UNIVERSIDAD DE TALCA
FACULTAD DE CIENCIAS AGRARIAS
DOCTORADO EN CIENCIAS AGRARIAS

“IMPLEMENTATION OF A METHODOLOGY TO ESTIMATE VINE WATER CONSUMPTION AND WATER STATUS THROUGH REMOTE SENSING AND SPATIALIZED WIRELESS SENSORS”

“IMPLEMENTACIÓN DE UNA METODOLOGÍA PARA ESTIMAR EL CONSUMO Y ESTADO HÍDRICO DE LA VID MEDIANTE TELEDETECCIÓN Y SENSORES INALÁMBRICOS ESPACIALIZADOS”

TESIS DE GRADO

FERNANDO PABLO FUENTES PEÑAILILLO

Start date: 25-11-2016 End date: 24-12-2020

Thesis submitted in fulfillment of the requirements for the degree of Doctor in Agricultural Sciences

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“IMPLEMENTATION OF A METHODOLOGY TO ESTIMATE VINE WATER CONSUMPTION AND WATER STATUS THROUGH REMOTE SENSING AND SPATIALIZED WIRELESS SENSORS”

POR

FERNANDO PABLO FUENTES PEÑAILILLO

TESIS DE GRADO

Presentada a la Universidad de Talca
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Prefacio

Este trabajo de doctorado se realizó como parte de una colaboracion conjunta entre investigadores pertenecientes al Centro de Investigacion y Transferencia en Riego y Agroclimatologia (CITRA), Centro Tecnologico de Conversion de Energias (CTCE) y Laboratorio de Investigación en Ciencias Ambientales (LARES). Este trabajo es parte de una larga historia de colaboración y complementariedad científica entre los cuatro equipos de investigación. La dirección de la tesis estuvo a cargo del Doctor SAMUEL ORLANDO ORTEGA FARIAS (Universidad de Talca, UTAL). Adicionalmente participaron los académicos; Doctor CESAR ANTONIO ACEVEDO OPAZO (Universidad de Talca, UTAL), Doctor MARCO RIVERA ABARCA (Universidad de Talca) y Doctor LUIS MORALES SALINAS (Universidad de Chile, UCHILE). Este proyecto de tesis fue financiado por una beca doctoral de la Universidad de Talca (2016-2017) y la Agencia nacional de Investigacion y Desarrollo, ANID (2018-2019). El trabajo de investigación presentado en este documento se refiere a la Implementación de una metodología para estimar el estado hidrico de la vid mediante percepcion remota y sensores inalámbrico-espacializados. Este trabajo es importante para el sector vitivinícola de Chile, es innovador y constituye un ejemplo notable del potencial de la tecnología digital y el desarrollo de tecnologia de bajo costo para mejorar la agricultura del mañana.

Valorizacion de los resultados obtenidos

Artículos

F. Fuentes-Peñailillo, C. Acevedo-Opazo, S. Ortega-Farías, M. Rivera and N. Verdugo-Vásquez. Spatialized system to monitor vine phenology: Towards a methodology based on a low-cost wireless sensor network. Enviado a **Computers and Electronics in Agriculture**

F. Fuentes-Peñailillo, S. Ortega-Farias, C. Acevedo-Opazo, M. Rivera, and M. Araya-Alman. Low-cost wireless Sensor Networks networks for monitoring spatial variability of plant water status in a commercial vineyard. Para ser enviado a **Sensors o Computers and Electronics in Agriculture**

Congresos

Fuentes-Penailillo, F., Ortega-Farias, S., Rivera, M., Bardeen, M., & Moreno, M. (2018, October). Using clustering algorithms to segment UAV-based RGB images. In 2018 IEEE International Conference on Automation/XXIII Congress of the Chilean Association of Automatic Control (ICA-ACCA) (pp. 1-5). IEEE. https://ieeexplore.ieee.org/document/8609822

Fuentes-Peñailillo, F., Ortega-Farias, S., Gutter, K., Vega, R., & Albornoz, J. (2020). Evaluation of a two-source model to estimate vineyard evapotranspiration using UAV-based thermal images and meteorological data. International Symposium on Irrigation of Horticultural Crops: Matera, Italy. International Society for Horticultural Science.

Proyectos

CORFO PRAE (**16PRAE-66973**), aSIMOV; Sistema inalambrico para el monitoreo de la vid. Beneficiario: Fernando Fuentes. Director: **Fernando Fuentes-Peñailillo**. Equipo: Fernando Fuentes-Peñailillo, Samuel Ortega, Cesar Acevedo, Marco Rivera.

Universidad de Talca, Fondo de Emprendimiento para la Investigación Científica de estudiantes de pregrado. Sistema inalambrico para el monitoreo de la Vid. Beneficiario: Martin Arraztio. Equipo: Marco Rivera, **Fernando Fuentes-Peñailillo**

Universidad de Talca, Fondo de Emprendimiento para la Investigación Científica de estudiantes de pregrado. Estimación del consumo hídrico de la vid usando sensores remotos montados en un vehículo aéreo no tripulado (VANT). Beneficiario: Joaquin Albornoz. Equipo: Samuel Ortega-Farias, **Fernando Fuentes-Peñailillo**.

FONDEF, Valorizacion de la investigacion en la Universidad (COD: **VIU-18P0132**), Plataforma geo informatica para el monitoreo del vigor y el consumo hidrico de frutales y vides, 2019. Beneficiario: Universidad de Talca. Director: **Fernando Fuentes-Peñailillo**. Equipo: Fernando Fuentes-Peñailillo, Samuel Ortega.

ANID-Concurso de Apoyo a la Formación de Redes Internacionales Entre Centros De Investigación 2019. **REDES190072**, Development of a computational technique to estimate vineyard water requirements and vine water status using high-resolution thermal and multispectral cameras placed on an unmanned aerial vehicle (UAV). Beneficiario: Universidad de Talca. Director: Samuel Ortega. Equipo: Samuel Ortega, **Fernando Fuentes-Peñailillo**.

Visitas a Laboratorios Internacionales

USON, Universidad de **SONORA, Mexico**. Invitacion efectuada por el Investigador: Dr. Julio Cesar Rodriguez. Objetivo: Colaboracion internacional en Investigacion, Extension y Transferencia Tecnologica.

