variation of each season. In general, for each vineyard, seasons with higher variability (high SD and CV values) showed higher W values.

Regarding the mean W value between all the seasons for each field, the SB vineyard presented the highest W value (0.77), while the CA vineyard presented the lowest (W=0.59). This result may justify, in our conditions, the use of early-acquired maps to define relevant maturity zones for differential harvest according to the TSS values.

To further investigate the ability of early TSS maps to identify maturity zones at harvest, the r_s between TSS measured at different dates before harvest and TSS measured at harvest were computed (Fig. 5). r_s values gradually increased from veraison to harvest for all vineyards and seasons. In general, from 40 days before harvest to harvest, r_s values were high (>0.5) and, therefore, the spatial patterns of TSS variability presented strong similarities with the ones at harvest. Before this period, i.e. 40-65 days before harvest, r_s values were lower than 0.5 and not statistically significant ($p<0.05$). Therefore, TSS spatial variability presented low similarity with TSS spatial patterns at harvest. For precision viticulture management purposes, these results show that, under our conditions, TSS maps obtained at least 40 days before harvest present the same spatial patterns as those at harvest. When considering an earlier date (>40 days before harvest), r_s values are no longer significant, and therefore the definition of maturity zones at these dates may be irrelevant for determining maturity zones for differential harvest purposes.

Dashed lines represent the threshold over which r_s are statistically significant at $p<0.05$. Arrows indicate the mean veraison date for each vineyard.

4. Inter-annual TSWFV

Regarding inter-annual TSWFV, observed W values were high (in general >0.50) and statistically significant for all vineyards and stages of maturity (Table 3). W showed a significant inter-annual TSWFV of TSS between years for the four stages of maturity. Regarding the mean W value between all the stages of maturity for each field, the SB vineyard presented the highest W value (0.74), while the CH vineyard presented the lowest (W=0.52). Table 4 shows the percentage (%) of pairs of sampling dates which present a significant ($p<0.05$) r_s value according to the stage of maturity for each vineyard. These results showed that when W was significant, the number of concordant pairs of sampling dates was higher than 2 in most vineyards and stages of

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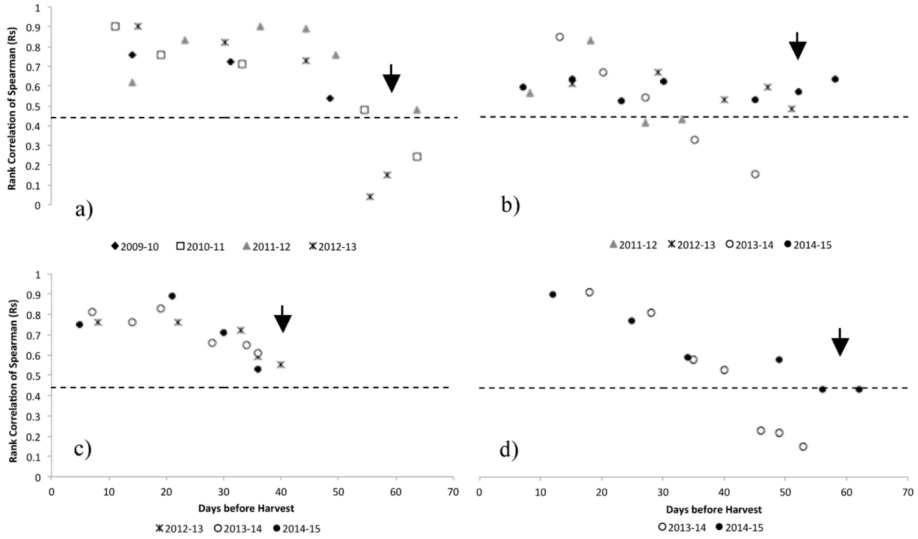


Figure 5. Changes in Spearman's rank correlation coefficient (r_s) between TSS measured at different dates before harvest and TSS measured at harvest for the four vineyards: a) cv Cabernet-Sauvignon, b) cv Chardonnay, c) cv Sauvignon blanc and d) cv Carménère.

Table 3. Inter-annual Kendall's coefficient of concordance (W) of TSS according to stage of maturity throughout the seasons (four, four, three and two seasons for cv Cabernet-Sauvignon, Chardonnay, Sauvignon blanc and Carménère, respectively).

