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Caractérisation et modélisation de la variabilité spatiale de la phénologie de la vigne à l'échelle intra-parcellaire

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Résumé

Le suivi et la connaissance de la phénologie de la vigne sur plusieurs saisons sont des informations essentielles qui permettent de caractériser les régions viticoles, d'étudier le changement climatique et de planifier des pratiques agricoles telles que l'irrigation, la fertilisation, l'application de pesticides et la vendange à l'échelle parcellaire. La plupart des études menées sur de la phénologie de la vigne, considèrent la parcelle comme une unité de gestion homogène, sans tenir compte de la variabilité spatiale qui existe à cette échelle. Sur la base de travaux précédents qui mettent en évidence une forte variabilité intra-parcellaire en viticulture, ce travail de thèse vise à caractériser la variabilité spatiale de la phénologie de la vigne et les principaux facteurs qui la déterminent à l'échelle d'une parcelle viticole. Il vise aussi à en proposer un modèle de prédiction spatiale qui considère la variabilité de la phénologie de la vigne à cette échelle. Pour répondre à ces objectifs, quatre parcelles expérimentales situées dans la Vallée du Maule (Talca, Chili) ont été utilisées. Celles-ci correspondent aux principaux cépages rouges (Cabernet Sauvignon et Carménère) et blancs (Chardonnay et Sauvignon Blanc) cultivés au Chili. Ce travail a été réalisé tout au long 6 années de 2009 et 2015, au cours desquelles entre de deux et quatre séries des mesures ont été effectuées selon la parcelle viticole. Pour chaque parcelle, une grille régulière de 12 sites d'échantillonnage par hectare a été définie, sur chaque site, des mesures de la phénologie de la vigne, de la maturité des baies (accumulation des sucres), de l'état hydrique de la plante, de l'expression végétative, du rendement, des variables climatiques (température et hygrométrie), des propriétés physique du sol, entre autres, ont été réalisées. Les principaux résultats ont montré l'existence d'une variabilité spatiale de la phénologie de la vigne importante à l'échelle intra-parcellaire. Cette variabilité a été observée autant pour tous les stades phénologiques clés (débourrement, floraison et véraison) et pour l'accumulation des sucres dans les baies. Elle est structurée spatialement et stable au cours du temps. Son importance est similaire à la variabilité observée à des échelles spatiales régionale. Au niveau intra parcellaire, la topographie (différence d'altitude) a été identifiée comme le principal facteur d'influence sur la variabilité spatiale de la phénologie et de l'accumulation des sucres dans les baies. Dans le cas où la variabilité de la topographie de la parcelle viticole est faible, les caractéristiques du sol sont le second facteur expliquant la variabilité spatiale de la phénologie, tandis que les variables de la plante (expression végétative et rendement) expliquent la variabilité observée dans l'accumulation de sucre. La stabilité temporelle de la variabilité spatiale des stades phénologiques et de l'accumulation des sucres dans les baies, a permis de proposer un modèle spatial empirique qui permet d'estimer la valeur ces variables à l'échelle d'une parcelle viticole. L'originalité de l'approche proposée est d'utiliser une mesure ponctuelle de la phénologie ou de la teneur en sucres des baies, effectuée dans la parcelle viticole (site de référence) et une combinaison de coefficients site-spécifiques estimés à partir des données historiques. Ce modèle spatial permet d'obtenir des estimations de meilleure qualité en comparaison avec des méthodes classiques d'échantillonnage. Il permet d'obtenir des cartes pour les stades phénologiques clés et pour l'accumulation des sucres. Cette méthode pourrait être utilisée comme un outil pratique pour la planification de la gestion modulée des opérations au niveau intra-parcellaire, où la connaissance de la phénologie est essentielle pour la prise de décisions.

Mots clés *: Viticulture de précision, variabilité intra-parcellaire, stades phénologiques de la vigne, maturité, Vitis vinifera, stabilité temporelle, précocité, zones homogènes de gestion, modèle spatial, modèles climatiques et analyse de sensibilité*

Abstract

The knowledge and monitoring of grapevine phenology over several seasons are important requirements for the characterization of vine regions, climate change studies and planning of various production activities such as irrigation, fertilization, phytosanitary applications and harvesting at the vine field scale. However, the main studies developed on grapevine phenology consider the vine field as a homogeneous unit of management and do not take into account the spatial variability observed at this spatial scale. Based on previous studies highlighting a significant variability at the within field level in viticulture, this doctoral research aims to characterize the spatial variability of grapevine phenology at the vine field scale, relating the main factors that determine this variability and proposing a spatial prediction model that considers the variability of phenology. In order to answer the above objectives, experiments were carried out in four vine fields located in the Maule Valley (Talca, Chile), considering the main red (Cabernet Sauvignon and Carménère) and white (Chardonnay and Sauvignon Blanc) cultivars planted in Chile. This experiment was carried out over 6 years between years 2009 and 2015. Within each vine field, a regular grid with 12 sampling sites per hectare was defined. Measurements of grapevine phenology, berry maturity (sugar accumulation), plant water status, vegetative expression, yield, climatic variables (temperature and relative humidity), soil physical properties, among others, were performed on each site. The main results showed the existence of a significant spatial variability of the phenological development at the within-field scale, observed for both key phenological stages (budburst, flowering and veraison) and sugar accumulation in berries. This spatial variability was spatially organized and stable over seasons, being comparable even with the observed variability at important spatial scales such as regional or vine valley. At the within-field scale, topography (elevation difference) was identified as the main integrative factor affecting the spatial variability of both grapevine phenology and maturity. If there is no variability in the topography, the soil characteristics become the second factor of the spatial variability of grapevine phenology, while plant variables (vegetative expression and yield) explained the observed variability in sugar accumulation at this scale. The temporal stability observed for the spatial variability of the phenological stages and sugar accumulation of berries allowed an empirical spatial model to be proposed. The model characterizes the spatial variability of these variables at the vine field scale. The originality of the approach is to use a single measurement of the grapevine phenology or sugar accumulation in the berries performed in the field (reference site) and a combination of site-specific coefficients estimated through historical data. The spatial model presented the best results when compared with classical sampling methods, allowing maps of key phenological stages and sugar accumulation to be obtained. This methodology could be used as a practical tool for the planning site-specific management operation at the vine field scale where phenology is essential for decision-making.

Keywords: *Precision viticulture, within-field variability, phenological stages of the grapevine, maturation, Vitis vinifera, temporal stability, precocity, homogeneous management zones, spatial model, climatic models and sensitivity analysis.*

Resumen

El monitoreo y conocimiento de la fenología de la vid durante varias temporadas son informaciones imprescindibles para caracterizar las regiones vitivinícolas, estudiar el cambio climático y planificar labores agrícolas tales como el riego, la fertilización, la aplicación de productos fitosanitarios y la cosecha a la escala del cuartel vitícola. Los principales estudios desarrollados en torno a la fenología de la vid, consideran el cuartel vitícola como una unidad de manejo homogéneo, no tomando en consideración la variabilidad espacial observada a esta escala espacial. Considerando esto, esta investigación doctoral tiene por objetivo caracterizar la variabilidad espacial de la fenología de la vid y los principales factores que la determinan a una escala de un cuartel vitícola, y proponer un modelo de predicción espacial que considere la variabilidad de la fenología de la vid a esta escala. Para responder a los objetivos anteriores, se dispuso de cuatro cuarteles experimentales ubicados en el Valle del Maule (Talca, Chile), considerando las principales variedades tintas (Cabernet Sauvignon y Carménère) y blancas (Chardonnay y Sauvignon Blanc) cultivadas en Chile. Este trabajo se llevó a cabo entre los años 2009 y 2015, considerando 2 a 4 temporadas dependiendo del cuartel vitícola. Dentro de cada cuartel se definió una grilla regular con 12 sitios de muestreo por hectárea, donde mediciones de fenología de la vid, madurez de baya (acumulación de azúcares), estado hídrico de planta, expresión vegetativa, rendimiento, variables climáticas (temperatura y humedad relativa), propiedades físicas de suelo, entre otras fueron realizadas. Los principales resultados de la tesis doctoral mostraron la existencia de una variabilidad espacial significativa en el desarrollo fenológico de la vid a la escala intra-cuartel, observada tanto para eventos fenológicos claves (brotación, floración y envero), como para la acumulación de azúcares en las bayas. Esta variabilidad espacial se presentó espacialmente organizada y estable entre temporadas, siendo comparable incluso con la variabilidad observada a escalas espaciales mayores, como por ejemplo a escala regional o de valle vitivinícola. Se identificó a la topografía (diferencia de altitud) como el principal factor integrativo que afecta la variabilidad espacial de la fenología y la acumulación de azúcar en las bayas al interior del cuartel vitícola. Si la variabilidad en la topografía del cuartel vitícola es muy pequeña, entonces las características del suelo pasaron a ser el factor explicativo principal de la variabilidad espacial de la fenología, mientras que las variables de planta (expresión vegetativa y rendimiento), explicaron la variabilidad observada en la acumulación de azúcar a esta escala. La estabilidad temporal observada para la variabilidad espacial de los estados fenológicos y la acumulación de azúcares de las bayas, permitió proponer un modelo empírico para estimar espacialmente estas variables a la escala del cuartel vitícola. Para la modelización, este modelo espacial usa una medición puntual realizada en el cuartel (sitio de referencia) y una combinación de coeficientes sitio-específicos calculados a través de datos históricos. Las estimaciones de la fenología y el contenido de azúcares en las bayas realizadas con el modelo espacial fueron mejores que los métodos tradicionales de muestreo, permitiendo obtener cartografías de estados fenológicos claves y de acumulación de azúcares. Esta metodología podría ser utilizada como una herramienta práctica para la planificación de manejos sitio-específicos a la escala del cuartel vitícola, donde la fenología es imprescindible para la toma de decisiones.

Palabras claves: *Viticultura de precisión, variabilidad intra-cuartel, estados fenológicos de la vid, maduración, Vitis vinifera, estabilidad temporal, precocidad, zonas de manejo homogéneo, modelo espacial, modelos climáticos y análisis de sensibilidad.*

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Verdugo-Vásquez, N., Acevedo-Opazo, C., Valdés-Gómez, H., García de Cortázar-Atauri, I., Tisseyre, B. Assessment of an empirical spatio-temporal model of the grapevine phenology at the within-field scale. In 11th *European Conference on Precision Agriculture.*

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Introducción General

El objetivo de esta sección del documento es mostrar el contexto en que se enmarca el presente trabajo de investigación, respondiendo a las principales preguntas científicas que fueron identificadas durante su desarrollo. Esta sección está dividida en diferentes puntos, donde en cada uno de ellos se hace una identificación de los principales vacíos científicos observados, los cuales se buscan responder en este manuscrito.

1.- Importancia de la viticultura en Chile

La vitivinicultura nacional es uno de los principales rubros agrícolas de exportación en Chile, donde la mayor proporción de la producción se destina a mercados extranjeros (Lacoste, 2005). El mercado nacional de vinos se destaca por producir vinos de buena calidad y a un bajo costo (Moguillansky, 2006), posicionándose como el cuarto país exportador de vino del mundo durante el año 2013 (OIV, 2014), exportando aproximadamente 801 millones de litros el año 2014, con un precio promedio de US$2.3 el litro (OEMV, 2014). Dado lo anterior, la superficie a nivel nacional de vides para vinificación ha aumentado sostenidamente en los últimos 4 años, alcanzado, según el último catastro vitícola disponible, 138.355 ha (ODEPA, 2015), de las cuales aproximadamente un 40% se encuentran en la Región del Maule, destacándose dentro de los cultivares establecidos para vinos tintos Cabernet Sauvignon con 31,4% a nivel regional y para vinos blancos Chardonnay con 7% a nivel regional (ODEPA, 2015).

Para poder mantener este sostenido aumento en la producción, la viticultura nacional en los próximos años deberá hacer frente a nuevos desafíos, como es el cambio climático global (IPCC, 2007) y la alta variabilidad espacial observada a nivel de campo (Tisseyre et al. 2007). Por un lado, el cambio climático afecta el crecimiento y desarrollo de la vid, aumentando la variabilidad inter-anual de la producción (cantidad y calidad de la fruta producida), mientras que la variabilidad espacial observada al interior de los viñedos aumenta la variabilidad intra-predial de la producción observada durante la temporada, afectando la competitividad de la industria nacional.
Para lo anterior, los viticultores nacionales deben adoptar tecnologías que permitan optimizar el manejo de los viñedos frente a los cambios planteados y así aumentar la eficiencia y competitividad de la industria (Lavín et al. 2001). Estas tecnologías consideran la fenología de la vid como uno de los pilares fundamentales que es necesario conocer para lograr un manejo óptimo del viñedo.

2.- **Definición y caracterización de la fenología de la vid**

La fenología de la vid (*Vitis vinifera*) se refiere al estudio de sus etapas de crecimiento, las cuales se repiten durante todas las temporadas, relacionándose principalmente a factores climáticos y hormonales (Mullins et al. 1992; Jones and Davis 2000). El ciclo anual visible de la vid se inicia con la brotación, y continua con el desarrollo vegetativo, floración, cuaja, desarrollo de las bayas, pinta o envero, maduración de las bayas (cosecha) y termina con la caída de hojas (Jones 2003). Dentro de estos estados fenológicos, diferentes órganos vegetales son observados con el objetivo de determinar en qué etapa del ciclo productivo se encuentra la planta. Por ejemplo, para la brotación se observa el número de yemas brotadas, luego en el desarrollo vegetativo se observan las hojas y en floración se cuantifica la cantidad de flores abiertas en cada inflorescencia. A partir de la cuaja, las observaciones se centran en las bayas hasta el envero. Este último estado fenológico (envero) se caracteriza porque las bayas inician un rápido periodo de cambios físicos y químicos como ablandamiento y elongación, cambios de color hacia el verde translúcido (variedades blancas) o hacia el color rojo-púrpura (variedades tintas) y el inicio de la acumulación de azúcares, entre otros componentes químicos, determinando el inicio de la maduración de las bayas (Jones 2003). A partir de envero, se realizan mediciones con instrumentos específicos para determinar componentes químicos de las bayas como la cantidad de azúcares, acidez, entre otros. De este modo, la fecha de cosecha es determinada por los viticultores, en base al estilo de vino a elaborar. Dentro de las mediciones que se realizan a las bayas para evaluar la evolución de la madurez, la acumulación de azúcares es una de las más utilizadas, ya que determina el alcohol probable del vino a elaborar (Sadras and Petrie 2012).

Para comparar las observaciones fenológicas realizadas en diferentes temporadas agrícolas o localidades es importante estandarizar las mediciones, tanto para fines productivos como de investigación. Aunque no existe un método global de observaciones fenológicos para la vid, hay diferentes sistemas descriptivos del crecimiento de la vid aceptados, tanto por los productores como por los investigadores. Estos sistemas descriptivos reciben el nombre de escalas fenológicas, siendo las más usadas la escala fenológica de Eichhorn y Lorenz modificada por Coombe (Coombe 1995), la escala BBCH (Meier 2001) y la escala de Baggiolini (1952). Estas escalas asignan un número o abreviatura a cada estado fenológico. El seguimiento y conocimiento de la fenología de la vid presenta múltiples aplicaciones en la viticultura, las cuales se detallan a continuación:
a).- Caracterización vitícola de las zonas geográficas, determinando las variedades mejor adaptadas a las condiciones climáticas de una zona específica (Ortega-Farías et al. 2002).
b).- Planificación de labores agrícolas realizadas en los cuarteles vitícolas (riego, fertilización, aplicación de productos fitosanitarios, cosecha), de tal forma de mejorar la eficiencia de la producción vitivinícola (Mariani et al., 2013).
c).- Estudio del sincronismo de crecimiento y desarrollo entre la vid y sus patógenos y plagas (Mariani et al. 2007).
d).- Estudio de los efectos de la fenología en la calidad del vino (Gris et al. 2010).
e).- Indicador y predictor de los efectos del cambio climático sobre las plantas (Marta et al. 2010; Moriondo et al. 2010; Caffarra and Eccel 2010, 2011). Esta información permitiría generar estrategias de adaptación (nuevas variedades, zonas productivas, etc.) que permitan mitigar los riesgos esperados por las posibles alteraciones en la ocurrencia de los eventos fenológicos.

Se presenta la necesidad de estudiar la fenología de la vid a distintas escalas espaciales y temporales. El caso a) se refiere a una escala de país, regional y de valle, de tal forma de definir zonas productivas, asociadas a cultivares específicos. Para b), c) y d) se asocia principalmente a escala de valle, cuartel e intra-cuartel. Finalmente, e) se refiere a la escala temporal, que permite obtener información comparable de un año a otro, de tal forma de observar la variabilidad inter-anual y para generar bases de datos (20-30 años) que permitan cuantificar los efectos del cambio climático.

Dada la importancia de la fenología de la vid, en la literatura, muchas investigaciones se han focalizado en estudiar esta variable a diferentes escalas espaciales, por ejemplo, a meso escala (viñedos, más de 200 ha de superficie) (Fourment et al. 2013; Malheiro et al. 2013; Ramos et al. 2015), donde se ha observado que existe una importante variabilidad en el desarrollo fenológico de la vid a esta escala espacial. Sin embargo, lo anterior no se relaciona con las necesidades de los viticultores, para quienes la unidad básica de manejo corresponde al cuartel vitícola (superficie menor a 5 ha), las cuales se caracterizan por presentar la misma variedad, sistema de conducción y prácticas de manejo.

En recientes años, varios autores (Arnó et al. 2009; Tisseyre et al. 2008; Trought and Bramley 2011) han postulado que en la agricultura y especialmente en la viticultura existe una alta variabilidad espacial en los cuarteles vitícolas, entendiéndose ésta como diferencias existentes en una unidad productiva básica, la cual se puede asociar principalmente a diferencias en el suelo y/o en el manejo del cuartel.

El uso de herramientas de Agricultura de Precisión (AP), ha permitido cuantificar la variabilidad espacial existente en los cuarteles vitícolas (Acevedo-Opazo et al., 2008), que afecta a las principales variables productivas, tales como el crecimiento vegetativo (densidad de la canopia), el rendimiento (número y peso de los racimos), la madurez (sólidos solubles, pH y acidez) y los componentes de calidad de las bayas (Bramley and Hamilton, 2004). Asimismo, en los últimos años se han desarrollado investigaciones donde ha sido posible cuantificar y manejar esta variabilidad, proponiéndose zonas de manejo homogéneo dentro del cuartel vitícola (Acevedo-Opazo et al. 2008; Tisseyre et al. 2007; Urretavizcaya et al. 2016).

Pese a la importancia de la fenología de la vid, no se han llevado a cabo estudios detallados de la variabilidad espacial existente de esta variable, al interior del cuartel vitícola (escala espacial). En base a lo anterior, se plantea la primera pregunta científica de esta tesis doctoral: ¿Existe variabilidad espacial en el desarrollo fenológico de la vid a escala del cuartel vitícola?, ¿es estable en el tiempo y espacio esta variabilidad?

En el **Capítulo 1** de la tesis doctoral se busca dar respuesta a estas preguntas, dejando en evidencia que la variabilidad espacial de la fenología de la vid al interior del cuartel vitícola es significativa y comparable con la observada a otras escalas espaciales, como por ejemplo a la escala regional o de valle vitivinícola. Asimismo, en este capítulo se observa que la variabilidad espacial de los eventos fenológicos son estables entre temporadas y estructurados en el espacio. En el **Capítulo 2** de la tesis se busca responder a las mismas preguntas científicas pero específicamente orientada a la acumulación de azúcar en las bayas desde el período fenológico de envero hasta cosecha. En este capítulo se puede evidenciar que la variabilidad espacial de la acumulación de azúcares a lo largo de la temporada y entre temporadas es estable entre temporadas y estructuradas en el espacio. Este nuevo conocimiento plantea la necesidad de realizar nuevas investigaciones en el tema, como por ejemplo en lo referente a los factores que afectan o inciden en esta variabilidad espacial y así mismo proponer la modelización de la variabilidad espacial de la fenología de la vid y la acumulación de azúcares a escala del cuartel vitícola. Estos aspectos serán abordados en las próximas secciones de la introducción.

3.- Factores que inciden en la variabilidad espacial de la fenología a diferentes escalas espaciales

Como se mencionó en la sección anterior, el estudio de la fenología de la vid es importante a diferentes escalas espaciales, las cuales se presentan a continuación:
1.- Escala de país: Considera el desarrollo fenológico de la vid a nivel de país, por ejemplo Chile, donde se observan diferentes regiones vitivinícolas (Escala superior a 1000 km).
2.- Escala Regional: Al interior de cada Región productora, existen diferentes Valles, por ejemplo, en la Región del Maule existen los Valles del Maule y Valle de Curicó (Escala superior a 200 km).
3.- Escala de Valle: Por ejemplo, dentro del Valle del Maule, se distinguen diferentes viñedos (conjunto de unidades productivas) (Escala espacial inferior a 200 km).
4.- Escala de viñedos: al interior de un viñedo, existen diferentes unidades de manejo (cuarteles vitícolas) (Escala espacial inferior a 10 km).
5.- Escala Intra-cuartel: se refiere a la unidad de manejo (cuartel vitícola), diferencias que se observan entre grupos de plantas a esta escala (Escala espacial inferior a 200 m).
6.- Escala Intra-planta: diferencias que se pueden observar entre brotes que se desarrollan en una misma planta (Escala espacial inferior a 2 m).

En cada una de las escalas espaciales anteriores, se observa que existe una importante variabilidad en el desarrollo fenológico del viñedo. Esta variabilidad puede ser explicada por diferentes factores, según la escala espacial en la que se trabaje. En literatura se comunica que ***la temperatura*** es el principal factor identificado, el cual es común a todas las escalas espaciales propuestas (Chuine et al. 2013; Jones 2003; Matese et al. 2014). Estas diferencias de temperatura se deben principalmente a diferencias en altitud entre los distintos sitios de un viñedo (Ramos et al. 2015) o a la presencia de cursos de agua (Fourment et al. 2013). La información de literatura referida a los factores que afectan la variabilidad de la fenología, muestra que esta problemática ha sido estudiada exclusivamente a escala regional y de valles vitivinícolas. Algunos autores han demostrado que diferencias en el suelo (características físico-hídricas) pueden afectar el desarrollo de la fenología de la vid a la escala de valle (Barbeau et al. 1998; Tesic et al. 2001; Jones 2003). Por otro lado, manejos productivos como el manejo de follaje o de carga frutal (microclima de follaje) pueden afectar el estado fenológico de pinta y la acumulación de azúcares de las bayas (Parker et al. 2014, 2015; Poni et al. 2013). Otros factores como la radiación solar también puede ser un factor que incida en el desarrollo fenológico de la vid (Failla et al. 2004).

En relación a la escala intra-cuartel, no existe información en literatura que identifique los principales factores que afecten el desarrollo de la fenología de la vid a esta escala. Es así que este trabajo de investigación busca aportar conocimiento en lo referente a la identificación de los factores explicativos de la variabilidad espacial observada en la fenología de la vid a la escala del cuartel vitícola. De este modo las preguntas a responder son las siguientes: ¿Cuáles son los principales factores que inciden en el desarrollo fenológico de la vid a nivel del cuartel vitícola? ¿estos factores son estables entre temporadas? Este conocimiento es presentado en el **Capítulo 3** de este trabajo. Entre los principales resultados observados se puede señalar que la topografía (diferencia de altitud) es el principal factor integrativo que afecta la variabilidad espacial de la fenología y la acumulación de azúcar en las bayas al interior del cuartel vitícola. Por otro lado, cuando no existe variación en la topografía del cuartel vitícola, las características del suelo pasan a ser el factor explicativo de la variabilidad espacial de la fenología, mientras que variables de planta (crecimiento vegetativo y rendimiento) explican la variabilidad observada en la acumulación de azúcares a esta escala. Esta información puede ser de mucha utilidad en futuras investigaciones orientadas a modelar la fenología y acumulación de azúcar en bayas a escala intra-cuartel. En la siguiente sección se presentan las metodologías más utilizadas para modelar la fenología de la vid a diferentes escalas espaciales.

4.- Métodos de estimación de la fenología a diferentes escalas espaciales

Para poder responder a las necesidades de los productores e investigadores en lo referente a la problemática de estimación de la fenología de la vid, se han propuesto varios métodos de estimación en función de la respuesta de la planta frente a la temperatura (Chuine et al. 2013; Jones 2003). Estos métodos de estimación, corresponden a modelos predictivos de la fenología de la vid, donde se distinguen los modelos estadísticos, que utilizan variables climáticas para estimar las fechas de ocurrencia de los estados fenológicos. Por otro lado, existen los modelos basados en los procesos, que simulan un estado fenológico a partir de una ecuación que representa el funcionamiento de la planta (Chuine et al. 2013).

Los modelos estadísticos de fenología se han desarrollado principalmente a grandes escalas espaciales (Ortega-Farías et al. 2002; García de Cortázar-Atauri et al. 2009; Caffarra and Eccel 2010; Nendel 2010; Parker et al. 2011; Sadras and Petrie 2012). Por ejemplo, a escala regional, existe una plataforma llamada Proyecto IPHEN (Italian Phenology) que modela la fenología de la vid con datos climáticos, observaciones puntuales y modelos geo-estadísticos, generando cartografías semanales a nivel país, para el caso de Italia, de los estados fenológicos (Mariani et al. 2013).

A escala regional y de valle, los modelos existentes se basan en ecuaciones, donde datos climáticos (principalmente temperatura del aire), obtenidos de estaciones meteorológicas ubicadas en las cercanías de los viñedos (10-5 km), se ingresan como variable explicativa en las ecuaciones, y la variable respuesta es la fenología, donde la información de salida corresponde a la fecha de ocurrencia de un evento fenológico dado (por ejemplo brotación, floración o envero). De este modo, se obtienen valores referenciales de las fechas de ocurrencia de los estados fenológicos de la vid a grandes escalas espaciales. Para poder caracterizar la variabilidad espacial observada a escala regional o de valle es necesario contar con una alta resolución de información climática a esta escala, complicando su aplicación práctica. Para el caso de los cuarteles vitícolas, que corresponde a la escala donde se planifican las labores agrícolas, los modelos de fenología también se pueden aplicar (Ortega-Farías et al. 2002), obteniéndose un valor referencial del estado fenológico, el cual es extrapolado a todo el cuartel, sin considerar la variabilidad espacial del desarrollo fenológico de la vid. De este modo, bajo condiciones de alta variabilidad espacial, la extrapolación de un valor referencial de la fecha de ocurrencia de los estados fenológicos obtenida a través de los modelos climáticos podría no ser representativo del comportamiento fenológico del cuartel. Una aproximación de estos modelos que considere la variabilidad espacial, podría ser un monitoreo a alta resolución espacial de la temperatura a partir de sensores inalámbricos que midan esta variable. Sin embargo, es importante definir el número y la ubicación de los sensores en el campo, junto con el costo de instalación y mantención del sistema, el cual podría limitar la aplicación práctica por parte de los viticultores (Kunz and Tatham 2012; Primicerio et al. 2013). En este trabajo científico, se plantea un método alternativo que permita modelar la variabilidad espacial de la fenología de la vid a escala del cuartel vitícola. Este método consiste en utilizar modelos empíricos espaciales, aplicados exitosamente para modelar la variabilidad espacial del estado hídrico de un viñedo (Acevedo-Opazo et al. 2013; Acevedo-Opazo et al. 2010). Estos modelos permiten caracterizar la variabilidad espacial de los cuarteles vitícolas, a través, de una medición puntual realizada en un sitio de referencia en el viñedo más la combinación de coeficientes de determinación sitio-específicos calculados a través de datos históricos. Esta aproximación permite estimar la precocidad (avance o retraso de la fecha de ocurrencia de un estado fenológico respecto al sitio de referencia) de la fenología de la vid. En el **Capítulo 4** de la tesis doctoral se presenta el modelo espacial de la fenología de la vid, mientras que en el **Capítulo 5** se presenta el modelo espacial de la acumulación de azúcares, ambos aplicados a la escala del cuartel vitícola. Los principales resultados de estos capítulos muestran que el uso de modelos espaciales permiten mejorar la estimación de estas variables si se compara con métodos tradicionales de estimación basados en muestreos aleatorios o modelos climáticos para el caso de la fenología de la vid.

Finalmente, en la última parte de este trabajo (**Capítulo 6**) se plantea la opción de combinar el modelo espacial de fenología propuesto en el Capítulo 4 junto a los modelos climáticos de fenología. Esta metodología utiliza la información estimada por el modelo climático como la información del sitio de referencia del modelo espacial, permitiendo predecir tanto espacial como temporalmente los distintos eventos fenológico de la vid. Los resultados de este capítulo muestran que la colaboración entre un modelo clásico de fenología basado en datos climáticos con un modelo espacial calibrado con información histórica de fenología mejora la estimación de estados fenológicos claves (brotación, floración y envero) a la escala intra-cuartel, cuando se compara con la utilización del modelo climático por sí solo.

CHAPTER I

CHAPTER 1: SPATIAL VARIABILITY OF PHENOLOGY IN TWO IRRIGATED GRAPEVINE CULTIVAR GROWING UNDER SEMI-ARID CONDITIONS

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Abstract

Knowledge and monitoring of the grapevine phenology during the season are important requirements for characterization of productive regions, climate change studies and planning of various production activities at the vine field scale. This work aims at studying the spatial variability of grapevine phenology at the within field scale. It was conducted on two fields, one of cv Cabernet Sauvignon of 1.56 ha and the other of cv Chardonnay of 1.66 ha, both located in Maule Valley, Chile. Within each vine field, a regular sampling grid was designed, to carry out weekly measurements of phenology and maturation. The main results show that there is a significant spatial variability in the phenological development and maturation at the within field scale for both fields. This variability is spatially organised and temporally stable from the beginning of the season (post-budburst) to harvest and over the years. A cluster analysis allowed us to define two clearly contrasted zones in terms of phenology and maturation in both fields, explained by the microclimate. The magnitude of difference between zones varied from 4 to 9 days depending on phenological stages and from 5 to 43 days for maturation. These differences are similar and comparable to that observed at larger scales or under scenarios of climate change. These results highlight the necessity to better take into account this variability to improve sampling and to base decisions of production activities (spraying, harvest, pruning, etc.) application on more relevant information. Further investigations should determine the environmental factors that determine the observed spatial variability.

Keywords: *Vitis vinifera*, berry maturity, within field variability, temporal variability, management zones, climate change.

Abbreviations

CV	Coefficient of variation
DESP	Degree of spatial dependence
ET_0	Reference evapotranspiration
Fl	Flowering
GDD	Growing degree-days
Ha	TSS measured at Days of the harvest
Ma	Maturation
MCD	Mean correlation distance
Max	Maximum
MI	Maturity index

Min	Minimum
Post-Bu	Post-budburst
Pre-Ha 1	TSS measured at 25 days before harvest
Pre-Ha 2	TSS measured at 12 days before harvest
PS	Units of Phenological Scale
Ps	Current phenological stage
Range	Range of variation
SD	Standard deviation
TSS	Total soluble solids
TSSV	Temporal Stability of the Spatial Variability
Ve	Veraison
W	Kendall coefficient of concordance

INTRODUCTION

Grapevine phenology is the study of the stages of growth as budburst, flowering and veraison, which are repeated every season and depend mainly on climatic and hormonal factors (Mullins et al. 1992; Jones and Davis 2000). Knowledge and monitoring of the different phenological stages of the grapevine during the season are important requirements for planning of various production activities at the vine field scale (Mullins et al. 1992). For example, for the management of powdery mildew in the vine there are control methodologies based on the monitoring of the pathogen and plant phenology so as to make phytosanitary applications at the most susceptible phenological stages (flowering and fruit set), thereby reducing the number of phytosanitary treatments (Campbell et al. 2007; Bramley et al. 2011). Likewise, for irrigation management it has been observed that the application of regulated deficit irrigation on specific phenological periods of post-setting and post-veraison optimizes the vegetative growth, the yield and the final quality of the berries (Ojeda et al. 2002; Acevedo-Opazo et al. 2010). Moreover, knowing the phenological development of the vine together with its fruit ripening makes it possible to optimize the harvesting process, often supporting a differentiated management of vine fields (Trought and Bramley 2011).
The importance of monitoring the phenology of the vine as a decision support information has motivated numerous investigations at different spatial scales, for example, at meso scale (vineyards, more than 200 ha surface) models that predict phenological events have been developed and can be used to plane farming operations at this scale (Ortega-Farías et al. 2002; García de Cortázar-Atauri et al. 2009; Caffarra and Eccel 2010; Nendel 2010; Parker et al. 2011; Sadras and Petrie 2012). Moreover, phenological process based models have also been used to assess the impact of climate change on the phenological development of grapevines at macro scales (regions) (Marta et al. 2010; Moriondo et al. 2010; Caffarra and Eccel 2010, 2011). There have also been studies on the spatial variability of the phenology of grapevines at the macro scale, in order to determine optimum pedo-climatic zones for the production of quality grapes (Tesic et al. 2001) and to establish spatial patterns of evolution of berry maturity in different areas of Australia (Petrie and Sadras 2008).

With regard to the spatial variability of climate at the meso scale, in recent years the TERADCLIM (Quénol and Bonnardot 2014) and ADVICLIM (Quénol et al. 2014) projects

modeled spatial variability of climate (temperature) in the main vine production areas of the world. Assuming the availability of relevant calibrated models linking climate variables to vine phenology, this information is important to model the spatial variability of vine phenology.
Generally speaking, the findings reported in these studies have large spatial scale application (macro and meso scales), which is at odds with the needs of growers for whom the basic unit of management is the vine field (surface less than 5 ha, micro scale) which is characterized by a same variety, training system and management practices.
In recent years, several authors have observed that in agriculture and especially in viticulture, there is significant spatial variability at the micro scale (within field level) in the production variables such as plant water status (Acevedo-Opazo et al. 2010; Acevedo-Opazo et al. 2013), vegetative expression (King et al. 2014), yield (Bramley and Hamilton 2004; Tardaguila et al. 2011) and the quality components of the berries (Bramley and Hamilton 2004; Baluja et al. 2013). This observed variability was mainly attributed to differences in soil (Tardaguila et al. 2011).
In this light, one wonders whether the vine field is a unit of homogeneous management in relation to the evolution of its phenological cycle during the season. If this is not the case, then the methods traditionally used by wine producers to characterize the phenological stage of their vine fields would not be appropriate to represent the spatial variability of the fields. Indeed, in practice, wine industry does not carry out more than two phenological observations per field. These two observations are assumed to be representative of the whole vine field and sometimes to other neighbouring fields of the same variety. Thus, traditional methods could result in inadequate decisions of interventions.
To our knowledge, studies on spatial variability on climate and phenology have focused at macro or meso scale (surface > 200 ha) (Bonnefoy et al. 2012; Irimia et al. 2015; Quénol 2013; Quénol et al. 2014), without considering the micro scale (spatial scale < 5 ha). The aim of this study is therefore to investigate the spatial variability of grapevine phenology at the within field scale, answering the following questions: i) is there a spatial variability in the phenological development of the vine at the field scale? ii) is the spatial variability observed stable over time? and iii) is it worth to define management zones in relation to the phenology of the fields?

MATERIALS AND METHODS

Experimental Fields

The study was conducted in two fields, one of cv. Cabernet Sauvignon of 1.56 ha (field 1) and the other of cv. Chardonnay of 1.66 ha (field 2), both located in the Panguilemo Experimental Station of the University of Talca (Maule Valley), Chile (Fig. 1). The characteristics of both fields are summarized in Table 1. The region is characterized by Mediterranean climatic conditions, while the soil belongs to the Talca and San Rafael series (Ultic Haploxeralfs) (Soil Survey Staff 1999). Both vineyards were managed according to the conventional agricultural practices used in the commercial vineyards of central Chile in terms of canopy management, fertilization, pest and disease control, pruning and irrigation, over all the seasons of the study period. Within each vine field a regular sampling grid was designed, one with 18 measurement sites (25x25 m) for field 1 (Fig. 2 a) and one with 19 measurement sites (25x25 m) for field 2 (Fig. 2 b). Each site of the grid was represented by four consecutive plants. The borders of the fields and sampling sites within each field were geo-referenced with a differential global positioning system receiver (DGPS) (Trimble, Pathfinder ProXRS, Sunnyvale, California, USA) and stored as Eastern and Northern coordinates (Datum WGS84, UTM projection, Zone 19S) to perform the mapping and spatial analysis.

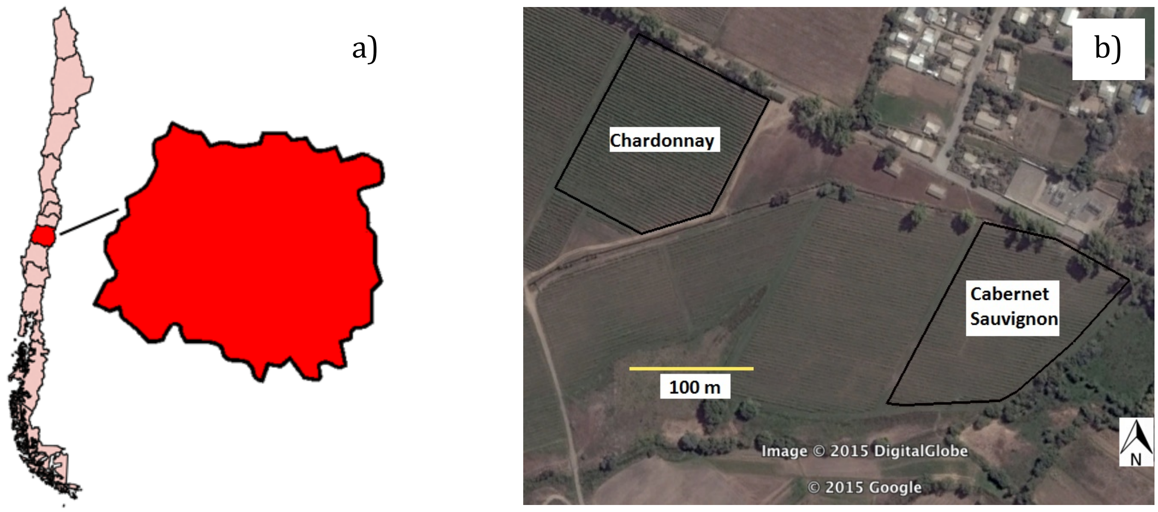

Fig. 1 Location of Maule Valley in Chile (a) and map of the study area (b).

An automatic weather station (Adcon Telemetric, A730, Klosterneuburg, Austria) installed under reference conditions, at 300 m from the vineyards, provided data such as air temperature, relative humidity, solar radiation, precipitation, wind speed and direction of the wind at 15-minute intervals. The sensors were installed at 2.5 m above the soil surface, except for the temperature and relative humidity sensors which were located 1.5 m above the soil surface. This information was used to estimate reference evapotranspiration (ET_0), using the Penman-Monteith equation (Allen et al. 2006) and the sum of growing degree-days (GDD), from 1^{st} May to harvest and for each phenological period considered (i.e. flowering or veraison). Sum of GDD was calculated as the sum of the daily difference between the average air temperature minus 10°C (Winkler 1974).
Additionally, considering that the main variable that affects phenological development of the grapevine is the temperature (Chuine et al. 2013; Quénol et al. 2014), 8 temperature sensors (Dickson, LogTK500, USA) were installed in the field 1 (cv Cabernet Sauvignon) with the aim to characterize the spatial variability of temperature at the within field scale.
The sensors were located according to a preliminary analysis of the 2009-10 season. Two zones of phenology were identified. Assuming temporal stability of these zones, 8 sensors (4 sensors for each zone) were installed (Fig. 3) at 1.5 m above the soil surface and on vine rows. Temperature was recorded every 30 minutes in the period of September (before budburst) until October (pre-flowering) during the 2011-2012 season, corresponding to a total of 37 days of measurements.

Table 1 Field characteristics of the Cabernet Sauvignon and Chardonnay experimental fields.

Property	Cabernet Sauvignon	Chardonnay
Experimental period	2009-13	2011-13
Vineyard age[a]	13-year-old	17-year-old
Rootstock	Own-rooted	Own-rooted
Location (WGS84)	35°22.0' S, 71°35.6' W	35°21.9' S, 71°35.8' W
Elevation (m above sea level)	121	121.8
Spacing (m x m)	3.0 x 1.5	3.0 x 1.25
Trellis/Pruning system	VSPSystem/Two-bilateral spur-cordon	VSPSystem/Guyot
Row orientation	330° NW	310°NW
Total root depth (m)	0.7	0.8
Soil characteristics		
Bulk density (g cm^{-3})	1.4	1.5
Field capacity (m^3 m^{-3})	0.34	0.26
Wilting point (m^3 m^{-3})	0.22	0.15
Available water (m^3 m^{-3})	0.12	0.11
Texture	Clay loam	Clay loam
Irrigation system	Furrow irrigation	Furrow irrigation

[a]: at the beginning of the experiment.
VSP: Vertical shoot positional

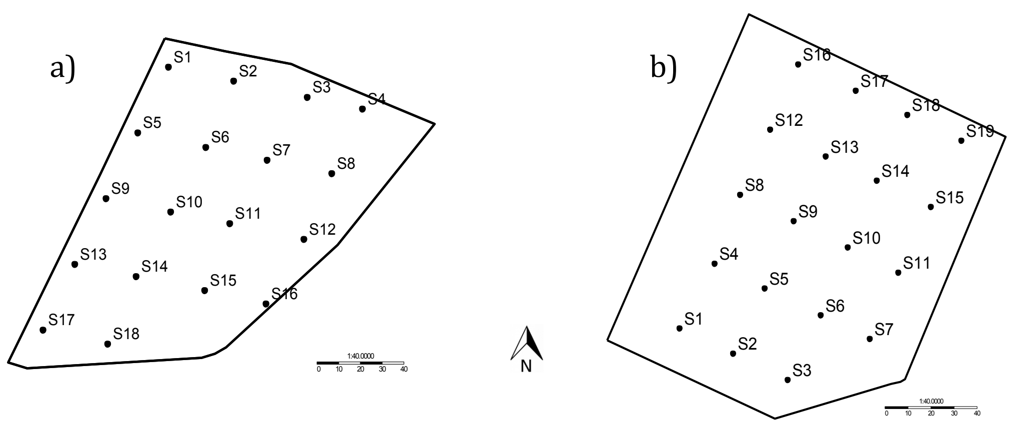

Fig. 2 Measurement grids used in the experiments. 18 grid sites for field 1, cv Cabernet Sauvignon (a) and 19 sites for field 2, cv Chardonnay (b). S_i represents the sampling site number i.

Measurements

a) Grapevine Phenology

The phenological observations were made from budburst to veraison, every 7 days in 30 shoots chosen systematically among the 4 vines of a site of the grid. The same shoots were always measured date after date over a season. On each site of the grid, mean value of phenology measured over the 30 shoots was calculated. Phenology was estimated using the Eichhorn and Lorenz phenological scale as modified by Coombe (Coombe 1995) (Table 2). It considers measurements of leaf number, length of shoots (cm) and berry diameter (mm).

The phenological scale assigns a number to each phenological measurement (expressed in units of Phenological Scale, PS, Table 2), allowing us to represents phenology as a numeric variable. For data analysis it was used only the three major phenological stages (post-budburst, flowering and veraison). Veraison for cv Cabernet Sauvignon was considered by berries colour change, while for cv Chardonnay it was considered by berry softness and colour change simultaneously.

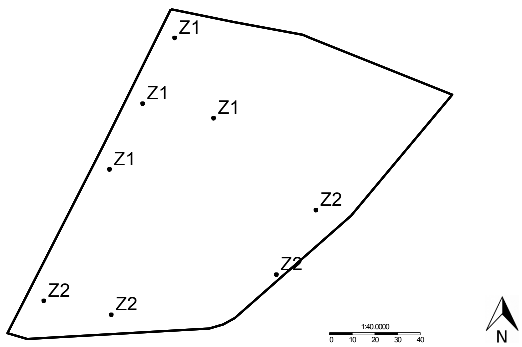

Fig. 3 Location of temperature sensors in the field 1 (cv Cabernet Sauvignon). Where: Z1 represents zone 1 and Z2 represents zone 2.

Table 2 Representation of the phenological scale of Eichhorn and Lorenz as modified by Coombe (Coombe 1995).