Instituto Federal de Educação, Ciência e Tecnologia do Rio Grande do Sul - Campus **Bento Gonçalves, Brasil**. Invitacion efectuada por el Investigador: Dr. Rodrigo Otávio Câmara Monteiro, Irrigation and Water Resources Engineer, Campus Bento Gonçalves, Instituto Federal do Rio Grande do Sul – BRAZIL. Objetivo: Colaboracion internacional en Investigacion, Extension y Transferencia Tecnologica.

UCLM, Universidad de Castilla de la Mancha, **Albacete-España**. Invitacion efectuada por el Investigador: Dr. Miguel Angel Moreno. Objetivo: Elaboracion Proyecto REDES-ANID.

Pasantias

UCLM, Universidad de Castilla de la Mancha, **Albacete-España**. Financiamiento: Programa de Doctorado en Ciencias Agrarias Universidad de Talca y Agencia Nacional de Investigacion y Desarrollo ANID. Periodo: 2019. Objetivo: Desarrollo e implementacion de metodologias y dispositivos de bajo costo para optimizar el uso del agua cuyo detalle especifico correspondio a; i) Desarrollo de equipamiento de bajo costo, ii) Programacion en Phyton, R, Matlab, iii) Desarrolo e implementacion de redes neuronales iv) Desarrollo e implementacion de Metodologias de procesamiento de imagenes termales y multiespectrales v) Adquisicion y procesamiento de informacion proveniente de receptores GPS-RTK.

Reportes de Invención

aSIMOV; Sistema Inalambrico para el Monitoreo de la Vid. Justificacion: Producto obtenido de Tesis doctoral bajo proyecto **16PRAE-66973**.

Telemap; Plataforma geo informatica para el monitoreo del vigor y el consumo hidrico de frutales y vides. Justificacion: Producto obtenido de Tesis doctoral bajo proyecto **VIU-18P0132**

Colaboraciones en el marco de la tesis Doctoral

Congresos internacionales

Fuentes-Peñailillo, F., Acevedo-Opazo, C., Ortega-Farías, S., Rivera, M., Moyano, J., & González, C. (2019, November). Semiautomatic system of intrapredial water management for small farmers. In *2019 IEEE CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON)* (pp. 1-4). IEEE. https://ieeexplore.ieee.org/document/8988011

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K. Gutter, S. Ortega-Farías, **F. Fuentes-Peñailillo**, M. Moreno, R. Vega-Ibáñez, C. Riveros-Burgos, and J. Albornoz. (2020). Estimation of vineyard water status using infrared thermometry measured at different positions of the canopy. International Symposium on Irrigation of Horticultural Crops: **Matera**, **Italy**. International Society for Horticultural Science (ISHS).

R. Vega-Ibáñez, S. Ortega-Farías, **F. Fuentes-Peñailillo**, K. Gutter and J. Albornoz (2020). Estimation of Midday Stem Water Potential in grapevine leaves (cv. Cabernet Sauvignon) using spectral reflectance indices. International Symposium on Irrigation of Horticultural Crops: **Matera**, **Italy**. International Society for Horticultural Science (ISHS).

Fuentes-Peñailillo, F., Ortega-Farías, S., de la Fuente-Sáiz, D., & Rivera, M. (2019, November). Digital count of Sunflower plants at emergence from very low altitude using UAV images. In 2019 IEEE CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON) (pp. 1-5). IEEE. https://ieeexplore.ieee.org/abstract/document/8988024

Articulos

C. Riveros-Burgos, S. Ortega-Farías, L. Morales-Salinas, **F. Fuentes-Peñailillo**, and Fei Tian. Assessment of the clumped model to estimate olive orchard evapotranspiration using meteorological data and UAV-based thermal infrared imagery. Irrigation Science. **ISI Accepted 25-11-2020**.

Participacion en tesis

Tesis de Magister; Assessment of midday stem water potential in grapevines (cv. cabernet sauvignon) using spectral reflectance indices. Student: Ricardo Vega Ibañez. Examining committee; Samuel Ortega- Farías, **Fernando Fuentes-Peñailillo**, Mauricio Zuñiga.

Tesis de Magister; Evaluation of a new low-cost wireless soil moisture sensor. Student: Carla Gonzalez. Examining committee; Cesar Acevedo-Opazo, **Fernando Fuentes-Peñailillo**.

Preface

This doctoral thesis was carried out as part of a collaboration between researchers belonging to the Center for Research and Transfer in Irrigation and Agroclimatology (CITRA), Center for Transfer in Energy Conversion (CTEC) and Laboratory for Research in Environmental Sciences (LARES). This work is part of a long history of scientific collaboration and complementarity between the four research teams. The thesis was supervised by Doctor SAMUEL ORLANDO-FARIAS (University of Talca). Additionally, the academics who have participated are Doctor CESAR ACEVEDO OPAZO (University of Talca), Doctor MARCO RIVERA ABARCA (University of Talca) and Doctor LUIS MORALES SALINAS (University of Chile). This thesis project was funded by a doctoral scholarship from the University of Talca (2016-2017) and the National Agency for Research and Development ANID (2018-2019). The research work presented in this document refers to the Implementation of a methodology to estimate the water status of the vine by remote sensing and wireless-spatialized sensors. This work is important for the Chilean wine sector, it is innovative and constitutes a remarkable example of the potential of digital technology and the development of low-cost technology to improve the agriculture of tomorrow.

Appreciation of the results obtained

Articles

F. Fuentes-Peñailillo, C. Acevedo-Opazo, S. Ortega-Farías, M. Rivera and N. Verdugo-Vásquez. Spatialized system to monitor vine phenology: Towards a methodology based on a low-cost wireless sensor network. Sent to **Computers and Electronics in Agriculture.**

F. Fuentes-Peñailillo, S. Ortega-Farias, C. Acevedo-Opazo, M. Rivera and M. Araya-Alman. Low-cost wireless Sensor Networks networks for monitoring spatial variability of plant water status in a commercial vineyard. To be sent to **Sensors or Computers and electronics in agriculture**

Conferences

Fuentes-Penailillo, F., Ortega-Farias, S., Rivera, M., Bardeen, M., & Moreno, M. (2018, October). Using clustering algorithms to segment UAV-based RGB images. In 2018 IEEE International Conference on Automation/XXIII Congress of the Chilean Association of Automatic Control (ICA-ACCA) (pp. 1-5). IEEE.