Vineyard	No. years	W Kendall	Significance (p<0.01)
Cabernet-Sauvignon			
Veraison	3	0.65	**
Post-veraison	4	0.66	**
Pre-harvest	4	0.70	**
Harvest	4	0.70	**
Chardonnay			
Veraison	4	0.40	**
Post-veraison	4	0.63	**
Pre-harvest	4	0.51	**
Harvest	4	0.52	**
Sauvignon blanc			
Veraison	3	0.72	**
Post-veraison	3	0.75	**
Pre-harvest	3	0.78	**
Harvest	3	0.70	**
Carménère			
Veraison	2	0.63	**
Post-veraison	2	0.74	**
Pre-harvest	2	0.63	**
Harvest	2	0.78	**

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maturity. There was a general increase in the W and the percentage of concordant pairs of sampling dates from veraison to harvest for the CS and SB vineyards. Note, however, that this tendency was not observed for the CH and CA vineyards. For these vineyards, low W values were associated with changes in the variability (SD and CV) observed between sampling dates.

This result demonstrates the value of using the data of year "n" to estimate the within-field variability of TSS of year "n+1". For example, zones defined at harvest for year "n" may be used to provide relevant quality zones at harvest in year "n+1".

The CH vineyard presented the lowest W values for all stages of maturity. This lower inter-annual stability was probably caused by two early spring frosts which occurred at the beginning of the 2013-2014 season, specifically on September 17th (min temperature=-0.6°C) and September 28th (min temperature=-0.4°C). Chardonnay, being an early maturing cultivar, was more affected than the other cultivars by these frost events. Early spring frost drastically reduced the yield, modifying the balance between leaf area and fruit load. This frost event may explain the change in spatial patterns of TSS during the 2013-2014 season, decreasing the inter-annual TSWFV (Table 3). If the 2013-2014 season is removed from the analysis (for cv Chardonnay), the W values increase by 31% and 7% for veraison and post-veraison, respectively, while for pre-harvest and harvest the W values remain similar.

Figures 6, 7, 8 and 9 show maps of TSS measured on CS, CH, SB and CA vineyards, respectively, over all the seasons and for three dates in each season. For each season, these three dates were chosen to best illustrate the 35-day period before harvest. This choice allows an illustration of the spatial organisation of TSS variability over a time range where the temporal stability was verified by the statistical test associated to the W coefficient. Inter-annual TSWFV is shown in each row, while intra-annual TSWFV is shown in each column. These figures confirm the spatial variability of TSS observed both at an intra- and inter-annual scale at the within-field level. Figures 6 to 9 exemplify the high TSWFV observed both at an intra- and inter-annual scale. It confirms the results obtained previously (Tables 2 and 3). Spatial patterns resulting from a simple classification based on the quartiles (low, medium and high TSS) remain stable throughout the season and between seasons. In general, for all vineyards, the class corresponding to "low TSS" is the most stable, i.e. zones with the lowest TSS values remain similar during the season and also between seasons. That fact was clearly observed on CS and CA vineyards (Figures 6 and 9, respectively).

The effect of early spring frosts on cv Chardonnay is clearly observed in figure 7a. For this vineyard, the 2013-2014 season shows that spatial patterns of TSS measured 35 days before harvest differ from patterns observed in other seasons at the same stage of maturity. During the season of early spring frost (2013-2014), the northern part of the field presents sites classified as "high TSS", whereas in the other seasons, these sampling sites were classified as "low TSS". This explains the lowest W value observed at veraison for the CH vineyard (Table 3). As previously mentioned, that fact was the result of a modification in the leaf area to fruit mass balance, this effect being more pronounced at the beginning of the maturation (35 days before harvest) than in more advanced stages of maturity.

Discussion and perspectives

This study confirms that the magnitude of variation of TSS may be significant at the within-field level, and that it changes during the maturity process. The within-field variability of TSS decreases from the beginning of maturation until harvest. This trend was already observed in the literature (Calderon-Orellana

Table 4. Percentage (%) of pairs of sampling dates that present a significant ($p<0.05$) Spearman's rank correlation coefficient (r_s) value according to the stage of maturity for each vineyard; n is the number of pairs of dates considered.