Main phenological stage	Assigned Number in Scale (PS)	Meaning
Budburst and Post-Budburst	4	Green tip: first leaf tissue visible (Budburst)
	5	Rosette of leaf tips visible
	7	First leaf separated from shoot tip
	9	2 to 3 leaves separated; shoots 2-4 cm long
	11	4 leaves separated
	12	5 leaves separated; shoots about 10 cm long; inflorescence clear
Flowering	19	About 16 leaves separated; beginning of flowering (first flower caps loosening)
	20	10% caps off
	21	30% caps off
	23	17-20 leaves separated; 50% caps off (full-bloom)
	25	80% caps off
	26	Cap-fall complete (100%)
Veraison	33	Berries still hard and green.
	34	Berries begin to soften.
	35	Berries begin to colour and enlarge (Veraison).
	36	Berries with intermediate °Brix values.

b) Maturation (expressed as total soluble solids, TSS)

From veraison to harvest, measurements of total soluble solids (TSS) were performed as indicator of grapevine maturity. TSS was chosen as the most typical indicator used to define harvest time. This measurement was done by a thermo-compensating refractometer (BRIX30 model, Leica, USA), by randomly selecting eight clusters from each site of the grid. For each cluster two berries were sampled at the top, the middle and the bottom of the cluster. Therefore, TSS value of each site of the grid and each date corresponded to a sample of 48 berries. Three sampling dates were considered, called Pre-Ha 1 (25 days before harvest), Pre-Ha 2 (12 days before harvest) and Ha (Day of the harvest). For both fields, harvest (Ha) was defined at 22°Brix. This last value corresponding to the optimal maturity at harvest in our conditions.

Analysis method

For main phenological stages and maturity dates, basic statistics such as standard deviation and coefficient of variation (CV) were calculated. These statistics were expressed in units of Phenological Scale (PS) and TSS (ºBrix) respectively for phenology and maturation.

Variographic analysis was performed to study the spatial structure of the phenological data and the maturity at each date for both experimental fields. Omnidirectional semivariograms were calculated according to the methodology proposed by Webster and Oliver (2001). The three basic parameters of the semivariogram were obtained: nugget (C_0), sill (C_0+C_1) and range (a), which define the degree and scale of spatial variation among the observations. The computation of a semivariogram is usually not recommended with a number of points as low (Webster and Oliver 1992). However, for this experiment, the quality of data collected (manual measurements averaged over a large number of individuals) and the significant spatial organisation of the fields allowed us to consider such an analysis. From semivariogram parameters the degree of spatial dependence (DESP) also called the Cambardella index, was derived by using the ratio between the nugget and the total semivariance of the semivariogram (sill), expressed as a percentage (Cambardella et al. 1994), Eq. 1.

$$DESP(\%) = \left[\frac{C_0}{C_0 + C_1}\right] * 100 \qquad (1)$$

The Cambardella index allowed us to compare the relative size of the nugget effect for each date of the experiment. Thus, the values of $DESP \leq 25\%$ indicate a strong spatial dependence; $25\% \leq DESP \leq 75\%$ indicate a moderate spatial dependence, and the values of $DESP > 75\%$ correspond to a weak spatial dependence (Wu et al. 2008). In addition to DESP, the mean correlation distance (MCD) (Han et al. 1996) was estimated (Eq. 2).

$$\mathrm{MCD}(m) = \frac{3}{8} * \left[\frac{C_1}{C_0 + C_1}\right] * \mathrm{a} \qquad (2)$$

The MCD provided an estimate of the distance at which the data have a high spatial dependence (Han et al. 1996).

Mapping spatial distribution

Maps with both phenological and maturation variables were done in order to visualize the phenology and maturation of the fields. To this end, the method of interpolation Block-Kriging as proposed by Baluja et al. (2013) was used. The scale of the maps was defined using an equidistant range, with two intervals.

Analysis of the Temporal Stability of the Spatial Variability (TSSV) of the grapevine phenology and maturation

To quantify the TSSV of both phenology and maturation, the Kendall coefficient of concordance (W) was calculated according to the methodology described by Tisseyre et al. (2008). W ranges from 0, in the case of no temporal stability (total disagreement in site

order between dates), to 1 in the case of temporal stability (Saporta 1990). This analysis was carried out in two ways:
- to quantify the TSSV of phenology and maturity over the seasons, it was performed separately on the main phenological stages (post-budburst, flowering and veraison) and on the maturation (Pre-Ha 1, Pre-Ha 2 and Ha),
- to quantify the intra-season TSSV, it was performed on the main phenological stages and maturation dates measured within each season.

Zoning of the vine fields based on grapevine phenology and maturation
For each field, the zoning of both phenology and maturation was conducted with a cluster analysis using the centroid squared euclidean distance (Flores 2005). For phenology zones most relevant phenological stages of the vineyard management (post-budburst, flowering and veraison) were considered while three main dates (Pre-Ha 1, Pre-Ha 2 and Ha) were considered for maturation. For both fields and each dates, two clustering operation were therefore performed, one related to phenology and the other one to maturation. The clustering was conducted to provide two classes for each field under consideration. Considering the high spatial organisation of our data, this clustering method was expected to highlight within field zones. In the rest of the document, zones will refer to the classes resulting from the clustering.

Phenological and maturation characterization expressed in days

a) Grapevine Phenology

In order to provide a practical interpretation of the spatial variability in the phenology observed between budbreak and veraison, the observed phenological stage was turned into chronological days for both fields. This transformation was performed through the implementation of a predictive model of phenology following to the methodology proposed by Ortega-Farías et al. (2002). This model uses the monomolecular Mitscherlich equation (Thornley and Johnson 1990), (Eq. 3). It estimates the phenological stage (expressed in units of Phenological Scale, PS) in terms of thermal accumulation from the time of the budburst. Based on observed values and meteorological data, the model was calibrated for each cultivar. Resulting model allowed us to estimate the growing degree-days required to fulfill a certain phenological stage. Fig. 4 represents the simulation of the proposed model for cv Cabernet Sauvignon and cv Chardonnay. On Fig. 4, vertical lines cutting x-axis correspond to the sum of GDD necessary to reach flowering (PS = 23). This approach is similar to that used in studies conducted by Jorquera-Fontena and Orrego-Verdugo (2010) who studied the effect of climate change on the phenological development of the vine.

$$Ps = Ps_f - \left(Ps_f - Ps_i\right)e^{-k(sGDD)} \quad (3)$$

Where: Ps = current phenological stage (PS), Ps_f = last phenological stage corresponding to PS = 38, Ps_i = first phenological stage corresponding to PS = 4, k = rate of phenological development and sGDD = sum of Growing degree-days (°C) from the date corresponding to Ps_i to the date of Ps.

Knowing observed GDD of each day from climatic data, Eq. (3) allowed us to transform PS values in a number of days necessary to reach the phenological stage (Ps) under consideration. At the field level, this approach was used to determine the number of days required to achieve a given phenological stage (Dat_{Fi}) considering the mean of PS observations on all sampling sites. It was also used to determine the number of days required to achieve a given phenological stage for a within field zone (Dat_{Zi}) by considering the mean of PS observations belonging to the considered zone. For a given phenological stage, this methodology was used to determine the difference, expressed in days between the average of the whole field and the specific zones of the same field (Eq. 4).

$$Difference\ in\ days = Dat_{Fi} - Dat_{Zi} \quad (4)$$

Where: Dat_{Fi} = estimated date of the phenological stage i for the whole field, Dat_{Zi} = estimated date of the same phenological stage i for the within field zone Z. Phenological stages i, corresponds to i = post-budburst, flowering and veraison.

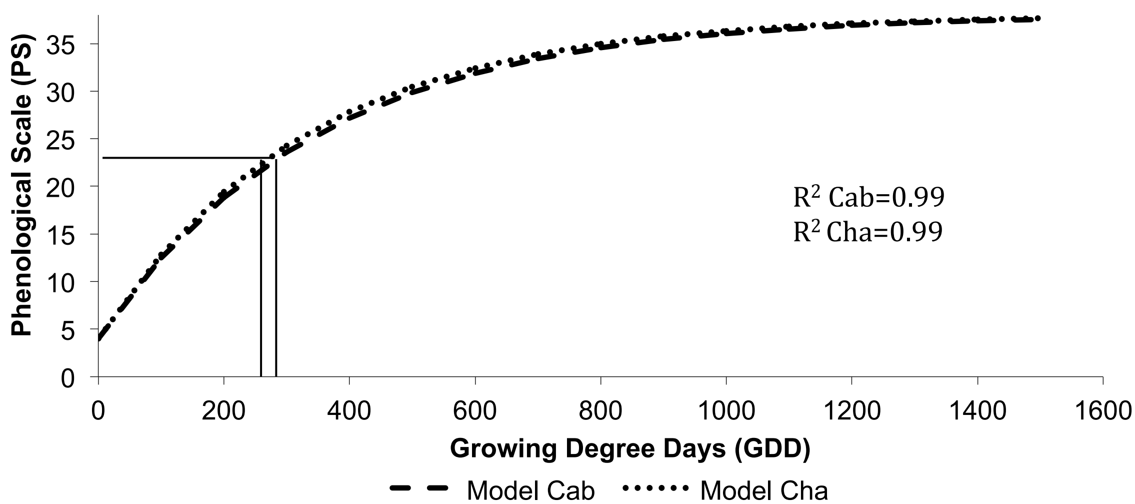

Fig. 4 Phenology model simulation for cv Cabernet Sauvignon (Model Cab) and cv Chardonnay (Model Cha). Where: Lines represent the sum of GDD necessary to fulfill the state 23 in PS (Flowering). R^2: Represents the degree of fit between phenological stage (PS) and growing degree days (GDD).

b) Maturation

For maturation the three dates (Pre-Ha 1, Pre-Ha 2 and Ha) were transformed into days through the implementation of a maturity index (MI). The MI quantifies the increase in TSS (°Brix) for each degree-day accumulation (Eq. 5):

$$MI = \frac{SS_H - SS_M}{\sum_{j=1}^{n} GDD} \quad (5)$$

Where: MI = maturity index (°Brix d °C^{-1}); SS_H = total soluble solids measured at harvest (°Brix); SS_M = total soluble solids measured at post-veraison (15 days after veraison, TSS >15°Brix); GDD = growing degree day (°C d^{-1}); j corresponds to the measurement day of SS_M and n to the day of SS_H.

This approach assumes that after a period of rapid increase in TSS (at veraison), TSS increases linearly over time (Sadras and Petrie 2012). The MI was estimated for both fields, obtaining a specific value for each cultivar. SS_M and SS_H were estimated by averaging values measured over the whole field for each field. MI was used to estimate the number of days explaining observed difference in maturity between the whole field and the within field zones. (Eq. 6).

$$Difference\ in\ days = \frac{SS_{Fi} - SS_{Zi}}{\mathrm{MI} * GDD_A} \qquad (6)$$

Where: SS_{Fi} = average total soluble solids of all sampling sites of the fields at date *i* (°Brix); SS_{Zi} = average total soluble solids of the sites belonging to zone *z* at the same date *i* (°Brix), *i* is the date of measurement corresponding to Pre-Ha 1, Pre-Ha 2 and Ha. *MI* = Maturity Index (°Brix d °C^{-1}); GDD_A = Daily mean of GDD from post-veraison (15 days after veraison) to harvest (°C d^{-2}).

Software and Tools

For the classical statistical analysis, the Statgraphics Plus 5.1 (StatPoint Inc., Virginia, USA) software was used, while for the geostatistical analysis, the *GS*+ version 9.0 (Gamma Design Software, LLC, 2008) software was used. For the design of the maps the 3DField (version 2.9.0.0., Copyrigtht 1998 – 2007, Vladimir Galouchko, Russia) software was used. Finally, the Matlab Software (The Mathwork Inc., Natick, MA, USA) was used for the calculation related to phenology model.

RESULTS AND DISCUSSION

Climate characterization

The climatic characterization for all the study seasons is presented in Table 3. The mean air temperature during the period between 1st May and the harvest ranged between 15 and 15.7 °C. The third season (2011-12) presents the highest temperature, showing this season was warmer (with mean temperature values above 20 °C) during the period from flowering to harvest. These temperatures lead to higher sum of growing degree-day values, which fluctuated between 1455 and 1640 °C d^{-1} for field 1 (cv Cabernet Sauvignon) and between 1385 and 1523 °C d^{-1} for field 2 (cv Chardonnay). These values are well above the 1150 and 1300 °C d^{-1} considered adequate to properly mature respectively, cv Chardonnay and cv Cabernet Sauvignon (Gladstones 1992). Regarding the precipitation, these were mainly similar during the last three seasons and 23% lower during the first season (2009-2010). As a result of the low rainfall and evapotranspiration, a climate water deficit (P-ET_0) was observed, which fluctuated between 464 and 553 mm for the different seasons; the first season showed the lowest water deficit. Finally, the climatic conditions of the seasons studied can be considered similar, except the 2012-2013 season which presents higher sGDD value.

Table 3 Summary of thermal time and main climatic variables, which characterize the growing conditions over the 4 years of experiment. Variables are presented by phenological stage (mean of the field) with Bu: Budburst, Fl: Flowering, Ve: Veraison and Ha: Harvest. Cab: cv Cabernet Sauvignon and Cha: cv Chardonnay.

Season	T_{mean} (°C)		$_S$GDD(°C)		P (mm)		ET_0 (mm)		P-ET_0 (mm)	
2009-2010	Cab		Cab		Cab		Cab		Cab	
1 May-Bu	8.8		123		515.8		180		336	
Bu-Fl	14.0		264		62.0		237		-175	
Fl-Ve	19.6		625		2.8		383		-380	
Ve-Ha*	17.4		499		0.2		245		-245	
1 May-Ha*	15.0		1510		580.8		1045		-464	
2010-2011	Cab		Cab		Cab		Cab		Cab	
1 May-Bu	8.5		103		398.2		206		193	
Bu-Fl	15.0		287		44.8		214		-169	
Fl-Ve	18.9		542		11.0		339		-328	
Ve-Ha*	18.3		524		30.2		266		-236	
1 May-Ha*	15.2		1455		484.2		1025		-541	
2011-2012	Cab	Cha	Cab	Cha	Cab	Cha	Cab	Cha	Cab	Cha
1 May-Bu	8.1	8.0	84	70	448.6	448.6	169	159	280	290
Bu-Fl	14.4	14.2	263	258	9.0	8.8	215	214	-206	-205
Fl-Ve	20.1	20.0	679	641	0.0	0.2	393	375	-393	-375
Ve-Ha*	20.2	20.4	497	416	7.0	7.0	241	208	-234	-201
1 May-Ha*	15.7	15.7	1523	1385	464.6	464.6	1018	956	-553	-491
2012-2013	Cab	Cha	Cab	Cha	Cab	Cha	Cab	Cha	Cab	Cha
1 May-Bu	9.2	9.1	171	157	323.3	323.3	180	166	143	158
Bu-Fl	14.6	14.1	297	268	85.7	85.7	220	201	-134	-115
Fl-Ve	19.4	19.0	597	589	41.1	41.1	338	349	-297	-308
Ve-Ha*	19.0	20.0	575	509	10	10	268	237	-258	-227
1 May-Ha*	15.5	15.5	1640	1523	460.1	460	1006	952	-546	-492

$T_{mean:}$ average mean temperature; $_S$GDD: Sum of growing degree-days; P: Precipitation; ET_0: Evapotranspiration.
*Harvest: the harvest was undertaken when the berries presented 22°Brix of total soluble solids.

Non-spatialized analysis of the grapevine phenology and maturation

Main statistics of the phenology and the maturity are presented in Table 4 and Table 5 respectively. For field 1, the phenological stages of post-budburst, flowering and veraison presented a range of variation between 1 and 6 units on PS for the 4 seasons. Meanwhile, for field 2, these ranges varied between 2 and 5 units of PS (Table 4). For both fields the stage of veraison presented the lowest dispersion during seasons (smallest range). For the maturation period, ranges of variation varied from 3.6 to 6.0 °Brix for field 1 whereas for field 2 they varied from 2.7 to 4.9 °Brix (Table 5). With regards to the variability between seasons, the range values remained similar over the seasons, suggesting that there is a temporal stability in the dispersion of the phenological stages and maturation.

The coefficients of variation (CV) for both fields show that the phenological stage with the greatest variation during all the seasons was post-budburst, with values that ranged between 8.3 to 12.8% and 6.4 to 15.6% for field 1 and field 2 respectively. The veraison presented the lowest variability. In both fields and over all seasons of the experiment, CV value decreases from post-budbreak to veraison. This result may be due to the proposed scale (Table 2) which is less sensitive to the changes observed at veraison. During maturation, CV values did not show great variations within each season.

Regarding the literature dealing with spatial variability at the within field scale, to our knowledge, no reference on CV values for the phenological stage is available. Concerning the maturation, especially for harvest, Baluja et al. (2013) obtained CV values for total soluble solids measured during the harvest ranging between 5.3 and 7.5% for cv Tempranillo in Spain. These values are similar to that observed in the present study. Similar range of variation were also observed by Tisseyre et al. (2008) and Bramley (2005) for TSS at harvest.

Table 4 Main statistics of grapevine phenology for the two fields studied.

Season	Min		Max		Range		SD		CV (%)	
2009-10	Cab		Cab		Cab		Cab		Cab	
Post- Bu	5		7		2		0.65		10.5	
Fl	20		23		3		0.87		3.9	
Ve	34		35		1		0.34		1.0	
2010-11	Cab		Cab		Cab		Cab		Cab	
Post- Bu	5		7		2		0.47		8.3	
Fl	20		26		6		1.47		6.1	
Ve	34		35		1		0.26		0.8	
2011-12	Cab	Cha	Cab	Cha	Cab	Cha	Cab	Cha	Cab	Cha
Post- Bu	5	9	8	11	3	2	0.89	0.64	12.8	6.4
Fl	21	22	25	25	4	3	1.35	0.69	5.6	3.0
Ve	33	33	35	35	2	2	0.54	0.52	1.5	1.5
2012-13	Cab	Cha	Cab	Cha	Cab	Cha	Cab	Cha	Cab	Cha
Post- Bu	7.0	7.0	11	11	4	4	1.05	1.36	12.1	15.6
Fl	18	20	21	25	3	5	0.77	1.46	3.9	6.5
Ve	34	33	35	35	1	2	0.28	0.97	0.8	2.9

Min:minumun, Max: Maximun, SD: Standard deviation, CV: Coefficiente of variation, Range: Range of variation. Post-Bu: Post-Budbreak, Fl: Flowering, Ve: Veraison. Post-Bu, Fl and Ve expressed in PS. Cab: cv Cabernet Sauvignon, field 1. Cha: cv Chardonnay, field 2.

Table 5 Main statistics of maturation, expressed in Total Soluble Solids (TSS), for the two fields studied.

Season	Min		Max		Range		SD		CV (%)	
2009-10	Cab		Cab		Cab		Cab		Cab	
Pre-Ha 1	17.6		21.2		3.6		0.96		4.8	
Pre-Ha 2	18.6		22.2		3.6		1.16		5.6	
Ha	19.8		24.0		4.2		1.20		5.3	
2010-11	Cab		Cab		Cab		Cab		Cab	
Pre-Ha 1	17.0		21.6		4.6		1.40		6.8	
Pre-Ha 2	17.2		22.5		5.3		1.56		7.4	
Ha	17.2		23.2		6.0		1.61		7.4	
2011-12	Cab	Cha	Cab	Cha	Cab	Cha	Cab	Cha	Cab	Cha
Pre-Ha 1	17.6	13.8	22.7	18.7	5.1	4.9	1.38	1.23	6.5	7.6
Pre-Ha 2	18.8	17.6	24.6	22.0	5.8	4.4	1.31	1.04	5.9	5.3
Ha	18.8	18.5	24.6	22.9	5.8	4.4	1.31	1.02	5.9	4.9
2012-13	Cab	Cha	Cab	Cha	Cab	Cha	Cab	Cha	Cab	Cha
Pre-Ha 1	15.6	15.0	20.9	19.0	5.3	4.0	1.38	1.16	7.1	6.7
Pre-Ha 2	17.2	18.8	22.4	21.5	5.2	2.7	1.37	0.76	6.5	3.8
Ha	18.3	21.0	23.9	23.9	5.6	2.9	1.50	0.77	6.8	3.4

Min:minumun, Max: Maximun, SD: Standard deviation, CV: Coefficiente of variation, Range: Range of variation. Pre-Ha 1: 20 days before Harvest, Pre-Ha 2: 12 days before Harvest. Ha: Harvest. Pre-Ha 1, Pre-Ha 2 and Ha expressed in °Brix. Cab: cv Cabernet Sauvignon, field 1. Cha: cv Chardonnay, field 2.

This first analysis highlight variability in the phenological development and maturation at the within field scale. Next sections aim at studying whether this variability is organised spatialy and if the observed variability is significant enough to justify site specific managements.

Spatial variability of the grapevine phenology and maturation

The semivariogram model which was generally better adjusted to the different phenological stages and maturation dates was the Gaussian model, with R^2 values ranging between 0.67 and 0.99 (Table 6 and 7). A significant variation is also observed in the range of the semivariogram which fluctuated between 22.8 and 150 m (Table 6 and 7). The range is in almost all cases higher than the sampling distance (25 m). This indicates the sampling distance is large enough to highlight the spatial variation. Range of the semivariogram exceeds in almost all cases length of the fields, showing the presence of a non-stationary phenomenon.

Table 6 Parameters of semivariogram adjusted for each phenological stage evaluated in the seasons.

Components of Semivariogram							
Season	Model	R^2	C_0	$C_0 + C$	a	DESP (%)	MCD (m)
2009-10 Cab							
Post- Bu	G	0.98	0.001	0.472	80.7	0.21	30.2
Fl	Sp	0.99	0.017	0.901	100.1	1.89	36.8
Ve	G	0.86	0.0002	0.162	92.3	0.12	34.6
2010-11 Cab							
Post- Bu	G	0.99	0.0018	0.266	72.6	0.68	27.0
Fl	G	0.77	0.001	2.85	81.8	0.04	30.7
Ve	G	0.99	0.0032	0.1053	112.4	3.04	40.9
2011-12 Cab							
Post- Bu	G	0.99	0.006	0.859	65.82	0.70	24.5
Fl	G	0.99	0.058	2.644	98.2	2.19	36.0
Ve	G	0.83	0.0001	0.298	95.44	0.03	35.8
2012-13 Cab							
Post- Bu	G	0.74	0.060	1.148	47.1	5.23	16.7
Fl	G	0.97	0.0010	0.686	67.4	0.15	25.2
Ve	G	0.97	0.0001	0.128	123.3	0.08	46.2
2011-12 Cha							
Post- Bu	G	0.93	0.034	0.676	115.4	5.03	41.1
Fl	G	0.95	0.0010	0.551	54.7	0.18	20.5
Ve	Sp	0.83	0.0010	1.520	97.3	0.07	36.5
2012-13 Cha							
Post- Bu	G	0.99	0.166	2.964	106.9	5.60	37.8
Fl	G	0.99	0.513	2.911	97.9	17.62	30.2
Ve	G	0.99	1.165	9.486	149.1	12.28	49.0

C_0: Nugget. $C_0 + C$: Sill. a: Range. DESP (%) Degree of spatial dependence. G: Gaussian, Ex: Exponential, Sp: Spherical, L: Linear. MCD: mean correlation distance. Post-Bu: Post-Budbreak, Fl: Flowering, Ve: Veraison. Post-Bu, Fl and Ve expressed in PS. Cab: cv Cabernet Sauvignon, field 1. Cha: cv Chardonnay, field 2.

For all seasons, all phenological stages and almost all maturation dates, a strong spatial dependence (DESP) was observed (Table 6 and 7). Indeed values of DESP are lower or equal to 25%. These results agree with those obtained by Baluja et al. (2013) at least for TSS measured at harvest.

The identification of a non-random spatial structure, for all the seasons throughout phenology and maturation could be explained by the environmental factors of the fields, such as the soil conditions and topography and their resulting effect on the microclimate of the canopy (Tesic et al. 2001). Thus, more research should be conducted to determine more precisely which factor or set of factors impact the within field microclimate and determine the spatial structure observed in phenology and maturation.

Table 7 Parameters of semivariogram adjusted for each maturation date evaluated in the seasons.

		Components of Semivariogram					
Season	Model	R^2	C_0	$C_0 + C$	a	DESP (%)	MCD (m)
2009-10 Cab							
Pre-Ha 1	G	0.94	0	1.041	32.9	0.00	12.3
Pre-Ha 2	G	0.93	0	1.420	41.0	0.00	15.4
Ha	G	0.91	0.001	1.470	68.4	0.07	25.6
2010-11 Cab							
Pre-Ha 1	G	0.98	0	2.031	31.6	0.00	11.8
Pre-Ha 2	G	0.96	0	2.625	30.3	0.00	11.4
Ha	G	0.76	0.0010	2.702	64.95	0.04	24.3
2011-12 Cab							
Pre-Ha 1	G	0.90	0.0000	1.846	31.6	0.00	11.8
Pre-Ha 2	G	0.92	0.0000	1.793	35.9	0.00	13.5
Ha	G	0.88	0.0010	1.687	58.72	0.06	22.0
2012-13 Cab							
Pre-Ha 1	G	0.91	0.2023	1.618	37.49	12.5	12.3
Pre-Ha 2	G	0.93	0.0000	2.161	39.98	0.00	15.0
Ha	G	0.99	0.0010	2.627	92.49	0.04	34.7
2011-12 Cha							
Pre-Ha 1	G	0.92	0.1319	1.693	38.2	7.79	13.2
Pre-Ha 2	G	0.93	0.0000	1.148	22.8	0.00	8.6
Ha	L	0.95	0.1415	-	-	-	-
2012-13 Cha							
Pre-Ha 1	G	0.89	0.4011	2.228	114.9	18.00	35.3
Pre-Ha 2	G	0.91	0.127	0.955	82.4	13.33	26.8
Ha	G	0.67	0.395	2.800	119.3	14.11	38.4

C_0: Nugget. $C_0 + C$: Sill. a: Range. DESP (%) Degree of spatial dependence. G: Gaussian, Ex: Exponential, Sp: Spherical, L: Linear. Pre-Ha 1: 25 days before Harvest, Pre-Ha 2: 12 days before Harvest. Ha: Harvest. Pre-Ha 1, Pre-Ha 2 and Ha expressed in °Brix. Cab: cv Cabernet Sauvignon, field 1. Cha: cv Chardonnay, field 2.

Fig. 5 and Fig. 6 show the spatial distribution of the main phenological stages and maturation respectively for field 1. Fig. 7 and Fig. 8 show the spatial distribution of the main phenological stages and maturation for field 2. For both fields and almost all the maps, two well-contrasted zones resulting from the clustering method can be observed. For field 1, more advanced phenological stages and maturation are observed in the North-Western part of the field. This zone is rather flat and is characterised by a deeper soil and less inclination. Meanwhile, for field 2 more advanced phenological stages and maturation occur in the southern part of the field. This latter zone is located in a slightly lower position, characterized by a higher total soil water availability (data not shown).

Relationship with canopy temperature

Regarding results of temperature sensors (Fig. 9) a relationship between phenology and canopy temperature is clearly highlighted. There are important differences in temperature between zones (defined in Fig. 3) throughout the 37 days of measurements (Fig. 9 a) for field 1. Sensor located in zone 1 (Fig. 3) showed higher temperature and GDD (Fig. 9 b), which may explain more advanced phenology and maturation stages (Fig. 5 and Fig. 6). The difference in temperature between zones was 0.4 °C per day and 15 GDD (between DOY 257 and 293).

Variability observed in both phenology and maturation (Fig. 5 and 6) may correspond to zones where microclimatic conditions are different. In our conditions, at within field scale, we can hypothesize that stable factors as differences in soil type, slope, topography and vegetative expression, could explain these differences in microclimatic conditions (temperature) and consequently differences in grapevine phenology and maturation. Then, determination of environmental factors which drive grapevine phenology and climate variability at the within field scale could constitute interesting investigations to map spatial variability of grapevine phenology at this scale.

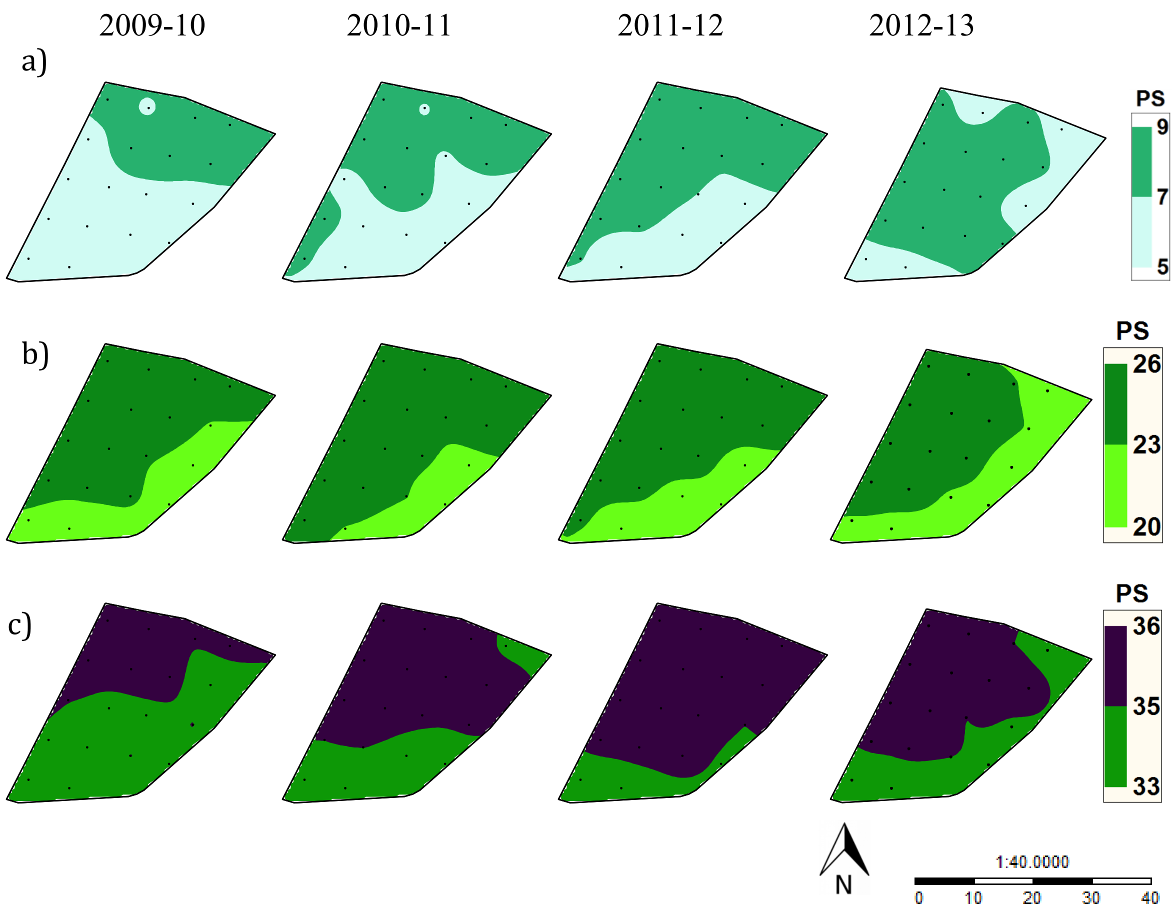

Fig. 5 Maps of spatial distribution of the main phenological stages, field 1, 2009-10, 2010-11, 2011-12 and 2012-13 seasons. a) Post-Budburst, b) Flowering and c) Veraison. a), b) and c) expressed in units of phenological scale (PS).

Temporal variability of the grapevine phenology and maturation

The spatial distribution of all maps (Fig. 5, 6, 7 and 8) presents fairly constant and well defined spatial patterns. These latter remain stable within each season and between seasons. This stability is observed for both fields. Baluja et al. (2013) reported a high temporal stability of spatial patterns of the TSS measured at harvest over 3 seasons in a plot of 2.2 ha of the cultivar Tempranillo in Navarra, Spain. In turn, results obtained by Bramley (2005) and Tisseyre et al. (2008) show that spatial patterns were not as stable over time for the same variable. In this way, the temporal stability is probably a characteristic of the specific conditions of each of the experimental sites, such as the weather and soil conditions and the choice of harvest date (Tisseyre et al. 2008; Baluja et al. 2013). It is worth mentioning that, in the present investigation, the environmental conditions over the seasons were quite similar (Table 3) and that the harvest date was considering when mean of the field reached 22 °Brix for each seasons, which would explain the stability of the observed patterns.

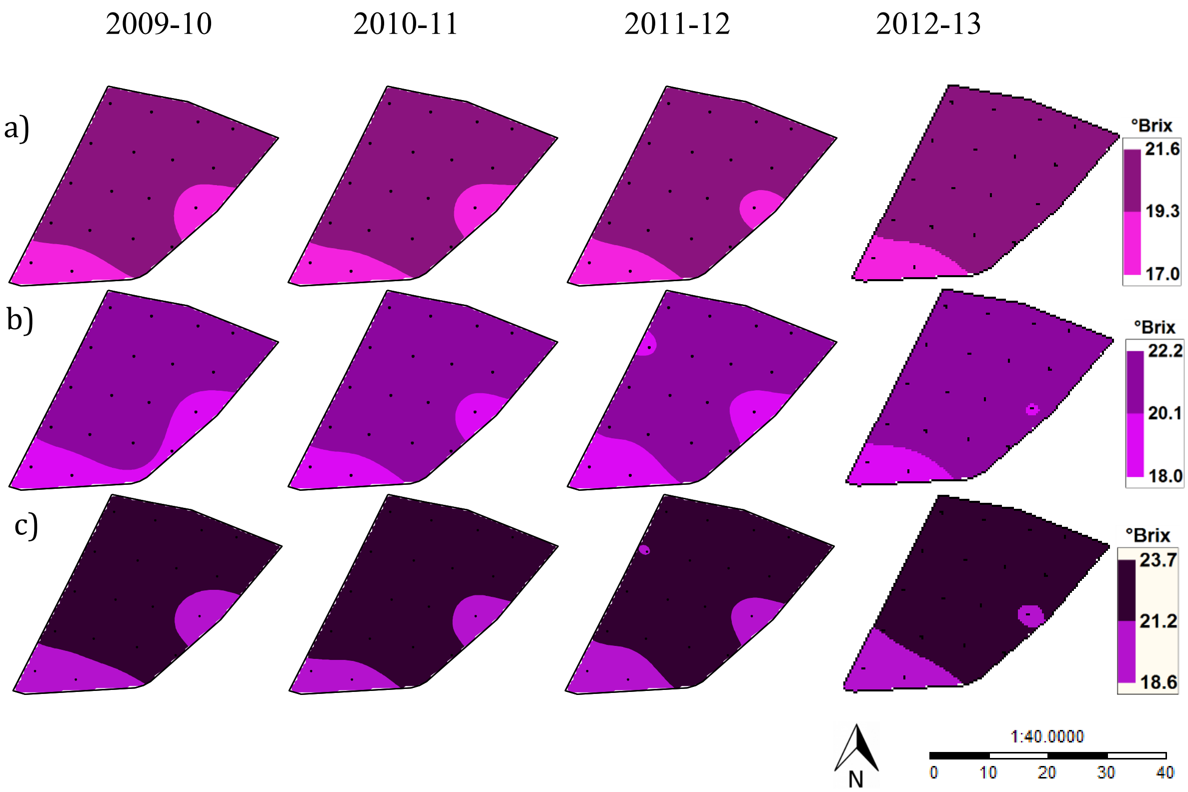

Fig. 6 Maps of spatial distribution of the maturation, expressed in total soluble solids (°Brix), field 1, 2009-10, 2010-11, 2011-12 and 2012-13 seasons. a) Pre-Ha 1 (25 days before harvest), b) Pre-Ha 2 (12 days before harvest) and c) Ha (Harvest).

The Kendall coefficient of concordance W (Table 8 and 9) was used to quantify the TSSV of phenological stages and maturation. Results of TSSV between seasons are shown in Table 8. Observed W values are high (W > 0.5) and statistically significant for both fields either for phenology or maturation. This result corroborates the temporal stability observed on maps presented previously (Fig. 5, 6, 7 and 8).
Results of within season TSSV are shown in Table 9. For both fields, observed W values are high and statistically significant either for phenology (W > 0.54) or maturation (W > 0.78). This high TSSV observed within each season suggests that information generated at the beginning of the season (post-budburst) can be used at a later date to characterize the spatial variability of both phenology and maturation.

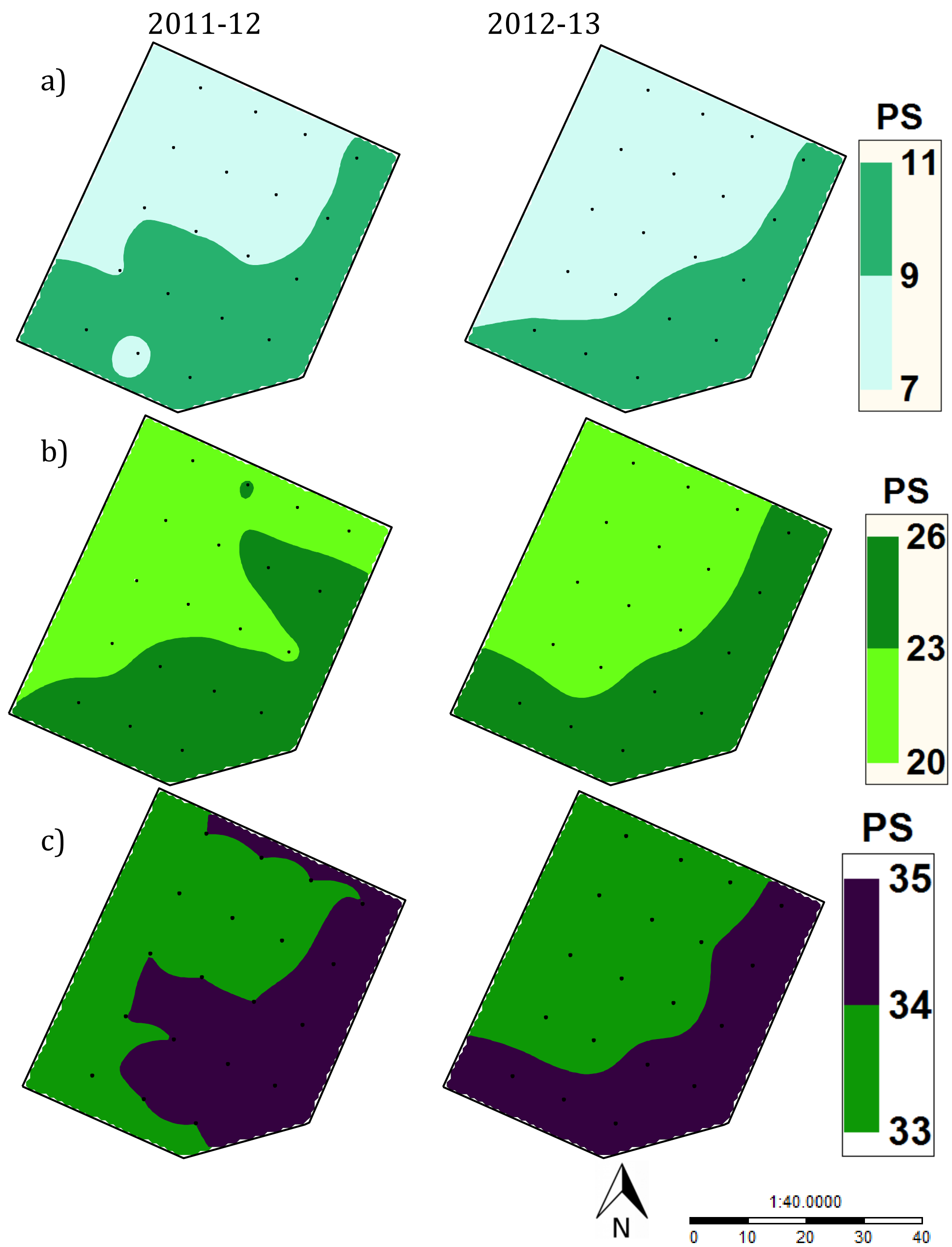

Fig. 7 Maps of spatial distribution of the main phenological stages, field 2, 2011-12 and 2012-13 seasons. a) Post-Budburst, b) Flowering and c) Veraison. a), b) and c) expressed in units of phenological scale (PS).

Zoning of the vine fields according to their phenology and maturation

The cluster analysis allowed us to define two clearly contrasted zones in terms of phenology (Fig. 10 a and b) and maturation (Fig. 10 c and d). As expected, zones obtained from the cluster analysis were very similar to zones observed on Fig. 5 to 8. Regarding the phenology, zone 1 (cluster 1) represents 78% and 42% of the area of the field 1 and 2, respectively (Fig. 10 a and b). For the maturation, zone 1 (cluster 1) represents 89% and 58% of the area of the field 1 and 2, respectively. Zone 1 presents the most advanced phenological stages (highest values of PS) and most advanced maturation (highest values of TSS), for both fields. Zones presented in Fig. 10 (a, b, c and d) integrates all the dates of the seasons. Therefore they highlight possible management zones. High similarity is observed between zones defined for phenological stage and maturity for both fields.

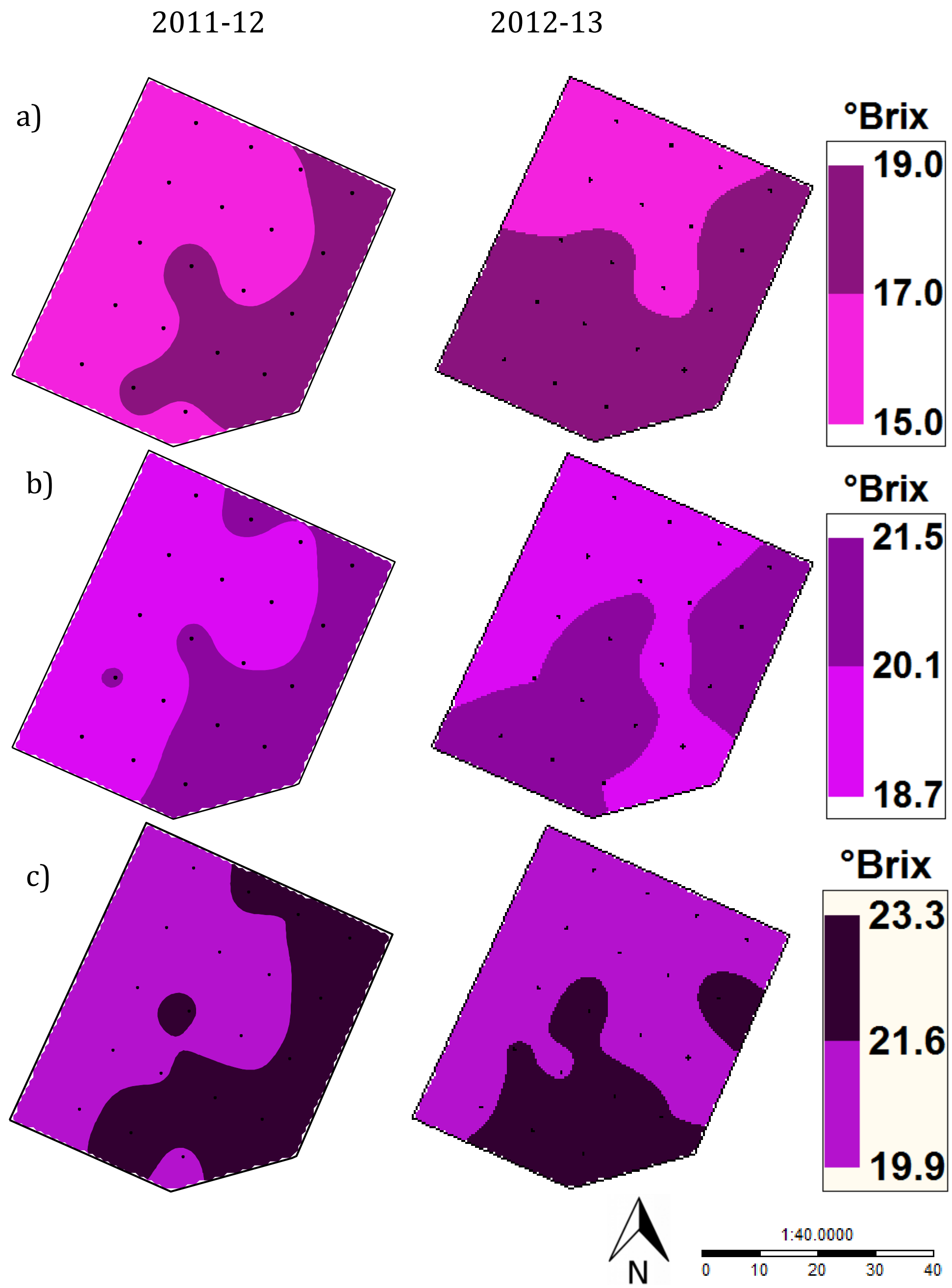

Fig. 8 Maps of spatial distribution of the maturation, expressed in total soluble solids (°Brix), field 2, 2011-12 and 2012-13 seasons. a) Pre-Ha 1 (25 days before harvest), b) Pre-Ha 2 (12 days before harvest) and c) Ha (Harvest).