Fuentes-Peñailillo, F., Ortega-Farias, S., Gutter, K., Vega, R., & Albornoz, J. (2020). Evaluation of a two-source model to estimate vineyard evapotranspiration using UAV-based thermal images and meteorological data. International Symposium on Irrigation of Horticultural Crops: **Matera**, **Italy**. International Society for Horticultural Science.

Projects

CORFO PRAE (COD-16PRAE-66973), aSIMOV; Wireless system for vine monitoring. Beneficiary: **Fernando Fuentes-Peñailillo**. Director: Fernando Fuentes-Peñailillo. Team: Fernando Fuentes-Peñailillo, Samuel Ortega, Cesar Acevedo, Marco Rivera.

Universidad de Talca, Entrepreneurship Fund for Undergraduate Students' Scientific Research. Wireless system for monitoring the Vine. Beneficiary: Martin Arraztio. Team: Marco Rivera, **Fernando Fuentes-Peñailillo**

Universidad de Talca, Entrepreneurship Fund for Undergraduate Students' Scientific Research. Estimation of vine water consumption using remote sensors mounted on an unmanned aerial vehicle (UAV). Beneficiary: Joaquin Albornoz. Team: Samuel Ortega-Farias, **Fernando Fuentes-Peñailillo**.

Valorization of research at the University (FONDEF VIU-18P0132), Geo informatic platform for monitoring the vigor and water consumption of fruit and vine, 2019. Beneficiary: Universidad de Talca. Director: Fernando Fuentes. Team: **Fernando Fuentes-Peñailillo**, Samuel Ortega.

ANID- Contest to Support the Formation of International Networks Between Research Centers. REDES190072. Development of a computational technique to estimate vineyard water requirements and vine water status using high-resolution thermal and multispectral cameras placed on an unmanned aerial vehicle (UAV). Beneficiary: University of Talca. Director: Samuel Ortega. Team: Samuel Ortega, **Fernando Fuentes-Peñailillo**.

Visits to International Laboratories

USON, University of **SONORA**, **Mexico**. Invitation made by the Researcher: Dr. Julio Cesar Rodriguez. Objective: International collaboration in Research, Extension and Technology Transfer.

Federal Institute of Education, Science and Technology of Rio Grande do Sul - **Bento Gonçalves** Campus, **Brazil**. Invitation made by the Researcher: Dr. Rodrigo Otávio Câmara Monteiro, Irrigation and Water Resources Engineer, Campus Bento Gonçalves, Instituto Federal do Rio Grande do Sul - BRAZIL. Objective: International collaboration in Research, Extension and Technology Transfer.

UCLM, University of Castilla de la Mancha, **Albacete-Spain**. Invitation made by the Researcher: Dr. Miguel Angel Moreno. Objective: Preparation of the REDES-ANID Project.

Research Stay

UCLM, University of Castilla de la Mancha, **Albacete-Spain**. Financing: Doctoral Program in Agrarian Sciences, University of Talca and National Agency for Research and Development ANID. Period: 2019. Objective: Development and implementation of low-cost methodologies and devices to optimize the use of water, whose specific detail corresponded to; i) Development of low-cost equipment, ii) Programming in Python, R, Matlab, iii) Development and implementation of neural networks iv) Development and implementation of thermal and multispectral image processing methodologies v) Acquisition and processing of information from GPS-RTK receivers.

Invention Reports

aSIMOV; Wireless System for Vine Monitoring. Justification: Product obtained from Doctoral thesis under project 16PRAE-66973.

Telemap; Geo-informatic platform for monitoring the vigor and water consumption of fruit trees and vines. Justification: Product obtained from Doctoral thesis under project VIU-18P0132

Collaborations within the framework of the Doctoral thesis

International conferences

Fuentes-Peñailillo, F., Acevedo-Opazo, C., Ortega-Farías, S., Rivera, M., Moyano, J., & González, C. (2019, November). Semiautomatic system of intrapredial water management for small farmers. In *2019 IEEE CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON)* (pp. 1-4). IEEE. https://ieeexplore.ieee.org/document/8988011

Fuentes-Peñailillo, F., Ortega-Farias, S., Rivera, M., Bardeen, M., & Moreno, M. (2018, October). Comparison of vegetation indices acquired from RGB and multispectral sensors placed on UAV. In 2018 IEEE International Conference on Automation/XXIII Congress of the Chilean Association of Automatic Control (ICA-ACCA) (pp. 1-6). IEEE. https://ieeexplore.ieee.org/document/8609861

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Fuentes-Peñailillo, F., Ortega-Farías, S., de la Fuente-Sáiz, D., & Rivera, M. (2019, November). Digital count of Sunflower plants at emergence from very low altitude using UAV images. In 2019 IEEE CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON) (pp. 1-5). IEEE. https://ieeexplore.ieee.org/abstract/document/8988024

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C. Riveros-Burgos, S. Ortega-Farías, L. Morales-Salinas, **F. Fuentes-Peñailillo**, and Fei Tian. Assessment of the clumped model to estimate olive orchard evapotranspiration using meteorological data and UAV-based thermal infrared imagery. Irrigation Science. **ISI** Accepted 25-11-2020.

Participation in thesis

Tesis de Magíster; Assessment of midday stem water potential in grapevines (cv. cabernet sauvignon) using spectral reflectance indices. Student: Ricardo Vega Ibañez. Examining committee; Samuel Ortega- Farías, **Fernando Fuentes-Peñailillo**, Mauricio Zuñiga.

Tesis de Magíster; Evaluation of a new low-cost wireless soil moisture sensor. Student: Carla Gonzalez. Examining committee; Cesar Acevedo-Opazo, **Fernando Fuentes-Peñailillo**.