	Vineyards							
	Cabernet-Sauvignon		Chardonnay		Sauvignon blanc		Carménère	
Stage of maturity	%	*n*	%	*n*	%	*n*	%	*n*
Veraison	67	3	33	6	100	3	0	1
Post-veraison	67	6	83	6	100	3	100	1
Pre-harvest	83	6	50	6	100	3	0	1
Harvest	83	6	33	6	100	3	100	1

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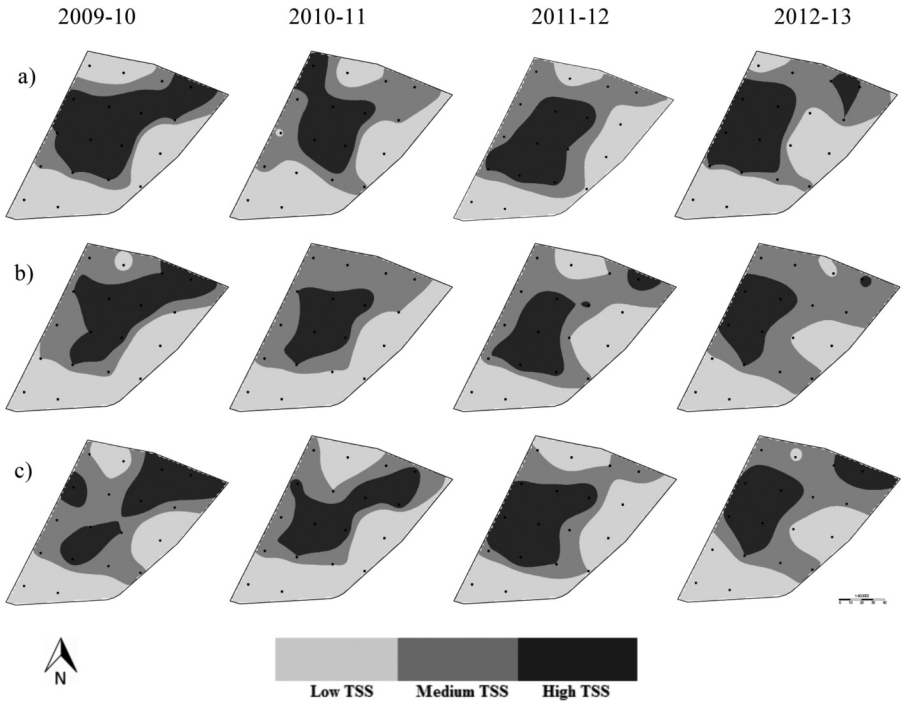


Figure 6. Maps of TSS measured for the Cabernet-Sauvignon vineyard over four seasons and three dates per season: a) 35 days before harvest, b) 20 days before harvest and c) harvest. Each class (greyscale) corresponds to 33% of the data.