The zone 1 of field 1 differ only in 1 site of the grid between phenology and maturation, while for field 2, it differs in 3 sites. This suggests a strong relationship between the phenological development of the grapevine and the maturation. Parker et al. (2014) observed that differences in maturation (expressed in TSS) at harvest were the result of changes observed at the onset of maturation, during veraison. Therefore, variability of phenology, for example at veraison, may constitute a relevant decision support to define harvest zones of different quality early in the season.

In order to verify the opportunity to manage specifically zones identified on our experiments, analysis of the delay in term of days has been performed. This analysis is presented in the next section.

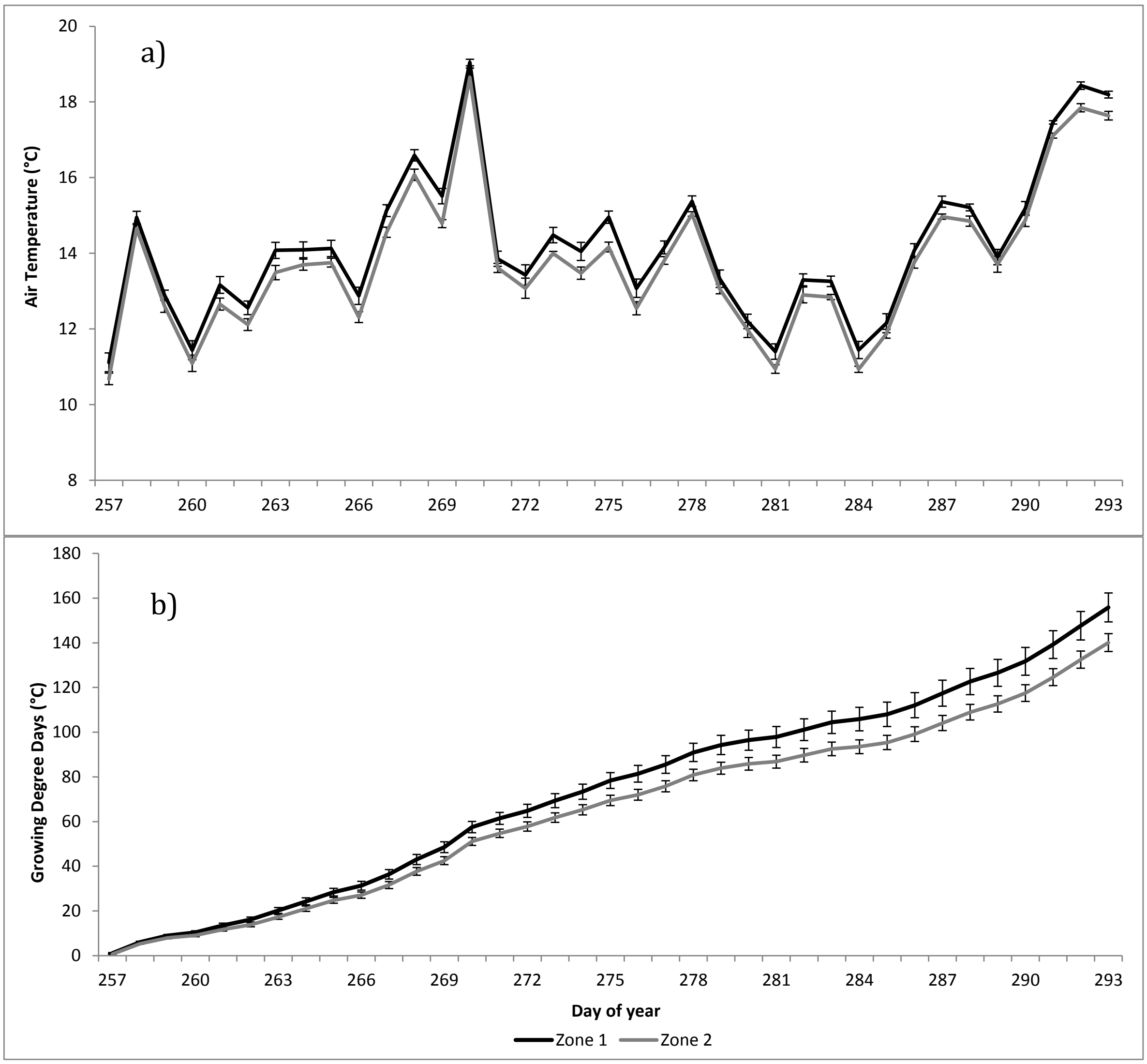

Fig. 9 Air temperature (a) and growing degree-days (b) for each zone (zone 1 and 2) from the field 1 (cv Cabernet Sauvignon). Each point on the figure represents the average of 4 sensors for each zone.

Grapevine phenology and maturation expressed in days

From an operational point of view, vinegrowers need to quantify the difference in days among the different phenological stages and maturation of the zones so as to plane their work. Thus, the numeric phenological stage was turned into chronological days through the implementation of a predictive model of phenology (Ortega-Farías et al. 2002). The calibration of this predictive model (Eq. 3) with our data led to a fit of R^2=0.99 for both cultivars. In the same way the maturity index (MI) used to turn into chronological days the difference in maturation (TSS, °Brix) yielded a value of 0.01 and 0.02 °Brix d $°C^{-1}$ for the cv Cabernet Sauvignon and cv Chardonnay, respectively. Differences between MI values is explained by the precocity of each cultivars.

Table 8 Kendall Coefficient of Concordance (W) for phenological stage and maturation throughout all the seasons (4 for field 1 and 2 for field 2).

Phenological Stage and maturation	W Kendall	Significance ($p<0.01$)
Cabernet Sauvignon (Field 1)		
Post-Budburst	0.51	**
Flowering	0.67	**
Veraison	0.67	**
Pre-Ha 1	0.69	**
Pre-Ha 2	0.65	**
Harvest	0.70	**
Chardonnay (Field 2)		
Post-Budburst	0.85	**
Flowering	0.77	**
Veraison	0.51	**
Pre-Ha 1	0.77	**
Pre-Ha 2	0.51	**
Harvest	0.65	**

Table 9 Kendall Coefficient of Concordance (W) for phenological stages and maturation within the seasons.

Season	W Kendall	Significance ($p<0.01$)
Cabernet Sauvignon (Field 1)		
2009-2010		
PS	0.72	**
Ma	0.83	**
2010-2011		
PS	0.76	**
Ma	0.87	**
2011-2012		
PS	0.85	**
Ma	0.80	**
2012-2013		
PS	0.72	**
Ma	0.88	**
Chardonnay (Field 2)		
2011-2012		
PS	0.54	**
Ma	0.80	**
2012-2013		
PS	0.81	**
Ma	0.78	**

Ps: Phenological stage, Ma: Maturation

Fig. 11 present results of the difference between within field zones relative to the mean field considered as reference level equal to 0. Positive values refer to advance in phenological stage and maturation, while negative values refer to delay in these parameters. For field 1 differences between each zone of the fields ranges from 3 to 5 days depending on the phenological stage considered and from 35 to 36 days depending on the maturity dates considered (Fig. 11 a). Regarding zone 2, it presents the highest deviation from the mean of the field. This is because zone 2 represents a small part of the field, therefore mean field is logically, closer to the mean of the zone 1.

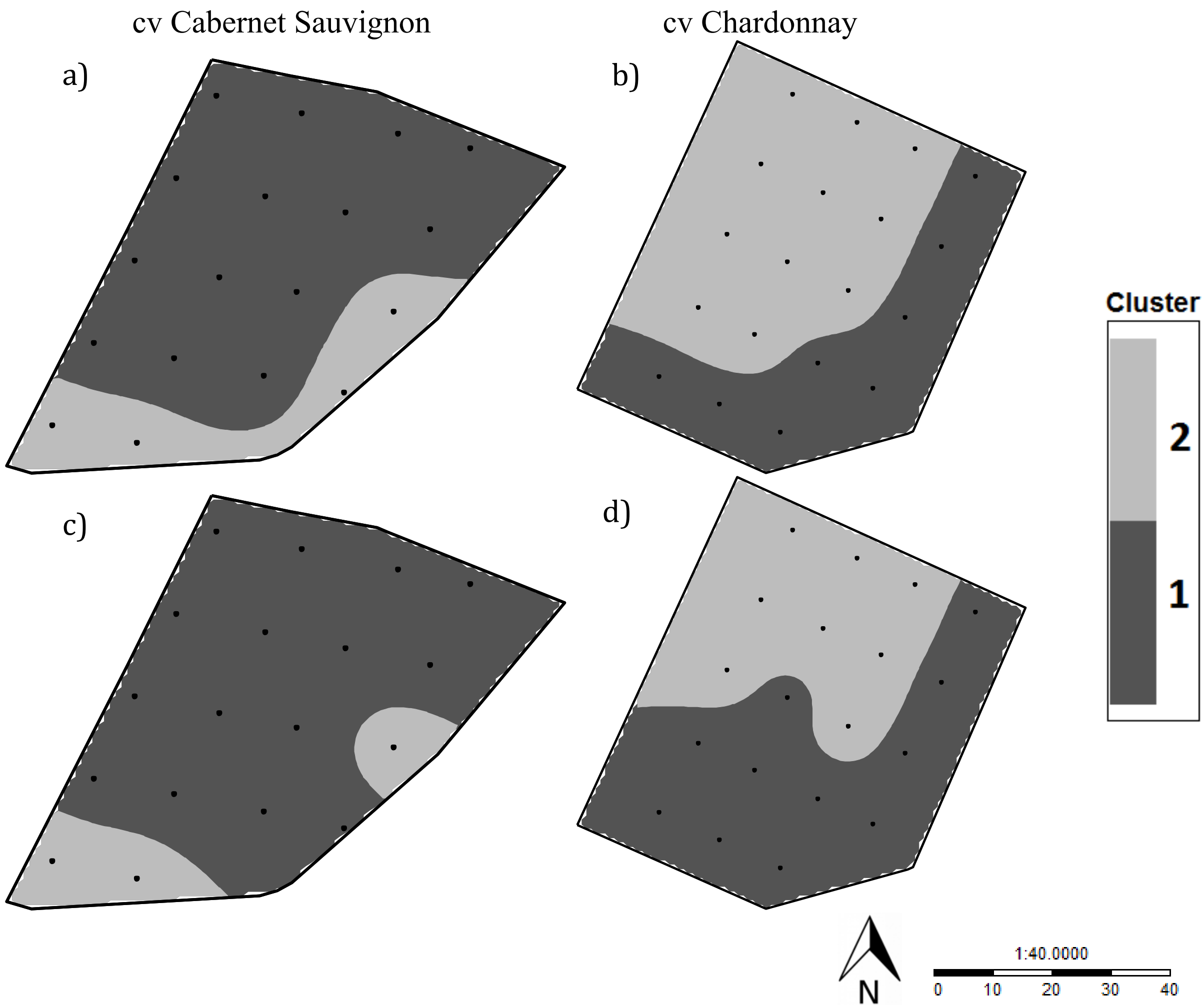

Fig. 10 Mapping of the cluster analysis for field 1 (a and c) and field 2 (b and d). a) and b) cluster analysis of the main phenological stages. c) and d) cluster analysis of the maturation (total soluble solids).

For field 2 (Fig. 11 b), observed differences in post-budburst (3 to 4 days) increase slightly in subsequent phenological stages, showing the veraison as the phenological stages that presents the highest difference (5 days) with respect to the mean field (value 0). For maturation, differences between 3 and 5 days were observed. In general, differences observed for field 2 are much smaller than those observed for field 1. This suggest that factors that explain observed differences in both fields may be different or present a lower magnitude of variation in field 2. The magnitude of difference (in days) between zones varied from 4 to 7 days for the phenological stages of field 1, with flowering presenting the higher difference. Regarding the maturity of field 1, the difference between zones varied from 42 to 43 days. For field 2, difference varied from 6 to 9 days for phenology, with veraison presenting the higher difference between zones. For maturity of field 2, this difference varied from 5 to 8 days. The variability of the phenological stages expressed in days (Fig. 11) was higher for veraison in both fields. Indeed it can be related to the subjectivity of measuring this stage (associated with colour change estimated visually), therefore the definition of zones within field could reduce variability to estimate this phenological stage, improving the accuracy of the estimation. With respect to maturation, variability in days was higher for field 1.

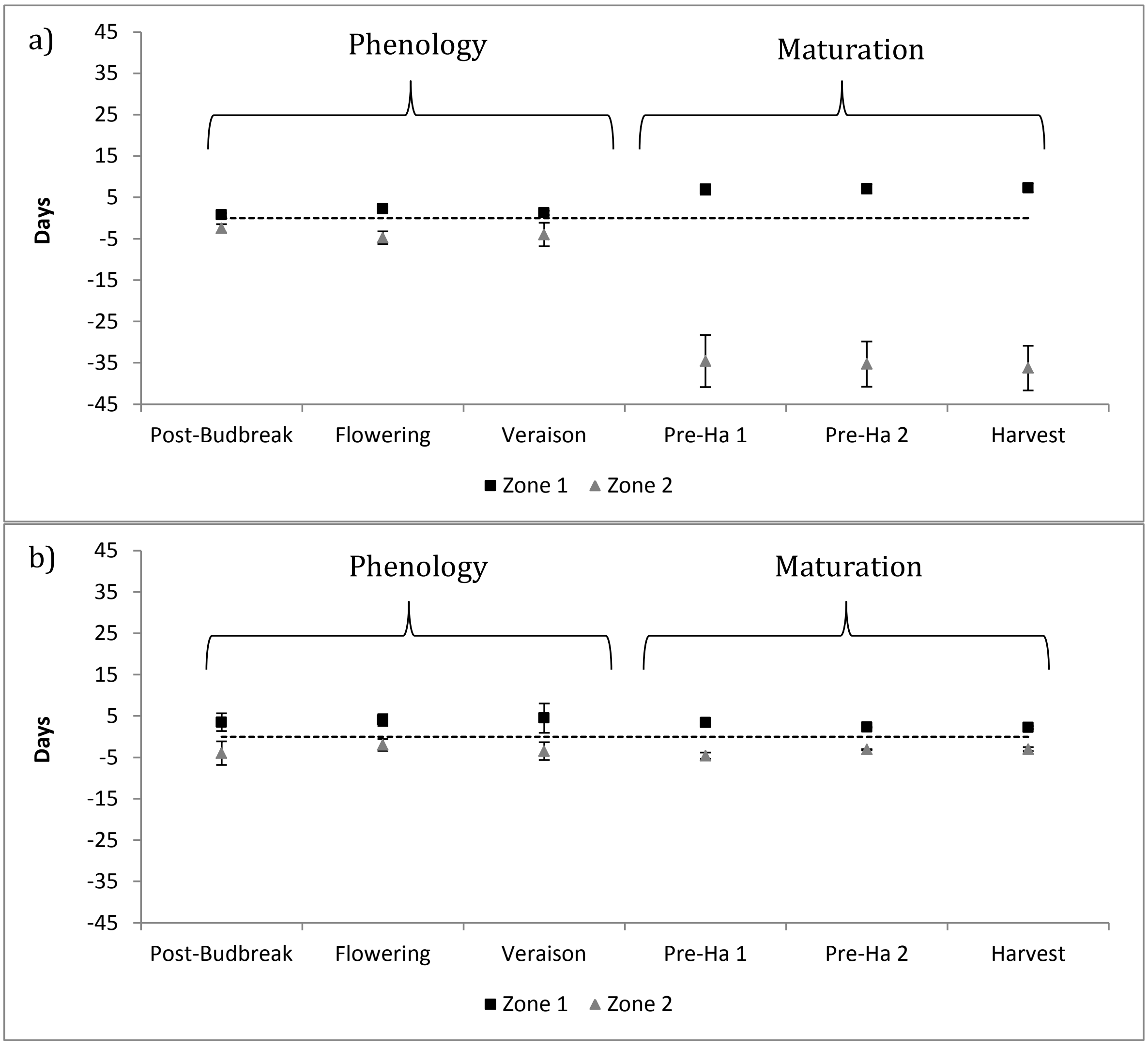

Fig. 11 Days difference between the defined zones (cluster analysis) according to the average of the fields, for the main phenological stages and maturation. (a) field 1 and (b) field 2. The dashed line represents the reference level (0). Each point on the figure represents the average of all seasons considered for each cultivar (4 for field 1 and 2 for field 2). Vertical bars represent the standard deviation.

General discussion

This work showed that there is a significant spatial variability in the phenological development and maturation within the studied vine fields. This variability was spatially organised and temporally stable from the beginning of the season (post-budburst) to harvest and over the years. This suggests that factors explaining this phenomenon would be related to stable parameters of the environment affecting microclimate conditions. This effect may be emphasized by the perennial specificity of grapevines. It was shown, for one field that the phenology and maturation zones correspond to zones where the microclimate was different. The observed differences in the microclimate of the field 1 can be explained by stable environmental factors (soil characteristics, slope, soil texture, presence of groundwater and compacted strata that limit the growth of the root, etc.), i.e., the spatial variability of stable environmental factors produced differences in the microclimate of each zone, which affected the phenology and maturity of the grapevine. This explains the observed high stability of zones between different seasons for field 1. There is no information on factors that determine the spatial variability of both microclimate conditions and phenological development at the within field scale in the litterature.

These results generate new questions concerning the modelling of the spatial variability of the grapevine phenology at the within field scale. Two approaches may be considered for further experiments: a) microclimate monitoring from wireless temperature sensors network, such as works carried out at the meso scale level (Quénol et al. 2014). However, it is important to define the number of sensors to be installed, location of those in the field and the maintenance cost of the system which may limit its practical application (Kunz and Tatham 2012; Primicerio et al. 2013). b) Characterisation of environmental factors at a high spatial resolution. This approach corresponds to using high spatial resolution data (topography, soil characteristics, slope) with low operational costs, for example, obtained by unmanned aerial vehicle (Matese et al. 2015). Assuming these factors explain the spatial variability of microclimate and the resulting variability in phenology and maturity, an empirical model combining observations and high resolution spatial data could be considered to model the microscale spatial variability of the phenology. The methodology used for the water status in grapevines (Acevedo-Opazo et al. 2010) could be a relevant approach in this case.

The observed within field differences may have important implications for crop management. The goal of the following section is to identify the opportunity to manage the observed within field variability for each phenological stages as well as for maturity.

For post-budburst, observed magnitude of variation may have practical applications concerning spring freeze event. Susceptibility of the buds to spring frost depends on the phenological stage of buds (Friend et al. 2011). In a controled experimentation, Friend et al. (2011) showed that the effect of frost was different when occuring on two treatments characterized by a difference of 1 PS (corresponding to 4 days in our study). A significant increase in primary shoots death for the most advanced treatment (at budburst) was observed while reduced damages were observed in delayed treatment. Differenciate effect of frost had a significant impact on yield at harvest. In our study, observed difference of 4 to 8 days (Fig. 8 a and b) corresponding to 2-3 PS (Fig. 3 and 5) for post-budburst could lead to significant differences between zones in case a frost event occurs at this period. Practicaly, the delineation of phenology zones is hardly manageable at this stage since spring frost events are hardly predictable. However, when it occurs, differential effect of the frost may be of importance to understand the resulting within field yield variability and to consider site specific management operations later in the season.

Flowering is considered as a critical stage for disease development such as powdery mildew and botrytis (Campbell et al. 2007). Therefore, this stage determines the application date of specific pesticides to control these diseases (Bramley et al. 2011). Thus, a delay in fungicide application, waiting for the slowest zone of the field to reach the flowering stage, could impact negatively on the proper control of the most advanced zones. In our study, the average differences between the zones were 7 days for field 1 and 6 days for field 2. To our knowledge, there is no information in the literature dealing with the effect of application time on diseases control. However our study provides new background information on the spatial variability of flowering. These results open opportunities to better understand the success or failure of control strategies and the resulting within field variability of diseases. Information on the spatial variability of the incidence and severity of diseases in vineyards is scarce. Bramley et al. (2011) found that incidence and severity of the two main diseases (powdery mildew and botrytis) was spatially variable at the within field scale. The same authors observed that diseases development was associated to the topography (slope), they hypothesised that topography explained differences in microclimate more or less favorable to diseases development. Regarding our results, it can also be hypothesized that topography and the resulting microclimate could affect the date of flowering. Considering homogeneous pesticides application over the vineyards, protection associated with the applications may vary according to spatial variability of flowering. Therefore, spatial variability of diseases may be due to either differences in phenology (and resulting pesticides efficiency) or to environmental factors that directly affect diseases development (Valdés-Gómez et al. 2011). These considerations highlight the necessity to take into account the spatial variability of phenology (and especially flowering) to better understand factors that affects diseases variability. Specific experiments based on phenology maps and differential application of pesticides should be considered to properly analyse the spatial variability of diseases development at the within field scale.

Regarding the period going from fruit setting to veraison, it is of critical importance to manage irrigation. Spatial variability of phenology may be a relevant decision support to consider site specific management zones of regulated deficit irrigation strategies in such a way to optimize the final quality of the grapes (Ojeda et al. 2002; Acevedo-Opazo et al. 2005; Girona et al. 2009; Acevedo-Opazo et al. 2010). For veraison, Parker et al. (2014) observed that differences in veraison remain stable until harvest affecting the final wine quality. It confirms our results of the temporal stability of the zones of phenology and maturity. Therefore, phenology maps may be useful to determine maturity zones at the within field scale. These maturity zones are the basis of a decision support to manage grape quality at harvest by considering, for example differential harvest over time and/or space (Bramley 2005). Note that in our experiment, differential harvest would be of great interest in the field 1. Indeed, for this field, zone 2 never reaches the expected maturity. This is probably due to the specific soil conditions associated to inadequate irrigation management (Acevedo-Opazo et al. 2013). In this case, zone 2 could be harvested separately.

Identifying the spatial variability of the phenology could be a useful decision support to suggest management strategies that seek to homogenize the vine field phenology. Authors have reported that a late winter pruning operations delayed by 4-5 days the date of budburst (Dunn and Martin 2000). Thus, site specific pruning operation could reduce differences in

phenological development. More generally, our study points out the interest in delineating phenology zones to optimise field sampling and to improve the efficiency of the various agricultural operations and decisions during the season.
This work focused on the variability of the phenology at the within field scale. For terroir delineation or climate change monitoring purposes, other studies focused on the phenology and its variability at meso scale (Barbeau et al. 1998; Webb et al. 2007). At the regional scale (denomination of Loire Valley, France), Barbeau et al. (1998) found differences in dates of budburst, flowering and veraison ranging from 6 to 8 days on cv Cabernet Franc. At the same scale Webb et al. (2007) in Australia and Valdés-Gómez et al. (2011) in Chile, reported the results of simulations on the effect of climate change on the phenological development of the grapevine. Under different climate change scenarios, these authors reported advances in budburst date ranging from 4 to 12 days for cv Cabernet Sauvignon. It is interesting to note that phenology variability observed at larger scales or under scenarios of climate change is similar and comparable to those obtained at the within field scale. This observation raises new questions:
- on the sampling strategy aiming at characterising grapevine phenology of a field at this scale. Indeed, regarding the observed within field variability, sampling quality is of paramount importance to guarantee that differences in phenology is related to macro scale factors and not to micro scale (within field) effects,
- on management practices adaptation to climate changes. Our work showed that observed within field variability encompasses change in phenology estimated from climate change scenarios. This may demonstrate the robustness of current vine fields to climate change since within field zones may still be well adapted to the expected climate change.

CONCLUSIONS

To our knowledge, this is the first study highlighting within field spatial variability in the phenological development of the grapevine and maturation simultenaously. In our conditions, this variability proves to be spatially organised and temporal stable since advanced and delayed zones remain stable throughout the growing season (from post-budburst to harvest). It was possible to identify two well-contrasted zones of phenology and maturity within each vine field. Observed magnitude of variation was similar to the one observed at larger scales or under scenarios of climate change. These results should be considered for the sampling strategy of phenology and maturation at within field scale and for planning production activities. Differences in phenology may explain the spatial variability observed in other variables such as yield and disease development. Further investigations should determine the environmental factors which drive the observed spatial variability in phenology and maturity, and if possible propose predictive models that consider this variability.

ACKNOWLEDGEMENTS

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CHAPTER II

CHAPTER 2: 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 the Within-Field Variability (TSWFV) of total soluble solids (TSS) as an estimate of grape maturity.

Methods and results: The experiment was carried out between years 2009 and 2015, taking into account two to four years for the different fields (4), corresponding to four different cultivars, all of them located in the Maule Valley, Chile, under irrigated conditions. A regular sampling grid was designed within each field. On each site of the grid, TSS was measured at 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 a high within-field variability in TSS. The W test showed a significant intra and inter-annual TSWFV and r_s values showed a high and significant correlation between sampling dates.

Conclusion: For precision viticulture, these results are of interest since in the conditions of the experiment, TSS maps obtained 40 days before harvest present the same spatial patterns 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, which allows estimation of TSS values for the whole field, using only one punctual reference measurement provided that historical data are available.

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

Introduction

One of the main goals of Precision Viticulture (PV) 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 to consider differential harvest in order to produce wines with different characteristics and properties (Trought and Bramley 2011; Baluja et al. 2013; Urretavizcaya et al. 2013). Defining zones of quality is therefore of paramount importance for differential harvest. Grape characteristics are commonly estimated by sampling on several dates during the maturity process (Sadras and Petrie 2012). Among all the berry parameters, total soluble solids (TSS) is commonly measured to monitor the maturity, berry composition and to determine the optimal date of harvest (Baluja et al. 2013; Hall et al. 2010; Sadras and Petrie 2012; Santos et al. 2012). TSS is a parameter which 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 soon 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. 2010). However, the correlation between NDVI maps and grape composition (TSS among others parameters) is not systematic in non-irrigated conditions (Acevedo-Opazo et al. 2008; Santesteban et al. 2013) or in irrigated conditions (Tagarakis et al. 2012). 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. (2013). It is based on the early sampling of grape composition in the vineyard. This approach assumes that, during the maturation, there is a temporal stability of 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 (Urretavizcaya et al. 2013) conditions. 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 practices (irrigation, fertilization, canopy management, training system, etc.), genetics (rootstock, cultivars), and soil and climate characteristics. These factors, altogether, can lead to stability or instability of quality zones, whether at an intra-annual and/or at an inter-annual scale. This complexity justifies performing specific studies in different soil and climatic conditions to produce guidelines for local growers and also for the scientific community.

The aim of this work is to study the temporal stability of the within-field variability (TSWFV) of total soluble solids as an estimate of grape maturity in semi-arid irrigated vineyards. The study of the TSWFV is justified by practical standpoints. Indeed, if proved, the presence of the TSWFV for TSS permits 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 of TSS to propose a local empirical spatial model at the within-field scale may be considered. This last point is discussed in the last part of this paper.

Materials and methods

Experimental Fields

The experiment was carried out on four fields (one cultivar each) of the cvs Cabernet Sauvignon (CS), Chardonnay (CH), Sauvignon Blanc (SB) and Carménère (CA), all of them located in the Maule Valley, Chile, under irrigated conditions (Fig. 1). The cultivars CS, CH and SB are located at the University of Talca's experimental vineyard, while the cultivar CA is located in a commercial vineyard in Pencahue, 18 kilometers away from the other fields. All vineyards were managed according to the conventional agricultural practices used in the commercial vineyards of central Chile in terms of canopy management, fertilization, pest and disease control, pruning and irrigation, for all the seasons of the study period. Characteristics of each field are summarized in Table 1.

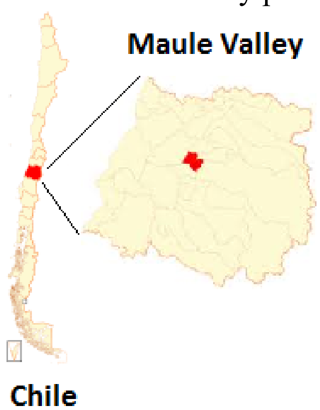

Figure 1 Location of the Maule Valley in Chile.

Table 1 Field characteristics of the 4 experimental fields.

Cultivars	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		

VSP: Vertical shoot positioned System

Within each vine field, a regular sampling grid of 20×20 m was designed (Fig. 2). According to the field area, 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 of the grid was represented by four consecutive plants in the same row. This sample grid was mainly conditioned by the operational constraints related to the time required to make the measurements over the fields. Note however, that in absence of other spatial information, considering 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 ProXRS, Sunnyvale, California, USA) and stored as East and North coordinates (Datum WGS84, UTM projection, Zone 19S).

Climatic data

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

Measurements of total soluble solids (TSS)

On each site of the grid (Fig. 2), TSS was measured using a thermo-compensated refractometer (BRIX30 model, Leica, USA) on a sample of 48 berries. Berries were selected following the same methodology for each site and proposed by Trought and Bramley (2011): for each of the 4 vines of a site, two clusters were randomly chosen, and for each cluster, two berries were sampled at the top, the middle and the bottom of the clusters to obtain a total of 6 berries per clusters which resulted in 48 berries per site. The 48 berries were crushed in a plastic bag and TSS was measured from the resulting juice. For each site, measurements were made from veraison to harvest at intervals ranging from 2 to 15 days. Measurements of phenology (budburst and veraison) was 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. 2001). The number of sampling dates was related to the precocity of each cultivar. This experiment lasted 4 years for CS and CH, 3 years for SB and 2 years for CA.

Analysis method

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, the Statgraphics Plus 5.1 (StatPoint Inc., Virginia, USA) software was used.

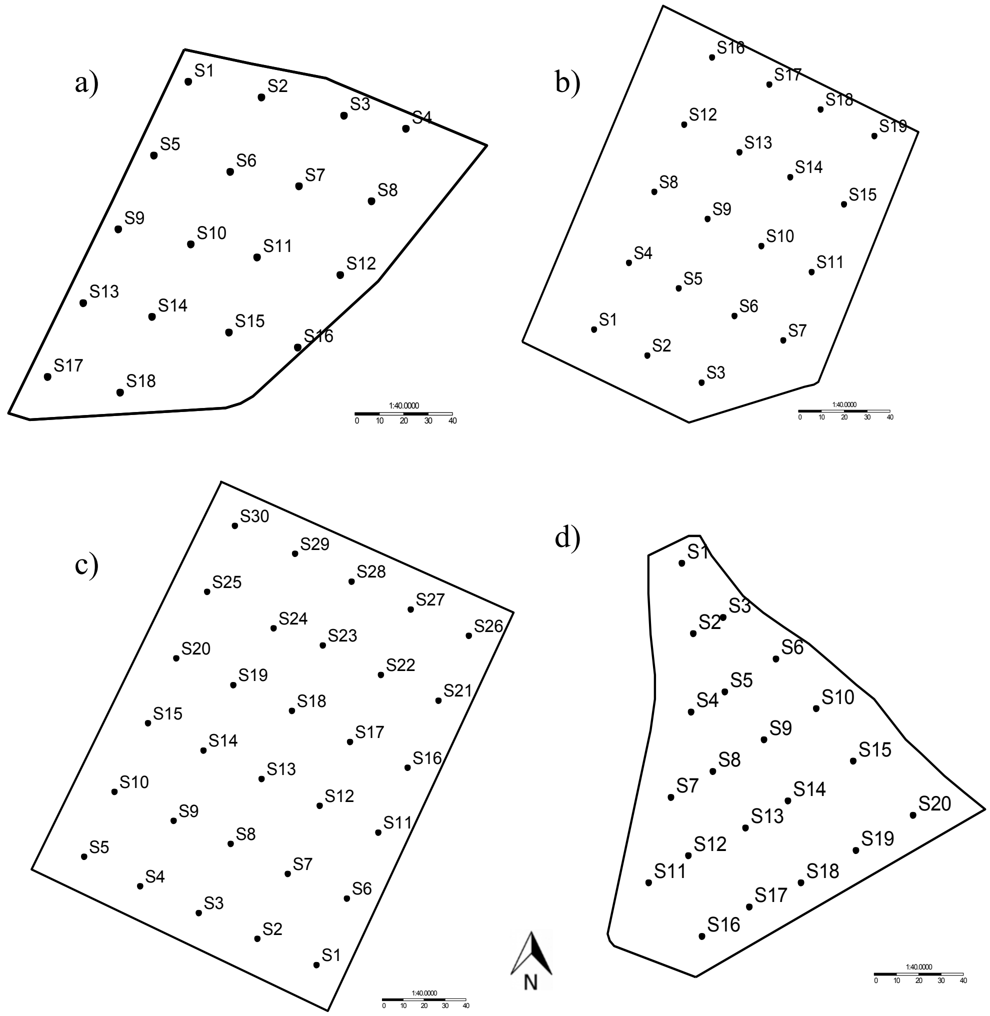

Figure 2 Measurement grids used in the experiments. 18 sites for cv Cabernet Sauvignon (a), 19 sites for cv Chardonnay (b), 30 sites for cv Sauvignon Blanc (c) and 20 sites for cv Carménère (d). S_i represents the sampling site number i.

Intra-annual TSWFV

In order to quantify the intra-annual TSWFV, two statistics were used: (i) The Kendall 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 cultivar and season. W focuses on the rank of the values and provides an assessment on 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 vine field (Fig. 2), and the "judges" were the different sampling dates measured in each season and cultivar. The analysis was then conducted on a matrix where the lines referred to the sampling sites and the columns to values of TSS measured at different dates for each season and cultivar. The

W varies from 0 (total disagreement or no temporal stability) to 1 (total agreement or high temporal stability). W was computed according to Eq. 1 (Saporta 1990).

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

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

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

Where:
n: is the number of sampling sites of each cultivar,
k: is the number of sampling dates considered,
$X_{i,t}$: is the rank of TSS value on the site i and the date t on each field, and
$\bar{R}$: is the average rank of the sampling site over all the considered dates.

When W value is significant, it means that at least one of the judge (in this case sampling dates) is concordant with one, or some of the others (Legendre 2005). Therefore, the W statistic was used to synthesize the results. The aim of the study is to generate information for harvest, for which a check was made to ensure and determine which dates are similar to the harvest. For the above, the Spearman's rank correlation coefficient (r_s) was used to analyse the relationship between sampling dates, using TSS measured at harvest as a reference. The aim of this analysis was to determine whether the same part of the vineyard systematically presents high, medium or low values of TSS, compared to TSS observed at harvest. The Spearman rank method does not require any assumptions either on the linearity of the relationship or on data distribution. The Spearman's rank correlation coefficient (r_s) was computed according to Eq. 2 (Saporta 1990).

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

Where:
n: is the number of sampling sites on each field,
X_{k,t_1}: is the TSS value on the site k and the date t_1 on each field,
X_{k,t_2}: is the TSS value on the site k and the date t_2 (date of harvest) on each field,
$R(X_{k,t_1})$: is the rank of X_{k,t_1} among all the values of the date t_1, and
$R(X_{k,t_2})$: is the rank of X_{k,t_2} among all the values of the date t_2 (date of harvest).

The 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 $p < 0.05$.

Inter-annual TSWFV
Depending on the field and the year, a different number of TSS measurements were performed (Table 2), from 4 to 8 measurement dates. In order to be able to analyse the

inter-annual TSWFV, only four 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 (4 for cv CS and CH, 3 for cv SB and 2 for cv CA). In this case, the *n* objects were the sampling sites of each cultivars (Fig. 2) and the "judges" were the different sampling dates measured according to each stage of maturity and cultivar. Similar to the Intra-annual TSWFV study, W value was used to synthesize the results. The W statistic does not allow to identify the number of pairs of judges (in this case sampling dates) that are concordant when W is significant (Legendre 2005). The Spearman's rank correlation coefficient (r_s) was used to verify the results obtained through W. For the above, 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 cultivars and stages of maturity.

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 cultivar, only 3 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 classes of TSS were therefore considered for each map: low (0-33% quantile), medium (34-67% quantile) and high (68-100% quantile).

Results

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 6 seasons of the experiment. Highest temperatures were recorded near veraison for all seasons (around 25ºC), while the lowest ones were observed at the beginning of the season. Regarding pattern of rainfall, this 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 for the same period. Accumulated rainfall in the veraison-harvest period was low (< 12 mm) for all the seasons, except for 2010-11 season (30 mm) (Fig. 3 b). These characteristics of high temperatures and the absence of significant rainfall during the veraison-harvest period are representative of environmental conditions of the Maule region.

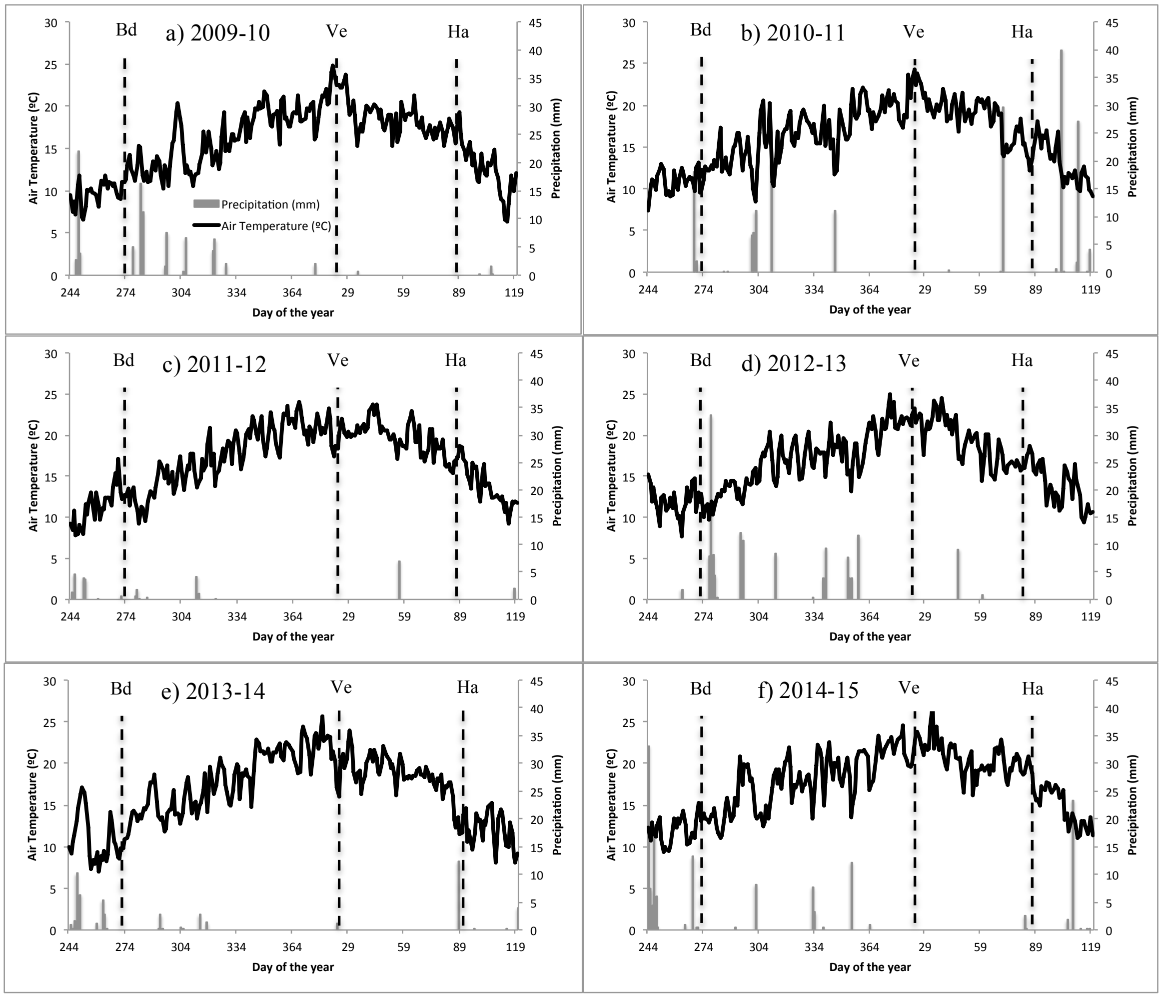

Figure 3 Air temperature and precipitation throughout all the seasons. Vertical dashed lines represent the average dates of phenological stages considering all cultivars together: budburst (Bd), veraison (Ve) and harvest (Ha).

Classical analysis

Fig. 4 shows the mean, the standard deviation (SD) and the coefficient of variation (CV) of TSS observed for each sampling date and each field over the different seasons. The magnitude of variation changes during the maturity process. For all the fields and the seasons a similar trend is observed, SD (like CV) decreases from veraison (~25 Day of the year, DOY) to harvest (DOY ~80-100). The highest values of CV occur when TSS has a value ranging between 8-13°Brix, which corresponds to veraison and the post veraison period (Parker et al. 2014), while lower values of CV occurs at harvest.

The change in CV is due both to an increase in the mean field value and a decrease in SD (Fig. 4). Comparing the variability between fields at harvest, the field of cv Sauvignon Blanc presented the highest variability (CV =8.2%) while cv Chardonnay presented the lowest CV (2.4 to 4.9%). These differences in CV may be explained by combined effects in both the characteristics of the cultivars and specific environmental conditions of each field. For example, cv Cabernet Sauvignon presents two series of soil that induce significant differences both in vine water status and vigour (Acevedo-Opazo et al. 2013) as well as in the phenology and fruit maturity (Verdugo-Vásquez et al. 2015).

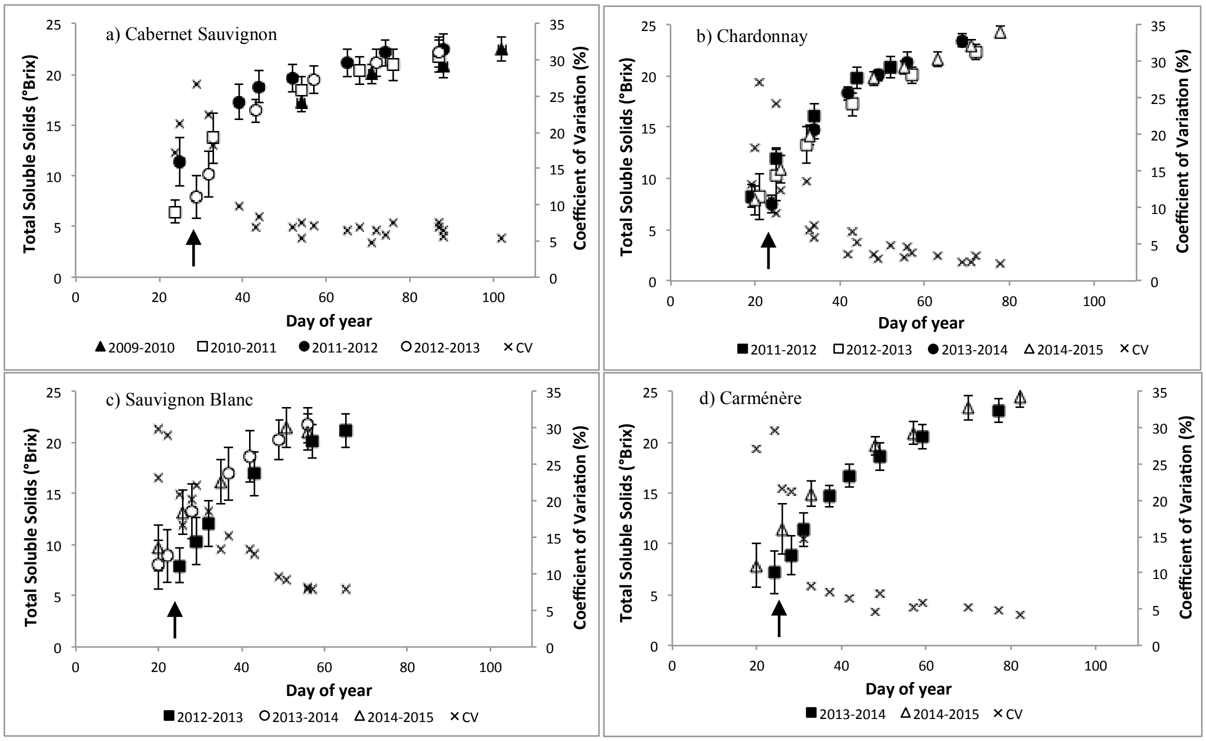

Figure 4 Total Soluble Solids (TSS, °Brix, circles, square and triangle) measured at different dates and Coefficient of Variation (CV, %) for the four fields. The bars represent the standard deviation (SD). The arrow indicates the mean date of veraison for each cultivar.

Intra-annual TSWFV

Coefficient W highlights a significant intra-annual stability from veraison to harvest for the four fields (Table 2). Observed W values were high (W >0.52) and statistically significant for all fields and seasons. Differences in W values in different seasons for each cultivar were related with the magnitude of variation of each season. In general, for each cultivar, seasons with higher variability (high SD and CV values) have higher W values.

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

Table 2 Kendall Coefficient of Concordance (W) of TSS measured within the seasons for each field (intra-annual stability).

Cultivar	N° dates	W Kendall	Significance (p<0.01)
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	**

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 increase regularly when advancing from veraison to harvest for all fields and seasons. In general, from 40 days before harvest to harvest, r_s values are high (>0.5) and therefore spatial patterns of TSS variability present strong similarities with ones at harvest. Before this period, i.e. 40-65 days before harvest r_s values are lower than 0.5 and are not statistically significant ($p < 0.05$). Therefore, TSS spatial variability present 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 until harvest. Considering an earlier date (>40 days before harvest), r_s values are not significant anymore, therefore the definition of maturity zones at these dates may be irrelevant for determining maturity zones for differential harvest purposes.