Implementación de una metodología para estimar el consumo y estado hídrico de la vid mediante teledetección y sensores inalámbricos espacializados

Resumen

Diversas investigaciones señalan que la disponibilidad del agua para riego ha disminuido considerablemente en los últimos años, por esta razón existe la necesidad de optimizar el uso de esta sin afectar la calidad y rendimiento. Con el fin de mejorar la eficiencia en el uso de los recursos hídricos, un factor clave para la programación del riego es la estimación de la evapotranspiración actual (ETa). Aunque este método proporciona un enfoque simple para estimar los requerimientos hídricos, existe una gran incertidumbre en la obtención de los valores de coeficiente de cultivo (Kc), debido a que en literatura se reportan valores empíricos que no están adaptados a las condiciones locales de suelo, clima, cultivar y sistema de conducción. Estas consideraciones son especialmente importantes en cultivos discontinuos como el viñedo, donde existe una gran variabilidad espacial asociada a la arquitectura del dosel. Para resolver esta problemática algunos autores han propuesto realizar una estimación directa de ET_a utilizando el modelo de Shuttleworth-Wallace (SW) mientras que otros autores han utilizado mediciones fisiológicas para la estimación del estado hídrico del viñedo, con el objetivo de proponer una estrategia de riego. Sin embargo, estas técnicas presentan limitaciones para ser implementadas a una escala predial mayor a 20 ha, por lo que recientemente se ha propuesto la utilización de técnicas de percepción remota para estimar indirectamente el estado hídrico de la planta a través de índices espectrales. Sin embargo, es importante considerar que aún existen importantes desafíos por resolver como; el costo del equipamiento y el desarrollo metodologías para utilizar apropiadamente estos dispositivos. Debido a esto el presente estudio busca determinar el consumo y estado hídrico del viñedo utilizando vehículos aéreos no tripulados y sensores inalámbricos espacializados de bajo costo. Los resultados obtenidos por esta investigación mostraron que para la utilización de las imágenes aéreas es fundamental efectuar una adecuada segmentación de la canopia mediante el uso de algoritmos de segmentación en donde los algoritmos k-means y Clara tuvieron un desempeño similar. Posteriormente la técnica k-means fue utilizada para implementar el modelo de Shuttleworth y Wallace en combinación con imágenes aéreas de alta resolución lo que permitió obtener el consumo hídrico tanto del suelo como la canopia con un error del 5%, un cuadrado medio del error

(RMSE) de 0.37 mm dia^{-1} y un error medio absoluto (MAE) de 0.27 mm dia^{-1}. Los capítulos siguientes estuvieron enfocados en el desarrollo de dispositivos de bajo costo en donde en primer lugar se desarrolló una red inalámbrica espacializada de termohigrómetros para la determinación del estado de desarrollo del viñedo (fenología), debido a su estrecha relación con el consumo hídrico. Finalmente, un segundo dispositivo de bajo costo (aSIMOV) fue desarrollado para la determinación del estado hídrico del viñedo basado en radiómetros infrarrojos de bajo costo desplegados en terreno. Este dispositivo permitió determinar el Crop Water Stress Index (CWSI) y posteriormente el potencial hídrico xilemático (SWP). El dispositivo fue capaz de predecir el SWP con un R^2 de 0.72 en contraste a los dispositivos tradicionales que permitieron predecir el SWP con un R^2 de 0.70, demostrando de esta forma la efectividad de estos dispositivos

Palabras claves: Percepcion remota, Sensoramiento, Estado Hídrico, Consumo Hídrico, Viñedo.

Implementation of a methodology to estimate vine water consumption and water status through remote sensing and spatialized wireless sensors

Abstract

Several investigations indicate that the availability of water for irrigation has decreased considerably in recent years, for this reason, there is a need to optimize its use without affecting quality and yield. To improve the efficiency in the use of water resources, a key factor for irrigation scheduling is the estimation of the actual evapotranspiration (ETa). Although this method provides a simple approach to estimate the water requirements, there is significant uncertainty in obtaining the crop coefficient values (Kc), since empirical values reported in the literature are not adapted to the local conditions of soil, climate, cultivar, and training system. These considerations are crucial in discontinuous crops such as vineyards, where there is great spatial variability associated with the canopy architecture. To solve this problem, some authors have proposed to make a direct estimation of ETa using the Shuttleworth and Wallace (SW) model, while other authors have used physiological measurements to estimate the water status of the vineyard, with the aim of proposing an irrigation strategy. However, these techniques have limitations to be implemented at a farm-scale greater than 20 ha, reason why the use of remote sensing techniques has recently been proposed to indirectly estimate the water status of the plant through spectral indices. However, it is important to consider that there are still critical challenges to be solved, such as the cost of equipment and the development of methodologies to use these devices properly. Due to this, the present study seeks to determine the consumption and water status of the vineyard using unmanned aerial vehicles and low-cost spatialized wireless sensors. The results obtained by this research showed that for aerial images, it is essential to carry out an adequate segmentation of the canopy using segmentation algorithms where the k-means and Clara algorithms had a similar performance. Subsequently, the k-means technique was used to implement the Shuttleworth and Wallace model in combination with high-resolution aerial images, which allowed obtaining the water consumption of both the soil and the canopy with an error of 5%, a mean square of the error (RMSE) of 0.37 mm day^{-1} and a mean absolute error (MAE) of 0.27 mm day^{-1}. The following chapters were focused on the development of low-cost devices where, in the first place, a spatialized wireless network of Thermo hygrometers was developed to determine the state of development of the vineyard (phenology) due to its close relationship with water consumption. Finally, a second low-cost device (aSIMOV) was developed to determine the water status of the vineyard based on low-cost infrared radiometers deployed in the field. This device made it possible to calculate the Crop Water Stress Index (CWSI) and subsequently the stem water potential (SWP). The device was able to predict SWP with an R^2 of 0.72 compared to traditional devices that allowed predicting SWP with R^2 of 0.70, thus demonstrating the effectiveness of these devices.

Keywords: Remote sensing, Sensing, Water Status, Water Consumption, Vineyard.

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Chapter 4: **Low-cost wireless sensor networks for monitoring spatial variability of plant water status in a commercial vineyard**

First Part

Context of the problem

General Introduction

1. General context

To contextualize the issues addressed in this research, the situation of Chilean viticulture is presented below. This will allow dimensioning the field of application of the proposed methodology to estimate water consumption and water status of the vineyard.