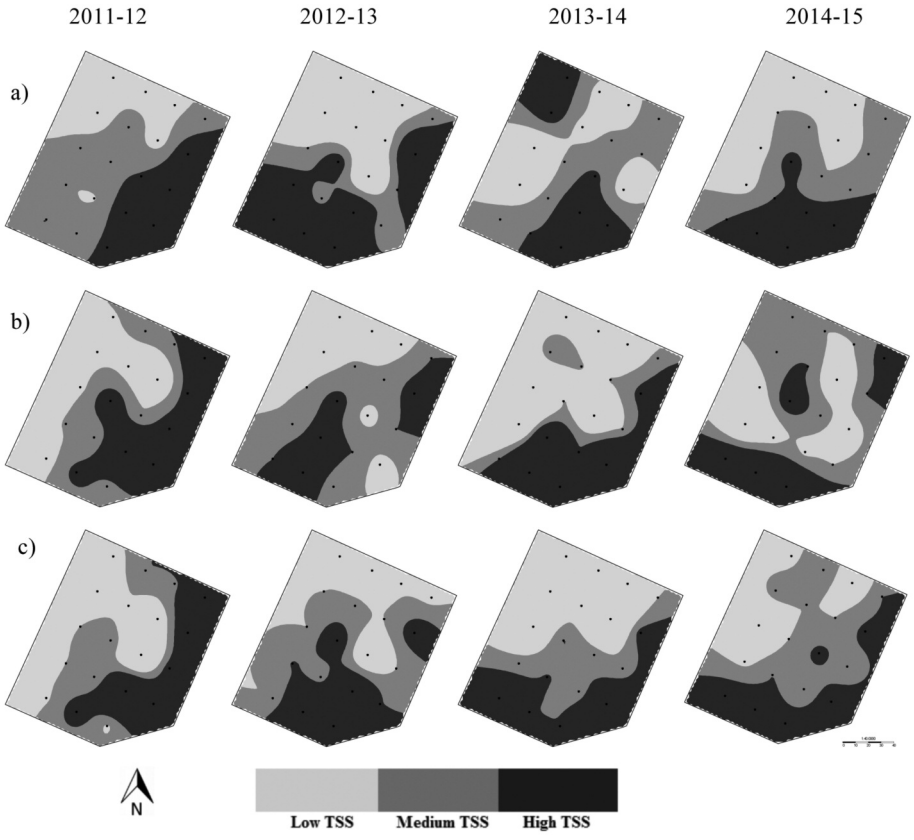


Figure 7. Maps of TSS measured for the Chardonnay vineyard over four seasons and three dates per season: a) 35 days before harvest, b) 20 days before harvest and c) harvest. Each class (greyscale) corresponds to 33% of the data.

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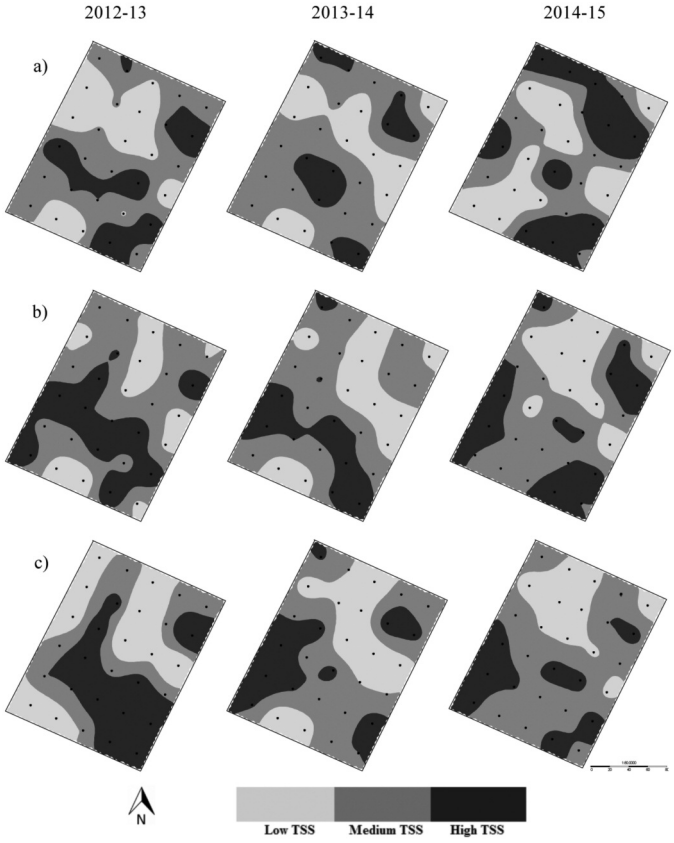


Figure 8. Maps of TSS measured for the Sauvignon blanc vineyard over three seasons and three dates per season: a) 35 days before harvest, b) 20 days before harvest and c) harvest. Each class (greyscale) corresponds to 33% of the data.

et al., 2014; Trought and Bramley, 2011; Urretavizcaya *et al.*, 2014). However, this work strengthened this knowledge on four different cultivars over several years. The decrease in TSS variability (for example, expressed as CV) from veraison to harvest is also associated with asynchrony of flower formation and berry development within a grape cluster (May, 2000). This asynchrony increases the heterogeneity of the cluster at the beginning of veraison. Therefore, it is possible to find berries at different stages of maturity within a grape cluster at veraison (Keller, 2015). This heterogeneity of the cluster decreases from the beginning of maturation until harvest and may explain the decrease in TSS variability during this period.