I*nter-annual TSWFV*

Regarding inter-annual TSWFV, observed W values are high (in general W >0.50) and statistically significant for all fields and stages of maturity (Table 3). W shows 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, cv Sauvignon Blanc presents the highest W value (0.74) while cv Chardonnay presents the lowest one (W =0.52). Table 4 shown the percentage (%) of pairs of sampling dates which present a significant ($p < 0.05$) value of Spearman's rank correlation coefficient (r_s) according to the stage of maturity for each cultivar. These results shown that when W is significant, the number of pairs of sampling dates that are concordant is higher than 2 pairs in most cultivars and stages of maturity. It is observed, in general, a gradual increase of the W and the percentage of pairs of sampling dates that are concordant from Veraison to Harvest for almost all the cultivars. It is important to note that, for the cv Chardonnay and Carménère this tendency is not observed. For these cultivars, when W values are low, it is associated with changes in the variability observed (SD and CV) between sampling dates compared.

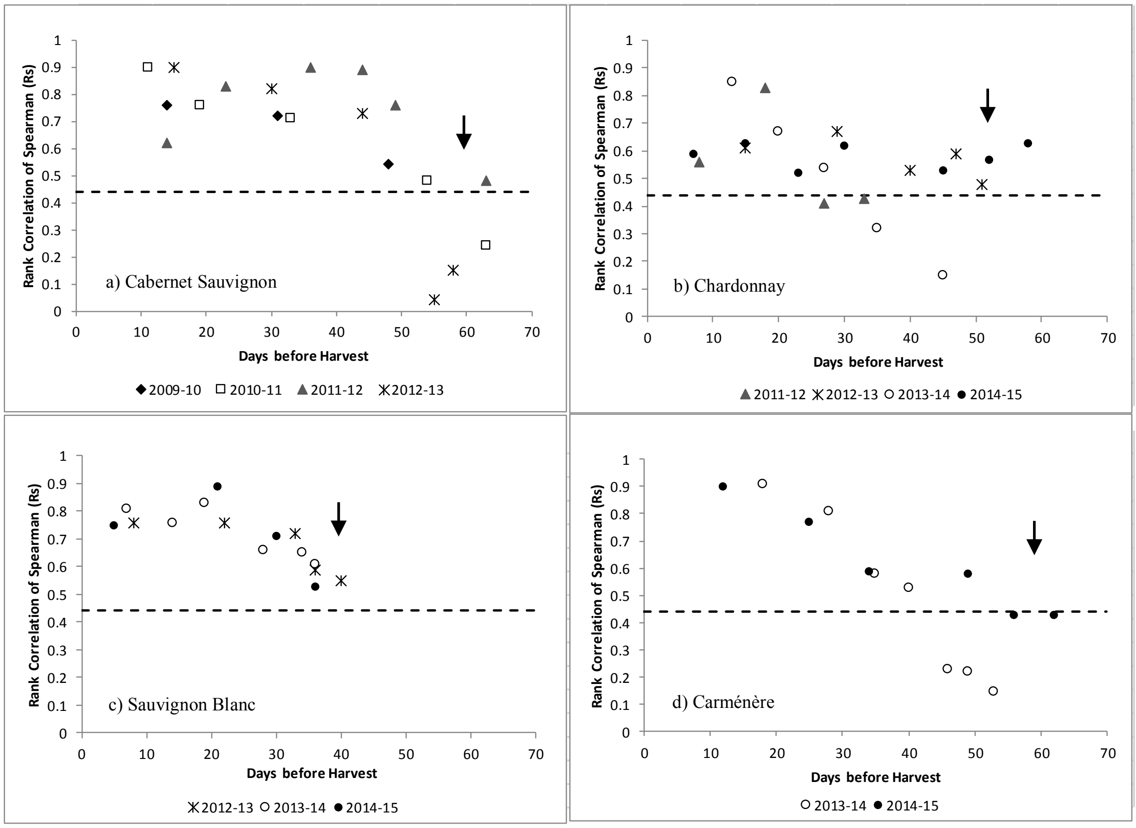

Figure 5 Change in Spearman's rank correlation coefficient (r_s) between TSS measured at different dates before harvest and TSS measured at harvest. Dashed lines represent the threshold over which r_s are statistically significant at $p<0.05$. The arrow indicates the mean date of veraison for each cultivar.

This result demonstrates the value of using data of the year "n" to estimate the within-field variability of the TSS for the year "n+1". For example, zones defined at harvest for year "n" may be used to provide relevant quality zones at harvest in the year "n+1".
The cultivar Chardonnay presents the lowest values of W for all stages of maturity. This lower inter-annual stability is probably caused by two early spring frosts which occurred at the beginning of the 2013-2014 season, specifically September 17th (minimum temperature = -0.6ºC) and September 28th (minimum temperature = -0.4ºC). cv Chardonnay being a cultivar with a high precocity, it was more affected than 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 between 31% and 7% for Veraison and Post-Veraison respectively, while for Pre-Harvest and Harvest the W values remained similar.

Table 3 Inter-annual Kendall Coefficient of Concordance (W) of TSS, according to stage of maturity, throughout all the seasons (4, 4, 3 and 2 seasons for cv Cabernet Sauvignon (CS), Chardonnay (CH), Sauvignon Blanc (SB) and Carménère (CA), respectively).

Cultivar	N° 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	**

Table 4 Percentage (%) of pairs of sampling dates which present a significant (p <0.05) value of Spearman's rank correlation coefficient (r_s) according to the stage of maturity for each cultivar.

	Cultivars							
	Cabernet Sauvignon		Chardonnay		Sauvignon Blanc		Carménère	
Stage of maturity	%	n[x]	%	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

[x]Total number of possible pairs.

Fig. 6, 7, 8 and 9 show maps of TSS measured for field cv CS, CH, SB and CA respectively, over all the seasons and for three dates in each season. For each season, these 3 dates were chosen to illustrate as best as possible a period of 35 days before the harvest. This choice allows for the illustration of the spatial organization of the variability of the TSS 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 the TSS observed both at an intra and inter-annual scale at the within field scale. Fig. 6 to 9 exemplified the high TSWFV observed both at an intra and inter-annual scale. It confirms the results obtained previously (Table 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 cultivars, the class corresponding to "low TSS" is the most stable, i.e. zones with the lowest values of TSS remain similar during the season and also between seasons. The above is observed clearly on cultivars Cabernet Sauvignon and Carménère (Fig. 6 and 9, respectively).

The effect of early spring frosts on the cultivar Chardonnay is clearly observed in Fig. 7 a. For this cultivar, 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 value of W observed at veraison for the cv Chardonnay (Table 3). As previously mentioned, the above is the result of modification of the leaf area and 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.

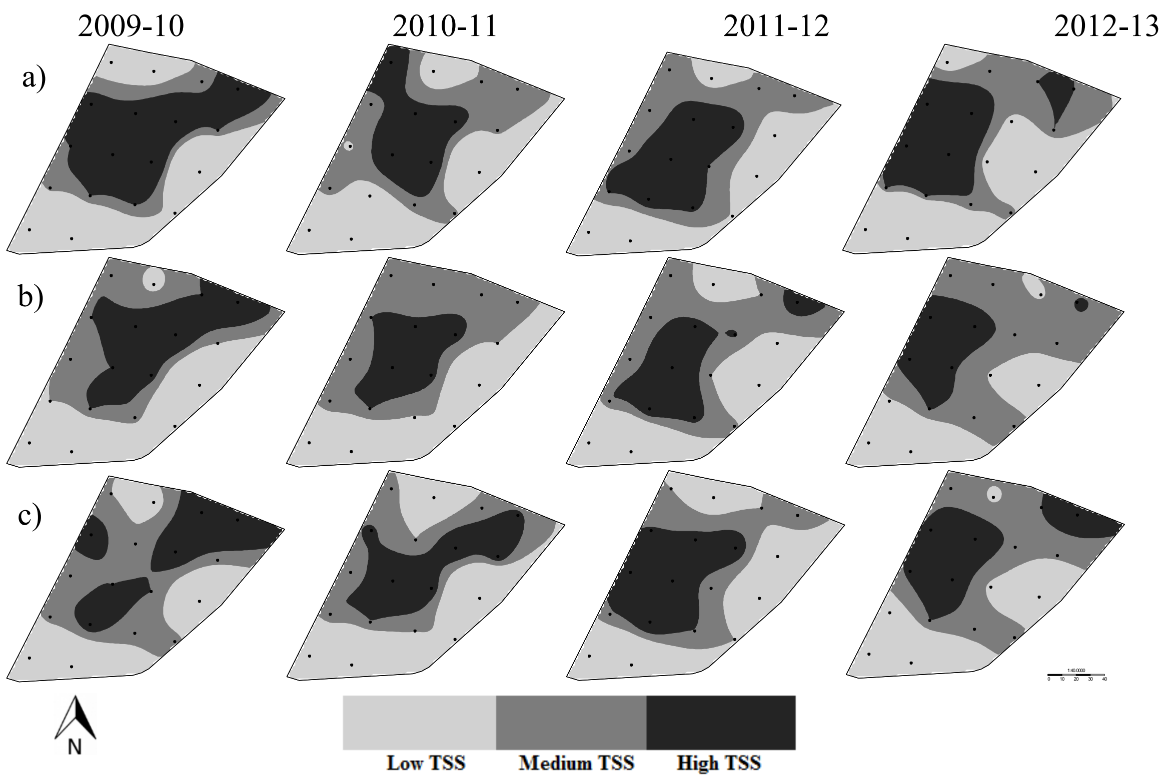

Figure 6 Maps of TSS measured for field cv Cabernet Sauvignon over 4 seasons and 3 dates for seasons, a) 35 days before harvest, b) 20 days before harvest and c) harvest. Each class (greyscale) corresponds to 33% of the data.

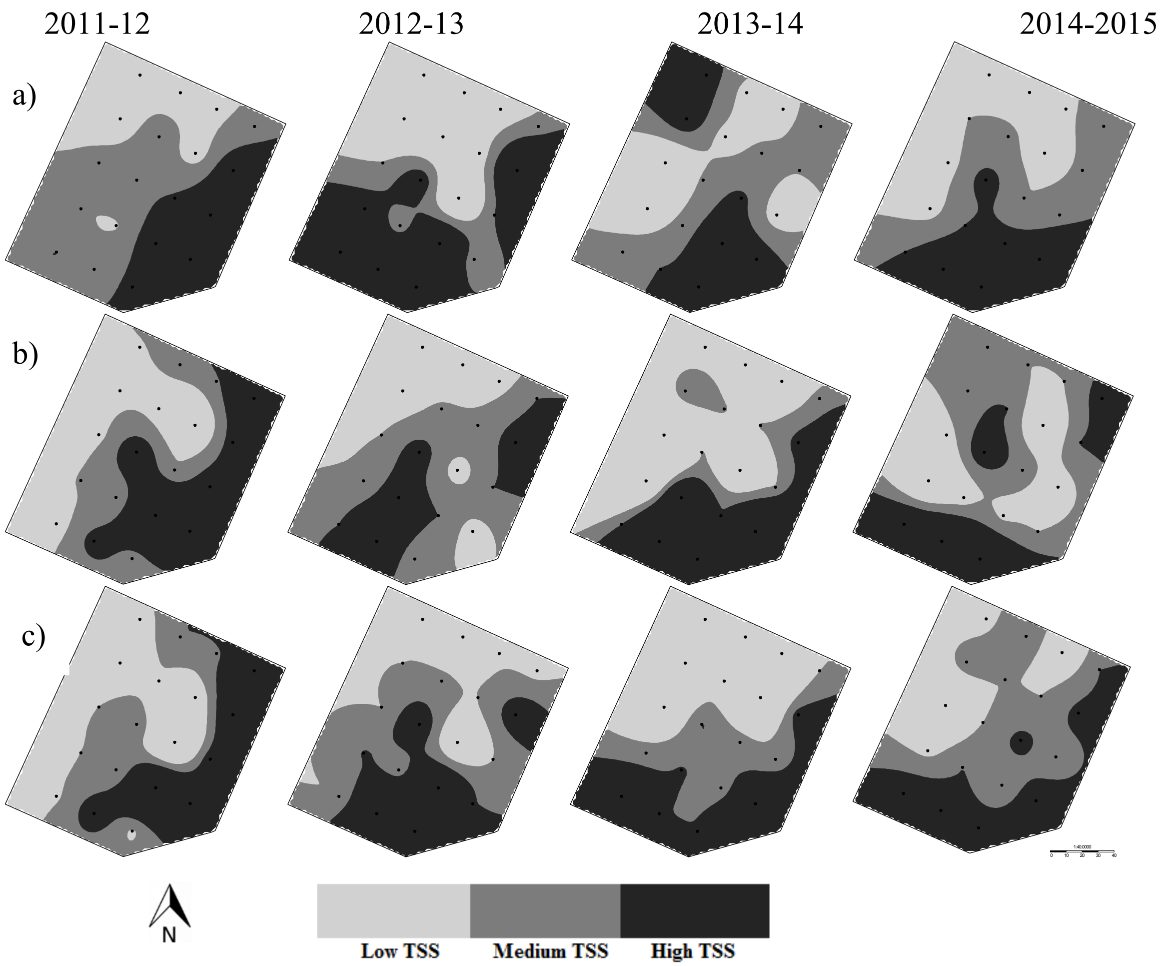

Figure 7 Maps of TSS measured for field cv Chardonnay over 4 seasons and 3 dates for seasons, a) 35 days before harvest, b) 20 days before harvest and c) harvest. Each class (greyscale) corresponds to 33% of the data.

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 et al. 2014; Trought and Bramley 2011; Urretavizcaya et al. 2013), however this work strengthened this knowledge on four different cultivars during several years. The decrease in variability of TSS (CV) from veraison to harvest is also associated with asynchrony of berry development. For example, veraison can take 7-10 days to complete within a grape cluster (Keller 2015).
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 the number until harvest.
The spatial variability of the TSS appears spatially organised and not random. Maps and statistical analysis over several years show that the spatial variability of the TSS is not random and that patterns repeated year after year are clearly observed. 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).

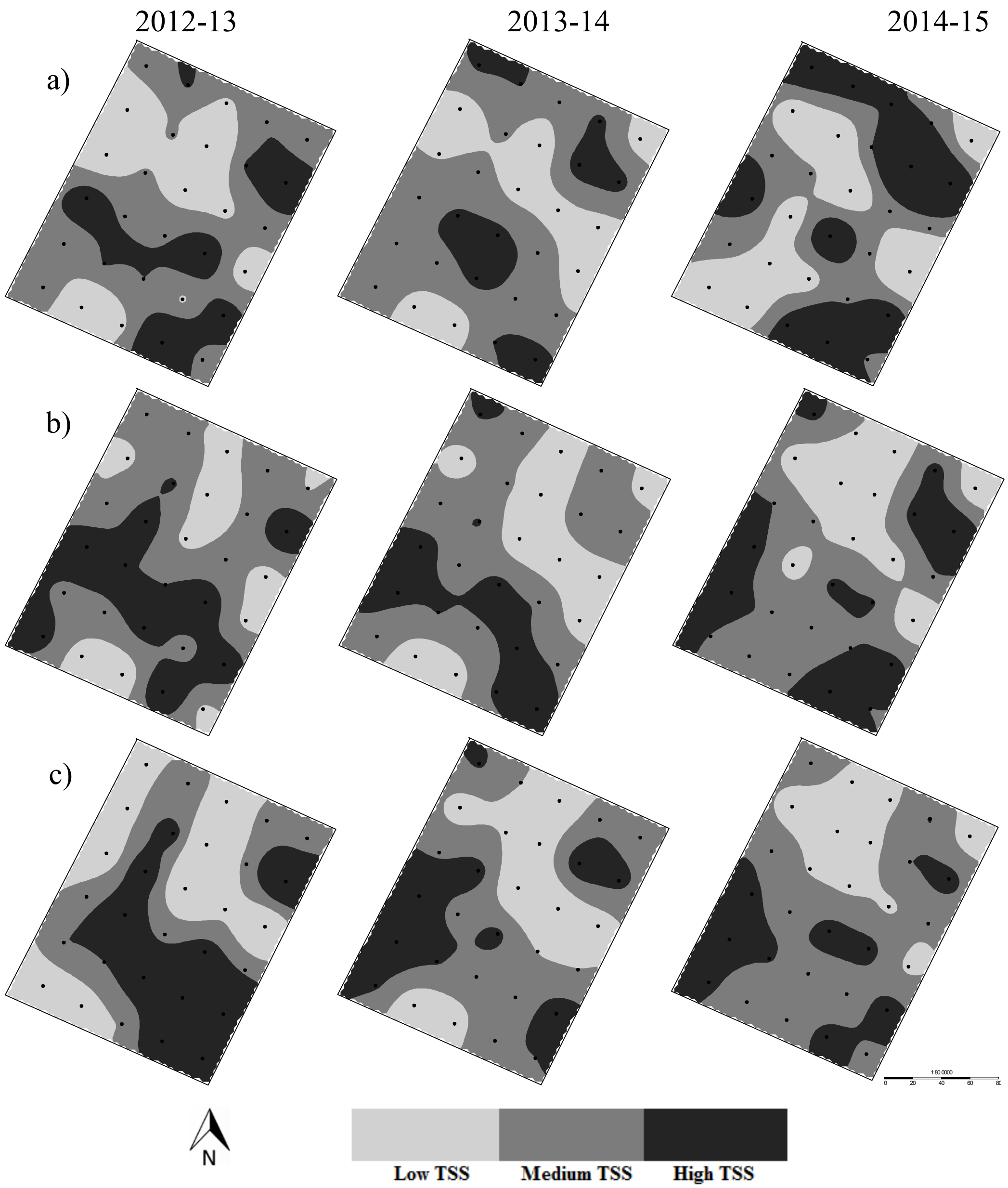

Figure 8 Maps of TSS measured for field cv Sauvignon Blanc over 3 seasons and 3 dates for seasons, a) 35 days before harvest, b) 20 days before harvest and c) harvest. Each class (greyscale) corresponds to 33% of the data.

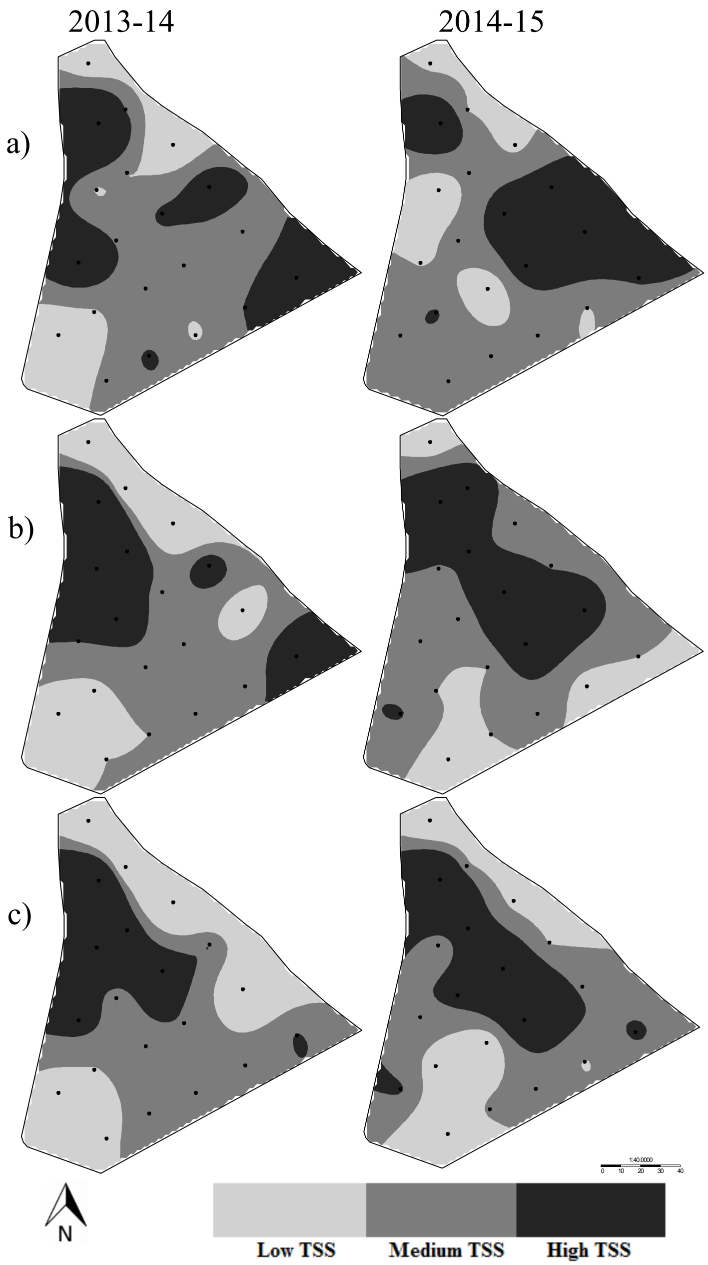

Figure 9 Maps of TSS measured for field cv Carménère over 2 seasons and 3 dates for seasons, a) 35 days before harvest, b) 20 days before harvest and c) harvest. Each class (greyscale) corresponds to 33% of the data.

This study highlights a high temporal stability of TSS in both intra-annual or inter annual on a significant number of cultivars and seasons. As already mentionned in the introduction, this observation is in agreement with some studies (Baluja et al. 2013; Trought and Bramley 2011; Urretavizcaya et al. 2013) and in contradiction with others (Bramley 2005; Tisseyre et al. 2008). This high stability of the spatial variability of the TSS in our conditions can certainly be explained by environmental growing conditions and management practices. The location of Maule Valley (Chile) is characterized by rather constant climatic conditions over the years. Seasons are characterized by low rainfalls during the ripening period (from veraison to harvest, Fig. 3) therefore, the water supply is mainly controlled by irrigation, which allow similar water status patterns experienced by the vines between seasons. Indeed, water stress is a major factor that determines the maturation of TSS (Acevedo-Opazo et al. 2010, 2013; Girona et al. 2009). The regularity of the climate conditions in association with irrigation control result 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 3 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 4 different cultivars and a larger period of investigation (4 years to 2 years).

Note, however, that this spatial stability was disrupted by a spring frost that affected the yield and changed the ratio load/vigor 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 fruit load ratio may affect the accumulation and concentration of TSS. This case shows how the temporal stability of the TSS is fragile and how changes in the balance of yield/vigour, whether related to climatic events or cultural practices such as cluster thinning, can affect its observation. This is a likely reason that explains the rather contradictory results of different studies dealing with the temporal stability of the TSS spatial patterns. The above, shows the importance of incorporating variables related to yield (i.e. number of bunches per plant, yield/plant, etc.) to define zones of maturity o quality, as described by Urretavizcaya et al. (2016).

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 methods for estimating the maturity 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 proposed is to achieve early maturity maps before harvest at a time when labor can be dedicated to the maturity controls and not to the organization of the harvest. 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 fields which present significant spatial variability, which can be potentially adapted to a differential harvest. Also note that the monitoring of the 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 parameters to define quality (TSS). To extend this study, it should include measurement of other parameters that define quality 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 fields 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 to consider empirical spatial models. The advantage being the estimation of TSS values spatially 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. 2010, 2013). Based on our results, it may also be transposed to maturity. The aim of the next section is to demonstrate its relevance and to introduce future research.
The approach proposed by Acevedo-Opazo et al. (2010) 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:
$\hat{z}(s_i, t_j)$ = Predicted TSS value at the location s_i and at time t_j.
a_{s_i}= Site-specific coefficients calibrated from historical data of TSS.
$z_{re}(s_{re}, t_j)$ = Reference measurement of TSS at the reference site (s_{re}) and at time t_j.
D = Vineyard field.

The spatial model corresponds to a collection of site-specific coefficients a_{s_i} 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, Fig. 10 a shows the results of such an approach with a model calibrated on the first three years of cv Cabernet Sauvignon. As a first attempt a_{s_i} coefficient was determined from our data with a classical least square method. Estimation of TSS values in the field were 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 shows the possibility to estimate TSS values in the field with only one measurement made on a reference site. The presence of two very different within field zones (Fig. 10 a) leads to two groups of points that may artifically increase the R^2 value. Note that the R^2 and the RMSE values remains high (R^2 =0.74; RMSE =0.27) when sites of the lower zones (TSS <19°Brix) are removed, showing the robustness of the approach. Fig. 10 b 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 the 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 of TSS changes, for example due to cultural practices such as cluster thinning performed between veraison and harvest, could decrease the effectiveness of the spatial model to predict TSS values.

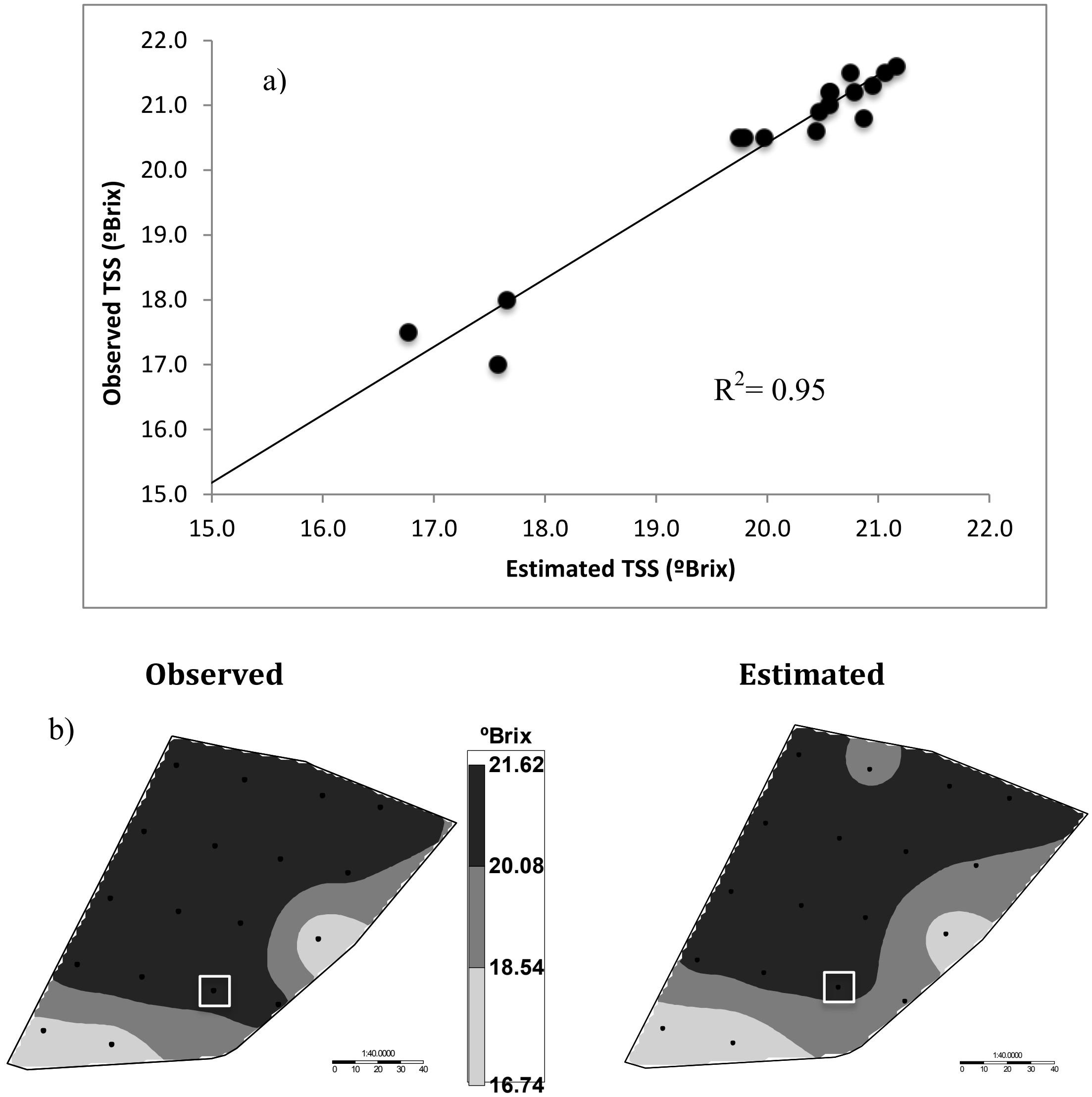

Figure 10 Result of the model calibrated from the first three years of cv Cabernet Sauvignon (Date: 19 days before harvest, 2010-11 season), a) predicted versus observed TSS values and b) maps of the observed and estimated TSS values (reference site in a white frame).

Conclusion

Under semi-arid irrigated vineyard (Maule Valley) conditions, a high spatial variability of TSS at the within-field level was observed. TSS present a high Temporal Stability of the Within-Field Variability (TSWFV) both within seasons (intra-annual) and between seasons (inter-annual). In these pedo-climatic conditions, this TSWFV of TSS was observed for all cultivars under study, over several seasons and stages of maturity. TSS maps obtained 40 days before harvest present the same spatial patterns until harvest. Therefore, 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:

- New sampling strategies based on early identification of TSS zones may be considered.
- The empirical model calibrated with TSS ancillary data of previous years may allow maturity monitoring to be optimized. Preliminary results show great expectations of such an approach, however, these results must be confirmed on all fields and grape cultivars of the study. Specific issues related to the election and the number of reference sites should be investigated as well as the quality of the predictions made for each stage of maturity. These issues will be studied in future research.

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CHAPTER III

CHAPTER 3: IDENTIFICATION OF MAIN FACTORS AFFECTING THE WITHIN FIELD SPATIAL VARIABILITY OF GRAPEVINE PHENOLOGY AND MATURATION: ZONING USING AUXILIARY DATA

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Abstract
Grapevine phenology and maturation are spatially variable at the within field scale. However, the factors that determine the observed spatial variability have not been identified. With the aim of identify the potential factors or auxiliary data that could be used to determine within field zones of phenology and maturity, a study was carried out in the Maule Valley, Chile, under semi-arid conditions. It considered two fields with different characteristics: field 1 (cv Cabernet Sauvignon) which present differences in topography and field 2 (cv Chardonnay) considered as flat. Within each vine field, a regular sampling grid was designed, to carry out measurements of phenology, maturation (total soluble solids), plant water status, vegetative expression, yield, soil physical properties and soil apparent electrical conductivity. The main results show that factors affecting the spatial variability of phenology and maturation are different for each field. For field 1, differences in topography explain differences in direct or indirect parameters like soil characteristics, water availability, soil temperature, level of the water table and air temperature of the field. Therefore, when variation in topography is significant, elevation was identified as the main integrating factor affecting the spatial variability of both phenology and maturation at the within field scale. For field 2, soil characteristics become the most important factor in explaining the spatial variability in phenology while plant variables (vegetative espression and yield) drive the maturation. These results provide a decision support on auxiliary data to consider for spatial modelling of phenology and maturation at the within field scale.

Keywords:
Vitis vinifera, Precocity, Berry maturity, Ripening, Management zones

INTRODUCTION
Many studies have shown and quantified the existence of a within field variability in vineyards (Arnó et al. 2009) in the main wine areas of the world, both in the "Wine New World" countries such as Chile (Acevedo-Opazo et al. 2013) and Australia (Bramley and Hamilton 2004) and in the "Old World" countries, such as France (Tisseyre et al. 2008) and Spain (Baluja et al. 2013). These works highlighted the significant within field variability for many variables of importance in viticulture, such as yield (Arnó et al. 2011; King et al. 2014), maturation and grape composition (Baluja et al. 2013; Trought and Bramley 2011; Verdugo-Vásquez et al. 2015), vegetative expression (Kazmierski et al. 2011; King et al.

2014), plant water status (Acevedo-Opazo et al. 2009), plant diseases (Bramley et al. 2011a), soil (Bramley et al. 2011b) and more recently precocity of the development (Verdugo-Vásquez et al. 2016).

The knowledge of the within field variability of vine parameters has been shown to be of importance to reduce management costs, to optimize harvest operation as well as grape and wine quality management (Baluja et al. 2013). However, some of these parameters, although they are very informative to support decision making, are sometimes difficult to measure at a high spatial resolution because appropriate on/the/go sensors are not available. This is a strong limitation since the cost of intensive sampling for mapping relevant information begins to exceed the benefits gained (Bramley et al. 2011). In this regard, an alternative approach is to use empirical models (mainly linear regression) to estimate time consuming and/or high-cost agronomic parameters from related factors or auxiliary data (AD) which are cheaper and/or easier to measure. In the literature, some examples can be found like the use of Normalised Difference Vegetative Index (NDVI) to estimate plant vigour, canopy density and size, plant water status as well as fruit quality (Acevedo-Opazo et al. 2008; Johnson et al. 2003; Lamb et al. 2004; Mann et al. 2010), visible and/or Near Infra-Red spectral images to evaluate nitrogen status (Kyveryga et al. 2012), soil electrical conductivity related to soil concentrations of selected mineral elements (Heiniger et al. 2003) or water content (Corwin and Lesch 2005). This approach shows the importance of identifying relevant factors or auxiliary data potentially available at a high resolution and at a low-cost and that are strongly related to useful agronomic information.

Among all critical agronomic variables allowing the management of the vineyard to be improved, vine phenology and fruit maturity are of particularly importance. In a recent work, Verdugo-Vásquez et al. (2016) has shown that the within field variability of vine phenology is significant enough to justify site specific management of vineyard operations. Indeed at larger-scale, monitoring vine phenology is commonly used to schedule vineyard operations like fertilization, irrigation and phytosanitary applications (Mullins et al. 1992). At the within field scale, Verdugo-Vásquez et al. (2016) has shown the knowledge of the spatial variability of the phenology may constitute a decision support to optimize the schedule and the management of these operations. Regarding fruit maturity, the evolution of the maturity of the berries (maturation), is mainly determined by the date of veraison (Parker et al. 2015; Sadras and Petrie 2011) since most advanced zones of veraison are more susceptible to provide early fruit maturation. The spatial variability of maturity has been studied in the literature (Trought and Bramley 2011). At a given date, the spatial variability of maturity can determine different qualitative zones. This knowledge is particularly interesting to implement differential harvest (Urretavizcaya et al. 2013).

The wine industry needs therefore to characterise precisely zones of phenology and maturity. However, this characterization is currently difficult since no online and non-destructive sensors are available commercially to provide information for both of these parameters at a high spatial resolution. Moreover, phenology and maturity are parameters difficult to measure at high spatial resolution because they correspond to dynamic variables that change over time, and highly demanding of time and manpower. Given this difficulty, some works (Acevedo-Opazo et al. 2008; Bonilla et al. 2015; González-Flor et al. 2014; Hall et al. 2010; Lamb et al. 2004) were directed towards the use of AD to define zones. To our knowledge, they were only applied to the definition of maturity zones (Bonilla et al.

2015; González-Flor et al. 2014). This is justified by the important challenge raised by quality management in viticulture and the ability to implement a differential harvest.
Regarding phenology, to our knowledge, there is no work on the use of AD to define within field zones of grapevine phenology. Literature concerning factors affecting the spatial variability of grapevine phenology have been conducted mainly at the regional scale (Quénol et al. 2014). At this scale, they identified climatic parameters like air temperature whose spatial variability is mainly determined by topography. Spatial variability of other parameters like soil conditions (texture, colour and water availability) were also identified to explain differences in grapevine phenology at the regional scale (Barbeau et al. 1998; Conradie et al. 2002; Tesic et al. 2001a). At the within field scale, recent work of Verdugo-Vásquez et al. (2016) has shown that spatial variability of both phenology and maturity was related to climate variability.
The goal of this work is to identify potential AD that could be used to determine within field zones of phenology and maturity. Previous results of Verdugo-Vásquez et al. (2016) has shown that phenology zones also determine maturity zones. Therefore, this work proposes to study all together these two critical variables for agricultural decision making in viticulture. This work focuses on the identification of significant links between phenology and maturity on one side and AD potentially available at high spatial resolution on the other side. It also aims at explaining these links in the specific semi-arid conditions of the Maule Valley, Chile for two of the principal cultivars of this growing region.

MATERIALS AND METHODS

Experimental Fields

The study was conducted in two of the principal cultivars of the Maule Valley, Chile: cv Cabernet Sauvignon (field 1, 1.56 ha) and cv Chardonnay (field 2, 1.66 ha), both located in the Panguilemo Experimental Station of the University of Talca (Fig. 1). The characteristics of both fields are described in Table 1. Within each vine field a regular sampling grid was designed, one with 18 measurement sites (25x25 m) for field 1 (Fig. 2a) and another with 19 measurement sites (25x25 m) for field 2 (Fig. 2b). The borders of the fields and sampling sites within each field were geo-referenced with a differential global positioning system receiver (DGPS) (Trimble, Pathfinder ProXRS, Sunnyvale, California, USA) and stored as Eastern and Northern coordinates (Datum WGS84, UTM projection, Zone 19S) to perform the mapping. Each site of the grid was represented by four consecutive vines. The elevation (ELE, m) of each site of the grid for field 1 was also obtained from the DGPS receiver. The elevation of the field 2 was not considered because elevation variability was very low and was assumed to have no incidence on the parameters under study. Field 2 was therefore considered as flat.

Field measurements

This experiment was carried out during 4 seasons for the field 1 (seasons 2009-10, 2010-11, 2011-12 and 2012-13) and 2 seasons for the field 2 (seasons 2011-12 and 2012-13). During this period the following measurements were performed:

I. - Plant measurements

a) Grapevine Phenology

The phenological observations were performed manually using the Eichhorn and Lorenz phenological scale (EL scale) as modified by Coombe (Coombe 1995), from budbreak to veraison, every 7 days on 30 shoots chosen systematically among the 4 vines of a site of the grid. For each site, the mean value of phenology was considered at each measured date. In the current study, only three major phenological stages, for each season and field, were considered: (i) post-budburst (Post-Bu, from code 5 to 11 of EL scale), (ii) flowering (Fl, from code 18 to 26 of EL scale) and (iii) veraison (Ve, from code 33 to 36 of EL scale). This stages were expressed in units of Phenological Scale (PS).

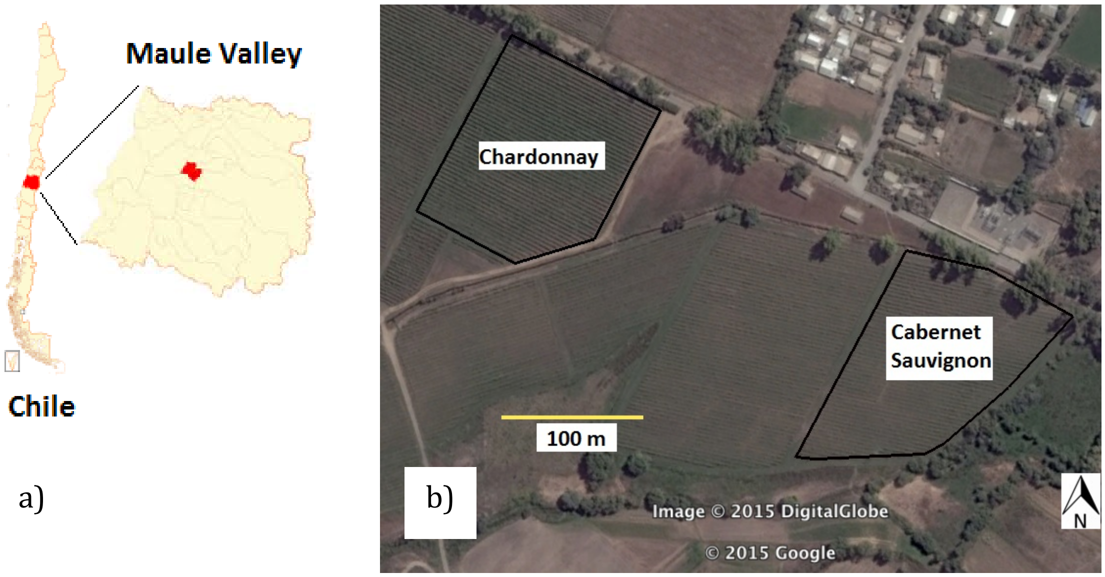

Fig. 1 Location of Maule Valley in Chile (a) and map of the study area (b).

Table 1 Field characteristics of the Cabernet Sauvignon and Chardonnay experimental fields.

Property	Cabernet Sauvignon (Field 1)	Chardonnay (Field 2)
Vineyard age[a]	13-year-old	17-year-old
Rootstock	Own-rooted	Own-rooted
Irrigation system	Furrow irrigation	Furrow irrigation
Trellis/Pruning system	VSPSystem/Two-bilateral spur-cordon	VSPSystem/Guyot
Spacing (m x m)	3.0 x 1.5	3.0 x 1.25
Location (WGS84)	35°22.0' S, 71°35.6' W	35°21.9' S, 71°35.8' W
Elevation (m above sea level)	121	121.8
Row orientation	330° NW	310°NW

[a]: at the beginning of the experiment.
VSP: Vertical shoot positional

b) Maturation

From veraison to harvest, total soluble solids (TSS, expressed in ºBrix) was measured using a thermo-compensating refractometer (BRIX30 model, Leica, USA), by randomly selecting eight clusters from each site of the grid (Fig. 2a, b). For each cluster, two berries were sampled at the top, middle and bottom of the cluster, to obtain a total of 48 berries per site and an average value of TSS for each date and site of the grid was recorded. Three sampling dates were considered: Pre-Ha 1 (25 days before harvest), Pre-Ha 2 (12 days before harvest) and Ha (days of the harvest) for each season and field.

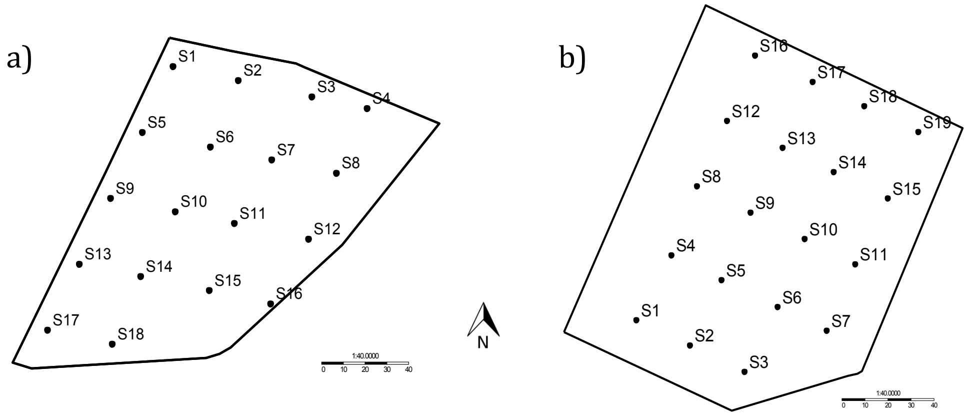

Fig. 2 Measurement grids used in the experiments. 18 sites for field 1, cv Cabernet Sauvignon (a) and 19 sites for field 2, cv Chardonnay (b). S_i represents the sampling site number i.

c) Plant water status

At setting (code 27 of EL scale), a specific phenological stage corresponding to young berries enlarging (>2 mm of diameters), plant water status was estimated through the Midday Stem Water Potential (MSWP Set, |MPa|) using a pressure chamber (PMS Instruments Co., Model 600, Corvallis, OR, USA) according to the methodology proposed by Scholander et al. (1965). Measurements were performed at each site of the grid (Fig. 2a, b) during each season of the experiment and for each field. Measurements of MSWP were performed following the protocol described by Acevedo-Opazo et al. (2013).

d) Vegetative expression

Spatial variability of the vegetative expression was estimated through the canopy porosity (CP, %) (Acevedo-Opazo et al. 2013). For each vine field CP measurements were collected for each site on the grid using image analysis during all the seasons. Images were taken at a fixed distance from the vine canopy (2 m) and at a fixed height (1.5 m above the soil). To increase the contrast between the leaves and the background, a red background was used following the methodology proposed by Drissi et al. (2009). The field of view was restricted to the middle zone of the canopy above the fruit zone. This measurement was performed on two representative vines at each grid point (Acevedo-Opazo et al. 2013). The red band of the image was then post-processed to identify the percentage of holes in the canopy corresponding to the porosity of the canopy (Drissi et al. 2009). Image processing was performed using a script written in MATLAB 7.0 (The Mathworks Inc., Natick, MA, USA). Measurements were performed for all the seasons at the phenological stage of veraison (code 35 of EL scale), when vegetative growth has stopped. Then, CP % corresponds to the proportion of canopy holes when canopy is at its maximum size.

e) Yield

For all seasons, at harvest, yield per vine was determined in the field. For both fields, all vines of each site of the grid were hand harvested. The collected clusters were weighed to assess total weight of production, which was subsequently expressed in kg $vine^{-1}$ to estimate the yield (Yi). An average value was obtained by site of the grid (mean of 4 vines).