1.1. A brief characterization of viticulture in Chile

The national viticultural surface is located between Arica and Los Lagos, which according to data from 2018, totaled 146,131.13 planted ha (SAG, 2018) where the most extensive area is situated between the regions of O'Higgins, and Maule, concentrating 68% of the established vineyards. Along with Chile, countries such as Australia, the United States, South Africa, New Zealand, and Argentina are the most important nations of the "New World" wine industry (Li et al. 2018), since all of them have experienced sustained growth in the participation of the international wine market in recent decades, mainly due to the investment in innovation and technology that has allowed them to exploit their varieties and Terroir characteristics (Gil and Pszczólkowski 2007). Our country's vineyards can be grouped into three large groups: vines destined to produce table grapes for export, vines destined to produce pisco, and vines destined to produce wines. Red varieties represent 74% of the total, characterized mainly by the presence of Cabernet Sauvignon, Merlot, and Carménère, which concentrate 30%, 9%, and 8% of the total area of such vines, respectively. On the other hand, white varieties represent 36% and, in this category, varieties such as Sauvignon Blanc and Chardonnay stand out (SAG, 2018). The conduction systems of the Chilean vineyard correspond mainly to high trellis (37%), low trellis (34%), and pergola type trellis (15%). Of this surface, 86% is under irrigation, which today is carried out by technified irrigation, while in dry land, this figure only reaches 13% (SAG, 2018).

1.2. Water scarcity and optimization in the efficiency of water use in the vineyard

Numerous studies have indicated that water availability will be significantly reduced, which will be accentuated by strong competition for this resource by agriculture, industry, and urban areas (Ortega-Farias et al. 2009). Particularly, in Chile's central zone, a decrease in precipitation that could vary from 20 to 40% has been forecasted (Garreaud et al. 2017). This problem will be more severe given the increase in the frequency of occurrence of “La Niña” phenomenon (Sarricolea Espinoza and Meseguer-Ruiz 2015), which will drastically limit the growth of the wine industry of our country. Because of this, there is a growing need to optimize water use without affecting quality or yield of the vineyard (Bellvert et al. 2020). Intending to improve water use efficiency, farmers have implemented technified irrigation systems in most of the national vineyards (Ortega-Farias et al. 2010). In this sense, a key factor for irrigation scheduling in vineyards is the accurate estimation of real evapotranspiration (ET_a), which allows quantifying water consumption and determining the optimal water volumes to be applied on irrigation (Ortega-Farias et al. 2009). Traditionally, ET_a can be estimated through the methodology proposed by Allen et al. (1998), which is calculated based on the multiplication of reference evapotranspiration (ET_o) by a crop coefficient (Kc). Even though this method provides a simple approach to estimate water demand of crops, there is great uncertainty regarding the obtention of Kc values (Fuentes-Peñailillo et al. 2018), given that literature reports empirical values that may not be adapted to the local conditions of soil, weather, cultivar, and training system (Ortega-Farias et al. 2009). These considerations are crucial on discontinuous crops such as vineyards, where there is a great spatial variability associated with canopy architecture and vegetal cover (Ortega-Farías and López-Olivari 2012). To address this problem, some authors suggest making a direct estimation of ETa (Ortega-Farias et al. 2007; Cammalleri et al. 2010) using the Shuttleworth-Wallace model (SW), which introduces a detailed description of the energy transport process of water at a surface level, calculating crop and soil transpiration and evaporation separately (Anadranistakis et al. 2000). Other authors propose the use of physiological measurements to estimate vineyard water status, to propose an irrigation strategy based on these measurements, among which midday stem water potential, stomatal conductance, sap flow, trunk diameter variation, the surface temperature measured with infrared sensors, reflectance indices and chlorophyll fluorescence stand out. These techniques have been widely used in different types of crops, highlighting the practical application of these types of measurements when it comes to irrigation scheduling (Choné et al. 2001; Intrigliolo and Castel 2007; Acevedo-Opazo et al. 2010; Ferreira et al. 2012). From these techniques, midday stem water potential (SWP) stands out as the most widely used by farmers at the field level, given its accuracy to determine plant water status and the ease of implementation by the producer. In our country, 70% of export vineyards use this methodology as a practical tool to define the optimum moment of irrigation of their productive units.

However, both methodologies have limitations to be implemented at a farm-scale, making it impractical to represent the field's natural variability. In the first place, the models that directly estimate ET_a consider specific data obtained from an automatic weather station (AWS), while the techniques based on physiological measurements, despite providing precise information, only consider the observation of a reduced number of plants at the field level, omitting the spatial variability of the soil and existing vigor inside the vineyard and therefore are not viable to propose site-specific irrigation management strategies (Acevedo-Opazo et al. 2013). Thus, spatially distributed measurements that consider the heterogeneity and existing surface within the vineyard are required to consider the spatial variability of water status. To face this problem, Zarco-Tejada et al. (2012) suggested using spectral and thermal indices to estimate the plant's water status. These are obtained from high-resolution aerial images captured by satellites, airplanes and/or drones (Acevedo-Opazo et al. 2013), which can detect physiological responses to water stress in large areas (Baluja et al. 2012; Zarco-Tejada et al. 2012). The latter exemplifies the variety of tools available to determine and monitor crops' water consumption considering the spatial variability of the fields. However, none of them provide a definitive solution to the problem but must be combined to manage the factors involved comprehensively.