From a practical standpoint, this result is interesting for defining optimal sampling procedures for estimating the average TSS of a field. Indeed, if the same confidence in TSS estimation is expected for the monitoring of the maturity of a field, the number of samples should vary, being more important at veraison and decreasing until harvest.

The spatial variability of TSS appears spatially organised and not random. Although the study could not provide objective criteria to support this conclusion, TSS maps and statistical analysis over several years clearly show that the spatial variability was organised in patterns that are repeated year after year. The objective of the study was not to identify the origin of these spatial patterns but their temporal stability. This temporal stability suggests that their origin could be related to stable environmental parameters such as soil, elevation, etc. (Tisseyre *et al.*, 2008).

This study also highlighted a high temporal stability of TSS at both intra- and inter-annual scales on a significant number of cultivars and seasons. As mentioned in the introduction, this observation is in agreement with some studies (Baluja *et al.*, 2013; Trought and Bramley, 2011; Urretavizcaya *et al.*, 2014) and in contradiction with others (Bramley, 2005; Tisseyre *et al.*, 2008). The high stability of the spatial variability of TSS in our conditions can certainly be explained by growing conditions and management practices. The Maule Valley (Chile) is

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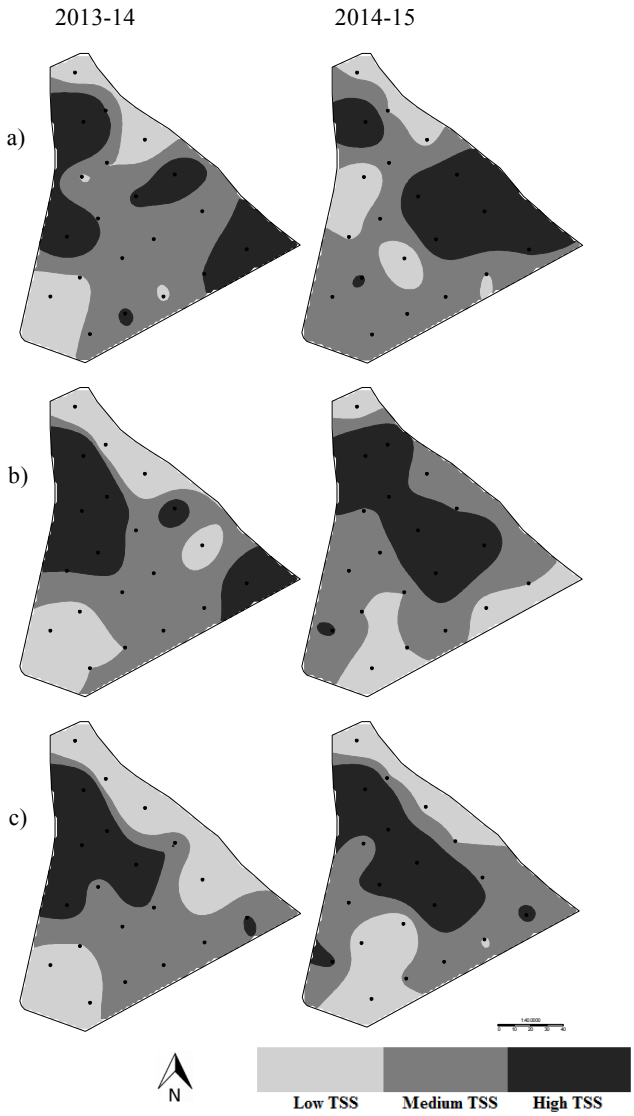


Figure 9. Maps of TSS measured for the Carménère vineyard over two seasons and three dates per season: a) 35 days before harvest, b) 20 days before harvest and c) harvest. Each class (greyscale) corresponds to 33% of the data.

characterized by rather constant climatic conditions over the years. Seasons were characterized by low rainfall during the ripening period (from veraison to harvest, figure 3) and, therefore, the water supply was mainly controlled by irrigation, which allows similar vine water status patterns between seasons. Indeed, water stress is a major factor that determines the maturation of TSS (Acevedo-Opazo *et al.*, 2010a, 2013; Girona *et al.*, 2009). The stable climatic conditions in association with irrigation control results in plant water restriction paths that are repeated year after year (Acevedo-Opazo *et al.*, 2013). Within-field soil variability is likely to result in zones with different water restriction that may explain the observed TSS patterns. These results are similar to those obtained by Baluja *et al.* (2013), who observed high stability of spatial patterns of TSS at harvest during three seasons. This temporal stability is mainly due to similar climatic conditions between seasons. This is verified in our conditions with a more significant database including four different cultivars and a longer period of investigation (two to four years).