II. - Soil measurements

a) Soil physical properties

In August 2010 for the field 1 and August 2012 for the field 2, for each site of the grid, soil samples were extracted from a combination of excavation pits and the use of a manual auger. To encompass rooting depth of the vines, two depths were defined for samples: (i) 0-0.16 m and (ii) 0.16-0.70 m. Physical and hydrological properties were estimated for both depths: bulk density (BD), field capacity (FC) and total soil water availability (TSWA). An average profile BD was calculated from a weighted mean of both depths while the soil moisture measurements (FC and TSWA) were summed to generate the whole profile values (0-0.70 m). Finally, Organic matter (OM) was measured at the topsoil (0-0.16 m).

b) Measurement of soil apparent electrical conductivity

Soil apparent electrical conductivity (EC, mS/m) was measured using a non-invasive electromagnetic induction (EMI) sensor (CMD Mini-Explorer model, GF Instruments, Czech Republic) (Bonsall et al. 2013; Shanahan et al. 2015). Measurements were made manually 72 hours after irrigation in January 2013 on each site of the grid for both fields. For each site of the grid, one repetition was carried out with the aim of testing the representativeness of measurement. Measurements were made parallel to the rows and with the sensor positioned up to 0.10 m above the ground. Soil electrical conductivity was obtained at 0.5 m depths (D1).

III. - Additional measurements for field 1 cv Cabernet Sauvignon

Considering the range of variation of elevation for field 1, additional information was collected, during 2011-2012 season. These additional measurements were performed in order to investigate potential effects of topography on the level of water table, but also on soil parameters and air temperature. Previous works show that these last parameters are strongly dependent on topography (Haitjema and Mitchell-Bruker 2005; Kang et al. 2000). Moreover, other works reported a significant effect of topography on vine phenology (Barbeau et al. 1998; Tesic et al. 2001a).

Level of the water table

Level of the water table was measured with a piezometer on 2 sites of the field. Piezometers were located according to elevation of the field. Piezometers measurements were identified by the zone they belonged to: high (ZH) and low (ZL) elevation (Fig. 3a). Piezometers were installed during July 2011 at 2 m depth on vine rows. A floating sensor with a tape measure was used to register the fluctuation of the water table. Depth of the water table was expressed in centimeters. It corresponds to the level of water from the soil surface. Measurements were made every 7 days during 2011-12 season, from July until October (post-budburst). A total of 16 measurement dates were therefore obtained. In case of precipitation, measurements were only performed 24 hours after the rain.

Soil temperature

Twelve temperature sensors (IButtons, Thermochron® DS1921G, USA) were installed on vine rows at 2 depths (0.15 and 0.30 m above the ground) with the aim to characterize differences in soil temperature at the within field scale. Sensors were located according to elevation of the field. Similarly to piezometers, two zones of elevation were considered: high (ZH) and low (ZL) elevation (Fig. 3b), with 6 sensors for each zone (3 sites of the grid for each zone with 2 sensors on each). Soil temperature was recorded every 30 minutes from September (before budburst) until October (post-budburst) during the 2011-12 season. 20 days of measurements were therefore available.

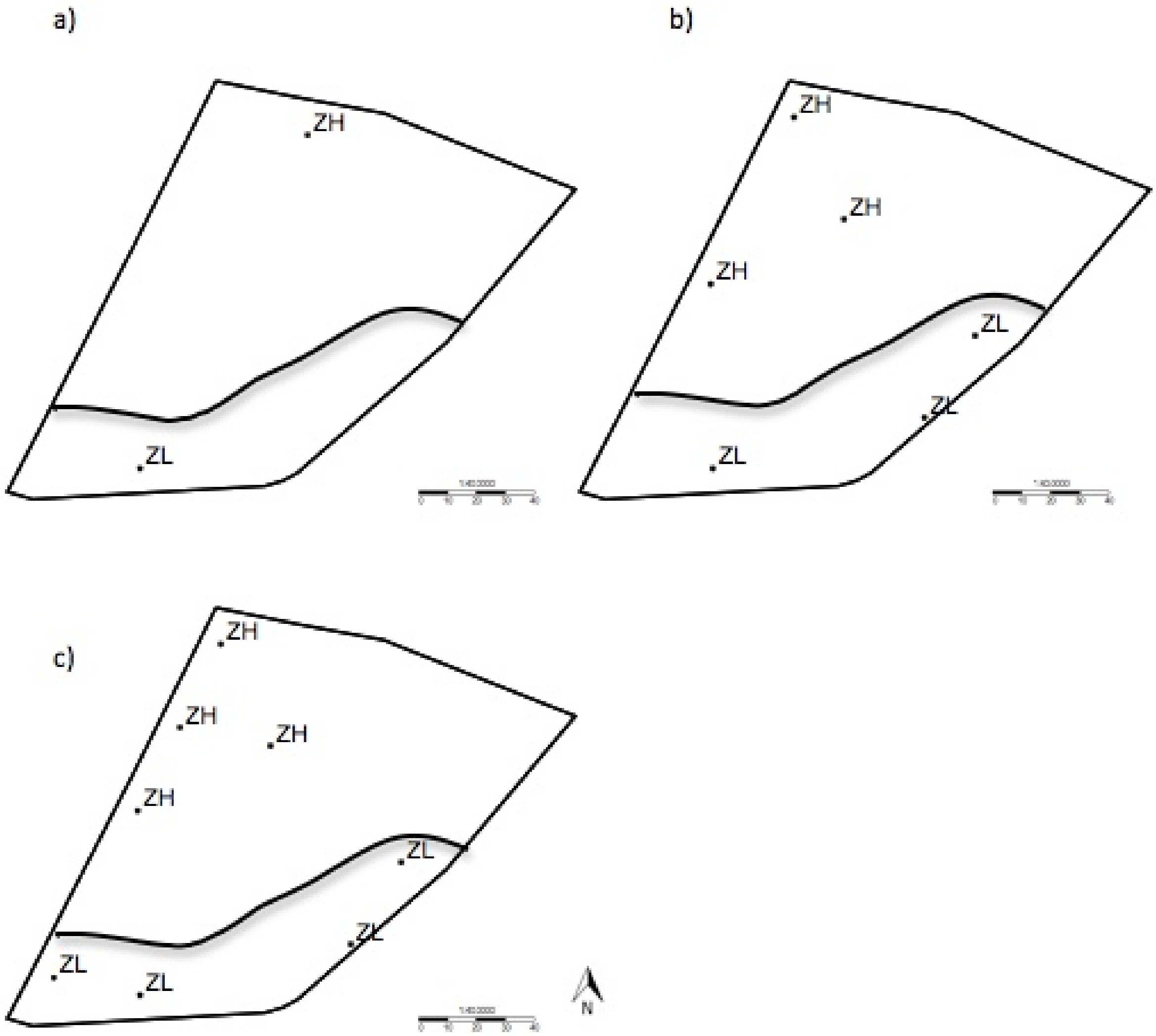

Fig. 3 Location of additional measurement of field 1 (cv Cabernet Sauvignon). Location of piezometer to assess the level of the water table (a); location of soil temperature sensors (b) and location of air temperature sensors (c). ZH: representing the "zone high" (zone of high elevation) and ZL the "zone low" (zone of low elevation).

Air temperature
Eight temperature sensors (Dickson, LogTK500, USA) were installed with the aim to characterize differences of air temperature at the within field scale. Sensors were located according to elevation of the field. Four sensors were installed in each of the elevation zone considered (ZH and ZL) (Fig. 3c). Sensors were installed on vine rows at 1.5 m above the ground. Air temperature was monitored during 37 days (from before budburst to pre-flowering).

Analysis method

Classical analysis
For all measurements, basic statistics, such as mean, standard deviation (SD), maximum/minimum values, range of variation and coefficient of variation (CV) were calculated. For the classical statistical analysis, the Statgraphics Plus 5.1 (StatPoint Inc., Virginia, USA) software was used.

Principal component analysis (PCA)
In order to identify the main relationships among variables, a principal component analysis (PCA) was computed for each field. In a first step, a preliminary PCA was performed for each field with all available variables. In a second step, in order to simplify the analysis, only variables that showed a strong correlation ($r^2 > 0.5$) with the first 3 factors of the PCA were selected in each field. The selected variables are shown in Table 2. For each field, data were standardized separately, using the values of mean and standard deviation estimated in each season. The "season effect" on the mean and standard deviation was therefore eliminated. The PCA analysis was performed using a script written in MATLAB v7.0 (The Mathworks Inc., Natick, MA, USA).

Table 2 Variables included in the PCA for each field.

Variables	Cabernet Sauvignon (Field 1)	Chardonnay (Field 2)
Phenology (post-budburst, flowering and veraison)	X	X
Maturation (Pre-Ha 1, Pre-Ha 2 and Ha)	X	X
Midday Stem Water Potential (MSWP)	X	X
Canopy porosity (CP)	X	X
Yield (Yi)	X	X
Bulk density (BD)	-	X
Field capacity (FC)	-	X
Total soil water availability (TSWA)	X	-
Organic matter (OM)	X	-
Soil electrical conductivity at 0.5 m depth (EC D1)	X	X
Elevation (ELE)	X	-

Data mapping
Maps of the first factor of the PCA analysis were performed to analyse the spatial distribution of both fields. To this end, the method of interpolation Block-Kriging was used. Depending on data distribution, classes were defined differently for the construction of the maps. In case, two populations were obvious in data distribution, two classes were defined. When no obvious class was detected in the distribution, 5 classes were considered based on 20% quantiles. Maps were performed with 3Dfield software (version 2.9.0.0., Copyrigtht 1998 – 2007, Vladimir Galouchko, Russia).

RESULTS AND DISCUSSION

Classical analysis

Main statistics of plant water status, vegetative expression (vigour), yield and soil measurements are presented in Table 3 and Table 4 for field 1 and 2 respectively. Main statistics of the phenology and maturation are presented in Table 5 and 6 for field 1 and 2 respectively.
For field 1, plant measurements (MSWP Set, CP and Yi) presented values of coefficients of variation (CV) above 31% in average for all the seasons. Yield (Yi) shows a significant variability with a CV of 44.1%. Soil measurements (BD, FC, OM, TSWA and EC D1) present in general a lower CV than plant measurements. Note however that among soil parameters, OM presents a high CV (30 %). Regarding elevation (ELE), the low CV may be explained by relatively high elevation values compared to the SD (CV = 0.7%), however, the range of variation corresponds to 2.5 m. This variation is considered high enough to generate significant differences in environmental (especially air temperature) conditions during the vegetative period.
For field 2, plant measurements (MSWP Set, CP and Yi) present lower CVs values than field 1. Canopy porosity shows the highest variability. Similarly to field 1, soil parameters (BD, FC, TSWA, OM) were less variable than plant measurements. Note however the exception of soil conductivity (EC D1) which presents a CV value twice the CV value of field 1 (CV = 35.5%).
Regarding the variability of phenology and maturation, both fields present the same features. CV values ranged from 1% to 11% (Table 5 and 6) in average for all the seasons, post-budburst stage showing the highest CV values (CV = 11 %). For both fields, CV values of each phenological stage decrease from post-budburst to veraison. During maturation, CV values remain similar (from 4.2 % to 7.2 %). Note however that spatial variability of maturation is more temporally stable since for this parameter, CV values range from 6.3% to 6.4%.
Field 1 shows a higher variability than field 2 for most of the variables. This can be noted focusing on yield variability where CV for field 1 and 2 were about 44% and 29% respectively in average for all the seasons. The CV values of plant variables (MSWP Set, CP), environmental variables (BD, FC, TSWA, OM and EC D1), phenology and maturation highlight a within field variability. The CV values observed in both fields are comparable to those reported in the literature (King et al. 2014; Acevedo-Opazo et al. 2008; Baluja et al. 2013). In the following sections, the goal is to establish whether there is a

relationship between the phenology and maturation variables with the plant and environmental variables at the within field scale.

Table 3 Main statistics of plant water status, vegetative expression, yield and soil measurements for the field 1 (cv Cabernet Sauvignon).

Variables (Units)	Nomenclature	Seasons	Mean	Min	Max	Range	SD	CV (%)
Midday Stem Water Potential (|MPa|)	MSWP Set	2009-10	0.46	0.17	1.33	1.17	0.25	53.5
		2010-11	0.56	0.24	1.18	0.94	0.21	37.5
		2011-12	0.71	0.40	0.90	0.50	0.12	16.8
		2012-13	0.70	0.44	0.83	0.39	0.10	14.8
		Mean	0.61	0.31	1.06	0.75	0.17	30.7
Canopy porosity (%)	CP	2009-10	40.1	27.3	62.8	35.5	8.6	21.4
		2010-11	33.0	14.1	72.7	58.6	13.5	41.1
		2011-12	46.6	20.7	67.4	46.6	13.0	27.8
		2012-13	32.5	12.1	57.2	45.1	10.9	33.6
		Mean	38.0	18.6	65.0	46.5	11.5	31.0
Yield (kg/vine)	Yi	2009-10	2.29	0.2	3.6	3.4	1.04	45.3
		2010-11	1.78	0.8	3.2	2.4	0.65	36.3
		2011-12	2.74	0.3	5.0	4.7	1.38	50.3
		2012-13	1.89	0.9	3.8	2.9	0.84	44.3
		Mean	2.18	0.55	3.9	3.3	0.98	44.1
Bulk density (g cm-3)	BD	August 2010	1.42	1.29	1.49	0.2	0.047	3.3
Field capacity (% vol)	FC		34.37	23.9	40.1	16.2	3.80	11.1
Total soil water availability (mm)	TSWA		108.3	69.6	142.0	72.4	21.49	19.9
Organic matter (%)	OM		2.7	1.85	4.94	3.09	0.82	30.5
Electrical Conductivity (mS/m)	EC D1	January 2013	16.6	10.2	21.6	11.38	2.94	17.8
Elevation (m)	ELE	November 2009	113.6	112.0	114.5	2.5	0.75	0.7

Min:minumun, Max: Maximun, Range: Range of variation, SD: Standard deviation, CV: Coefficient of variation.

Table 4 Main statistics of plant water status, vegetative expression, yield and soil measurements for the field 2 (cv Chardonnay).

Variables (Units)	Nomenclature	Seasons	Mean	Min	Max	Range	SD	CV (%)
Water status (|MPa|)	MSWP Set	2011-12	0.75	0.55	1.05	0.5	0.14	18.3
		2012-13	0.54	0.37	0.72	0.35	0.098	18.1

		Mean	0.65	0.46	0.89	0.43	0.12	18.2
Canopy porosity (%)	CP	2011-12	45.8	31.5	84.4	52.9	13.88	30.3
		2012-13	32.8	17.54	58.0	40.46	10.48	32.0
		Mean	39.3	24.52	71.2	46.68	12.18	31.2
Yield (kg/vine)	Yi	2011-12	5.02	2.54	7.88	5.34	1.37	27.3
		2012-13	3.82	0.96	5.59	4.63	1.13	29.6
		Mean	4.42	1.75	6.74	4.99	1.25	28.5
Bulk density (g cm-3)	BD	August 2012	1.49	1.4	1.53	0.13	0.03	2.1
Field capacity (% vol)	FC		26.29	21.3	29.5	8.2	2.09	7.9
Total soil water availability (mm)	TSWA		110.53	80	130	50	12.7	11.5
Organic matter (%)	OM		2.31	1.41	3.45	2.04	0.47	20.1
Electrical Conductivity (mS/m)	EC D1	January 2013	11.5	5.7	21.5	15.8	4.1	35.5

Min:minumun, Max: Maximun, Range: Range of variation, SD: Standard deviation, CV: Coefficient of variation.

Table 5 Main statistics of phenology and maturation for the field 1 (cv Cabernet Sauvignon).

Variables (Units)	Nomenclature	Seasons	Mean	Min	Max	Range	SD	CV (%)
Phenology (PS)	Post-Budburst (Post-Bu)	2009-10	7	5	7	2	0.65	10.5
		2010-11		5	7	2	0.47	8.3
		2011-12		5	8	3	0.89	12.8
		2012-13		7	11	4	1.05	12.1
		Mean		6	8	3	0.77	10.9
	Flowering (Fl)	2009-10	23	20	23	3	0.87	3.9
		2010-11		20	26	6	1.47	6.1
		2011-12		21	25	4	1.35	5.6
		2012-13		18	21	3	0.77	3.9
		Mean		20	24	4	1.12	4.9
	Veraison (Ve)	2009-10	35	34	35	1	0.34	1.0
		2010-11		34	35	1	0.26	0.8
		2011-12		33	35	2	0.54	1.5
		2012-13		34	35	1	0.28	0.8
		Mean		34	35	1	0.36	1.0
Maturation (ºBrix)	Pre-Ha 1	2009-10	20.4	17.6	21.2	3.6	0.96	4.8
		2010-11	20.4	17.0	21.6	4.6	1.40	6.8
		2011-12	21.2	17.6	22.7	5.1	1.38	6.5
		2012-13	19.5	15.6	20.9	5.3	1.38	7.1
		Mean	20.4	17.0	21.6	4.7	1.28	6.3
	Pre-Ha 2	2009-10	20.8	18.6	22.2	3.6	1.16	5.6

		2010-11	20.9	17.2	22.5	5.3	1.56	7.4
		2011-12	22.1	18.8	24.6	5.8	1.31	5.9
		2012-13	21.2	17.2	22.4	5.2	1.37	6.5
		Mean	21.3	18.0	22.9	5.0	1.35	6.4
		2009-10	22.5	19.8	24.0	4.2	1.20	5.3
		2010-11	21.8	17.2	23.2	6.0	1.61	7.4
	Ha	2011-12	22.5	18.8	24.6	5.8	1.31	5.9
		2012-13	22.2	18.3	23.9	5.6	1.50	6.8
		Mean	22.3	18.5	23.9	5.4	1.41	6.4

Min:minumun, Max: Maximun, Range: Range of variation, SD: Standard deviation, CV: Coefficient of variation. Min, Max, Range and SD expressed in units of Phenological scale (PS) for Phenology and ºBrix for Maturation.

Table 6 Main statistics of phenology and maturation for the field 2 (cv Chardonnay).

Variables (Units)	Nomenclature	Seasons	Mean	Min	Max	Range	SD	CV (%)
Phenology (PS)	Post-Budburst (Post-Bu)	2011-12		9	11	2	0.64	6.4
		2012-13	9	7	11	4	1.36	15.6
		Mean		8	11	3	1.00	11.0
	Flowering (Fl)	2011-12		22	25	3	0.69	3.0
		2012-13	23	20	25	5	1.46	6.5
		Mean		21	25	4	1.08	4.8
	Veraison (Ve)	2011-12		33	35	2	0.52	1.5
		2012-13	34	33	35	2	0.97	2.9
		Mean		33	35	2	0.75	2.2
Maturation (ºBrix)	Pre-Ha 1	2011-12	16.0	13.8	18.7	4.9	1.23	7.6
		2012-13	17.3	15.0	19.0	4.0	1.16	6.7
		Mean	16.7	14.4	18.9	4.5	1.20	7.2
	Pre-Ha 2	2011-12	19.8	17.6	22.0	4.4	1.04	5.3
		2012-13	20.1	18.8	21.5	2.7	0.76	3.8
		Mean	20.0	18.2	21.8	3.6	0.90	4.6
	Ha	2011-12	20.9	18.5	22.9	4.4	1.02	4.9
		2012-13	22.3	21.0	23.9	2.9	0.77	3.4
		Mean	21.6	19.8	23.4	3.7	0.90	4.2

Min:minumun, Max: Maximun, Range: Range of variation, SD: Standard deviation, CV: Coefficient of variation. Min, Max, Range and SD expressed in units of Phenological scale (PS) for Phenology and ºBrix for Maturation.

Principal component analysis (PCA) for field 1 and 2

The PCA results are presented in Fig. 4a for field 1 and Fig. 4b for field 2. These figures show the scatter plot of the first two factors of the PCA for each field. The variables are presented with red crosses and sampling sites in each field with specific black symbols for each season.

For field 1, principal component 1 (PC 1) and 2 (PC 2) account for 59.6% of the total variability (46.6% and 13.0% respectively). Variables of phenology (Post-Bu, Fl and Ve), maturation (Pre-Ha 1, Pre-Ha 2 and Ha) and soils (TSWA and ELE) are negatively correlated to PC 1 while the soil OM is positively correlated. The second factor (PC 2) is correlated to plant measurements (CP and Yi) and in a less extent to soil measurements

(OM and EC D1). Note that Yi is positively correlated to PC 2 while CP, MSWP Set, OM and EC D1 are negatively correlated.
For field 1, the distribution of sampling sites (18 sites) along the PC 1, show two distinct patterns corresponding to two classes. Thus, classes are formed by the sampling sites whose values are lower (class 1) or higher (class 2) than 0.27 on PC 1. Class 1 represents approximately 78% of the sites and corresponds to the sampling sites where the phenology (Post-Bu, Fl, and Ve) presents higher precocity. Maturation is also more advanced in this class (TSS values at Pre-Ha 1, 2 and Ha are higher). Regarding environmental parameters, class 1 corresponds to sites characterized by a high elevation (ELE), a higher total soil water availability (TSWA), a lower organic matter (OM) and low values of electrical conductivity (EC D1). Class 2 represents approximately 22% of the sites. It presents an opposite behaviour to class 1 with sites characterized by a late phenology and maturity. A high temporal stability was observed since classes remain stable over the 4 seasons of the experimentation. Regarding the distribution along the PC 2, note that both classes present a regular distribution along PC 2 (Fig. 4a). This distribution is explained mainly by plant parameters such as yield (Yi) and canopy porosity (CP). This phenomenon will be detailed later in the paper (complementary study for field 1).

For field 2, PC 1 and 2 represent 46.8% and 14.1% of the variation, respectively, accounting for 60.9% of the total variability. Phenology, maturation, plant measurements (CP and Yi) and soil measurements (EC D1) are strongly correlated to PC 1. Yi and EC D1 are positively correlated to PC 1, while phenology, maturity and CP are negatively correlated to PC 1. The PC 2 is correlated to soil parameters (BD and FC). BD is positively correlated to PC 2 while FC is negatively correlated. Finally, MSWP Set is mainly correlated to PC 3 (data not shown).
For field 2, the distribution of sampling sites present very different characteristics when compared to PCA of field 1. Sampling sites are not organised in classes but more regularly distributed along the PC 1. Sampling sites are organised along a gradient where positive values on PC 1 correspond to sites with a less advanced phenology and maturity, a lower CP values, and high values in Yi, EC D1 and BD. Contrariwise, negative values on PC 1 correspond to sites with a high precocity either in phenology and maturity, high CP and FC values, and low value in Yi, EC D1 and BD. Although, it is difficult to observe on the PCA, a temporal stability was observed since the distribution of sampling sites along PC 1 is rather consistent for both years of the experiment.
Parameters affecting within field phenology and maturity are different for both fields. For field 1, differences in phenology and maturity are mainly explained by soil and topography. These parameters result in two clear classes. For field 2, in addition to soil parameters canopy and yield may explain within field differences in phenology and maturity. For both fields, MSWP Set variable did not affect much the variability showing that plant water restriction is not a significant driver neither of phenology nor or maturity in our conditions. Note that for both fields, the observed temporal stability of the distribution suggests a dominant effect of stable parameters of the environment.

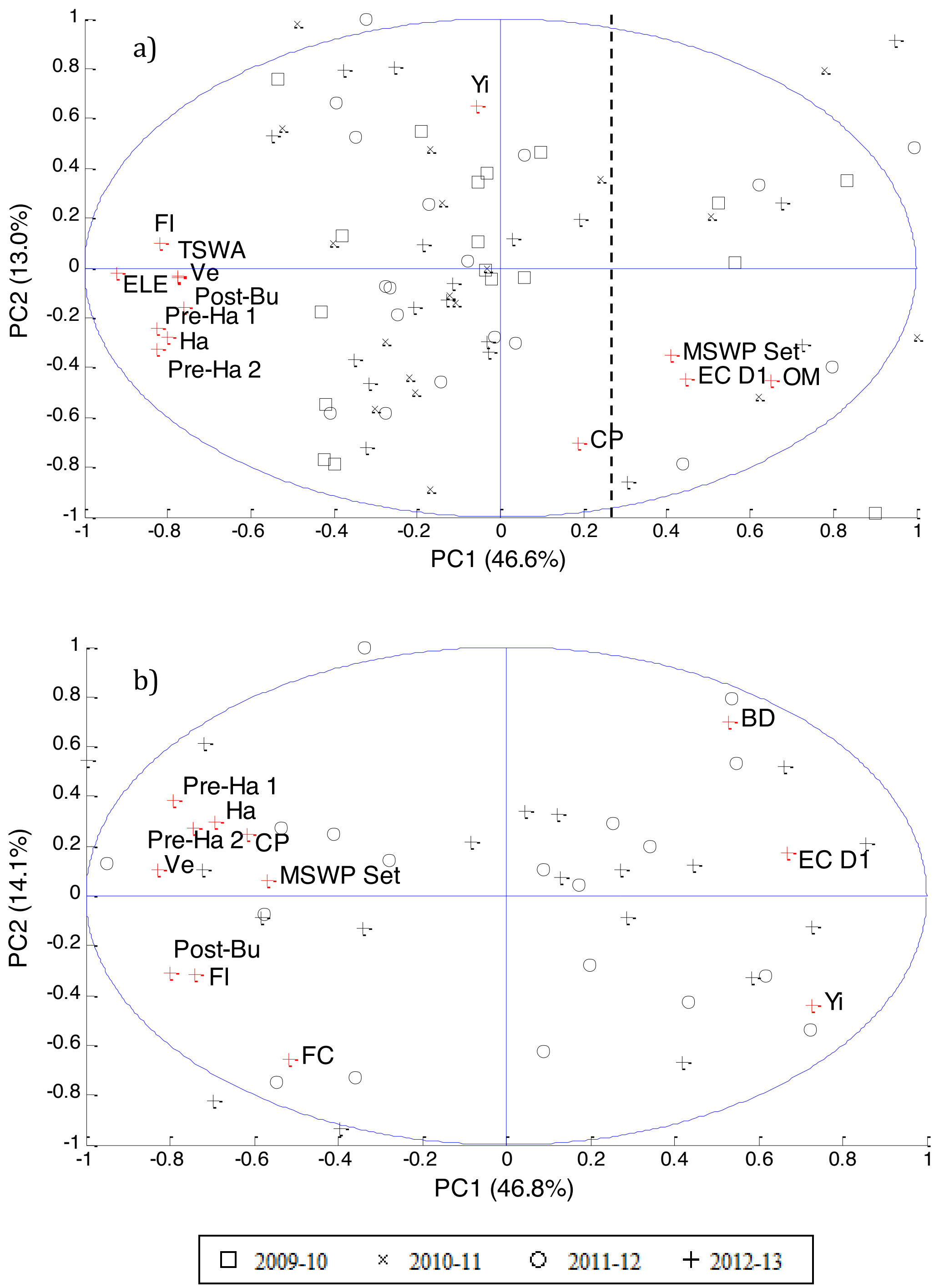

Fig. 4 Principal component analysis (PCA) for field 1, cv Cabernet Sauvignon (a) and field 2, cv Chardonnay (b). Variables are abbreviated as in Table 1 and 2. Vertical dashed lines in figure 1 (a) divides the 2 classes identified in the analysis. Where: Post-Bu: Post-Budbreak, Fl: Flowering, Ve: Veraison, Pre-Ha 1: TSS 20 days before Harvest, Pre-Ha 2: TSS 12 days before Harvest and Ha: TSS at Harvest.

Mapping of the PC 1 for field 1 and 2.

Coordinates of the sites on the PC 1 were mapped to show how values are spatially distributed. Resulting maps are shown in Fig. 5 and 6 for field 1 and 2, respectively. For field 1, assuming a temporal stability of the site distribution, a mean PC 1 coordinate was computed for each site over the seasons. For this field, classes identified in the PCA correspond to two zones. As a result, each class correspond to a specific zone of the field.
Class 1 corresponds to zone 1 (North-western part of the field) and represents 78% of the field area (14 sampling sites), while class 2 corresponds to zone 2 in Fig. 5 (Southern part of the field) and represents 22% of the field area (4 sampling sites). Considering correlations observed on the PCA with a strong spatial organisation of the phenomena, more detailed explanations may be advanced. Zone 1 present the highest precocity and is characterized by a high elevation and high water availability (high TSWA). On the other hand, zone 2 is late, either in phenology and maturity and is characterized by low elevation and TSWA values. Zone 2 is assumed to have a soil layer thinner and more compacted which limits natural water flow and then produce a saturated zone that affect the roots growth (shallow root-depth) and a lower TSWA, but high electrical conductivity. Contrariwise, zone 1 is assumed to have a deeper soil with no subsoil constraints, leading to a deeper rooting depth and therefore to a higher TSWA. For field 1, within field differences in phenology and maturity are mainly associated to environmental characteristics (soil and topography). The differences in elevation and in water availability, affect the phenological and maturity development throughout the season. This would explain the high temporal stability observed over the seasons. No effect of plant variables (CP and Yi) on the behaviour of phenology and maturity at the within field scale is observed.

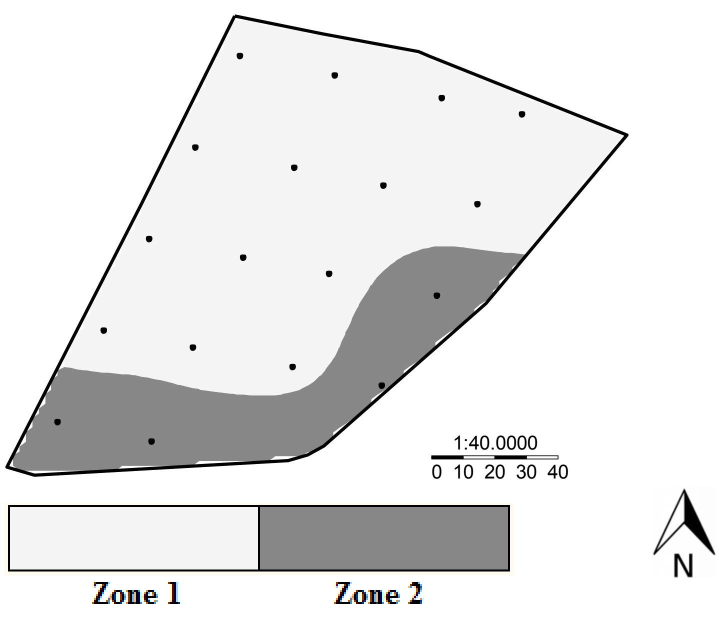

Fig. 5 Map of the first component from the PCA cv Cabernet Sauvignon (mean all of the seasons). Classes are ranked according to the 2 classes identified in the PCA analysis.

For field 2, maps of PC 1 sites coordinates are presented in figures 6a and 6b for seasons 2011-12 and 2012-13 respectively. In addition, a map of mean coordinates over both seasons is presented (Fig. 6c). The trend identified along the PC 1 of the PCA corresponds to a clear spatial gradient (Fig. 6 a, b and c). This gradient is organised along a north-south direction and is temporal stable (at least for both seasons). The northern part of the field is characterized by a late phenology and maturity. It corresponds to a low CP (higher vegetative expression), high yield (Yi) and high EC D1 values. The southern part of the field presents exactly the opposite characteristics: high CP (lower vegetative expression), low Yi and low EC D1. For field 2, observed differences in phenology and maturity at within field scale, are mainly associated with plant variables (such as canopy porosity and yield) and soil EC D1.

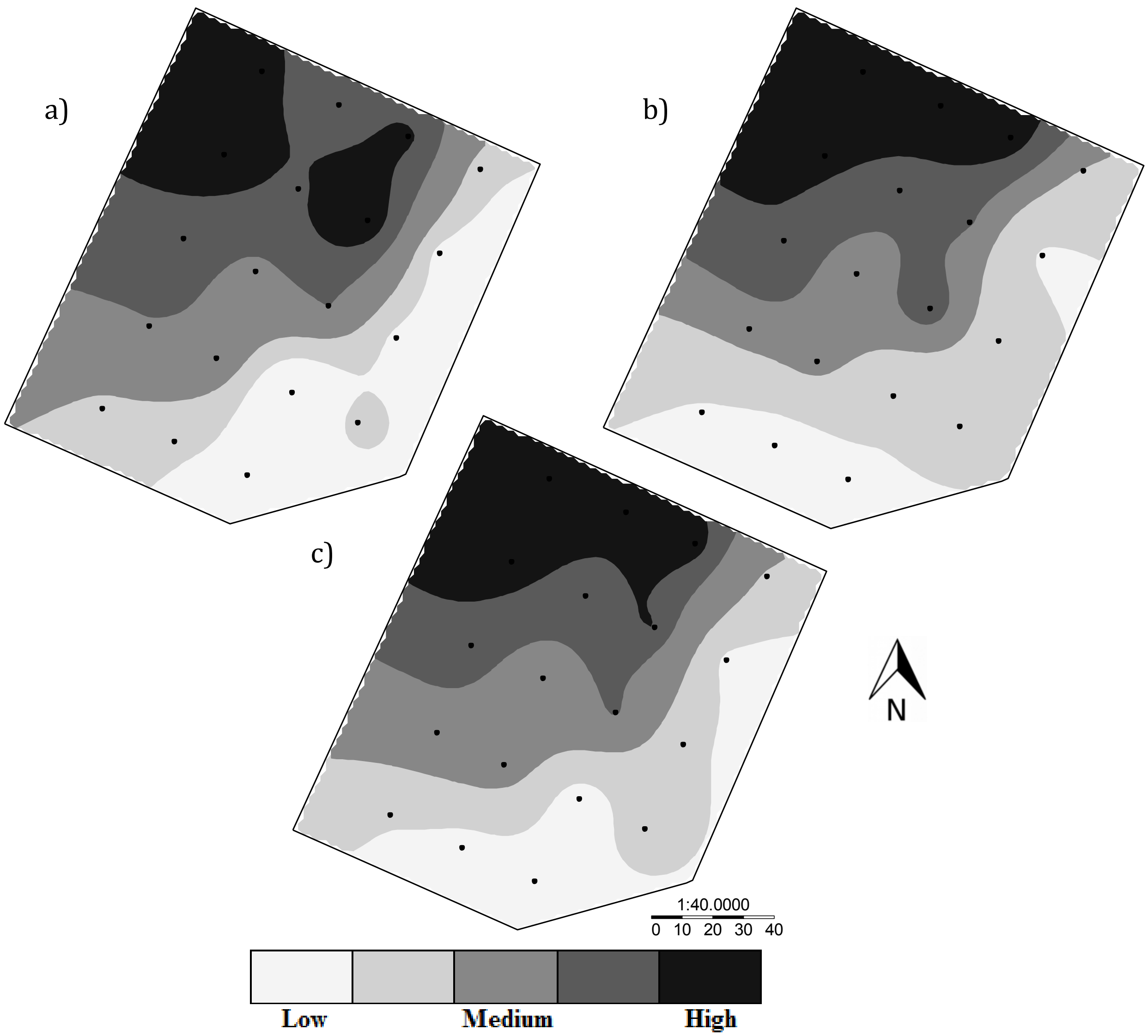

Fig. 6 Map of the first component from the PCA field 2 (cv Chardonnay). a) Season 2011-12, b) season 2012-13 and c) mean all of the seasons. Classes are ranked from white for the lowest values to black for the highest values (each quantile represented 20% of data).

As previously mentioned, spatial structure of the fields (respect to PC 1) was different, for field 2 a gradient was identified, while for field 1, two very different zones were identified. However, for the largest zone (zone 1) of field 1 a regular distribution was observed along the PC 2. A complementary study was therefore carried out on the site belonging to zone 1. Results of this analysis are presented below.

Complementary study for field 1

PCA of sites belonging to zone 1 is presented in Fig. 7. PC 1 and PC 2 represent 29% and 22.6% of the variation, respectively, accounting for 51.6% of the total variability of the zone 1. The PC 1 is strongly correlated to phenology (Post-Bu, Fl and Ve) and environmental parameters (ELE, OM, TSWA and EC D1) while PC 2 is mainly correlated to maturation (Pre-Ha 1, Pre-Ha 2 and Ha), and plant variables (CP and Yi). The distribution along both PCs is temporally stable since sites are more or less at the same part of the PCA. The PCA of zone 1 highlights a complex phenomenon where phenological development is mainly driven by environmental variables (soil and topography), while maturation is mainly driven by plant variables (canopy porosity and yield). In order to verify the spatial organisation of the PCA site coordinates, Fig. 8a and b show maps of PC 1 and PC 2 respectively. Maps only focus on zone 1, zone 2 is therefore shown as a hatched area. Very similar patterns were observed for all the seasons for both PC 1 and PC 2, therefore figures 8 (a and b) show the mean values computed over the four seasons.

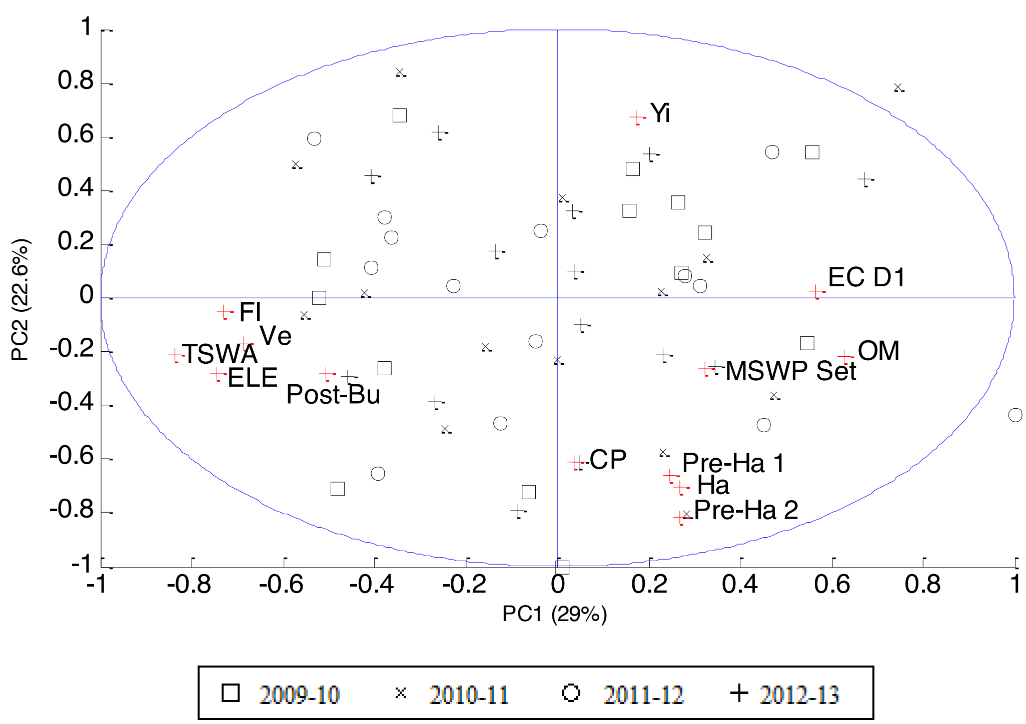

Fig. 7 Principal component analysis for field 1 cv Cabernet Sauvignon, sampling sites from zone 1 (class 1 identified in the first PCA of field 1). Variables are abbreviated as in Table 1. Where: Post-Bu: Post-Budbreak, Fl: Flowering, Ve: Veraison, Pre-Ha 1: TSS 20 days before Harvest, Pre-Ha 2: TSS 12 days before Harvest and Ha: TSS at Harvest.

Figure 8a shows a clear gradient of the phenology mainly explained by soil parameters and topography. The southern part of the zone 1 is characterized by a late phenology, low ELE and TSWA and high OM and EC D1. The northern part of zone 1 presents the opposite features. For maturation (Fig. 8b) very different spatial patterns were observed. Precocity in maturity is mainly observed (for the four years) in the central part of zone 1 (white quantile). Late maturity is observed at the edges of the field. This spatial organization is only driven by plant parameters (Yi and CP) determined by cultural practices. In particular, the balance between vegetative expression (CP) and fruit mass (Yi) appears to be determinant to explain the variability of maturation on zone 1. This dual effect highlights the importance of cultural practices on the maturation and the importance of the environment variables on phenology.

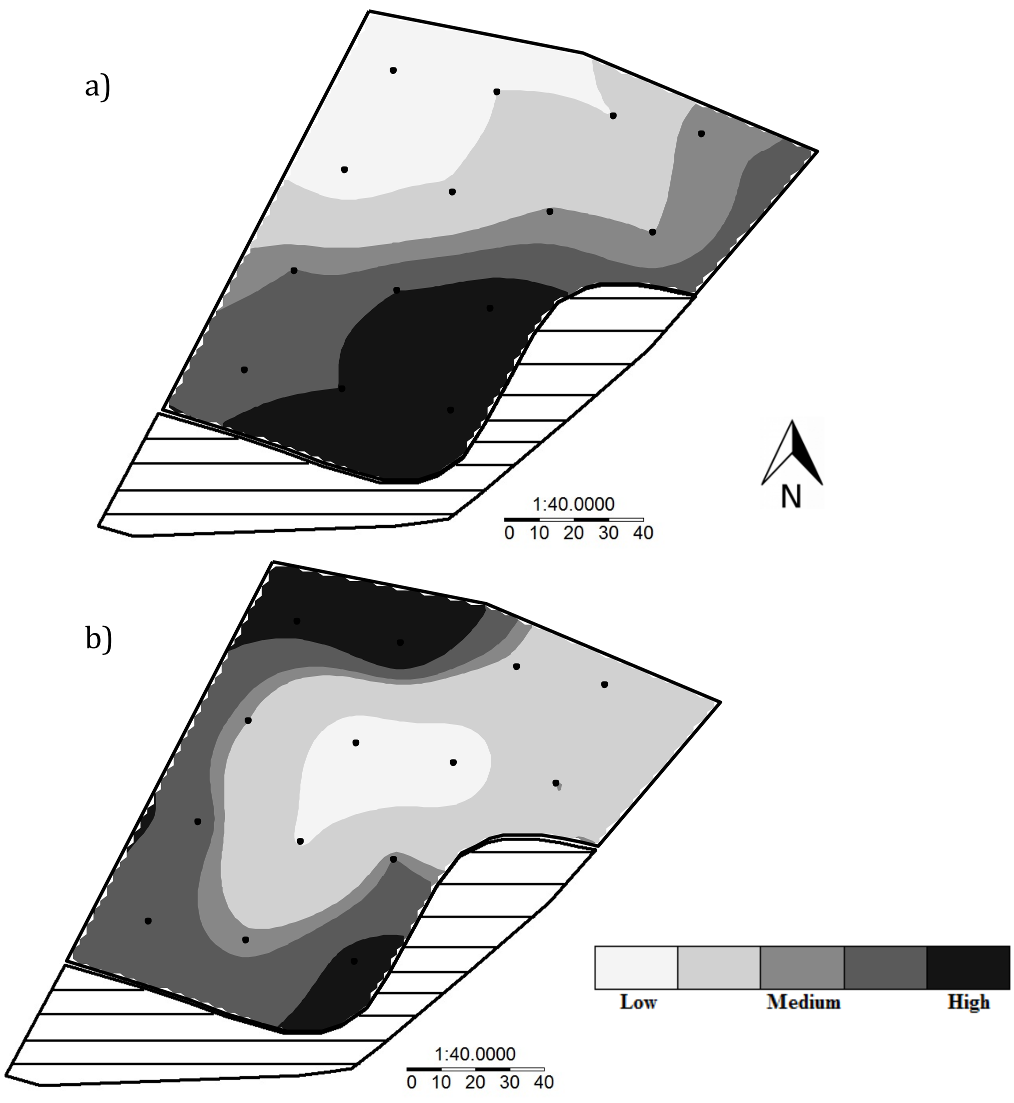

Fig. 8 Map of both first (a) and second component (b) from the PCA cv Cabernet Sauvignon sites zone 1, mean of all seasons for each PC is presented. Classes are ranked from white for the lowest values to black for the highest values (each quantile represented 20% of data). Hatched area represents the zone 2 of the field 1.

Regarding the whole field (zone 1 and zone 2), field 1 presents a complex phenomenon. When variability in phenology and maturation is significant (for the whole field 1), the variability is mainly driven by environmental parameters like soil and topography. When variability in phenology is low, like that observed over the zone 1 of the field 1 (Table 7), effect of environmental parameters remain determinant to explain the phenology. However, their incidence does not seem significant enough to counterbalance the effect of cultural practices on maturation.
In order to better explain the incidence of environmental parameters on phenology and maturity, additional measurements, on field 1 were performed during one season (2011-2012).

Table 7 Variability observed in the phenology and maturation in both field (1 and 2) and zones defined in the field 1 (zone 1 and 2).