2. Vine water consumption and vine water status

2.1. Why phenology is an important factor to consider when irrigation management is made?

As it was mentioned above, accurate and precise management of water resources becomes essential in regions were water for irrigation is scarce, which is the case of arid and semi-arid regions, where most of the cultivated vineyards are established (Chaves et al. 2007). This management becomes essential since water has been recognized as the main factor controlling vegetative growth and grapes' final quality (Romero et al. 2010). In this sense, the application of water stress at specific phenological stages where the crop is less sensitive to it has been proven to improve grape quality with almost no yield reduction (Gonzalez-Dugo et al. 2013), whereas the application of water stress in phenological stages sensitive to this reduction can result in a significant yield loss, and in extreme cases, a decrease in quality (Munitz et al. 2017). This scenario can also be observed in cases where continuous and severe water stress is applied, which can drastically reduce the vineyard's lifespan. Problems can also be derived from excessive irrigation, since this strategy entails higher costs along with an increase in vegetative growth that generates shading of clusters and a reduction in grape quality (Chorti et al. 2010), therefore, an accurate irrigation management strategy is sought aiming to maximize grape quality and to reduce overall water use which should be based on changes in vine water consumption as a function of climate conditions and phenological development. However, the traditional methods used by growers to characterize the vineyard's phenology (spot measurements or use of predictive models) would not be an adequate methodology to represent the spatial variability of the vineyard. In this regard, it can be observed that in the wine industry, field professionals do not perform more than two to three phenological observations per productive unit per season, assuming that these measurements are representative of the entire vineyard (Verdugo-Vásquez et al. 2019). For this, they use automatic weather stations that collect information from a single site in the field, which does not represent the real spatial variability of the vineyard or the plant's micrometeorological condition. Therefore, this traditional method results in inappropriate and inefficient decisions from an agricultural point of view since it does not characterize the vineyard spatial variability in key growth stages to produce high-quality grapes. In this sense, Tisseyre et al. (2005) have shown that there is a high spatial variability in the fields in viticulture. Recently, the existence of spatial variability in climatic conditions has been studied at intra-predial scale (Matese et al. 2014) and at the level of the valley or productive region, which shows that the recording made by the weather station does not necessarily represent the micro climatic condition of the vineyard, and therefore, it is not possible to assume that this information represents the entire production unit (Matese et al. 2014). Recent research shows that the classical methodology used to predict vine phenology temporarily, should be used with caution due to the significant spatial variability observed, both in climatic variables and in the vine phenology. The above poses a new challenge for the modeling of vine phenology:

Is it possible to model the spatial and temporal variability of the vineyard’s phenology? To answer this question, a probable approach can be done through the implementation of affordable new technologies in combination with traditional methods so that phenological development can be accurately determined so that in combination with water management techniques it can increase the efficiency of water under the current climate change scenario.

2.2. Water status measurements at the plant level

Currently, there is a wide range of tools to measure the water status of plants, such as stomatal conductance, sap flow, variation in trunk diameter, surface canopy temperature, and plant water potential, among others. These methods provide a direct measurement of the plants' biophysical parameters and reflect with great precision the water status of these.

Below, a brief description of each of these methods is presented:

Stomatal conductance (gs): It consists of measuring the flow of water vapor that leaves the plant towards the atmosphere, through the stomata. gs is the first factor affected by the lack of water since stomatal regulation occurs in the leaves as a way of controlling the loss of water in the plant. It has been observed that there is a high correlation between gs and the relative water content inside the plants (water potential) (Flexas et al. 2002).

Sap flow (SF) sensors: These are sensors that measure the speed with which the sap rises through a plant's xylem because of atmospheric demand. The main methodologies are heat balance (Langensiepen et al. 2014), speed of the heat pulse (Forster 2020), and heat dissipation (Cammalleri et al. 2013). These methods allow estimating the transpiration rate of a plant during the day as sensors are directly coupled to the plant's trunk.

Trunk Diameter Variation (TDV): The contraction and dilation of the extensible tissues of a tree provide an indirect measure of its transpiration during the day (light period) and are related to changes in the water content and turgor of the plant (Ortuño et al. 2010). Dendrometry has been proposed as a precise tool to assess the plant's water status since the diameter of the trunk has been shown to be related to the water status of the plant.

Infrared thermometry (IT): Several investigations indicate that both leaf temperature and canopy temperature depend on the transpiration of the plant, therefore they could be used as a useful indicator of the water status of these (Jones et al. 2002). A higher temperature in the leaf indicates a lower water loss in the plant because of stomatal closure and therefore suggests a stress condition in the crop.

Water potential (Ψ): Many authors have suggested the "Scholander" pressure chamber as the most accurate tool to measure the water status of plants, both under irrigation and rainfed conditions (Levin 2019), as well as a practical tool and easier to use than porometers. The Ψ can be evaluated using different techniques: i) leaf water potential (Ψ L) (Girona et al. 2006), ii) stem water potential (ΨX) (Leeuwen et al. 2009) and iii) leaf water potential before dawn (ΨPD) (Santesteban et al. 2011). Of the three techniques, ΨX is the most recommended for monitoring orchards under irrigated conditions since it is a sensitive physiological indicator of the plant's water condition. On the other hand, ΨPD is recommended for non-irrigated (rainfed) management conditions, where very severe water stress levels are reached.

The main advantage of these methods corresponds to the ability to characterize the plants' water status based on plant-to-plant measurements and the continuous monitoring of the information over time. However, they have significant disadvantages when applied over large areas due to the limited number of possible measurements to perform in the field. These limitations constitute strong conditioning factors for using manual plant measurement methods when they want to be applied to an important farm scale. Therefore, the development of autonomous monitoring systems will allow the estimation of the water status to increase representativeness over time and use less human resources. On the other hand, the cost and maintenance drastically limit the implementation of new technologies, which restricts the knowledge of the spatial variability of the water status of the vineyard.

2.3. Estimation of water consumption

An important number of empirical and semi-empirical models were developed to estimate the water consumption of crops, which combine the energy balance with the mass transference method. These are intended for irrigation scheduling and the design of pressurized systems in new plantations. Water consumption of plants or ET_a is determined using empirical methods such as the Penman-Monteith model (Allen et al. 1998). This method requires climatic information to estimate water consumption at the field level, obtained from Automatic Weather Stations (AWS). AWSs have been available for a long time in our country, with wide adoption by fruit and wine growers. However, the zone of influence in which the climatological data is representative can vary drastically depending on the edaphoclimatic conditions, such as the terrain's topographic characteristics, which directly influence the microclimate of the vineyard. Therefore, the combination of climatic information with other data sources is of vital importance for determining the water consumption of the vineyard. This is especially important if we consider using new methodologies to obtain spatially distributed information on the vineyard. In this sense, authors such as Fuentes-Peñailillo et al. (2018) have successfully implemented models from more than one source combined with high-resolution satellite images to obtain spatialized data on the water consumption of fruit trees. However, there are still pending challenges since satellite information has limitations that do not allow obtaining data with a stable temporal frequency. In this way, the use of other technologies such as unmanned aerial vehicles (UAV) make it possible to solve these challenges, allowing to obtain information independent of the meteorological conditions, making it possible to obtain data with a stable temporal frequency as well as a higher spatial resolution.