Note, however, that this spatial stability was disrupted by a spring frost that affected the yield and changed the load/vigour ratio and the resulting accumulation of TSS at the beginning of ripening (veraison and post-veraison). Several authors (Bobeica *et al.*, 2015; Parker *et al.*, 2014; Parker *et al.*, 2015; Poni *et al.*, 2013) have shown that modifying the leaf area to

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fruit load ratio may affect the accumulation and concentration of TSS. This case shows how the temporal stability of TSS was fragile and how changes in the yield/vigour balance, whether related to climatic events or cultural practices such as cluster thinning, can affect its observation. This is a likely reason for the rather contradictory results of different studies dealing with the temporal stability of TSS spatial patterns. The above shows the importance of incorporating variables related to yield (i.e. number of bunches/plant, yield/plant, etc.) to define zones of maturity or quality, as described by Urretavizcaya *et al.* (2017).

This study shows that under the specific conditions of the Maule region, maturity zones can be considered stable. This allows the consideration of various applications to improve maturity estimation methods and better take into account the within-field variability at harvest. From a practical standpoint, this result leads to simple recommendations for the wine industry:

- The first recommendation is to achieve early maturity maps before harvest at a time when labour can be dedicated to maturity controls and not harvest organisation. These maps could be made 30 to 40 days before harvest. These early maturity maps can be used to define maturity zones as they will be at harvest. They also allow early identification of vineyards presenting significant spatial variability, which can be potentially adapted to differential harvest. Also, note that the monitoring of maturity until harvest could be simplified by proposing a target sampling strategy based on the early defined zones of TSS. It is important to note that the definition of the time of harvest, considered one of the critical stages in the annual calendar of the wine industry, is multifactorial and depends on the objectives of each grapegrower. This study focuses on one of the quality parameters (TSS). To extend this study, it should include measurement of other quality parameters such as pH, titratable acidity, anthocyanins and phenolic content.

- The second recommendation is to value historical data (ancillary data) of the TSS survey. In conditions similar to this study, the maturity maps obtained at harvest during previous years can be an interesting source of information. Similar to early maps of maturity, these historical maps help identify suitable vineyards for differential harvest. They also allow the optimization of maturity monitoring based on a target sampling on TSS zones of previous years. Note, however, that TSS ancillary data are only relevant if the weather features and the cultural practices remain stable from one year to another.

From a research perspective, the temporal stability of TSS zones opens up the possibility of considering empirical spatial models. The advantage being the spatial estimation of TSS values while minimizing the number of measurements. Such an approach has already been proposed in the literature to estimate the water status of the vine (Acevedo-Opazo *et al.*, 2010b, 2013). Based on our results, it may also be transposed to maturity. The approach proposed by Acevedo-Opazo *et al.* (2010b) is based on the collaboration between a spatial model calibrated with ancillary data and a measurement performed on a reference site. The measurement performed on the reference site aims at "updating" the spatial model at a desired date. Formally, this approach is summarized by Eq. 3:

$$\hat{z}(s_i, t_j) = a_{s_i} \, x \, z_{re}(s_{re}, t_j);\ s_{re} \in D, \forall\, s_i \in D, a_{s_i} \in \Re \quad \text{(Eq. 3)}$$

Where:

$\hat{z}(s_i, t_j)$: is the predicted TSS value at location s_i and time t_j,

a_{s_i}, : is the site-specific coefficients calibrated from historical data of TSS,

$z_{re}(s_{re}, t_j)$: is the reference measurement of TSS at the reference site (s_{re}) and time t_j, and

D : is the vineyard field.