	Phenology						Maturation					
	Post-Budburst		Flowering		Veraison		Pre-Ha 1		Pre-Ha 2		Harvest	
Field 1	SD	CV	SD	CV	SD	CV	SD	CV	SD	CV	SD	CV
2009-10	0.7	10.5	0.9	3.9	0.3	1.0	1.0	4.8	1.2	5.6	1.2	5.3
2010-11	0.5	8.3	1.5	6.1	0.3	0.8	1.4	6.8	1.6	7.4	1.6	7.4
2011-12	0.9	12.8	1.4	5.6	0.5	1.5	1.4	6.5	1.3	5.9	1.4	6.4
2012-13	1.1	12.1	0.8	3.9	0.3	0.8	1.4	7.1	1.4	6.5	1.5	6.8
Field 2												
2011-12	0.6	6.4	0.7	3.0	0.5	1.5	1.2	7.6	1.0	5.3	1.0	4.9
2012-13	1.4	15.6	1.5	6.5	1.0	2.9	1.2	6.7	0.8	3.8	0.8	3.4
Zone 1 (Field 1)												
2009-10	0.6	9.6	0.5	2.4	0.3	1.0	0.4	1.9	0.4	1.8	0.6	2.8
2010-11	0.3	5.5	0.9	3.5	0.2	0.5	0.4	1.9	0.6	2.8	0.6	2.5
2011-12	0.7	9.1	0.9	3.8	0.2	0.6	0.5	2.5	0.7	3.3	0.9	4.0
2012-13	0.8	9.5	0.7	3.4	0.3	0.7	0.4	2.0	0.5	2.2	0.7	3.2
Zone 2 (Field 1)												
2009-10	0.1	2.5	0.6	2.7	0.3	0.8	1.0	5.6	0.5	2.7	1.4	6.6
2010-11	0.4	8.5	1.7	7.5	0.2	0.7	1.6	8.5	1.8	9.5	2.0	10.3
2011-12	0.8	13.6	1.0	4.5	0.5	1.5	1.7	8.8	1.4	6.9	1.5	7.2
2012-13	1.2	15.4	0.4	2.1	0.1	0.4	1.9	10.8	2.0	10.1	2.0	9.7

SD: Standard deviation, expressed in units of Phenological scale (PS) for Phenology and ºBrix for Maturation.
CV: Coefficiente of variation, expressed in percentage for both variables (Phenology and Maturation).

Additional measurements for field 1 cv Cabernet Sauvignon

On field 1, additional measurements were initially positioned in function of elevation on high (ZH) and low elevation (ZL) zones (Fig. 3). Considering the analysis performed in the previous section, ZH corresponds to zone 1 and ZL to zone 2. In the following, zone 1 and 2 will therefore refer to ZH and ZL respectively.
For zone 1, the level of the water table ranges from 0.6 m to 1.5 m below the soil surface, while for zone 2, it doesn't decrease beyond 0.65 m (Fig. 9). These variations are mainly driven by the cumulative precipitations during the measurement dates. These results highlight differences in the physical space available for root development between zones in relation with topography. As mentioned above, zone 2 has compacted soil problems affecting growth and root activity. Although there are no quantitative measurements of the number of roots on each zone, no active roots were observed in the pits of zone 2 while the

presence of iron-manganese concretions in the profile was observed. This last characteristic is usually associated with soils where the water table is high during an important period of the year due to drainage problems and excess of water. These observations may also explain the presence of high level of organic matters (OM) in zone 2.

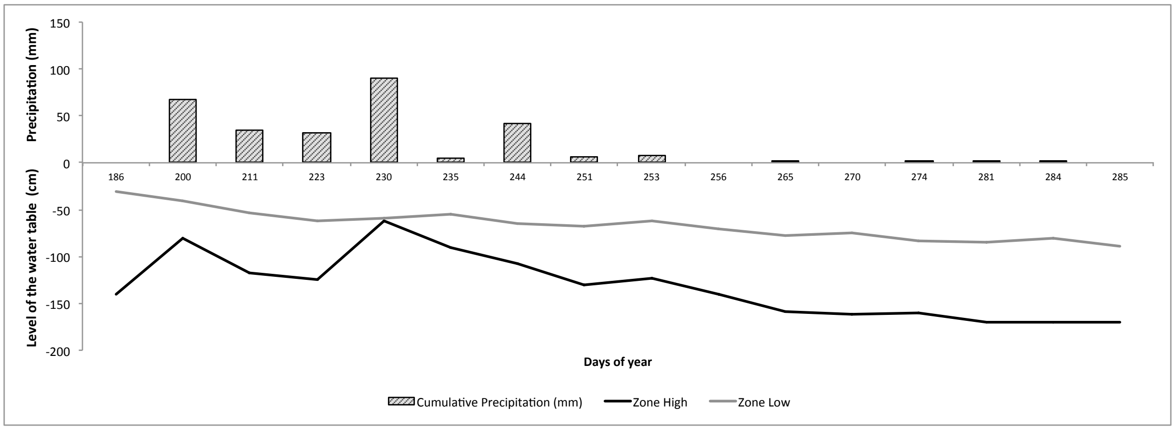

Fig. 9 Level of the water table from the field 1 (cv Cabernet Sauvignon) for each zone (zone H and L).

Regarding mean daily soil temperature at 0.15 m (Fig. 10 a) and 0.30 m depth (Fig. 10 b), it is slightly higher in zone 1 compared to zone 2 over the period of measurement. These differences range from 0.5 ºC to 1.5 ºC during the measurement period. For 0.30 m depth, no differences between the two zones of the field are observed.
Air temperature is higher for zone 1 during the whole period of measurement (Fig. 11a). The difference in temperature between zones was approximately of 0.4 ºC per day on average (Fig. 11a) which corresponds to 15 growing degree days (GDD) during the whole period of measurement (Fig. 11b). These differences in air temperature may be related to soil characteristics and topography, and the lower zone (zone 2) being cooler. These differences may have a significant impact on variability observed in phenology and maturation between zones.
Additional measurements performed on field 1 highlight the direct and indirect incidence of topography on (i) space available for root growth, (ii) soil temperature and (iii) microclimatic conditions (air temperature). These parameters all together explain the different phenological development and maturity between zone 1 and zone 2.

General Discussion

To our knowledge, this study is a first attempt to identify the principal factors affecting the spatial variability of phenology and maturation at the within field scale. It considered two fields with different characteristics: (i) field 1 (cv Cabernet Sauvignon) which present differences in topography and (ii) field 2 (cv Chardonnay) considered as flat. In general, spatial variability observed for plant, soil, phenology and maturation variables is higher in field 1. Factors affecting the spatial variability of phenology and maturation are different for each field.

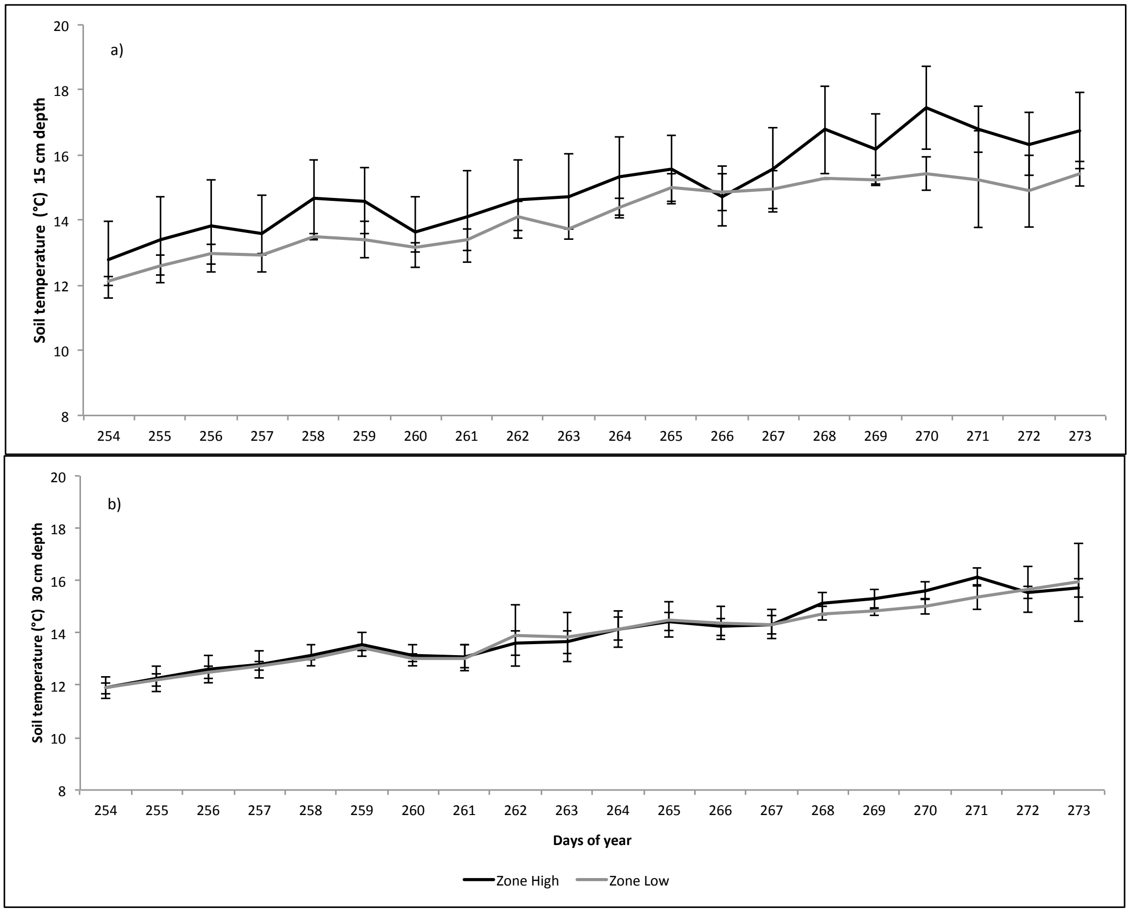

Fig. 10 Soil temperature from the field 1 (cv Cabernet Sauvignon) for each zone (zone H and L). (a) 15 cm depth and (b) 30 cm depth.

For field 1, the main factors of variability are related to environmental parameters: topography (elevation) and its resulting effect on soil characteristics (water availability) and temperature. These factors lead to two clear zones of phenology and maturity. Similar results were observed at a larger spatial scale. In the Loire and Hawke's Bay valleys, Barbeau et al. (1998) and Tesic et al. (2001a, 2001b) demonstrated that soil characteristics as well as soil compaction and the presence of a water table affect phenology and maturation of the grapevine. They observed that sites with good drainage characteristics (light texture, high depth and low water table) are characterised by a high precocity in phenology and maturation while sites that present heavy clay soils and high water table present late phenology and maturation. At the regional level, differences in phenology, expressed in days, in the case of Barbeau et al. (1998) are similar to those obtained at the within field level (Verdugo-Vásquez et al. 2016). Regarding the soil temperature, Conradie et al. (2002) found that, at the regional level, the presence of a water table delayed the date of budburst by 4 days because of lower soil temperature. Canopy temperature (air temperature) can be affected by different environmental parameters like soil characteristics (soil composition and colour), the local topography and drainage capabilities (Jones 2013; Tesic et al. 2001b). Many works have shown that air temperature significantly affects grapevine phenology and maturation (Chuine et al. 2013; Falcão et al. 2010; Jones 2013;

Quénol et al. 2014; Ramos et al. 2015; Sadras and Petrie 2012; Winkler et al. 1974). For field 1, differences in topography explain differences in direct or indirect parameters like soil characteristics, water availability, soil temperature, level of the water table and microclimate conditions (air temperature) of the field. Variability of these parameters all together drives the spatial variability of both phenology and maturation. Considering the peculiar case of field 1, topography may therefore constitute relevant auxiliary data to define within field zones of phenology and maturation.

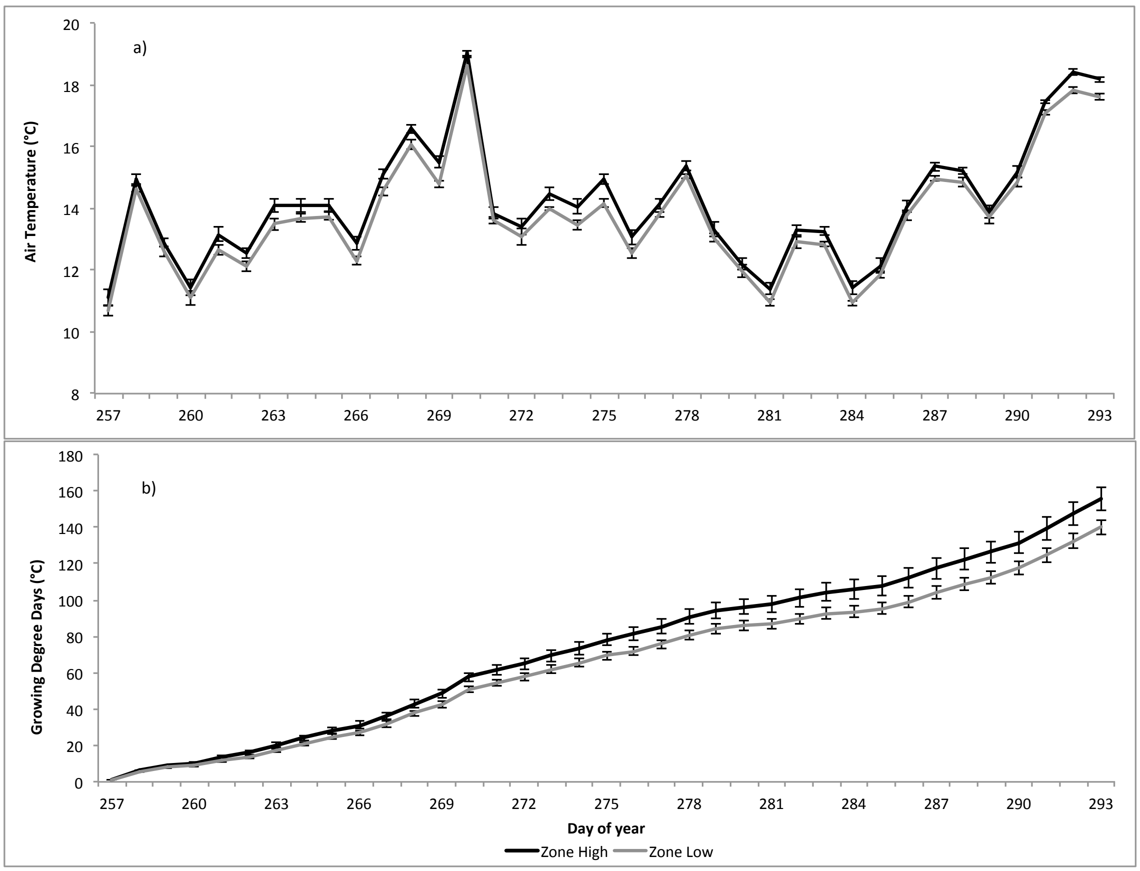

Fig. 11 Air temperature (a) and growing degree-days (b) from the field 1 (cv Cabernet Sauvignon) for each zone (Zone H and L). Each point on the figure represents the average of 4 sensors for each zone.

When differences in topography are small, as shown in field 2 and in zone 1 of field 1, factors which explain the variability of phenology remain the environmental parameters like soil (EC D1) and slight variations in elevation. However, for maturity the problem seems for complex since plant variables (canopy porosity and yield) have a significant incidence. Accumulation of sugar depends mainly of the canopy area (CA) to fruit load (FL) ratio, that is to say, carbohydrate source-sink partitioning. Several studies have shown that changes in CA:FL ratio, change both the date of veraison as well as the dynamic of TSS accumulation (Bobeica et al. 2015; Filippetti et al. 2015; Parker et al. 2014, 2015). In the case of field 2, spatial patterns of CA:FL ratio are mostly driven by soil parameters (Fig. 4b). As a result, the spatial patterns of maturity fit with that of phenology. For the zone 1 of field 1, spatial patterns of CA:FL ratio may be explained by a more complex interaction between environmental parameters, cultural practices and phytosanitary problems. This explains that for this zone, the spatial trend of maturity differs from that of phenology.

Practical significance of the results

At the within field level, topography is a key parameter to delineate phenology and maturity zones. It may explain the variability in soil characteristics, soil temperature and air temperature at the within field scale. It shows the advantage of a temporal stable parameter, which requires being measured only once. Moreover, this information is becoming easier to obtain at a high spatial resolution with low operational costs either from soil apparent conductivity survey (Bramley et al. 2011), airborne LIDAR (Tarolli et al. 2015) or UAV photogrammetry (Murphy et al. 2008; Ouédraogo et al. 2014). When a significant variation in elevation is observed, it may constitute the most relevant information to plan target sampling of phenology and maturity. It may also constitute interesting auxiliary information to consider for the calibration of empirical spatial models to map the spatial variability of phenology and maturation at the within field scale. For example, the approach used by Acevedo-Opazo et al. (2009) to spatialize the water status of grapevines could be used. Such an approach would provide up to date maps of phenology and maturation using only one punctual field measurement, optimizing the sampling time and spatial resolution. These maps may constitute a decision support to improve the timing of pesticide applications, fertilization, irrigation and harvest.
Monitoring temperature is also a key parameter to delineate zones of phenology and maturity. Wireless Sensor Network (WSN) deployment is an interesting opportunity for this purpose. Indeed a large number of low-cost sensors would characterize the within field variability of the microclimate. Two types of WSN may be necessary: soil temperature to characterize variability of early phenology stage like budburst and air temperature to characterize spatial variability of late phenology stages and maturity. Considering the cost and maintenance constraints of WSN (Kunz and Tatham 2012; Primicerio et al. 2013), two options may be considered. The first option is a temporary deployment (several weeks) over the fields in order to identify the within field patterns of soil and air temperature. This option assumes these patterns are temporally stable and may well be used to target sampling of phenology and maturity. The second option is to use high resolution topography data to define the location of a small number of sensors to be deployed. This last option is similar to that performed on field 1 in this study.
When fields are flat (i.e. topography presents low spatial variability), soil characteristics (color, depth and texture) become key parameters to delineate zones of phenology. In this case, soil apparent electrical conductivity (EC) may be relevant auxiliary data to define these zones. However, EC may be limited to define maturity zones. Indeed spatial variability of maturity is predominantly determined by the Canopy Area:Fruit Load ratio. Vegetative index, i.e. Normalised Difference Vegetation Index (NDVI), derived from remote sensing technologies are strongly related to the vegetative expression and canopy area (Acevedo-Opazo et al. 2008; King et al. 2014). They may therefore be used to delineate maturity zones. This approach was demonstrated by Bramley et al. (2011) and González-Flor et al. (2014). However, considering vegetative index alone, assumes the fruit load and the resulting yield is homogeneous over the fields, which is far from the case in

most vineyards (Taylor et al. 2005). To be fully operational, this approach would require the knowledge of the fruit load at a high spatial resolution. This information is difficult to obtain before harvest. Different approaches could however be considered, for example the use of machine vision to estimate the number of bunches before harvest (Diago et al. 2012; Dunn and Martin 2004). Assuming the temporal stability of the variability of yield (Tisseyre et al. 2008), another option could be to use yield map of previous year to estimate the fruit load of the year.

CONCLUSIONS

This study is a first approach to identify the main factors affecting the spatial variability of phenology and maturation at the within field scale. In two different fields, it showed that environmental parameters like topography and soil characteristics have a significant incidence and may well constitute auxiliary data to identify spatial patterns of phenology. When variation in topography is significant, spatial variability in both phenology and maturity is high. In this case, elevation was identified as the main integrating factor affecting the spatial variability of both phenology and maturity at the within field scale. When the magnitude of variation of elevation is small, spatial variability in phenology and maturity is less significant. Soil characteristics become the most important factor in explaining the spatial variability in phenology while plant variables (vigour and fruit load) drive the maturity. Providing validation at other location, these results provide a decision support on auxiliary data to consider for spatial modelling of phenology and maturation at the within field scale.

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CHAPTER IV

CHAPTER 4: TOWARDS AN EMPIRICAL MODEL TO ESTIMATE THE SPATIAL VARIABILITY OF GRAPEVINE PHENOLOGY AT THE WITHIN FIELD SCALE

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Abstract

Knowledge and monitoring of the grapevine phenology throughout the season are important requirements for planning many productive activities at the vine field scale. However, there is spatial variability of grapevine phenology at the within-field scale and traditional methods of sampling and modeling do not consider this variability. The aim of this study is to propose an empirical spatial model to estimate the spatial variability of grapevine phenology at the within-field scale. This spatial model allows the characterization of the spatial variability of the fields through a single measurement performed in the field (reference site) and a combination of site-specific coefficients calculated through historical data. This approach was compared to classical approaches requiring extensive sampling and phenology models based on climatic data. The study was conducted in two fields, one of cv Cabernet Sauvignon (CS, 1.56 ha) and the other one of cv Chardonnay (CH, 1.66 ha) located in the Maule Valley, Chile. Measurements of the date of occurrence of grapevine phenology (budburst, flowering and veraison) were taken at the within field level following a regular sampling grid (18 sites for cv CS and 19 sites for cv CH) during 4 seasons for cv CS and 2 seasons for cv CH. The spatial model was calibrated using data collected during the first 3 seasons of cv CS and the 2 seasons of cv CH, while the last season of cv CS was used for the validation process. Comparing the different approaches, the best results were obtained with the spatial model in almost all cases, with a Root Mean Square Errors (RMSE) lower than 3 days. However, if the variability of phenology is low, the traditional method of sampling could obtain better results. This study is the first step towards a modeling of the spatial variability of grapevine phenology at the within-field scale. However, to be fully operational in commercial vineyards, the calibration process needs simplification, for example, using low cost, inexpensive ancillary information to zone vineyards according to grapevine phenology. This study opens up the opportunity to combine classical models of phenology based on climatic data with spatial models, with the aim of predicting the grapevine phenology both, in time and space.

Keywords: Spatial model, Climatic models, Extensive sampling, Sensitivity analysis.

Introduction

During the last years, several authors have shown that there is a significant spatial variability in vineyards for many variables at the within-field scale (Arnó et al. 2009; Tisseyre et al. 2008). These variables are related to environmental parameters of the vineyards such as soil (Corwin and Lesch 2005) and microclimate conditions (Matese et al. 2014) and plant characteristics such as water status (Acevedo-Opazo et al. 2010), vegetative growth (King et al. 2014), vine yield (Arnó et al. 2011; Taylor et al. 2005), grape chemical composition (Baluja et al. 2013; Bramley et al. 2011), plant diseases (Bramley et al. 2011) and precocity of the phenology (Verdugo-Vásquez et al., 2016). This last study showed that under certain conditions the within-field spatial variability of grapevine phenology may be as important as the within-regional scale and may justify site-specific management practices. Knowledge and monitoring of the grapevine phenology throughout the season are important requirements for planning many productive activities at the vineyard scale (Mullins et al. 1992). For example, practices such as irrigation, fertilization, phytosanitary application and harvest are scheduled based on the monitoring and the evolution of the grapevine phenology. For a proper planning of the practices mentioned above, the vine-growers need to monitor and know in advance the date of occurrence of the key phenological stages. Therefore, due to the observed spatial variability, new challenges are generated in relation to the monitoring and modeling of grapevine phenology at the within-field scale. Traditionally, the method used by the vine-growers on his or her vineyards consists of making two or three phenological observations per field. These observations are assumed to be representative of the whole vineyard and sometimes other neighboring fields of the same cultivar too (Verdugo-Vásquez et al., 2016). Thus, traditional methods would not be appropriate to represent the spatial variability of the fields and therefore could result in inadequate intervention decisions.

In relation to the modeling of grapevine phenology, climate variables such as air temperature are used to predict phenological stages (Chuine et al. 2013). Through the relation between phenology and air temperature, classical climatic models of phenology have been proposed, mainly developed in the Northern Hemisphere (Caffarra and Eccel 2010; García de Cortázar-Atauri et al. 2009; Molitor et al. 2013; Parker et al. 2011) and in some cases in the Southern Hemisphere (Jorquera-Fontena and Orrego-Verdugo 2010; Ortega-Farías et al. 2002). These climatic models predict the date of occurrence of the key phenological stages (budburst, flowering and verasion) using air temperature as the only variable. Thus, by means of these climatic models it is possible to estimate the date of occurrence of the phenological stages. Temperature data used for these models usually come from meteorological stations or service providers. Whatever their origin, meteorological data are usually available at a medium or low spatial resolution, therefore depending on the vineyard location (and environmental attributes), air temperature used to run the models may differ from real air temperature observed in the field, as described by Matese et al. (2014). In addition, data resolution is too low to consider the within-field scale level, as a result, meteorological data are generally applied at the vineyard or field scale. Therefore, climatic models provide an average value of the date of occurrence of the phenological stage, which is extrapolated to the whole vineyard without considering the spatial variability. Under conditions of high spatial variability, the extrapolation of the average value obtained through the climatic models may not be representative of the whole fields. An approximation of the climatic model that considers the spatial variability could

be a microclimate monitoring of the field using a wireless temperature sensor network. However, it is important to define the number and location of sensors to be installed in the field and the maintenance cost of the system, which may limit its practical application on the vineyards (Kunz and Tatham 2012; Primicerio et al. 2013).
An alternative approach to overcome the above problem is the use of an empirical spatial model. The empirical spatial model allows the estimation of a variable over the whole field while taking into account the spatial variability. This model has been used successfully to estimate vine water status under non-irrigated (Acevedo-Opazo et al. 2010) and irrigated conditions (Acevedo-Opazo et al. 2013). Therefore, spatial models allow the characterization of the spatial variability of the fields through a single measurement performed in the field (reference site) and a combination of site-specific coefficients calculated through historical data. This approach might estimate the precocity (delay or advance of the date of occurrence of phenological stages with respect to a reference site) of the grapevine phenology. A recent study (Verdugo-Vásquez et al. 2016) showed that there is a high temporal stability of the within-field variability of phenology under semi-arid conditions. This knowledge opens up the opportunity to use ancillary data of phenology (historical data) measured at the within-field scale with the aim of developing empirical methods for the calibration of spatial models. The advantage of such an approach is to allow the estimation of phenology spatially with a low number of field measurements allowing grapevine phenological stages to be mapped more precisely. However, the spatial model has never been used to estimate grapevine phenology at the vine field scale. Therefore, the aim of this study is to propose an empirical spatial model to estimate the spatial variability of grapevine phenology at the within-field scale, answering the following questions: (i) Is it possible to propose an empirical approach based on ancillary data to improve the estimation of the spatial variability of the grapevine phenology at the within-field scale? and (ii) Is it possible to provide a better estimation compared to classical approaches based on extensive sampling or climatic data?

Materials and methods

1.- Experimental Fields

The study was conducted in the Panguilemo Experimental Station of the University of Talca, Maule Valley, Chile. Two fields were chosen, one of cv Cabernet Sauvignon (CS, 1.56 ha; 35º22.0' S, 71º35.6' W) and the other of cv Chardonnay (CH, 1.66 ha; 35º21.9' S, 71º35.8' W). Within each vine field, a regular sampling grid was designed, one with 18 measurement sites (25x25 m) for cv Cabernet Sauvignon (Fig. 1a) and another one with 19 measurement sites (25x25 m) for cv Chardonnay (Fig. 1b). Each site of the grid was represented by four consecutive vines, located in the same row. For both fields, two specific sites were considered to test the model approach: the first one is a reference site (Fig. 1, in a square) and the other two sites were randomly selected (Fig. 1, in a circle). An explanation on how these specific sites are used for each field is given in section 3.
The borders of the fields and sampling sites were geo-referenced with a differential global positioning system receiver (DGPS) (Trimble, Pathfinder ProXRS, Sunnyvale, California, USA) and stored as eastern and northern coordinates (Datum WGS84, UTM projection, Zone 19S) to perform the mapping.

2.- Field measurements

This experiment considered 4 seasons for the cv Cabernet Sauvignon (seasons 2009-10, 2010-11, 2011-12 and 2012-13) and 2 seasons for the cv Chardonnay (seasons 2011-12 and 2012-13). During this period, the phenological observations were estimated using the Eichhorn and Lorenz phenological scale as modified by Coombe (Coombe 1995). The phenological scale assigns a number to each phenological stage (expressed in units of Phenological Scale, PS). Phenological measurements were performed from pre-budburst (PS 2 to 3) to post-veraison (PS 36), every 5-7 days in 30 shoots chosen systematically among the 4 vines of a site from the grid. For each site, the date of occurrence of key phenological stages were calculated by linear interpolation between the recorded values. In this study, the dates of following phenological stages were considered:

a) Budburst: Green tip, first leaf tissue visible (PS 4).
b) Flowering: 50% caps off (PS 23).
c) Veraison: Berry softening and colouring begins (PS 35).

For a given site, a phenological stage was considered reached when it was observed over 50% of the shoots.

Climate data (air temperature) were collected using an automatic weather station (Adcon Telemetric, A730, Klosterneuburg, Austria) installed under reference conditions at 300 m from the vineyards. Air temperature was measured at 15-min intervals.

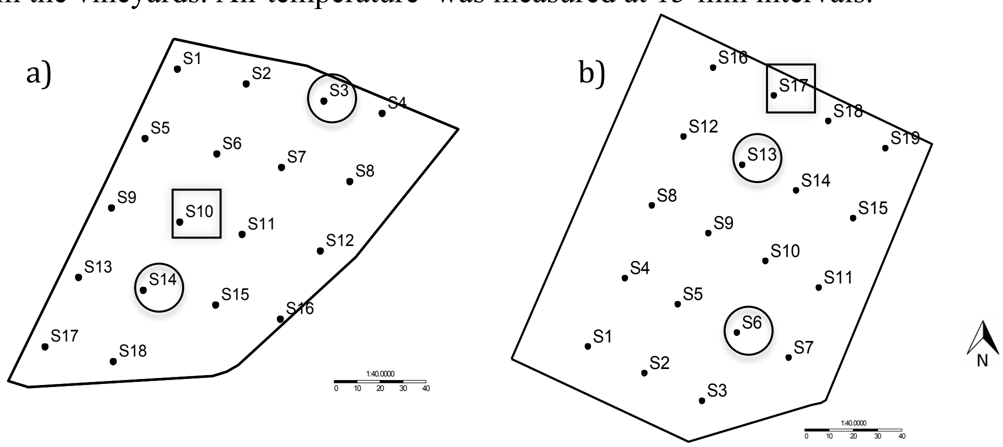


Figure 1 Measurement grids used in the experiments. a) 18 sampling sites for cv Cabernet Sauvignon and b) 19 sampling sites for cv Chardonnay. S_i represents the sampling site number i. Random sites of the classical approach are shown in a circle, while the reference site of the spatial model is shown in a square. More details of these sites are given in section 3.

3.- Model approaches

3.1 Climatic model

There are different climatic models to predict grapevine phenology (Chuine et al. 2013). In this study, the Growing Degree Day model (GDD model) was used to predict the date of occurrence of the phenological stages of budburst, flowering and veraison. The GDD model is based on the classical thermal time concept (Bonhomme 2000). It assumes that the date of occurrence t_s of a phenological stage (*DatePS* in day of the year, DOY)) occurs when a critical state of forcing S_f, defined as a sum of growing degree days from a starting date t_0, reached a particular value F^* (Eq. 1) (García de Cortázar-Atauri et al. 2009; Parker et al. 2013).

$$S_f(t_s) = \sum_{t_0}^{t_s} GDD(x_t) = F^* \qquad \text{(Eq. 1)}$$

The state of forcing is described as a daily sum of the rate of forcing, (Eq. 2) which starts at t_0, x_t is the daily mean temperature and *Tb* corresponds to a base temperature above which the thermal summation is calculated.

$$GDD(x_t) = \begin{Bmatrix} 0 & if \ x_t < T_b \\ x_t - T_b & if \ x_t \geq T_b \end{Bmatrix} \qquad \text{(Eq. 2)}$$

This approach has three parameters: t_0 , F^* and *Tb*. Litterature largely provide values for the above parameters. Table 1 shows the values used specifically in this study for the different phenological stages in both cultivars studied.

Table 1 Parameter values considered for the climatic model (GDD model, Eq. 1 and 2)

		Parameter values			
Cultivar	**Phenological stage (PS)**	***Starting date of GDD acumulation,*** **(t_0) (Days of the year, DOY)**	**Base Temperature (t_b) (ºC)**	F^*	**Source**
CS	**Budburst (PS 4)**	182	5	318.6	García de Cortázar-Atauri et al. (2009)
	Flowering (PS 23)	241	0	1299.0	Parker et al. (2013)
	Veraison (PS 35)	241	0	2689.0	
CH	**Budburst (PS 4)**	182	5	220.1	García de Cortázar-Atauri et al. (2009)
	Flowering (PS 23)	241	0	1217.0	Parker et al. (2013)
	Veraison (PS 35)	241	0	2547.0	

CS: Cabernet Sauvignon, CH: Chardonnay

For the computation of GDD (Eq. 2), air temperatures collected by the automatic weather station were used. Only a value of date of occurrence of each phenological stage is estimated for the whole field (for each cultivar). The predicted date by the climatic model (*DatePS*) corresponds to the days of the year (t_s) when GDD reach the value F^*.
Two approaches were considered to apply the climatic model:

a) Climatic Model Direct (Cl-M Direct): This approach directly uses the climatic model, assuming that the parameter values are correct for the conditions of this study. Therefore, the dates predicted through the model were used (*DatePS*) without considering adjustments or improvements through a calibration process.

b) Climatic Model Improved (Cl-M Improved): In order to take into account possible differences between field climatic conditions and the weather station located more than 300 m away. A correction parameter *C* was introduced in the climatic model (Eq. 3).

The correction coefficient C was expressed in days, it was determined by computing the difference between the average observed date of occurrence of the phenological stage (all sites) and the date predicted by the climatic model for each phenological stage (mean of the first 3 seasons for cv Cabernet Sauvignon and the 2 seasons for cv Chardonnay).

$C = \bar{X}\ [Date_{\overline{PS}}(All\ sites) - \ DatePS]$ (Eq. 3)

Once C was determined, it was incorporated (adding or subtracting) to the date estimated with the climatic model (GDD Model). The resulting corrected climatic model (Eq. 4) is referred to the Climatic Model Improved in the rest of this document.

$DatePS\ Clim.Improved = \ DatePS + C$ (Eq. 4)

3.2 Classical Sampling

Classical sampling of the phenological stages corresponds to visual observations made by vine growers. To perform these observations, phenological scales are used, such as the Eichhorn and Lorenz phenological scale as modified by Coombe (Coombe 1995). Usually, the vine grower performs a few measurements of the grapevine phenology (2 or 3 per field), depending on the size of the field, that are spatially spread over the field without considering the spatial variability of the field. The average of these measurements is then assigned to the whole field. Two approaches were considered in this study, differing in the number of sites considered to estimate the average date of occurrence of the phenological stage.

a) Classical Sampling All Sites (Cl-S All Sites): The average date of occurrence of each phenological stage considering all sampling sites. Note that this aproach is cumbersome since a lot of sites have to be monitored manually all along the vegetative cycle. On a practical stanpoint, it may result in an unrealistic approach if it has to be performed every year. However in this work, it was considered as a reference since it provides the best possible estimation of the phenology of the fields as well as their variability.

b) Classical Sampling 2 Sites (Cl-S 2 Sites): The average date of occurrence of each phenological stage considering 2 random sampling sites as if performed by a vine grower. In this case, the sampled sites were randomly selected from each field. For cv Cabernet Sauvignon, sites 3 and 14 were chosen (Fig 1a, in a circle), while for the cv Chardonnay, sites 6 and 13 were chosen (Fig 1b, in a circle).

3.3 Spatial models

This approach assumes a temporal stability of the within-field variability (TSWF) of grapevine phenology (Verdugo-Vásquez et al. 2016). In the case of a TSWF, the spatial model considers that ancillary data of phenology may also be used to learn the spatial structure of the fields. Once learned, the spatial structure is updated with a phenological measurement carried out on a single reference site, which makes it possible to estimate the phenology on all the sites of the field. This is a spatial extrapolation.

The approach used in this work was the one proposed by Acevedo-Opazo et al. (2010). It was successfully applied to estimate the vine water status at the within-field scale. In the present work, the spatial model was used to propose an estimate of the date of occurrence of the phenological stage PS on site s_i ($\widehat{DatePS}(S_i)$) using observation performed on a reference site ($DatePS(s_{ref})$). The spatial model corresponded to a spatial extrapolation that allows modeling the relative differences of the date of occurrence of PS between each site s_i and the reference site. This approach therefore predicts the precocity of PS by considering the delay or the advance in respect to a reference site s_{ref}. Several functions may be considered to model this delay or this advance. As a first attempt, a simple linear function was considered (Eq. 5). Therefore, as indicated in Eq. 5, the spatial model is based on a collection of linear coefficients a_{S_i} :

$\widehat{DatePS}(S_i) = a_{s_i}\ x\ DatePS(S_{ref})$ (Eq. 5)

Where

$DatePS(s_i)$ = Date of occurrence of phenological stage PS at site s_i.

$DatePS(s_{ref})$ = Date of occurrence of phenological stage PS at a reference site s_{ref}.

PS : corresponds to the phenological stage of budburst, flowering or veraison.

Calibration of the spatial model is based on the estimation of a_{S_i}. This calibration requires ancillary data (historical information) of the date of occurrence of the phenological stage at the vine field scale. In the rest of the study, the collection of a_{S_i} coefficient will be called vector a. Two approaches were considered for the calibration:

a) Spatial Model All PS (S-M All PS): this approach assumes the spatial model is stable over the time for all the phenological stages. This means that delay or advances remain constant whatever the phenological stage under consideration. In the "Spatial Model All PS" calibration, historical information of phenology are considered all together (budburst, flowering and veraison) and therefore one value of a_{s_i} is obtianed for each site.

b) Spatial Model Each PS (S-M Each PS): this approach assumes the delay or advances in phenological stages may differ according to the period of the year and the phenological stage under consideration. In the "Spatial Model Each PS" calibration, historical information of phenology are considered separately for each phenological stage and therefore, a value of a_{s_i} is obtained for each site and each phenological stage (budburst, flowering and veraison).

In a first approach, the reference site for each cultivar was selected at random. For cv Cabernet Sauvignon and cv Chardonnay, site 10 of the sampled grid (Fig. 1a, in a frame) and site 17 of the sampled grid (Fig. 1b, in a frame) were chosen, respectively. a_{S_i} coefficients were determined with a classical least square method as described by Acevedo-Opazo et al. (2010). A summary of all the models used in this study along with their characteristics is presented in Table 2.

Table 2 Summary of the different models used and their characteristics.

Type of model	Model name	Use of historical information?	Use of phenology observations?	Use of reference site?	Prediction of phenology?	Characterization of spatial variability?
Climatic	**Cl- M Direct**	No	No	No	Yes	No
	Cl-M Improved	Yes	Yes	No	Yes	No
Classical Sampling	**Cl-S All sites**	No	Yes	No	No	No
	Cl-S 2 sites	No	Yes	Yes	No	No
Spatial	**S-M All PS**	Yes	Yes	Yes	No	Yes
	S-M Each PS	Yes	Yes	Yes	No	Yes

4.- Calibration and validation of the models

Different approaches were used in the calibration process of both cultivars. For cv Cabernet Sauvignon, the data of the first 3 seasons were used to calibrate the model, while for cv Chardonnay the data of the 2 available seasons were used. On the other hand, the validation process was performed in cv Cabernet Sauvignon using the fourth season (2012-2013). This procedure was performed to evaluate the performance of the model prediction using data not used in the calibration process. Thus, for calibration and validation processes, the root mean square error (RMSE, Eq. 6) was used to characterize the accuracy of each model for each phenological stage.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(DatePS_{sim} - DatePS_{obs})^2}{n}} \qquad \text{(Eq. 6)}$$

Where $DatePS_{sim}$ is the estimated date of occurrence of the phenological stage; $DatePS_{obs}$ corresponds to the observed date of occurrence of the phenological stage and n is the number of observations. The RMSE was estimated for each phenological stage separately.

Additionally, differences (expressed in days) between the observed date of occurrence of the phenological stages and the mean date estimated through the Cl-S All Sites model for both cultivars were calculated for each site of the sampling grid using data from the calibration process. These differences were used to show potential spatial patterns in error (spatial error) for the Cl-S All Sites model.

5.- Sensitivity analysis

As several approaches relied on the selection of specific sites to perform estimations, a sensitivity analysis was performed to determine the incidence of this choice. This concerns two approaches: (i) the Cl-S 2 Sites where estimation of the phenological stage of the field relies on the observations performed on two sampling sites and (ii) the S-M (All PS and Each PS) where estimation is based on the extrapolation of the phenological stage performed on a reference site. In order to estimate the error associated with these approaches, two different methodologies were used:

- For the Cl-S 2 Sites model, all the possible pairs of site combinations were used to estimate the field average value of the date of occurrence for each phenological stage. This was performed with the 2012-13 season (validated season).
- For the S-M, calibrated models (using data provided for the 2009-10, 2010-11 and 2011-12 seasons) were validated with the 2012-13 season, where each of the 18 sample sites was used as the reference site. The analysis was performed for each phenological stage separately and all together.

The sensitivity analysis considered the probability of obtaining a root mean square error (RMSE) lower than a threshold value (expressed in days).

6.- Time (hours) spent on implementation of each proposed model

In order to assess practical constraints (time) required for each approach, the time spent on the implementation of each approach was estimated. For that purpose, only the time for field measurements (phenology observations) on the different sites was taken into account considering the following assumptions:

(i) Field measurements were performed by an experienced technical person (skilled labor).

(ii) Time required to perform an observation on a sampling site corresponded to 0.17 hours (10 minutes) and it is the same for the different phenological stages.

(iii) The date of occurrence of the phenological stages was calculated by linear interpolation between the recorded values. Therefore, 2 measurement dates were considered for the estimation of each phenological stage.

(iv) The time used to collect and process the weather data was not considered (value = 0 hours).

Using the above assumptions, the time required for each approach was estimated for the calibration process of both cultivars. In addition, for the cv CS, the time spent on each approach was calculated assuming a commercial use of the different model, that is, by calculating only the time spent in the season of use (without considering the implementation time used in the calibration process).

7.- Mapping

Maps of the vector *a* (Spatial model) and spatial errors were performed in order to visualize the spatial distribution. The interpolation method used in this study was based on a determinist function (inverse distance weighting) due to the small number of sampling sites (n < 20 sites). Vector *a* and spatial errors were mapped in 33% quantiles for each phenological stage using the 3D-field software (version 2.9.0.0., Copyrigtht 1998-2007, Vladimir Galouchko, Russia).

RESULTS

Within-field variability of phenology

Table 3 presents the observed variability of dates of occurrence at different phenological stages (budburst, flowering and veraison) at the within-field scale for both cultivars. At the within field level, the magnitude of variation (MV) varies between 4 to 12 days for cv Cabernet Sauvignon and 4 to 9 days for cv Chardonnay. For both cultivars, the phenological stage that presented the highest MV corresponded to veraison. With respect to standard deviation (SD), for both cultivars and all phenological stages, SD values were less than 4 days. These preliminary results show that the within-field variability in the date of occurrence of key phenological stages is significant and therefore, if the variability is spatially structured, the planning of operations based on the mean date of occurrence may be inappropriate for a large part of the field.

Table 3 Variability of the phenology at the within-field scale observed for both cultivars over the seasons (values expressed in days).

		Budburst					Flowering					Veraison				
cv	Season	Mean (DOY)	SD	Min	Max	MV	Mean (DOY)	SD	Min	Max	MV	Mean (DOY)	SD	Min	Max	MV
CS	2009-10	272	2.0	270	277	7	338	2.6	335	343	8	37	2.3	34	40	6
	2010-11	275	1.4	274	278	4	329	2.5	327	336	9	26	2.1	23	31	8
	2011-12	266	2.4	264	272	8	324	2.6	321	331	10	23	2.5	21	30	9
	2012-13	270	2.5	268	276	8	327	1.7	324	331	7	29	3.4	23	35	12
CH	2011-12	264	2.6	259	267	8	320	1.0	318	322	4	19	2.0	15	22	7
	2012-13	263	2.5	258	265	7	323	2.3	319	325	6	22	3.5	17	26	9

CS: Cabernet Sauvignon, CH: Chardonnay, SD: Standard deviation, Min: Minimum, Max: Maximum, MV: Magnitude of Variation. DOY: Day of the year.

Model calibration

The errors, expressed as RMSE, obtained by the different models are shown in Table 4. For both cultivars, the magnitude of variation of RMSE values range from 1 to 13 days, showing a high variability in the quality of estimation according to the model used. In relation to the estimation of key phenological stages, veraison is the phenological stage that systematically presents the highest RMSE values, whatever the model used for both cultivars. Therefore, the phenological stage of veraison is the most difficult to estimate, whereas budburst and flowering show very similar behaviour.