2.4. High-resolution images for estimation of water consumption in the vineyard

Based on the aforementioned, it is important to consider that new technological tools such as unmanned aerial vehicles (UAV) have now been developed, which allow the positioning of thermal and multispectral optical sensors at a shorter distance from the crop, obtaining images with higher spatial, spectral and temporal resolution, which is a great advantage in estimating water consumption. Remote sensors mounted on UAVs could be an alternative to satellite platforms because they provide a lower-cost solution to meet current needs (Berni et al. 2009). In the literature, some authors have successfully implemented these technologies, such as Zarco-Tejada et al. (2012), who developed a methodology for a UAV System that allows studying the spatial variability of the water consumption in a vineyard using thermal images. Also, Turner et al. (2011) studied UAVs' potential to determine soil moisture content, evaluate irrigation efficiency, and monitor spatially and temporally the vigor of the vineyard through the Normalized difference vegetation index (NDVI). Therefore, we can establish that UAV-mounted sensors provide an accessible platform for generating high-resolution spatial data. These sensors could even allow us to separate the transpiration and evaporation components of the vineyard, giving us the possibility to study the energy fluxes in greater detail (Comba et al. 2015). The aforementioned allows the combination of this information with traditional water consumption models, thus generating an innovative and useful methodology to determine the water consumption of the vine at high spatial resolution. In this sense, several researchers have suggested using the Shuttleworth and Wallace (SW) model in vineyards to estimate water consumption more accurately by calculating transpiration and evaporation independently. However, to date, few studies have been carried out studying the combination of these complex models in conjunction with high spatial resolution images to study the vine's water status.

2.5. Monitoring vineyard water status using wireless sensor networks (WSN)

The vineyard's water status can be determined indirectly by measuring the water content in the soil or directly by monitoring the plant's response to water stress. Measurements of soil water content are spot measurements and are limited by the difficulty and cost of representing the orchard root zone's heterogeneous conditions. Furthermore, soil water content measurements do not integrate the combined effect of the soil properties, climatic conditions, and characteristics of the variety on the water consumption and the water status of the plant (Ortega-Farías and López-Olivari 2012). In this regard, Jones (2004) suggested that the greater precision in the application of irrigation can be obtained using physiological measurements of the plant compared to the monitoring of the water content in the soil. The main irrigation scheduling technique based on physiological measurements are the plant's water potential (ΨPD, ΨX and ΨL), stomatal conductance, sap flow, trunk diameter variation, surface temperature measured with infrared cameras, reflectance indices, and the fluorescence of chlorophyll. Among these techniques, the use of ΨX stands out, which is currently used to monitor vines' water status (Girona et al. 2006; Acevedo-Opazo et al. 2010). Despite the fact that all these techniques present a good degree of precision in the measurement of water status, their commercial application for site-specific irrigation management is limited since many of them can only monitor some plants within an orchard, therefore, to consider the spatial variability of the vineyard's water status, several measurements are required, which is time consuming and increases operating costs (Jones 2004). In this way, specific physiological measurements are challenging to perform on a larger spatial scale, mainly due to the lack of simple and low-cost tools that allow measuring these variables with high spatial intensity. A simple alternative to determine the water status is the relationship between the transpiration rate and the temperature of the vegetation, which has been verified and documented a couple of decades ago, confirming the ability of this technique as a diagnostic tool for the water status of crops (Jackson, R.; Idso, S.; Reginato, R.; Pinter 1981).

The leaves' temperature allows defining the water status of plants, since transpiration (transfer of water from the interior of the leaves to the atmosphere through stomata) involves a phase change (liquid to gas), which requires a significant amount of energy. For this reason, the higher the transpiration rate, the lower the temperature of the leaf with respect to the air temperature. On the contrary, the lower the transpiration rate, the higher its temperature. Limitations in the water availability in the soil (or lack of irrigation) induce the stomata's closure and, therefore a decrease in the transpiration rate. This situation is commonly known as water deficit and/or water stress. The adaptation of this technique on spatialized systems at the field level opens a door to the evaluation of temperature with infrared sensors at field scale. In this way, the information can be collected at different sites on the surface, incorporating the spatial distribution of the evaluated parameters. From these spatialized records it is possible to create easily interpretable maps. Additionally, the spatial characterization of the parameters allows defining homogeneous management sectors and thus achieving a more efficient planning of irrigation use. The simplicity of the technique allows tours of personnel without further training and can be carried out with a high temporal frequency.

3. Objectives of the thesis

The main objective of this work was to determine actual water consumption (ET_a) and water status over a drip-irrigated vineyard, using information obtained from remote sensing and spatialized wireless sensor networks. In this regard, this thesis was organized into four chapters detailed as follow:

Chapter 1: Using clustering algorithms to segment UAV-based RGB images

Chapter 2: UAV-based estimation of actual vineyard evapotranspiration using the Shuttleworth and Wallace model

Chapter 3: Spatialized system to monitor vine phenology: Towards a methodology based on a low-cost wireless sensor network

Chapter 4: Low-cost wireless sensor networks for monitoring spatial variability of plant water status in a commercial vineyard

4. Stages of research, scientific questions, and definition of the problem

After the bibliographic review and the establishment of this work's objectives, we can establish four significant findings on estimating the crop water consumption and water status of the vine using new technological tools, from which the following scientific research questions arise.

I) Using clustering algorithms to segment UAV-based RGB images

Is it possible to use traditional image segmentation algorithms to identify objects of agricultural interest in RGB digital images?

II) UAV-based estimation of actual vineyard evapotranspiration using the Shuttleworth and Wallace model

Is it possible to accurately estimate the vine's water consumption using the Shuttleworth and Wallace model and thermal images?

III) Spatialized system to monitor vine phenology: Towards a methodology based on a low-cost wireless sensor network

Are inexpensive spatialized sensors a useful tool for determining grapevine phenology stages?