The spatial model corresponds to a collection of site-specific coefficients a_{si} calibrated with ancillary data. In this first approach, ancillary data correspond to historical data of TSS. It allows estimation of all TSS values of a field from a single TSS measurement performed on a reference site. As a first example, Figure 10a shows the results of such an approach with a model calibrated on the first three years of the CS vineyard. As a first attempt, coefficients were determined from our data with a classical least square method. Estimation of TSS values in the field was carried out from a reference site selected at random, for the date "19 days before harvest" of the year 2010-11. The R^2=0.95 and the root mean square error (RMSE=0.28) between predicted and observed values show the possibility to estimate TSS values in the vineyard with only one measurement made on a reference site. The presence of two very different within-field zones (Figure 10a) leads to two groups of points that may artificially increase the R^2 value. Note that the R^2 value remains high while the RMSE

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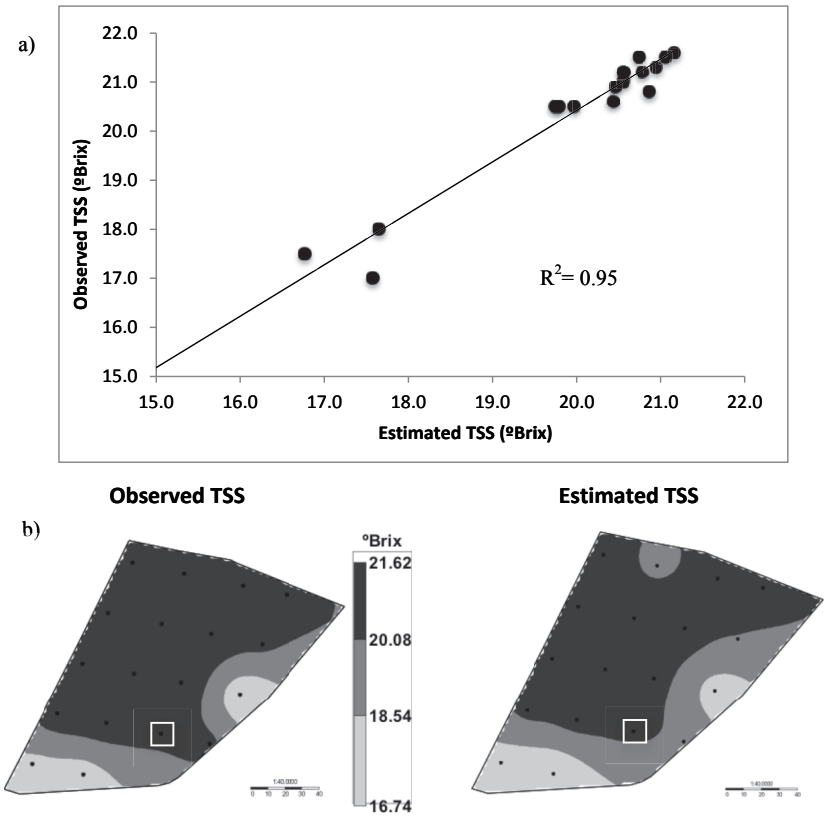


Figure 10. Result of the model calibrated from the first three years of the Cabernet-Sauvignon vineyard (date: 19 days before harvest, 2010-11 season): a) predicted versus observed TSS values and b) maps of the observed and estimated TSS values (reference site in a white frame).

value does not change (R^2=0.74; RMSE=0.27) when the lower zone sites (TSS<19°Brix) are removed, showing the robustness of the approach. Figure 10b shows observed and estimated TSS maps. The similarity of patterns highlighted by these maps confirms the interest of such an approach to estimate the spatial variability of TSS from a single measurement on a reference site. It is important to note that the empirical spatial model is based on the temporal stability of TSS. Therefore, if this temporal stability changes, for example due to changes in cultural practices such as cluster thinning performed between veraison and harvest, the effectiveness of the spatial model to predict TSS values could decrease.

Conclusion

Early target sampling of TSS may provide a good estimate of the spatial variability of grape maturity at harvest. From a practical point of view, these results open up new opportunities to consider field TSS estimation in order to optimize vineyard quality management: (i) new sampling strategies based on early identification of TSS zones and (ii) empirical models calibrated with TSS ancillary data of previous years to optimize maturity monitoring. For the latter, preliminary results showed the potential of this approach, although these must be confirmed. Specific issues related to the selection and the number of reference sites should be investigated as well as the quality of the predictions made for each stage of maturity.

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