On average (last rows in Table 4), if the results are ordered from the lowest to the highest RMSE, the order of the models is generally always the same: The S-M (All PS or Each PS) always shows the lowest RMSE, followed by the Cl-S (All Sites and 2 Sites). The Cl-M (Direct and Improved) shows the highest RMSE systematically. The adjustment of Cl-M (Improved) substantially reduces RMSE compared to the results observed with the Cl-M Direct. In some cases, RMSE of Cl-M Improved are similar to those observed for other approaches (cv Chardonnay, flowering and veraison). The higher RMSE values observed for the Cl-M (Direct and Improved) may be explained by predictions performed with indirect information (air temperature) and the associated model. Two main sources of errors may result from an approach based on climatic data: firstly climatic data provided by a weather station that is not located on the field but nearby, therefore climatic data may differ from that experienced by the field under study, secondly the model itself is general enough but may not be well adapted to the peculiarities of the fields under study. As shown in Table 4 with Cl-S and S-M (and to a lesser extent with Cl-M Improved), the use of direct phonological measurements within the field improves significantly the quality of estimations.

The RMSE values of the Cl-S models (All Sites and 2 Sites) are similar and lower than 3 days for both cultivars. For cv Cabernet Sauvignon, both S-M (All PS and Each PS) generate lower RMSE than those obtained with the Cl-S (All Sites and 2 Sites). However, for cv Chardonnay, only the S-M Each PS, the RMSE values are lower than those estimated by the Cl-S. Note that, with the S-M Each PS, it is possible to obtain RMSE values near to 1 day for both cultivars.

These results show that there are significant differences in the quality of the estimation obtained with the different models. To explain these differences, a comparison between the different models, using the Cl-S (All Sites) as a reference, was carried out and is presented in the following section.

Table 4 Errors (RMSE) obtained by the different model approaches for both cultivars (calibration process).

		RMSE (Days)					
		Climatic (Cl-M)		Classical Sampling (Cl-S)		Spatial (S-M)	
Cultivar	Phenological stage	Direct	Improved	All Sites	2 Sites	All PS	Each PS
CS	Budburst	7.2	5.0	2.0	2.1	1.3	1.0
	Flowering	7.0	3.5	2.5	2.7	1.3	1.1
	Veraison	13.0	3.5	2.2	2.3	2.9	2.4
CH	Budburst	13.1	3.1	2.4	2.5	1.1	0.2
	Flowering	7.5	2.4	1.8	1.9	1.9	1.6
	Veraison	9.7	3.0	2.7	2.7	4.2	1.2
CS	Mean of all PS	9.0	4.0	2.2	2.4	1.8	1.5
CH		10.1	2.9	2.3	2.4	2.4	1.0

*PS: Phenological stages. CS: Cabernet Sauvignon, CH: Chardonnay.

Comparison between the Classical Sampling model (All Sites) and the Climate model Direct.

In this study, the Cl-S (All Sites) is considered the best possible estimation, since for the estimation of the phenological stages, it uses all available phenological measurements. For this model, the RMSE values correspond to the standard deviation of the field and therefore, are considered as a reference value for all the phenological stages and models.

In order to better understand the observed differences in RMSE values between the Cl-M Direct and Cl-S (All Sites and 2 Sites) for the calibration, a histogram of the dates of occurrence of the phenological stages observed for all sites were compared with the estimations by the models (Fig. 2). The lines represent the date of occurrence estimated by the Cl-M Direct (dashed lines), Cl-S All Sites (black lines) and Cl-S 2 Sites (dotted lines). This figure only shows results observed over one season for each cultivar, however, similar results were observed for other seasons of the experiment (data not shown). For both cultivars and all the phenological stages, Figure 2 shows that there is a bias between the average date of occurrence and field estimation provided by Cl-M (Direct). This bias explains the high RMSE observed for this method (Table 4). Confirming previous results, the dates of occurrence estimated by both Cl-S (All Sites and 2 Sites) are very similar. Note, however, that the distance (in day) between both methods changes with the phenological stage, showing that the selection of the 2 sites may adversely affect the quality of the estimation. Figure 2 shows that the Cl-S (All Sites and 2 Sites) are not able to characterize the variability of the date of occurrence of the phenological stages at the within-field scale. Dispersion, caused by the within-field variability, is the remaining variability at this scale.

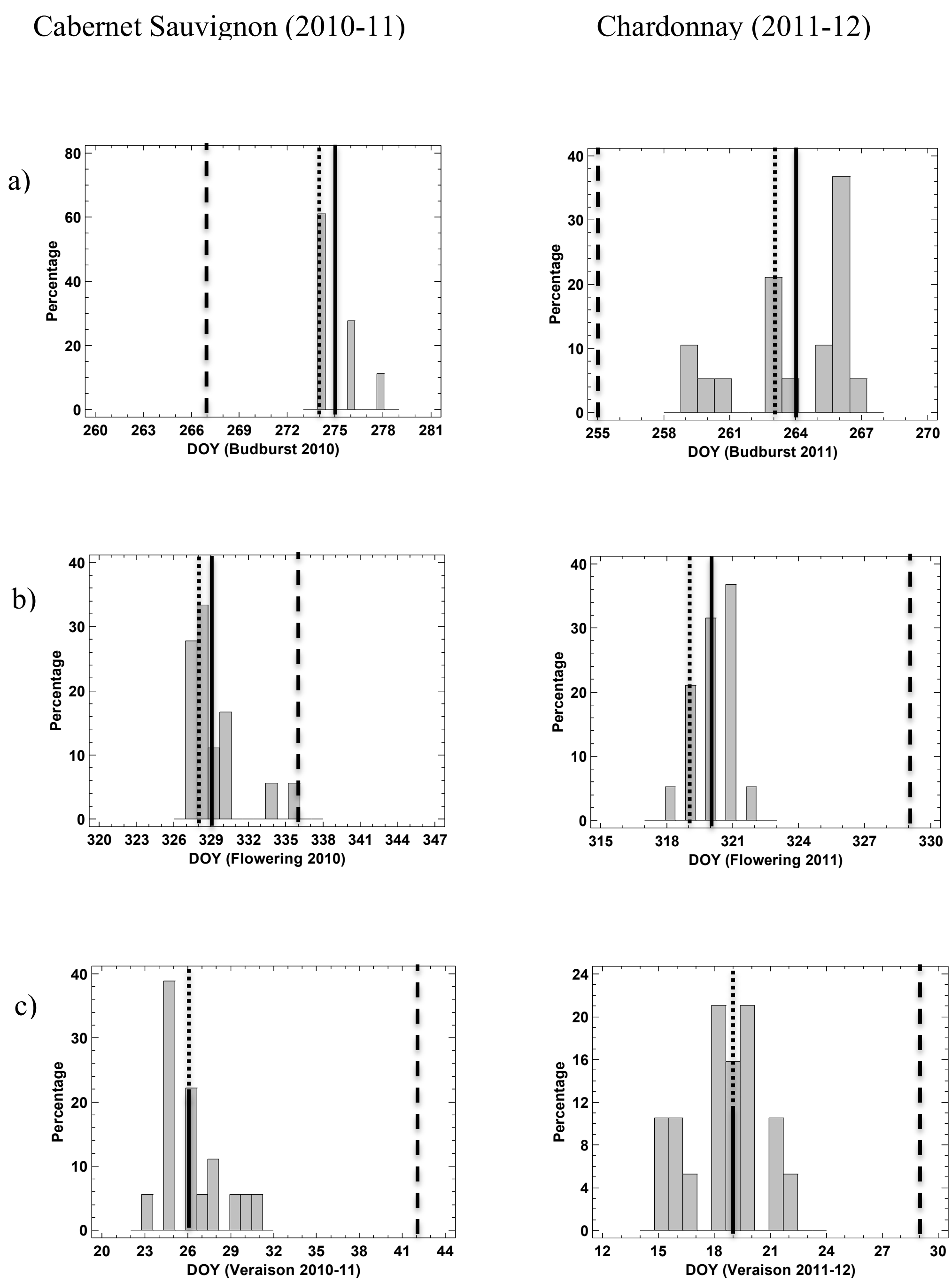


Figure 2 Histogram of the date of occurrence (DOY) of budburst (a), flowering (b) and veraison (c), for cv Cabernet Sauvignon (seasons 2010-11) and cv Chardonnay (season 2011-12) for all the sites. Black lines: date of occurrence of phenological stage observed (mean of all sites); Dotted lines: date of occurrence of phenological stage observed (mean 2 sites); Dashed lines: date of occurrence estimated by the Climatic model (Direct).

Considering all the experiment seasons, Table 5 confirms the trend observed in Figure 2. The bias between the average date of occurrence (Cl-S) and the date estimated by Cl-M

Direct is observed over the seasons. For budburst, this difference is positive (except CS 2011-12) showing that Cl-M Direct underestimates the date of occurrence of this phenological stage. For flowering and veraison, differences are negative, indicating that the Cl-M Direct overestimates the date of occurrence of both these phenological stages. This result justifies the analysis that allows generating the Cl-M Improved using average information of each phenological stage (Table 5) to calculate the correction coefficient C (Eq. 3).

Figure 2 and Table 5 show the limitation of the Cl-M Direct. This may be, as was previously mentioned, due to the distance between the weather station and the vineyards. It is possible to hypothesize that the climate information does not represent the climate of the field (plant micro-climate). These results justify the use of the Cl-M Improved.

Table 5 Date of occurrence of phenological stage (DOY) estimated by the Climatic model Direct (Est) and by classical sampling of all sites as a reference (observed – Obs). Range represents the largest differences between the dates of occurrence observed (Obs) and estimated (Est) expressed in days and Growing Degree Day (GDD).

		Budburst				Flowering				Veraison			
		DOY		Range		DOY		Range		DOY		Range	
cv	Season	Est	Obs	Days	GDD	Est	Obs	Days	GDD	Est	Obs	Days	GDD
CS	2009-10	263	272	9	51.9	341	338	-3	-51.4	46	37	-9	-176.3
	2010-11	267	275	8	50.6	336	329	-7	-122.4	42	26	-16	-321.4
	2011-12	267	266	-1	-8.9	333	324	-9	-164.1	36	23	-13	-264.4
	Mean	266	271	5	31.2	337	331	-6	-112.6	41	29	-13	-254.0
CH	2011-12	253	264	11	78.7	329	320	-9	-152.5	29	19	-10	-197.9
	2012-13	248	263	15	97.7	328	323	-5	-84.6	30	22	-8	-171.1
	Mean	251	263	13	88.2	329	321	-7	-118.5	30	20	-9	-184.5

CS: Cabernet Sauvignon, CH: Chardonnay. DOY: Days of the years.

Comparison between the Classical Sampling model (All Sites) and the Spatial model

As previously mentioned, the Cl-S are not able to characterize the variability of date of occurrence of the phenological stages at the within-field scale. This effect is shown by maps presented (Fig. 3). These maps represent the difference between the phenological stage observed on each site and the mean of the field (All Sites) for both cultivars for the same seasons as shown in Fig. 2. Figure 3 highlights high spatial structures of the Cl-S (All Sites) errors for both cultivars. Thus, it can be seen that the dispersion observed in Figure 2 is spatially structured in the three phenological stages in the study. For all the phenological stages and both cultivars, zones in advance (negative values) and zones in delay (positive values) of the date of occurrence of the phenological stage in respect to the mean of the field (All Sites) are observed. Therefore, these maps show that making a planning decision, for example, the application of phytosanitary products at flowering, based on the mean of the field, may not be representative and inappropriate for a significant surface of the field. The above zones in delay or advance are stable between the different phenological stages for both cultivars. For example, for cv Cabernet Sauvignon, the southern part of the field (dark gray), systematically presents zones in delay, where the differences, with respect to the mean of the field, vary between 3 to 7 days according to the phenological stage (for the 2010-11 season). For cv Chardonnay, the northern part of the field (light gray), systematically presents zones in advance, where the differences, with respect to the mean of the field, vary between -6 to -3 days according to the phenological stage (for the 2011-12 season). These zones in delay or advance were also observed for the other seasons under study (data not shown).

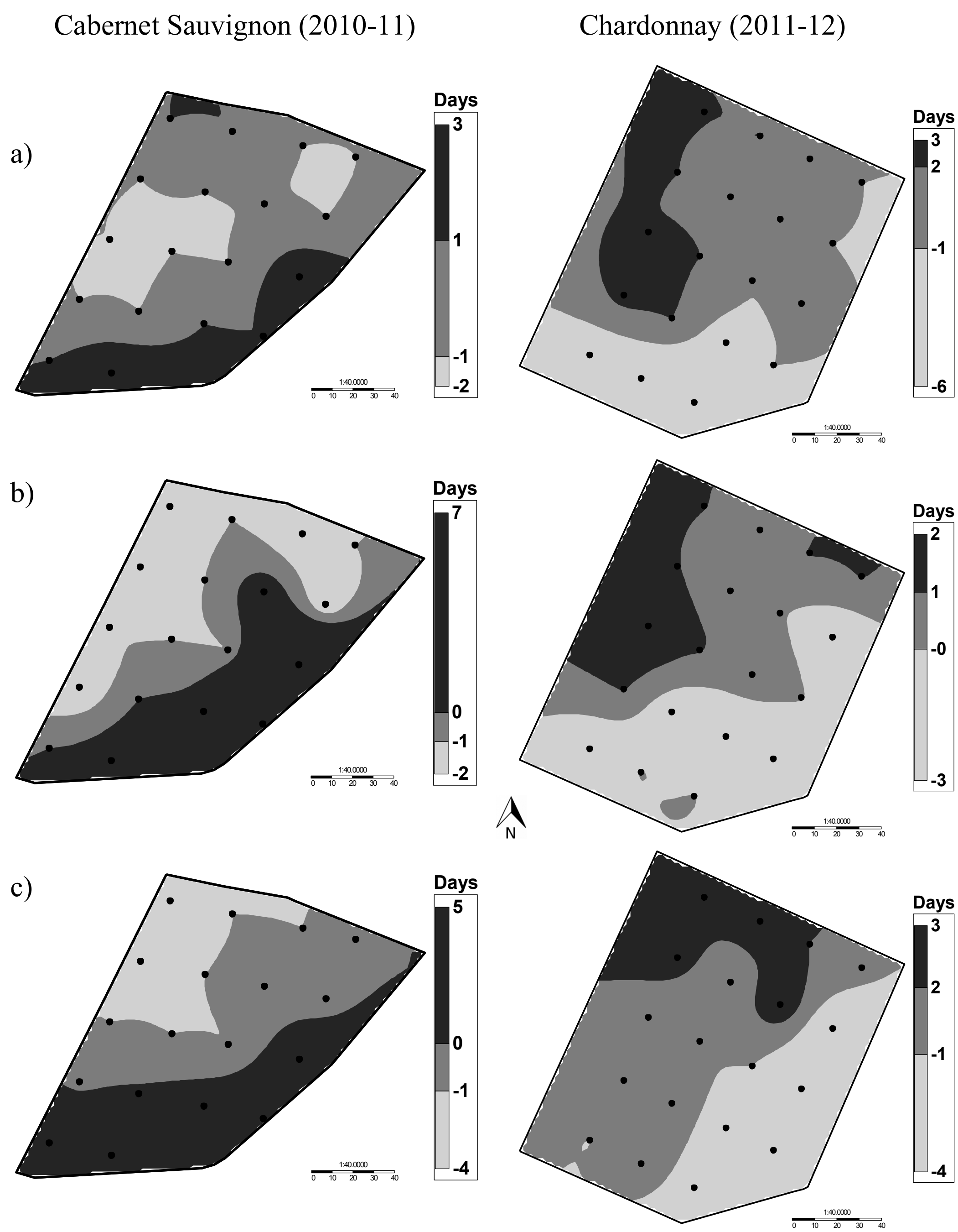


Figure 3 Differences (spatial error) between the observed date of occurrence of phenological stages and the mean date estimated through the Classical Sampling (All Sites) for both cultivars, cv Cabernet Sauvignon (season 2010-11) and cv Chardonnay (season 2010-11). a) Budburst, b) Flowering and c) Veraison.

The spatial variability observed is taken into account by the spatial model. Figure 4 shows the maps of Vector *a* of the S-M (All PS) obtained through the calibration process for both cultivars. Values were mapped using 3 quantiles (each class corresponds to 33% of the data). This figure highlights high spatial structures of the vector *a* obtained for both cultivars. The spatial structure of Vector *a* are similar to those observed spatial errors (Figure 3). Vector *a* is able to model the spatial errors, taking into account the spatial variability observed and therefore, obtaining the best results compared to the other models (lower RMSE values, Table 4). The spatial structures of Vector *a* obtained with the S-M Each PS are similar to those observed in Figure 3 for both cultivars (data not shown). Using Vector *a* and the date of occurrence of each phenological stage observed on the reference site, it is possible to generate maps of these phenological stages. These maps can be used as tools for planning site-specific management practices at the within-field scale.

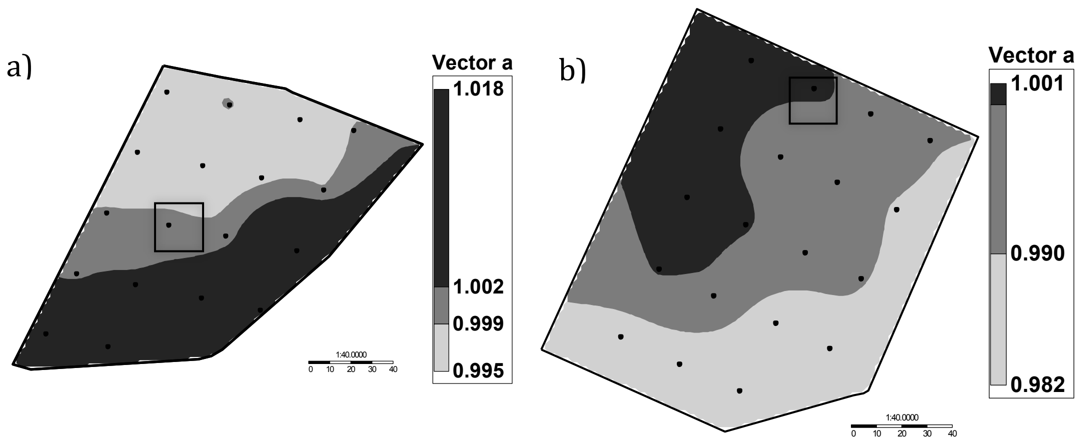


Figure 4 Vector *a* obtained through the calibration process, cv Cabernet Sauvignon (a) and cv Chardonnay (b) for the spatial model "All PS". Reference site is shown in a square.

Model validation

Table 6 presents the RMSE values obtained in a data set independent of those used for the calibration process. Thus, a small increase in RMSE values obtained between the calibration and validation process is observed. This result was expected for the Cl-S, since it does not present a strictly predictive process that considers all the observations made in the field, regardless of the process considered in its execution. On the other hand, this result highlights the ability of all other models to estimate the date of occurrence of key phenological stages in data that are not used for model calibration. The amplitude of RMSE values ranges from 2 to 9 days, showing a high variability in the quality of estimation according to the model used. If the results of RMSE are ranked from low to high, it is possible to observe that the position of the models coincides with the classification of the calibration process, presenting the best results (lower RMSE values) for almost all the phenological stages with the S-M (All PS and Each PS), followed by the Cl-S. Meanwhile the Cl-M obtained the worst results (Direct and Improved). Table 6 highlights the relevance of the S-M, since even without a database for calibration, this provides the best possible estimation.

With respect to the estimation of key phenological stages, it is similar to the calibration process, where the veraison is the phenological stage that systematically presents the highest RMSE values independent of the model used. On the other hand, flowering was the phenological stage that presented the lowest RMSE values. The accuracy of the models is different according to the phenological stages considered. If the Cl-S and S-M show the best results for all the stages, the Cl-M predict very well the flowering and worst the budburst and veraison. This aspect may be of interest from a practical point of view, since depending on the expected accuracy, different approaches can be considered for each phenological stage. Note, however, that a 5 day error on phenology estimation may be sufficient for many applications and that the choice of a more precise estimation method should take into account the operational constraints. These constraints differ greatly from one method to another. For example, the Cl-S requires observations to be made on all sites systematically and the S-M requires a single observation on a reference site (provided that a historical database is available for their calibration). More details about operational constraints will be presented in another section.

Table 6 Errors (RMSE) obtained by the different model approaches (cv Cabernet Sauvignon), validation process.

	RMSE (Days)					
	Climatic (Cl-M)		Classical Sampling (Cl-S)		Spatial* (S-M)	
Phenological stage	Direct	Improved*	All Sites	2 Sites	All PS	Each PS
Budburst	8.5	4.1	2.4	3.3	2.3	2.2
Flowering	5.1	1.9	1.6	1.7	2.0	1.9
Veraison	7.7	6.5	3.2	3.4	3.1	2.5
All PS (Mean)	7.1	4.2	2.4	2.8	2.5	2.2

*Only for Improved and Spatial models is considered as a validation process.

Sensitivity analysis of the selection of the sample sites (Classical Sampling) and the reference site (Spatial model)

The sensitivity analysis was conducted for the Cl-S (2 Sites) and S-M (All PS and Each PS). For the S-M, the choice of the reference site was focused on, while for the Cl-S (2 Sites), the choice of the two sites was focused on to be used for calculating the mean date of occurrence of the phenological stages of the field. The result of this analysis showed that in general, when all phenological stages are considered together (Fig. 5a), the best results are obtained with the S-M (Each PS), followed by the Cl-S and finally, with the S-M (All PS). The probability of obtaining more accurate models is higher with the S-M (Each PS) since, for example, to obtain a RMSE value less than 3 days, it is 90% possible with of the S-M (Each PS), while with the Cl-S and S-M (All PS) is only possible with about 60% of the combinations (Fig. 5a). Comparing the prediction quality of both Spatial models, the S-M Each PS always obtained the best results, independent of the phenological stages.

When analyzing each phenological stage separately, it is observed that for budburst (Fig. 5b), both Spatial models obtained a very good quality in the prediction. The Spatial models obtained a good quality in the prediction, since with all the sites chosen as reference sites, it is possible to obtain RMSE values less than 3 days. Therefore, there was no effect of choice of the reference site on the quality of the prediction. However, for the Cl-S (2 Sites), approximately 30% of the combinations were able to obtain RMSE values between 3 to 6 days, showing that the selection of the 2 sampling sites had an impact on the quality of the

prediction. For the phenological stage of flowering (Fig. 5c), the Cl-S obtained the best results, where the highest RMSE values that could be obtained corresponded to 3 days, while for Spatial models, the highest RMSE value that could be obtained ranged from 4 to 5 days. Independent of the approach, an effect of the choice of the 2 sites or the reference sites in the quality of the prediction was not observed. For the phenological stage of veraison (Fig. 5d), the best results were obtained with the S-M Each PS, where 60% of the combinations were able to obtain RMSE values equal or less than 3 days. For this phenological stage, it was observed that, independent of the model used, the choice of either the reference site or 2 sampling sites affects the quality of the prediction.
It was observed that the results differ according to the phenological stage. This may be due to the magnitude of variation (MV, Table 3) observed during the validation season. For budburst, the MV observed during the validation season was similar to that observed in the calibration seasons, while for flowering it was lower and for veraison higher. Therefore, when the observed variability is low (for example at flowering), the Cl-S (2 Sites) can give better results compared to the S-M (All PS and Each PS).
These results stated above highlight the interest and potential value in obtaining a good prediction using the Spatial model (especially the Spatial model Each PS) compared to a classical approach based on the selection of 2 sampling sites for grapevine phenology.

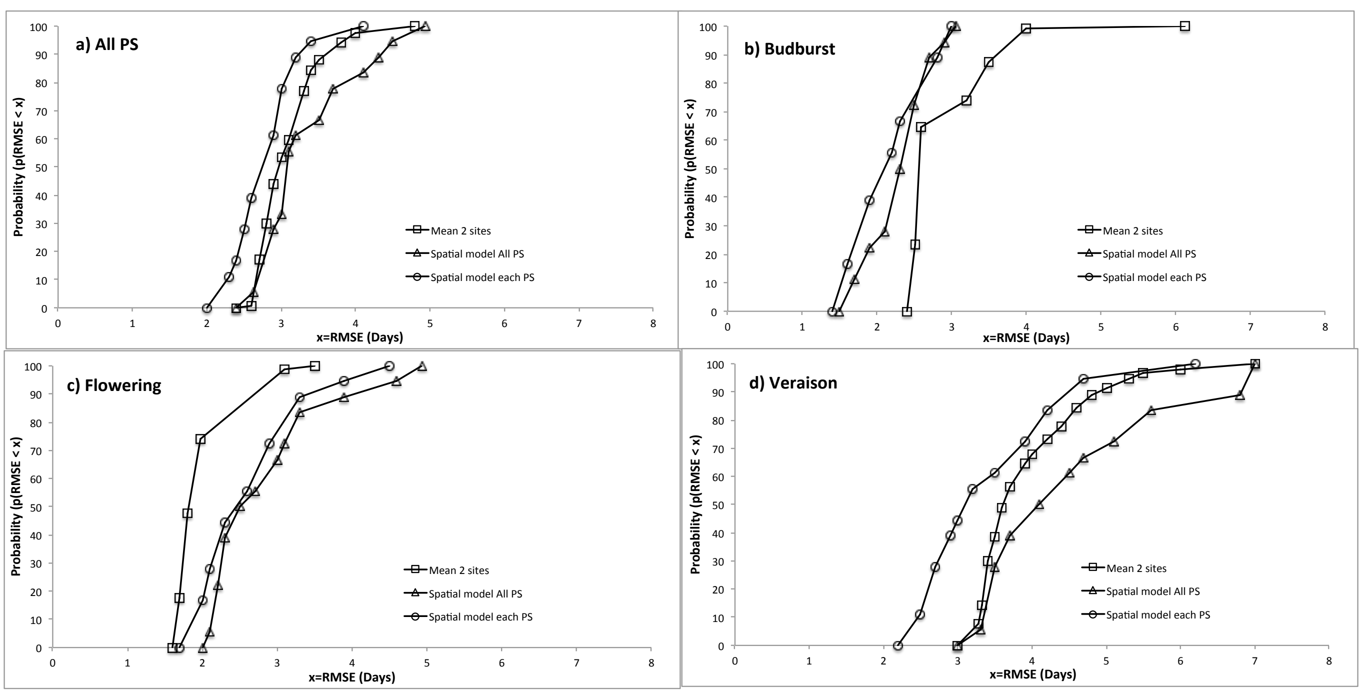
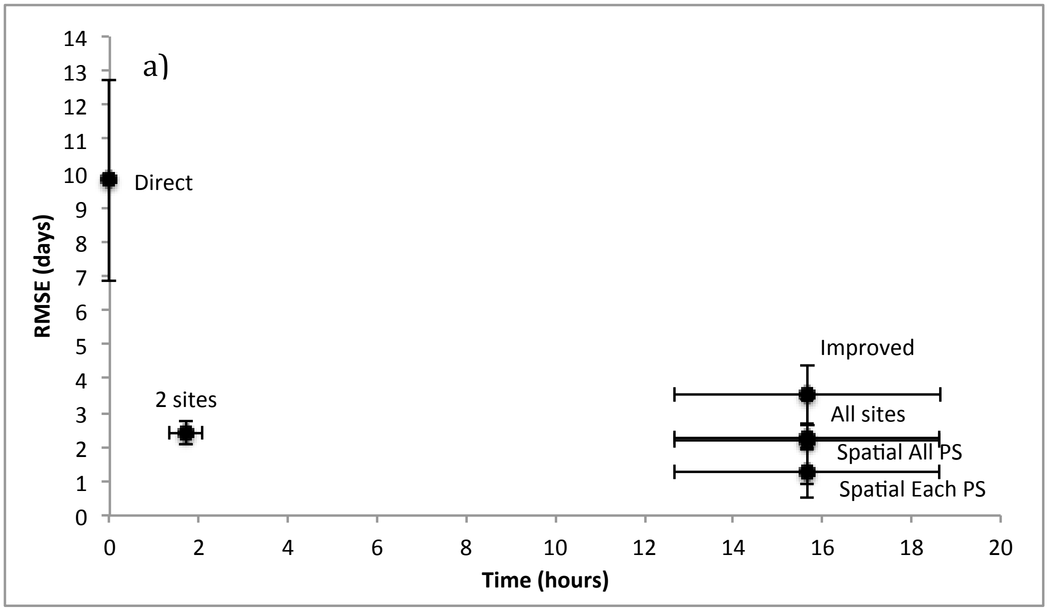


Figure 5 Sensitivity analysis of the choice of reference sites for Spatial models (All PS and Each PS) and the choice of the two sites for the Classical Sampling model (2 sites), cv Cabernet Sauvignon. Figures represent the probabilities of obtaining a RMSE below a threshold value.

Time spent on implementation of each model approach

In order to consider operational aspects of the different approaches, the time spent on implementation of each model was estimated and compared with the quality of the prediction obtained by each of them. The results of this analysis are shown in Figure 6.



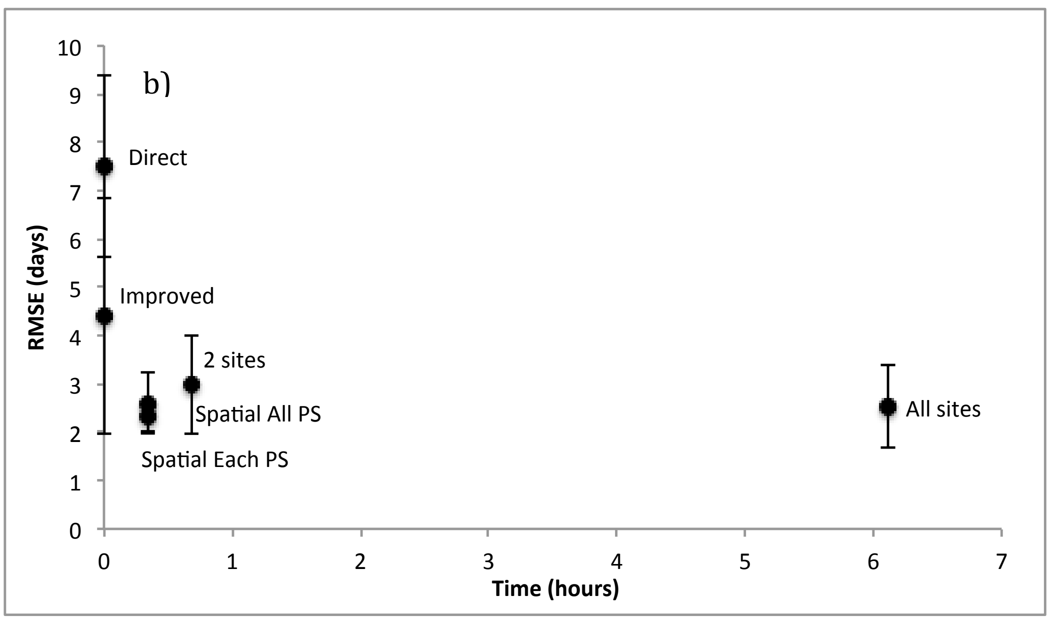


Figure 6 RMSE (days) obtained with the different approaches versus the time (hours) spent on its implementation (mean of all phenological stages). a) Calibration process (both cultivars) and b) Commercial use (only for cv Cabernet Sauvignon). The bars represent the standard deviation.

For the calibration process (Fig. 6a), a high difference was observed in the time spent between the different approaches. For example, for the Cl-M Direct, the implementation

time is zero (0 hours), while for the Cl-M Improved, Cl-S (All Sites) and S-M (All PS and Each PS) were approximately 16 hours (mean of all the phenological stages and both cultivars) and for the Cl-S (2 Sites) was approximately 2 hours. This last model (Cl-S, 2 Sites) was the one that obtained the best results (lower RMSE values) compared to the time spent on its implementation (located closer to the origin of both axes). Although the Cl-M (Improved), Cl-S (All Sites) and S-M (All PS and Each PS) obtained the same time of implementation, it was observed that the precision (RMSE values) is not the same between them. The best accuracy (lowest RMSE values) was obtained with the Spatial models. As the time to collect and process the climatic data was not considered (value = 0), the time of implementation of the Cl-M (Direct) was 0. However, with this model the worst results are obtained, where, on average, RMSE values are higher than 1 week (10 days).
For commercial use (Fig. 6b), it was observed that for all the models, the time spent is lower than the observed in the calibration process (Fig. 6a). The models that use less time in their commercial implementation (time = 0 hours) correspond to both Cl-M (Direct and Improved), however, with these models the worst results are obtained (higher RMSE values). With respect to the Cl-S (All Sites and 2 Sites), a high difference is observed in the time spent for commercial use. For Cl-S 2 Sites the time is approximately 1 hour, while for the Cl-S All Sites it is approximately 6 times higher. Note that, however, the prediction quality of both Cl-S is similar and less than 3 days of error. The best results (lowest RMSE values) compared to the time spent on its implementation (located closer to the origin of both axes) were obtained with the Spatial models, being slightly better the S-M Each PS than the S-M All PS. With both Spatial models it is possible to obtain errors in the prediction lower than 3 days. These results show that once the Spatial models are calibrated, it is possible to use this approach, spending less time and obtaining the best results (lower RMSE values) compared with the Climatic and Classical Sampling approaches.

DISCUSSION

This study showed that the magnitude of variation (MV) of the date of occurrence of key phenological stages at the within-field scale might be more than 1 week (Table 3). For planning agricultural activities (such as fertilization, irrigation, phytosanitary management, harvest, etc.) where the phenology monitoring is important, these observed differences suggest that it may be valuable to manage fields taking into account this variability. For budburst, differences of approximately one week could determine differences in susceptibility to weather risk like frost events that may occur early in the season. Flowering is considered as a critical growth stage for planning the application of plant protection products for diseases such as botrytis and powdery mildew (Campbell et al. 2007; Valdés-Gómez et al. 2017). Differences of 1 week in the date of occurrence of flowering could affect the selection of the best timing for phytosanitary application. Veraison determines the onset of the ripening period. These differences in the date of occurrence of veraison might affect the final wine quality because the differences in veraison may remain stable until harvest (Parker et al. 2014). On the other hand, it is important to note that the mean date of each phenological stage changes between seasons and cultivars (Table 3). Therefore, vine growers cannot rely on fixed dates to plan productive activities. The previous results show the need for the vine growers to estimate the grapevine phenology each season, considering the spatial variability. In this study, different approaches or models (Table 2) were compared with the objective of estimating grapevine phenology at the within-field scale. The goal of the following section is to compare the different approaches, highlighting the advantages and disadvantages of each.

Climatic model approaches
Of all the approaches, the only one that can anticipate the date of occurrence of the phenological stages, that is, to predict the occurrence of a particular phenological stage, are the climatic models (Table 2). For budburst of both cultivars, the errors (RMSE values) of the Cl-M Direct observed were similar to those obtained under conditions where the model was calibrated (García de Cortázar-Atauri et al. 2009), while for the phenological stage of flowering and veraison, the errors observed were higher compared to those obtained under the conditions where the model was calibrated (Parker et al. 2013). These results showed that the climatic models developed under other conditions are available to be used under different conditions to those where they were calibrated. This may be due to the fact that for the build up and calibration of these climatic models, an extensive database was used (García de Cortázar-Atauri et al. 2009; Parker et al. 2013). However, it is important to note that, the Cl-M Direct was the one that presented the worst results, independent of the phenological stage and cultivar. On the other hand, the incorporation of a correction factor in the Cl-M Direct, considering observations performed in the field, substantially improved the results (Cl-M Improved). This result highlights the fact that to obtain better results, it is necessary to consider a calibration process in the climatic models build up under other conditions. Both approaches of the Cl-M (Direct and Improved) for commercial use do not require implementation time, being one of the main advantages of these models. However, if there is not high spatial resolution of climate data, it is not possible to characterize the spatial variability of phenology at the within-field scale. On the other hand, this approach is the one that obtains the worst results. To improve the results obtained by these models, future work could consider the use of climate information measured in the field, which may differ from that measured by meteorological stations located near the vineyards (Matese et al. 2014).

Classical Sampling approaches
With respect to the classical approach based on extensive sampling (Cl-S), 2 approaches were used in this study. The Cl-S All Sites was considered as the best estimation possible, corresponding to the standard deviation of the field. This model was used as a reference value to compare all approaches. It is important to note that the Cl-S All Sites is highly demanding of manpower and therefore, requires a lot of time for its implementation (Fig. 6), obtaining results similar to the other approaches that require less time. On the other hand, if mean field information is used, the distribution of spatial errors in the field is highly structured for both cultivars. This shows that the variability of grapevine phenology is a phenomenon that has a spatial dependence (Verdugo-Vásquez et al. 2016). The approach used traditionally by the vine growers to monitor the phenological stages of his or her vineyards corresponded to Cl-S 2 Sites. The results obtained by this model were similar to those observed with the Cl-S All Sites. For this approach, it is observed that the choice of the 2 sampling sites affects the quality of the estimation and this effect may vary according to the phenological stage. For example, for budburst and veraison, an effect of the choice of

the 2 sampling sites on the quality of prediction was observed (Fig. 5). This shows the importance of the selection of sampling sites for an optimal estimation of these phenological stages. The spatial variability information of these phenological stages could serve as the basis for selecting target sites at the within-field scale or separating the vineyard into different sampling zones based on observed variability. The choice of sites and the type of sampling (random, target, etc.) to estimate phenological stages at this scale using an extensive monitoring require further study. However, for flowering of the validation season (cv Cabernet Sauvignon), it was observed that the Cl-S 2 Sites presented the best results, independent of the selected sites. This result can be explained by the fact that the observed variability was low compared to the other seasons (Table 3). This shows that the Cl-S 2 Sites is a real alternative when the variability of phenology is low at the within-field scale. Additionally, one of the main advantages of Cl-S 2 Sites is the low implementation time required. With the Classical Sampling models (Cl-S All Sites and Cl-S 2 Sites) it is not possible to map the date of occurrence of the phenological stages, obtaining a mean value of the vineyard. The planning of management activities based on mean information at the within-field scale when a high spatial variability occurs may be inappropriate for a large part of the field, affecting the sustainability of the vineyards.

Spatial model approaches

This study presents a new method for estimating the grapevine phenology at the within-field scale, through empirical spatial models using historical data of phenology together with a measurement performed at a reference site. It was shown that the methodology used for vine water status under irrigation (Acevedo-Opazo et al. 2013) and non-irrigation conditions (Acevedo-Opazo et al. 2010) can be applied to other variables of agricultural interest, such as grapevine phenology. The predictions of the model are good enough to be used as a decision support system for vineyard management, since the RMSE values for validation are lower or similar to those observed by the best estimation possible (Cl-S, All Sites). Within the S-M, the S-M Each PS was the most appropriate, since it always obtained the best results compared to S-M All PS. Thereby, the use of this model is a step forward towards a more sustainable vineyard system due to the possible implementation of site-specific labor. For example, the mapping of the date of occurrence of the phenological stages can be used to determine zones of frost risk (maps of budburst), zones for the application of plant protection products (maps of flowering) or define zones of differentiated maturity (maps of veriason).

The S-M was robust, since with data not used in its calibration, in almost all cases it obtained the best results, with values close to 2 days of errors (RMSE values). But as mentioned above, if the variability of phenology is low, the traditional method of sampling (Cl-S 2 Sites) could obtain better results. These sub-optimal results when there is low variability of phenology may be explained by the fact that only one value was used to predict the remaining values (17 for cv CS and 18 for cv CH). As was observed with the spatial model for vine water status, when there is low variability classical methods may be better than the spatial model because the proposed method may amplify the error made on the measurement at the reference site (Acevedo-Opazo et al. 2010).

On the other hand, this study shows that the approach was not sensitive to the choice of the reference site. However, slight differences in accuracy may be observed; the choice of the reference site did not change the accuracy of the model much. Thus, as has been

recommended for spatial models of vine water status, it is suggested to avoid some sites such as the field borders and unhealthy vines (Acevedo-Opazo et al. 2010).
It was observed that one aspect that limits the used of spatial models is the high time required for their calibration. However, once calibrated, the commercial use of the spatial models uses less time than the other approaches, obtaining the best results. Therefore, future research should focus on the optimization of the calibration process of spatial models.

Perspectives and improvements of the Spatial models
This study shows that the use of the spatial models that provides new knowledge that can be used to identify areas that present a systematical advance or delay in respect to the reference site for the date of occurrence of the phenological stage. However, in the currently proposed methodology, the approach used is not realistic for commercial vineyards. The model calibration requires a lot of manual measurements in the field, which is expensive. As proposed for the spatial models of the vine water status, it is possible to consider a simplification of the calibration procedure by decreasing the number of grapevine phenology observations in the field. Used of ancillary information of relative low cost, easy acquisition and high-spatial resolution such as airborne imagery, soil electrical conductivity measurements (Tisseyre et al. 2007) or manual medium-spatial resolution measurements, such as shoot length and exposed leaf area (Acevedo-Opazo et al. 2010), could also be used to zone vineyards according to grapevine phenology and simplify the development and calibration of the spatial models. Verdugo-Vásquez et al. (2016) suggested that the spatial variability of stable environmental factors (soil characteristics, slope, soil texture, etc.) would produce differences in the microclimate of the field, which affected the phenology, being able to explain the observed spatial variability. Therefore, characterization of environmental factors at a high spatial resolution could serve as auxiliary information to simplify the calibration of spatial models, as proposed by Acevedo-Opazo et al. (2010) for the vine water status.
Finally, it is important to note that the different approaches presented in this study may be complementary. For example, field observations (Cl-S) can be used to calibrate climatic models of phenology, improving the results obtained. On the other hand, the combination of the climatic model of phenology and the Spatial model would allow the prediction of the date of occurrence of the grapevine phenology by taking into account the spatial variability of the field. For this, the date of occurrence predicted by the climatic model is incorporated into the Spatial model as the measurement of the reference site, allowing to extrapolate the estimated date of occurrence to the whole field. This last approach has not been tested for grapevine phenology. Thus, this possible approach will be tested in a further step.

CONCLUSIONS

In this study, different approaches were compared in order to estimate the spatial variability of grapevine phenology at the within-field scale. The classical approaches based on climatic data (Climatic models, Cl-M) or extensive sampling (Classical Sampling, Cl-S) are not available to estimate the spatial variability of grapevine phenology at the within-field scale. For the Cl-M (Direct) it was observed that to obtain more accurate results it is necessary to calibrate the climatic models, for example, using phenology observations performed in the vineyard. The Cl-S (2 Sites) is a real alternative to be used by vine growers when the spatial variability of phenology is low, as observed for flowering of cv Cabernet Sauvignon in this study. With respect to the Spatial models, results showed that this approach is available to estimate and characterize the spatial variability of the key phenological stages of grapevines, obtaining the best results with RMSE values close to 3 days. Likewise, the Spatial model was robust to the choice of the reference site. This study is the first step towards a modeling of the spatial variability of grapevine phenology at the within-field scale. Through the Spatial models, it is possible to obtain maps of the date of occurrence of the key phenological stages, such as budburst, flowering and veraison, which can be used for planning site-specific labor, increasing the sustainability of vineyards. However, to be fully operational in commercial vineyards, the calibration process needs simplification, reducing the time needed for implementation. To achieve this, it may be possible to use low cost, inexpensive ancillary information to zone vineyards according to grapevine phenology. On the other hand, this study opens the opportunity to combine classical models of phenology based on climatic data with spatial models, with the aim of predicting the grapevine phenology both, in time and space, through the building of spatio-temporal models of low cost and easy implementation. Further studies should consider this last point.

ACKNOWLEDGEMENTS

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CHAPTER V

CHAPTER 5: TOWARDS AN EMPIRICAL SPATIAL MODEL TO ESTIMATE THE SPATIAL VARIABILITY OF THE TOTAL SOLUBLE SOLIDS OF GRAPEVINE AT THE WITHIN FIELD SCALE

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Abstract
The aim of this work is to validate an empirical approach to estimate spatial variability of the total soluble solids (TSS) of grapevines at the within field scale. Estimation of TSS involves a spatial model calibrated with historical TSS data. The novelty of the approach is to provide collaboration between historical data (calibrated model) and a punctual reference measurement (reference site) of TSS to estimate the TSS values over the whole field at a given date. The experiment was carried out between 2009-2015 in two fields (cv. Cabernet Sauvignon, cv. Chardonnay), both located in the Maule Valley, Chile. A regular sampling grid was designed within each field. On each site of the grid, TSS was measured on different dates (from veraison to harvest). The reference site on each field was chosen randomly. The ability and quality of the model to estimate TSS values was tested on an independent data set, using classical statistics (R^2 and Root Mean Square Error- RMSE). For both fields, the results highlighted a high spatial variability of the TSS at the within field scale. Also, TSS estimation using the model yielded high R^2 values, where the best results were observed in the Cabernet Sauvignon field. This is related to the quality of historical data used to calibrate the spatial model. For both fields, RMSE temporal values were less than the standard deviation in most dates. These results highlighted the opportunity and the relevance of using the proposed spatial model to estimate the spatial variability of TSS of the whole field through a punctual measurement of a reference site. Further studies should consider other cultivars and determine if the reference site selection influences the results.

Keywords: harvest zoning, precision viticulture, ripening, temporal stability, *Vitis vinifera*

INTRODUCTION
Estimation of the total soluble solids (TSS) is an important issue for the wine industry for characterizing the maturity, berry composition and determining the optimal date of harvest (Sadras and Petrie 2012). Authors have shown there is a high spatial variability of TSS at the within field scale (Bramley 2005; Tisseyre et al. 2008; Baluja et al. 2013; Verdugo-Vásquez et al. 2015a; Verdugo-Vásquez et al. 2015b), therefore, for adequate sampling and to propose

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zones of differential harvest, it is necessary to know this variability. However, measurement of TSS at high spatial resolution is difficult because it corresponds to a dynamic variable that changes over time and is highly demanding in manpower. To solve this problem, several strategies have been proposed in the literature. For example, Hall et al. (2010) proposed to use remote sensing and derived vegetative indices (i.e. Normalized Difference Vegetation Index, NDVI) to delineate within-vineyard zones of vigor assuming that there is correlation between NDVI maps and TSS maps. However, this assumption is not always achieved in non-irrigated (Acevedo-Opazo et al. 2008) or irrigated conditions (Tagarakis et al. 2012).
A recent study showed that there is a high temporal stability of the within field variability of TSS under semi-arid conditions (Verdugo-Vásquez et al. 2015b). This knowledge opens up the opportunity to use ancillary data of TSS measured at the within field scale with the aim of developing empirical methods for calibration of spatial models. The advantage of such approaches is to allow estimation of TSS values spatially while minimizing the number of measurements. The spatial model allows the estimation of the TSS value of the whole field using only one measurement of the TSS performed on a pre-defined site (site of reference). Spatial models have been used successfully to estimate vine water status under non-irrigated (Acevedo-Opazo et al. 2010) and irrigated conditions (Acevedo-Opazo et al. 2013). It has also been used more recently to estimate the precocity of the grapevine phenology (Verdugo-Vásquez et al. 2015c). However, the spatial model has never been used to estimate TSS value at the within field scale.
The aim of this first work is to calibrate and validate an empirical approach to estimate spatial variability of TSS throughout the grapevine season at the within field scale.

MATERIALS AND METHODS

Experimental fields

The experiment was carried out on two vine fields: cv. Cabernet Sauvignon (CS) of 1.56 ha and cv. Chardonnay (CH) of 1.66 ha, both located in the Maule Valley, Chile, under irrigated conditions. Within each vine field a regular sampling grid was designed, one with 18 sampling sites for cv. CS (Fig. 1a) and the other one with 19 sites for cv. CH (Fig. 1b).

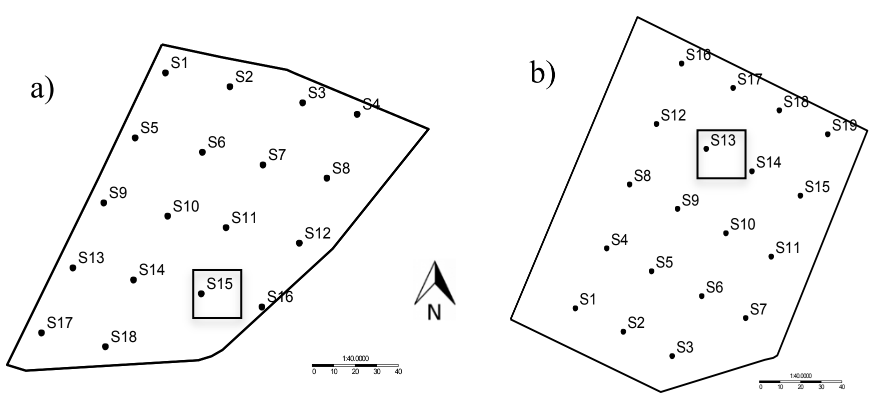

Figure 1. Regular sampling grid used in the experiments. a) cv. Cabernet Sauvignon and b) cv. Chardonnay. S_i represents the sampling site number i. Square corresponds to the reference site in each field.

Measurements of total soluble solids (TSS)
On each site of the grid (Figure 1 a and b), TSS was measured using a thermo-compensated refractometer (BRIX30 model, Leica, USA) by randomly selecting 8 clusters and 6 berries per clusters (48 berries per site). The average value of TSS for each date and site of the grid was then calculated. Measurements were made from veraison to harvest at intervals ranging from 2 to 15 days during 4 seasons (in the period of 2009-2015) for both fields. For cv. Cabernet Sauvignon the seasons measured encompassed the seasons 2009-2010 to 2012-2013, while for cv. Chardonnay the period of measurement was from 2011-2012 to 2014-2015 season.

Model description
The spatial model used in this study was described by Acevedo-Opazo et al. (2010). The general form of the model is (Acevedo-Opazo et al. 2010):

$$\hat{z}(s_i,t_j) = a_{s_i} \quad x \quad z_{re}(s_{re},t_j) \; ; \; s_{re} \in D, \; \forall s_i \in D, \; a_{s_i} \in R \qquad (1)$$

Where:

$\hat{z}(s_i,t_j)$ = Predicted TSS value of the location s_i at time t_j .

a_{s_i} = Site-specific coefficients (Vector a).

$z_{re}(s_{re},t_j)$ = Reference measurement of TSS at the reference site (s_{re}) and at time t_j .

D = Vineyard.

The goal of the model is to extrapolate TSS measured at time t_j , from the reference site $z_{re}(s_{re},t_j)$ to a vineyard (D) at the same time (t_j). From the above, equation (1) assumes that there is a collection of site-specific coefficients (a_{s_i}) that are able to model the difference in TSS between each location s_i and the location s_{re} of D (spatial variability). The evolution of TSS value (temporal variability) is only taken into account by the measurement on the reference site $z_{re}(s_{re},t_j)$.

The novelty of the approach is to provide a collaboration between historical data of TSS (calibrated model) and a punctual reference measurement (reference site) of TSS to estimate the TSS values over the whole field at a given date t_j .

The reference site s_{re} was chosen randomly (site 15 for cv. CS and 13 for cv. CH, in a square, Figure 1 a and b). The spatial model (equation 1) was calibrated with data from the first 3 seasons of each cv. using a classical square approach. The model validation was performed using an independent data set, corresponding to the last season measured for each cv. (4th season in both fields).

Statistical analysis
For both processes (calibration and validation) the following statistical analyses were estimated using Matlab Software (The Mathwork Inc., Natick, MA, USA): R^2 and root mean

square error (RMSE) between observed and estimated TSS values for each date t_j (RMSEt). Additionally, the differences between observed and estimated TSS values for each site s_i (Spatial Error) were estimated. Maps of the results were performed with 3DField Software (version 2.9.0.0, Copyright 1998-2007, Vladimir Galouchko, Russia). The classes used to build up the map corresponded to 33% quantiles.

RESULTS AND DISCUSSION

Calibration process

Figure 2 shows maps of Vector a (a_{s_i} , equation 1) obtained during the calibration process for both fields (reference site is shown in a square). Values were mapped using 3 quantiles (each class corresponds to 33% of the data). The light gray area (values < 1) represents the zone where the TSS values are systematically lower than the reference site, while the black area represents the zone where the TSS values are higher than the reference site. The gray area represents the zone where the TSS response is similar to the reference site. The areas identified (Figure 2) present a significant spatial organization.

The percentage of variance explained by the model (R^2) and the root mean square error temporal (RMSEt) obtained during the calibration process are presented for cv. Cabernet Sauvignon (Table 1) and for cv. Chardonnay (Table 2). For cv. Cabernet Sauvignon, R^2 values are high (R^2> 0.58). Only one sampling date presents a low value of R^2 (0.29), which corresponds to the mean TSS value near veraison (6.4 ºBrix, Table 1). When the mean value of TSS is increasing, R^2 values increase. The average R^2 value of all dates is 0.80. Regarding the RMSEt, it is lower than the standard deviation (SD) for more than 80% of the sampling dates (Table 1). This result shows that the spatial model is able to estimate the TSS values over the whole field better than the mean of all the sampling sites. The spatial model provides an estimate of TSS values with a RMSE lower than 1ºBrix (at harvest), with only one measurement performed on the reference site.

For cv. Chardonnay (Table 2), R^2 values are lower than cv. Cabernet Sauvignon. For the first 2 seasons (2011-2012 and 2012-2013) RMSEt values are similar to the standard deviation (SD). For the last season (2013-2014) R^2 values are low (R^2 < 0.55). This result is explained because the cv. Chardonnay during this season was affected by two early spring frosts. This climatic event reduced drastically the yield by modifying the balance between leaf area and yield, affected and changed the spatial patterns of TSS during this season, and therefore decreasing the temporal stability of the within field variability of TSS (Verdugo-Vásquez et al. 2015b). This atypical year in the calibration database certainly explains the poor results observed for this cultivar.

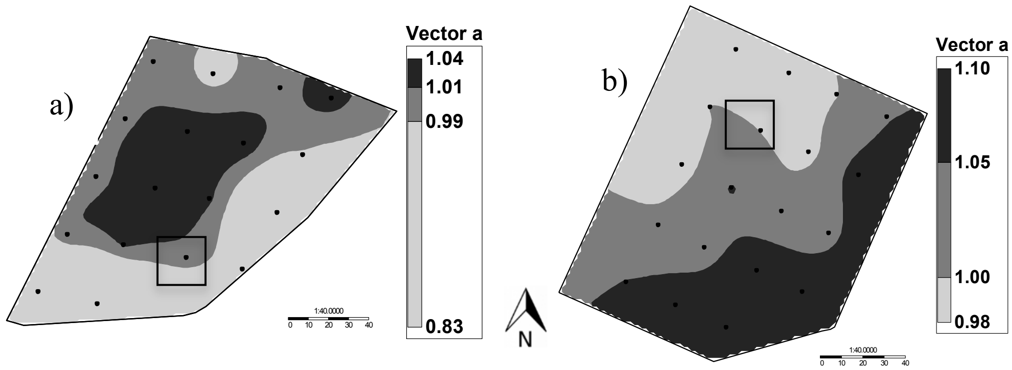

Figure 2. Maps of "Vector a" of the model (a_{s_i} , Eq. 1) obtained by the calibration process. a) cv. Cabernet Sauvignon and b) cv. Chardonnay. Reference site in a square.

Validation process

The validation process was performed with an independent database (4th season in both fields). As observed for the calibration process, the results are better for cv. Cabernet Sauvignon with respect to cv. Chardonnay (Table 3). R^2 values for cv. Cabernet Sauvignon are higher compared to cv. Chardonnay. For cv. Cabernet Sauvignon the validation results are better starting from 55 days before harvest. Therefore, through the proposed model, it is possible to predict the spatial variability of TSS in advance using only one measurement of TSS (reference site). For all dates of cv. Cabernet Sauvignon, RMSEt values are lower than SD and close to 1ºBrix (Table 3). For cv. Chardonnay, the results are more complex to analyze. Highest R^2 values are observed between 58 days to 30 days before harvest. RMSEt values are similar and only on certain dates lower than the SD (Table 3). These results (cv. Chardonnay), as mentioned above, may be explained by the quality of the database used in the calibration process.

Figure 3 shows the spatial error calculated for date "25 days before harvest" for cv. Cabernet Sauvignon (Figure 3 a) and "30 days before harvest" for cv. Chardonnay (Figure 3 b). For both cultivars, errors are distributed randomly. For cv. Cabernet Sauvignon, positive and negative error values are observed, indicating that there is over and under estimation of the TSS values. For cv. Chardonnay, only negative values are observed, indicating that the spatial model overestimates the TSS values. For both cv. errors are lower than 2ºBrix.

Finally, Figure 4 shows the maps of TSS observed (a and c) and TSS estimated by the spatial model (b and d) at the date where the best estimation was obtained (highest R^2, Table 3). For cv. Cabernet Sauvignon, it is observed that the spatial patterns are very similar (Figure 4 a and b), which corroborates the opportunity to use the proposed spatial model as a tool for grape-growers. This tool will generate a map of TSS only performing a punctual measurement of TSS in a reference site. For cv. Chardonnay, the spatial patterns of high and medium TSS values (black and gray areas, respectively) are similar (Figure 4 c and d) meanwhile the patterns of the low TSS values (light gray area) are different, showing that the spatial model, in this case, is not able to predict with a good fit these values.

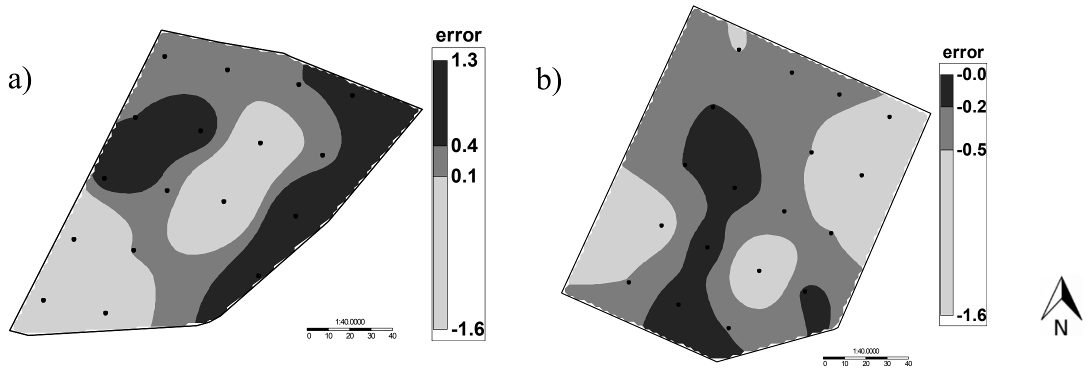

Figure 3. Map of the spatial error (ºBrix) for cv. Cabernet Sauvignon (a) and cv. Chardonnay (b), validation process.

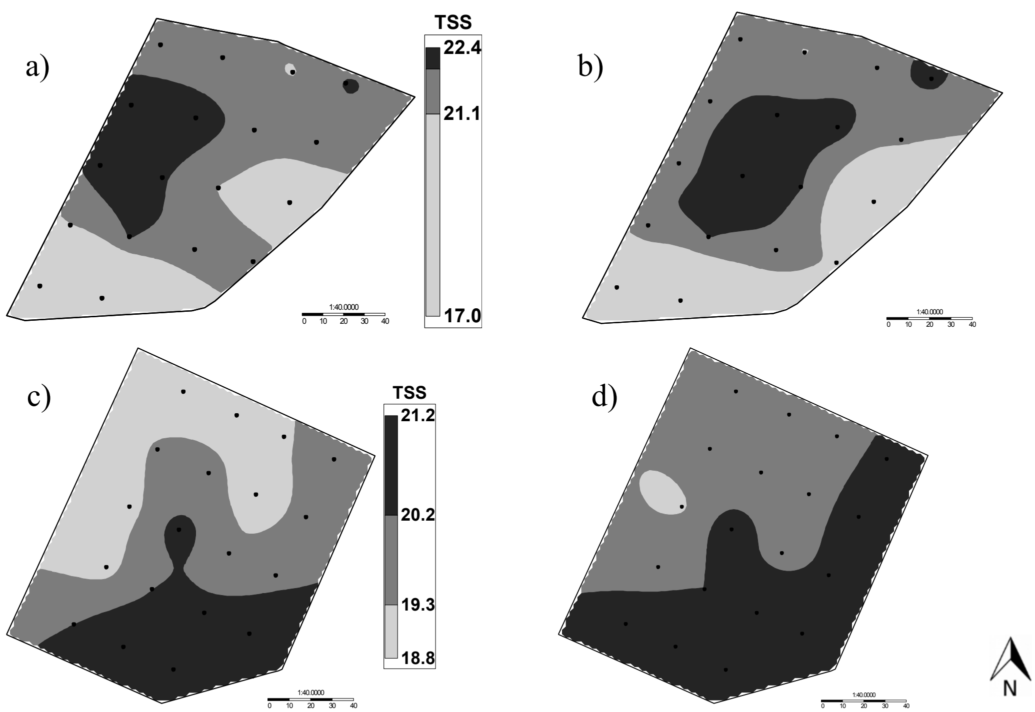

Figure 4. Maps with the measured TSS values (°Brix) (a and c) and its corresponding estimated TSS values (b and d) for the best date obtained from the validation process. a and b cv. Cabernet Sauvignon; c and d cv. Chardonnay.

CONCLUSIONS

This study highlights the opportunity and the relevance of using the proposed spatial model to estimate the spatial variability of TSS of the whole field through a punctual measurement of a reference site. It is noted that the quality of the database used (historical data) for the calibration process determines the quality of the results obtained. Further studies should consider other cultivars and determine if the reference site selection influences the results.

ACKNOWLEDGEMENTS

National CONICYT Doctoral Fellowship 2013 N°21130504, FONDECYT Project 11110137 and PIEI Program of Agricultural Adaptation to Climate Change funded by the University of Talca.

Table 1. Statistics for calibration process in cv. Cabernet Sauvignon. Root Mean Square Error temporal (RMSEt), standard deviation (SD), mean of TSS, Coefficient of variation (CV) and percentage of variance explained by the spatial model (R^2).

CS	2009-2010				2010-2011						2011-2012						
Days before harvest	48	31	14	0	63	54	33	19	11	0	63	49	44	36	23	14	0
TSS Mean (ºBrix)	17.2	20.0	20.8	22.5	6.4	13.7	18.4	20.4	20.9	21.8	11.4	17.3	18.8	19.6	21.2	22.1	22.5
CV (%)	5.5	4.8	5.6	5.3	17.2	18.3	7.4	6.8	7.4	7.4	21.1	9.8	8.3	6.8	6.5	5.9	6.4
SD (ºBrix)	0.9	1.0	1.2	1.2	1.1	2.6	1.4	1.4	1.6	1.7	2.5	1.7	1.6	1.4	1.4	1.2	1.5
RMSEt (ºBrix)	2.0	0.6	0.5	0.7	1.9	2.4	0.5	0.5	0.5	0.7	1.9	1.0	0.5	0.7	0.6	2.2	0.7
R^2	0.58	0.86	0.90	0.82	0.29	0.59	0.86	0.95	0.90	0.83	0.69	0.83	0.94	0.85	0.94	0.83	0.83

Table 2. Statistics for calibration process in cv. Chardonnay. Root Mean Square Error temporal (RMSEt), standard deviation (SD), mean of TSS, Coefficient of variation (CV) and percentage of variance explained by the spatial model (R^2).

CH	2011-2012					2012-2013									2013-2014							
Days before harvest	33	27	18	8	0	83	71	66	62	55	44	30	15	0	53	49	45	35	27	20	13	0
TSS Mean (ºBrix)	8.3	11.9	16	19.8	20.8	4.1	5.3	8.2	10.3	13.3	17.2	20	22.3	24	5	5.4	7.5	14.7	18.3	20.1	21.4	23.5
CV (%)	13.2	9.3	7.6	5.3	4.9	5.8	14.8	27.2	24.2	13.7	6.7	3.8	3.4	2.1	6.2	9.4	11.2	5.9	3.7	2.9	4.7	2.6
SD (ºBrix)	1.1	1.1	1.2	1	1	0.2	0.8	2.2	2.5	1.8	1.2	0.8	0.8	0.5	0.3	0.5	0.8	0.9	0.7	0.6	1	0.6
RMSEt (ºBrix)	1.1	1.6	1.1	0.8	0.8	0.2	0.9	2.4	2.8	2.2	1	0.8	0.8	0.8	0.4	0.6	1	0.9	0.9	0.8	1.1	0.9
R^2	0.51	0.53	0.50	0.37	0.43	0.42	0.65	0.75	0.68	0.64	0.60	0.50	0.57	0.75	0.04	0.01	0.01	0.16	0.41	0.44	0.32	0.55

Table 3. Statistics for validation process in cv. Cabernet Sauvignon and cv. Chardonnay. Root Mean Square Error temporal (RMSEt), standard deviation (SD), mean of TSS, Coefficient of variation (CV) and percentage of variance explained by the spatial model (R^2).

Season (2012-2013), cv. Cabernet Sauvignon					
Days before harvest	69	55	40	25	0
TSS Mean (ºBrix)	16.4	19.5	21.2	22.2	22.9
CV (%)	6.9	7.1	6.5	6.8	6.7
SD (°Brix)	1.1	1.4	1.4	1.5	1.5
RMSEt (°Brix)	0.9	0.6	0.6	0.7	1.1
R^2	0.47	0.82	0.84	0.81	0.59

Season (2014-2015), cv. Chardonnay								
Days before harvest	58	52	45	30	23	15	7	0
TSS Mean (ºBrix)	7.9	10.9	14.2	19.8	20.8	21.7	23.0	24.3
CV (%)	18.2	12.3	6.9	3.6	3.1	3.3	2.5	2.4
SD (°Brix)	1.4	1.3	1.0	0.7	0.7	0.7	0.6	0.6
RMSEt (°Brix)	1.9	1.1	1.0	0.6	1.1	0.7	1.0	0.9
R^2	0.58	0.55	0.37	0.73	0.24	0.32	0.16	0.35

CHAPTER VI

CHAPTER 6: ASSESSMENT OF AN EMPIRICAL SPATIO-TEMPORAL MODEL OF THE GRAPEVINE PHENOLOGY AT THE WITHIN-FIELD SCALE

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Abstract
The aim of this work is to calibrate and validate an empirical approach to predict the date of occurrence of the grapevine phenology (budburst, flowering and veraison) temporally and spatially at the within-field scale. It is based on the collaboration between a classical model of phenology based on climate data and a spatial model calibrated with ancillary data of phenology observations. This approach was tested and validated on a field of cv Cabernet Sauvignon. Results showed that the spatial component improved the fit of the climatic model, allowing the generation of maps of the grapevine phenology with errors lower than 5 days of prediction. Spatio-temporal model errors were mainly associated with the temporal component of the model.

Keywords: within field variability, *Vitis vinifera*, homogeneous management zones, modelling

Introduction

Knowledge and monitoring of the grapevine phenology during the season are important requirements for planning various production activities at the vine field scale (Mullins et al. 1992). For example, practices such as fertilization, irrigation, application of phytosanitary products and harvest are programmed based on the evolution of the grapevine phenology. For a correct planning of the practices mentioned above, the wine growers need to know in advance the date of occurrence of the key phenological stages such as budburst, flowering and veraison. Traditionally, the evolution of the grapevine phenology is related to climatic variables, specifically with air temperature (Chuine et al. 2013). Through this relation, classical climatic models of phenology have been proposed in the literature (Chuine et al. 2013). These climatic models predict the date of occurrence of the key phenological stages using air temperature as the only variable. Temperature data used for these models come from meteorological stations or service providers. Whatever their origin, meteorological data are usually available at a medium to low spatial resolution, therefore depending on the location of a field (and environmental attributes), air temperature used to run the models may differ from air temperature really experienced by the field. In addition, data resolution is too low to work at the within field scale, as a result, meteorological data are generally applied at the vineyard or field scale. Therefore, climatic models provide generally an average value of the date of occurrence of the phenological stage which is extrapolated to the whole vineyard without considering the spatial variability.

Previous studies have shown that within-field variability of grapevine phenology may be significant and may justify site-specific management practices (Verdugo-Vásquez et al. 2016). Therefore, under conditions of high spatial variability, the extrapolation of the average value obtained through the climatic models may not be representative of the whole fields.

An alternative approach to solve the above problem is to use a spatial model. The spatial model allows the estimation of a variable over the whole field taking into account the spatial variability. Spatial models have been used successfully to estimate vine water status under non-irrigated (Acevedo-Opazo et al. 2010) and irrigated conditions (Acevedo-Opazo et al. 2013). It has also been used more recently to estimate the precocity (delay or advance of the date of occurrence of phenological stages with respect to a reference site) of the grapevine phenology (Verdugo-Vásquez et al. 2015). Therefore, spatial models allow the characterization of the spatial variability of the fields through a single measurement on the field (reference site) and a combination of site-specific coefficients calculated through historical data.

The combination of the classical climate model of phenology and a spatial model would allow predicting the date of occurrence of the grapevine phenology taking into account the spatial variability of the field. For this, the climate model is used to predict the date of occurrence of the phenological stage (for example: budburst, flowering or veraison). This information is incorporated in the spatial model as the measurement of the reference site, allowing to extrapolate estimated date of occurrence to the whole field. This approach has not been tested for the grapevine phenology. In literature, information about spatio-temporal modeling of the grapevine phenology at the within-field scale is scarce. There is a spatio-temporal model of phenology, but developed to work at regional scale (Mariani et al. 2013). This model uses climatic data, specifics observations of phenology and geo-statistical analyzes to predict temporally and spatially the phenology at the regional scale.

The aim of this work is to calibrate and validate an empirical approach to predict the date of occurrence of the grapevine phenology temporally and spatially at the within-field scale. The goal is also to characterize the different sources of inaccuracy when mixing a spatial model with a temporal model and to test its relevancy on a real phenological data set.

Materials and methods

Fields charateristics and measurements

The experiment was performed on a field of cv Cabernet Sauvignon (1.56 ha) located in the Panguilemo Experimental Station of the University of Talca (Maule Valley), Chile, under irrigated conditions. The phenological observations were estimated using the Eichhorn and Lorenz phenological scale as modified by Coombe (Coombe 1995). Measurements of the date of occurrence of the grapevine phenology (budburst, flowering and veraison) were performed on each site of a regular sampling grid (18 sites) during 4 consecutive seasons (from 2009-10 to 2012-13 season). Climate data (air temperature) were collected using an automatic weather station (Adcon Telemetric, A730, Klosterneuburg, Austria) installed under reference conditions, at 300 m from the vineyards. Air temperature were measured at 15-min intervals.

Spatio-Temporal model of the grapevine phenology

a) The temporal model

In this study, the Growing Degree Day model (GDD model) was used to predict the date of occurrence of phenological stages (PS) of budburst, flowering and veraison. This model assumes that the date of occurrence t_s (day of the year, DOY) of a phenological stage ($Date_{PS}$) occurs when a critical state of forcing S_f, defined as a sum of growing degree days from a starting date t_0, reached a particular value F^* (Eq. 1) (García de Cortázar-Atauri et al. 2009; Parker et al. 2013).

$$S_f(t_s) = \sum_{t_0}^{t_s} GDD(x_t) = F^* \qquad \text{(Eq. 1)}$$

The state of forcing is described as a daily sum of the rate of forcing, (Eq. 2) which starts at t_0, x_t is the daily mean temperature and Tb corresponds to a base temperature above which the thermal summation is calculated.

$$GDD(x_t) = \begin{Bmatrix} 0 & if\ \ x_t < T_b \\ x_t - T_b & if\ \ x_t \geq T_b \end{Bmatrix} \qquad \text{(Eq. 2)}$$

This approach has three parameters: t_0, F^* and Tb. Parameters values used in this study are shown in Table 1.

Table 1 Parameters values considered for the climatic model (GDD model, Eq. 1 and 2)

	Parameters values			
Phenological stage (PS)	*Starting date of GDD acumulation,* (t_0) (Days of the year, DOY)	Temperature threshold (t_b) (ºC)	F^*	Source
Budburst	182	5	318.6	García de Cortázar-Atauri et al. (2009)
Flowering	241	0	1299.0	Parker et al. (2013)
Veraison	241	0	2689.0	

For the computation of *GDD* (Eq. 2) information of air temperature collected by the automatic weather station were used. The date predicted by the climate model ($Date_{PS}$) corresponds to the days of the year t_s when GDD reach the value F^*. In order to take into account possible differences between field climatic conditions and weather station located more than 300 m away, a correction parameter *C* was introduced in the climatic model (Eq. 3). The correction coefficient C was expressed in days, it was determined by computing the difference between the average observed date of occurrence of the phenological stage (all sites) and the date predicted by the climatic model (mean of the first 3 seasons for each phenological stage).

$$C = \bar{X}\ [Date_{\overline{PS}}(All\ sites) - \ Date_{PS}] \qquad \text{(Eq. 3)}$$

Once determined C, was incorporated (adding or subtracting) on the date estimated with the climatic model (GDD Model). The resulting corrected climatic model (Eq. 4) was called temporal model in the rest of the document.

$Date_{PS}Climatic = Date_{PS} \pm C$ (Eq. 4)

b) The spatial model
The approach used in this work was the one proposed by (Acevedo-Opazo et al. 2010) successfully applied to model the spatial variability of vine water status at the within field scale. The aim of the spatial model is to produce an estimate of the date of occurrence of the phenological stage PS on site s_i ($Date_{PS}\hat{S}_i$), from a reference site $Date_{PS}s_{ref}$. This estimation is performed using a simple linear function. (Eq. 5). The spatial model corresponded to a spatial extrapolation that allows modelling the relative differences of the date of occurrence of the phenological stage (*PS*) between each site s_i and the reference site s_{ref}. This model predicts the precocity of the phenological stage (*PS*) of the grapevine by considering the delay or the advance of the date of occurrence of the *PS* with respect to a reference site s_{ref}. It was applied at the vine field scale. The spatial model is based on a collection of linear coefficients a_{S_i} (Eq. 5) called vector a.

$Date_{PS}\hat{S}_i = a_{s_i}\ x\ Date_{PS}S_{ref}$ (Eq. 5)

Estimation of a_{S_i} requires historical information of the date of occurrence of the phenological stage at the vine field scale. In this study, a value of a_{S_i} for each phenological stage (budburst, flowering and veraison) was calculated.
In this approach, a virtual site was added to the database, corresponding to the average (all sites of the field) date of occurrence of each *PS* calculated for each date. This virtual site was then considered as the reference site (s_{ref}) for the calculation of a_{S_i} of the spatial model.

c) Spatio-Temporal model
Finally, assuming the date estimated by the temporal model ($Date_{PS}Climatic$) component corresponded to the average phenological stage of the field, the Spatio-Temporal model was defined by considering $Date_{PS}Climatic$ value as the reference site (Eq. 6).

$Date_{PS}\hat{S}_i = a_{s_i}\ x\ Date_{PS}Climatic$ (Eq. 6)

Calibration and validation of the different models
The different models (GDD Model, Temporal, Spatial and Spatio-Temporal) were calibrated using data collected during the first 3 seasons. A fourth season was used as a validation dataset to evaluate the ability of prediction with data not used to calibrate the model. For both processes (calibration and validation), the root mean square error (RMSE) was used to characterize the accuracy of each model for each phenological stage. Additionally, the observed standard deviation of the field was considered as a reference value for all the phenological stages. This standard deviation corresponds to the RMSE when the mean of all sites is used to estimate the phenological stage of the field. In this study, the standard deviation was considered to characterize the error when a very simple model of estimation corresponding to the mean is considered.
Differences (expressed in days) between observed date of occurrence of the phenological stage and estimated date for the temporal and spatial component were also calculated (validated process) for each site of the sampling grid. These differences were used to show potential spatial patterns in error either for the temporal model or the spatial model. Errors

were mapped in 33% quantiles for each phenological stage, using the 3D-field software (version 2.9.0.0., Copyrigtht 1998-2007, Vladimir Galouchko, Russia).

Results and discussion

Table 2 and 3 shows the RMSE obtained by the different approaches for calibration and validation processes, respectively. For both processes, the GDD and temporal model shows the highest RMSE values, while the lowest RMSE value is obtained with the spatial model. For almost all cases, the RMSE values obtained by the GDD model were similar or lower than those obtained under the calibration conditions of these models (García de Cortázar-Atauri et al. 2009; Parker et al. 2013). Note that, the incorporation of the C in the Temporal model improved the result of the GDD model. Focusing on the average RMSE observed over all seasons (last row in Table 2 and 3), note that the order of the models is always the same. The spatial model always has the lowest RMSE, followed by the mean model. Models integrating the temporal component (based on temperature) systematically present significantly higher errors. The integration of a spatial model makes it possible to slightly improve the error during the calibration. This improvement is perceptible during the prediction but it is much less marked. In general, the higher RMSE values observed for the GDD and temporal models may be explaind by the fact that these models predicts the date of occurrence of the phenological stage with indirect information (air temperature), while other models (Mean of all the sites and Spatial model) use measurements of phenology performed in the field to estimate the values of the other sites.

There is a very small increase in RMSE between calibration and prediction steps. This result was expected for the mean model since there is no strictly speaking a prediction for this model which takes into account the observations made over the field whatever the considered step. On the other hand, this result highlights the ability of all other models to predict the phenology of the field on data that are not used for model calibration.

The precision of the models is different according to the phenological stages considered. If the mean and spatial models show the best results for all the stages, the temporal models predict very well the flowering and worse the veraison. This aspect may be of interest from a practical point of view, since depending on the expected accuracy different approaches can be considered for each phenological stage.

Table 2 Errors (RMSE) of calibration obtained by the different model approaches

	RMSE (Days)				
Phenological stage	Mean of all the sites	GDD Model	Temporal Model	Spatial Model	Spatio-Temporal Model
Budburst	2.0	7.2	5.1	0.8	4.8
Flowering	2.5	7.0	3.6	1.1	2.8
Veraison	2.2	13.0	3.6	1.3	3.1
All PS (Mean)	2.2	9.0	4.1	1.1	3.6

This work will focus on the study of the models and will not take into account the operational aspects. Note however, that a 5-day error on phenology estimation may be sufficient for many applications and that the choice of a more precise estimation method should necessarily take into account the operational constraints. These constraints differ greatly from one method to another. For example, the average model requires observations to be made on all sites systematically, the spatial model and the spatio-temporal models require a single observation on a reference site (provided that a historical database is available for their calibration).

Table 3 Errors (RMSE) of prediction obtained by the different model approaches

			RMSE (Days)		
Phenological stage	Mean of all the sites	GDD Model	Temporal Model	Spatial Model	Spatio-Temporal Model
Budburst	2.5	8.5	4.3	1.7	4.0
Flowering	1.7	5.1	2.0	2.0	2.0
Veraison	3.4	7.7	5.2	2.5	4.7
All PS (Mean)	2.6	7.1	3.8	2.1	3.6

Regarding the spatial error, Figure 1 shows the maps of the spatial error (expressed in days) of the phenological stage of budburst (validation process) obtained for the temporal (a) and spatial (b) model. It is observed that the distribution of the errors for the temporal model has a high spatial structure, where the highest errors (> 4 days) are distributed in the southern part of the field (Fig 1 a). On the other hand, for the spatial model, errors are more randomly distributed (Fig. 1 b) and never exceed 3 days. For the temporal model, only positive values of error are observed, therefore, this model underestimates the date of occurrence of the phenological stage of budburst. This result shows that the correction coefficient (Eq. 4) may not be sufficient to model the eventual difference between field conditions and weather station conditions. For the spatial model, errors are centered on 0 showing that integration of observations performed on the field limit bias (over or under estimation). Very similar results were observed for flowering and veraison stages, (data not shown). In summary, for these phenological stage, the temporal model overestimates the date of occurrence.

The incorporation of the spatial component in the spatio-temporal model (a_{S_i}, Eq. 7) allows for the randomized distribution in the field of the date of occurrence estimated by the temporal model (*Date*$Date_{PS}Climatic$, Eq. 7). This improves the results obtained when considering only the temporal model (Table 2 and 3). However, to obtain better results with the spatio-temporal model it is necessary to improve the estimation of the value of the reference site, that is to say, of the temporal model.

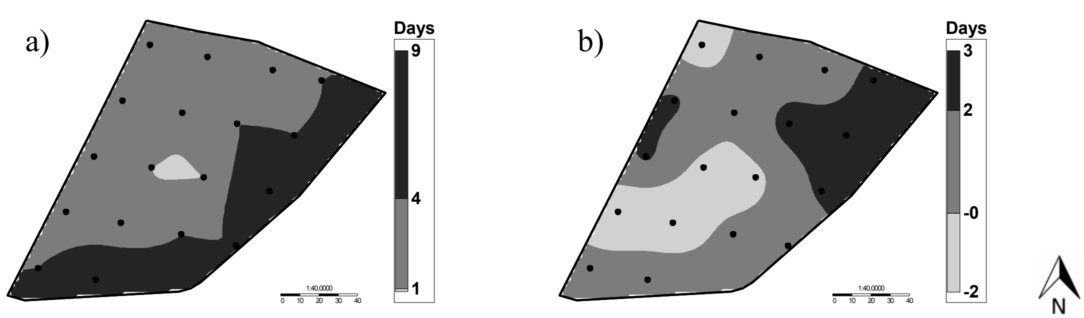

Figure 1 Maps of the spatial error (expressed in days) of the phenological stage of budburst (validation process) obtained for the temporal (a) and spatial (b) model.

Another limit is naturally the calibration of the spatial model which requires a large amount of historical database of phenology measured at the within field scale. The above, may be a significant practical drawbacks to implement the approach. With the aim of simplifying the spatial component of the model, the relation between the vector a (a_{S_i} , Eq. 7) and the elevation of the field was calculated. For the field under consideration, the spatial component was strongly related to the elevation of the field for all the phenological stages (Fig. 2 a,b and c), although there is only 2.5 meters of difference between the highest and lowest site of the field (Fig. 2 d). The relation between vector a and elevation reflects the high stability of vector a, since the topography corresponds to a factor that does not change with the time. This is associated with the high stability of the spatial variability of phenology observed in this field (Verdugo-Vásquez et al. 2016). In the future, this relationship between the spatial component and the elevation of the field would allow the implementation of a fast and easy-to-start spatio-temporal model, where only climate information and field topography are needed to generate maps of the key phenological stages, considering the spatial variability of the field.

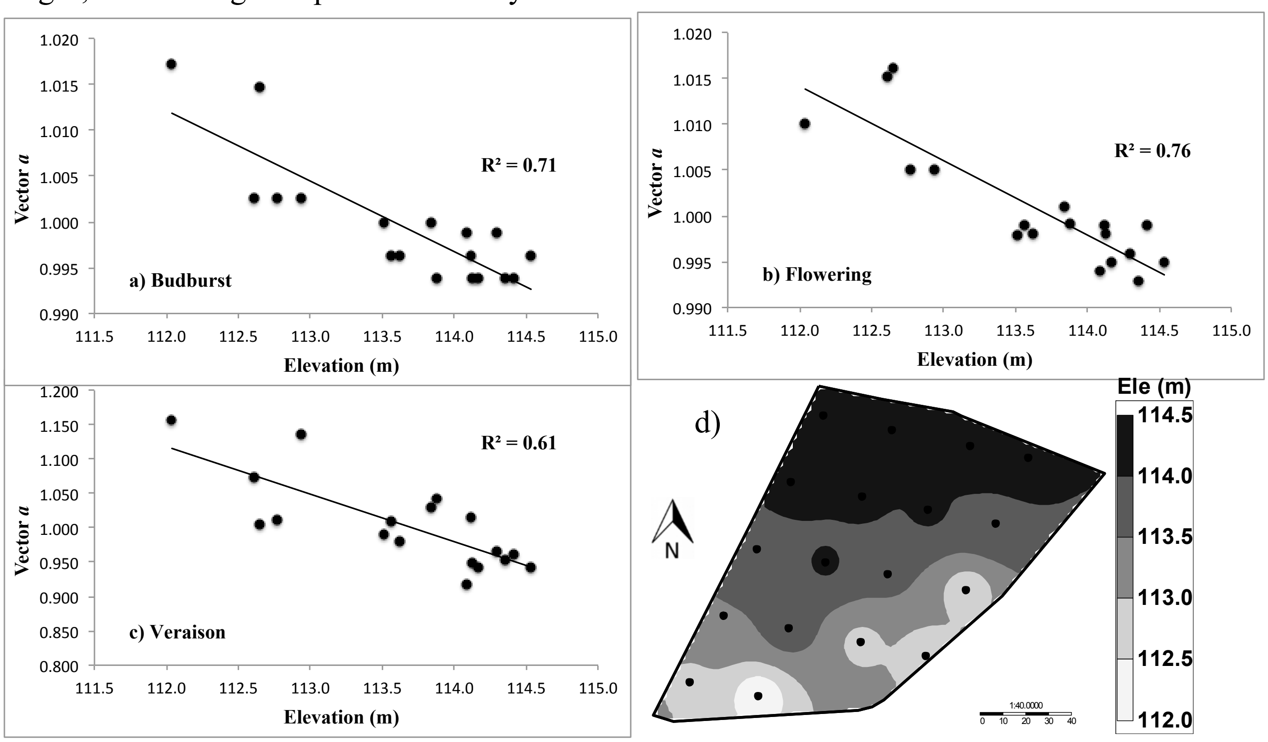

Figure 2 Relationship between vector a of the spatial model and the elevation of the field, for each phenological stage. a) Budburst, b) Flowering and c) Veraison. d) Field elevation (Ele).

Conclusion

This study showed that collaboration between a classical model of phenology based on climate data and a spatial model calibrated with ancillary data of phenology observations may improve the estimation of key phenological stages at the within field scale compared to when only the temporal model is considered. This work offers great promises to improve the calibration of a site-specific phenology model in grapevines. Indeed future research should focus on improving the link between temporal and spatial part of the model as well as estimating the spatial component using auxiliary information like elevation.

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Conclusiones Generales y Perspectivas

El presente trabajo doctoral realizó un aporte significativo en lo referente a la caracterización y modelación de la variabilidad espacial de la fenología de la vid y la acumulación de azúcar en las bayas a la escala del cuartel vitícola. Por primera vez, se demostró que existe una alta variabilidad espacial en el desarrollo de la fenología de la vid a la escala intra cuartel. Lo anterior también se observó para la acumulación de azúcares (sólidos solubles totales) en las bayas. Para ambas variables, la variabilidad espacial observada a esta escala se presentó estructurada en el espacio y estable en el tiempo (durante y entre temporadas). Por lo tanto, para las estrategias de muestreo de estas variables y la planificación de labores agrícolas (riego, fertilización, aplicaciones de productos fitosanitarios, cosecha, etc.) se debe considerar esta variabilidad.

Una vez caracterizada la variabilidad espacial de la fenología de la vid y la acumulación de azúcares fue posible determinar los principales factores que explican esta variabilidad a la escala intra cuartel. Se determinó que parámetros medio ambientales como la topografía y características del suelo tienen una incidencia significativa y podrían ser utilizados como información auxiliar para identificar patrones espaciales de fenología y acumulación de azúcares a esta escala.

Por otro lado, esta información, permitió proponer modelos empíricos espaciales, utilizando datos históricos en combinación con mediciones puntuales realizadas en diferentes sitios de referencia. Desde un punto de vista científico, se mostró que la metodología propuesta obtiene mejores resultados cuando se compara con métodos tradicionales de muestreo y modelización. Sin embargo, si la variabilidad espacial observada de la fenología de la vid es baja, con los métodos tradicionales de muestreo (muestreo al azar) se obtienen resultados similares a los obtenidos con los modelos espaciales. Esta nueva metodología podría ser utilizada por los productores vitícolas como una herramienta práctica para la planificación de manejos sitio-específicos a la escala del cuartel vitícola, donde el seguimiento de la fenología de la vid y la acumulación de azúcares son imprescindibles para la toma de decisiones.

Sin embargo, una de las limitaciones de los modelos espaciales propuestos es que para su calibración requieren de una base de datos con registros históricos de fenología y acumulación de azúcares, las cuales pueden ser de difícil acceso y alto costo para los productores vitícolas y por lo tanto, limitar la aplicación práctica de estos modelos. De este modo, la calibración de estos modelos espaciales requieren de un proceso de optimización. Para este proceso de optimización se propone utilizar la información de los principales factores que explican la variabilidad espacial observada al interior del cuartel vitícola, tanto de la fenología de la vid como de la acumulación de azúcar en las bayas. Para lo anterior, la información de los factores identificados medida a alta resolución espacial podría ser utilizado como información base para el cálculo de coeficientes de determinación sitio-específicos de los modelos espaciales, reduciendo la cantidad de información histórica necesaria para la construcción de estos modelos. Esto permitiría la obtención de modelos espaciales de rápida y fácil construcción y combinados con modelos climáticos, podrían predecir la fenología de la vid en las más diversas condiciones edafo-climáticas. De este modo, como perspectiva de trabajo futuro se plantean las siguientes preguntas científicas:

1.- ¿Es posible modelar la variabilidad espacial de la fenología de la vid, usando información auxiliar de media y alta resolución espacial?

2.- ¿Es posible modelar la variabilidad espacial de la acumulación de azúcares, usando información auxiliar de media y alta resolución espacial?

Por otro lado, este trabajo doctoral como primera aproximación se realizó a la escala del cuartel vitícola, considerada la unidad básica de manejo por parte de los productores. Sin embargo, las metodologías generadas pueden ser aplicadas a otras escalas espaciales, por ejemplo a la escala regional (diferentes valles vitícolas). De este modo, la utilización de modelos espaciales de fenología y acumulación de azúcares a la escala regional permitiría mejorar la gestión de los viñedos, generando información general para la industria vitícola. Este último punto requiere más estudio y se plantea la siguiente pregunta científica:

3.- ¿Es posible modelar la variabilidad espacial de la fenología y acumulación de azúcares a escala regional, usando información histórica?

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