IV) Low-cost wireless sensor networks for monitoring spatial variability of plant water status in a commercial vineyard

Are inexpensive spatialized sensors a useful tool to determine the water status of the vine?

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Second Part

Remote sensing

Chapter 1: Using clustering algorithms to segment UAV-based RGB images

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Abstract

This article describes the implementation of two segmentation algorithms combined with the RGB Triangular Greenness Index (TGI) derived from images obtained from an unmanned aerial vehicle (UAV), to segment shaded soil and crop data obtained from a commercial vineyard cv. Cabernet Sauvignon. This segmentation's importance lies in the recent development of tools that allow remote monitoring of crops but that nevertheless still have unresolved methodological aspects. The precise differentiation of these classes would allow the development of more complex monitoring techniques based on multispectral and thermal sensors. The results of this investigation showed that both k-means and Clustering Large Applications (CLARA) allowed differentiating three classes in the images corresponding to soil, shade, and crop. However, CLARA showed a better performance when determining the layer corresponding to vegetation, identifying the class corresponding to crop in a more precise way.

Keywords: Agricultural engineering, Image processing, Open-source software, Unmanned aerial vehicles

Introduction

Clustering analysis is an exploratory technique belonging to the unsupervised learning family of machine learning algorithms (Leiva Valdebenito & Torres Avilés, 2010; Nayini et al., 2018; Sonka et al., 2008). It performs data grouping characterized by within-class homogeneity and intra-class variation (Alrabea et al., 2013). The k-means algorithm is one of these methods that is widely used (MacQueen, 1967; Patel & Mehta, 2011). It partitions a set of n objects into k clusters so that the resulting intracluster similarity is high, but the inter-cluster similarity is low (Jain, 2010). Contrastingly, algorithms such as Partitioning Around Medoids (PAM) and Clustering Large Applications (CLARA) have not been widely disseminated (Gentle et al., 1991), despite having the advantage of processing large data sets, as in the case of CLARA (Leiva Valdebenito & Torres Avilés, 2010). Currently, clustering analysis is a method widely used in different areas of knowledge such as genomic studies (Baldi & Hatfield, 2002), ecology (McGarigal et al., 2000), marketing (Arabie & Hubert, 1994), and even precision agriculture (PA) applications (Burgos-Artizzu et al., 2011), as no statistical assumption is required for the grouping process (Leiva Valdebenito & Torres Avilés, 2010).

Regarding clustering applications in the field of precision agriculture, the main challenge has been the identification of objects in images obtained from ground-level robots or unmanned aerial vehicles (UAVs) for agricultural management purposes (Zheng et al., 2009). Efforts to achieve segregation are reflected in the development of techniques such as the dynamic thresholding method (Rovira-Más et al., 2005), Otsu-based thresholding methods (Meyer & Neto, 2008; Shrestha et al., 2004), and statistical means-based segmentation of the image (Guijarro et al., 2011). These methods assume that the resulting histogram presents a bi-modal tendency. Nevertheless, in real situations (e.g., differences in lighting conditions) these methods do not allow the separation of the vegetation from the background without compromising the clustering technique performance.

Commonly, analyzed images contain three dominant spectral signatures corresponding to plants, soil, and shadow. Methodological approaches used to obtain this segmentation correspond to Spectral index-based methods. Specifically, the Visible Atmospheric Resistant Index (VARI) (Gitelson et al., 2002), which monitors the vegetation fraction (VF); Normalized Excess Green Index (ExG) (Woebbecke et al., 1995) that distinguishes the living plant material from a non-plant background; the Triangular Greenness Index (TGI) (Hunt et al., 2013), which determines the leaf chlorophyll content and the Normalized Green-red Difference Index (NGRDI) (Gitelson et al., 2002).

A critical stage of these approaches is determining a threshold value to binarize near-binary images resulting from the aforementioned spectral index-based methods (Moorthy et al., 2015). Therefore, the implementation of image segmentation from indices remains a research challenge.

This is particularly important in fruit growing locations as these techniques have the potential to accurately determine parameters that will increase water use efficiency. However, for these applications to be viable from a scientific and technological point of view, segmentation methods must still be improved. This study proposes a methodology to segment images of vineyards based on an RGB index and two clustering methods (k-means and CLARA). Moreover, we argue that the Triangular Greenness Index (TGI) combined with a clustering method facilitates the differentiation of pixels representing vegetation from those representing soil and/or shadow.

Materials and methods

Experimental setup and Image acquisition

The experiment was carried out during the 2017-2018 season in a commercial drip-irrigated vineyard located in Pencahue, Maule Region, Chile. For image acquisition, a DJI Phantom 3 advanced was used. The UAV was pre-programmed with a flight plan to ensure that all study site was covered, considering an overlapping between images of about 90%. To obtain RGB images, a sensor of 12.76 megapixels was used, giving a pixel size of 0.86 cm. Finally, the flight time was 15 minutes with a speed of 1.8 meters per second, considering an altitude of 30 meters over the soil surface.

Greenness Index

From the RGB images obtained from the UAV, a Triangular Greenness Index (TGI) (Hunt et al., 2013) was computed for each pixel as follows:

$$\mathrm{TGI} = \mathrm{G} - 0.39 * \mathrm{R} - 0.61 * \mathrm{B} \tag{1}$$

where R, G, and B are the digital numbers (0–255) of the red, green, and blue color channels, respectively.

The mosaics of the RGB camera were assembled using the Pix4D software (Pix4D, Lausanne, Switzerland), and index processing was performed using a script developed with open-source software (R studio).

Image segmentation algorithm

The k-means algorithm is one of the most popular partition methods (MacQueen, 1967). In simple terms, it has the objective of splitting a set of n observations in k groups in which each observation belongs to the group whose average value is nearer. In our study, k-means was implemented considering the following steps (Bradley & Bradley, 1998):

i) First, the k objects that will be the centers of the conglomerates must be arbitrarily selected,
ii) Each object is assigned to the conglomerate with the nearest centroid, based on the average value of the objects in the conglomerate
iii) Centers of the conglomerates are recalculated
iv) Steps 2 and 3 are iterated until the stopping criterion's convergence is reached, or until the centroids are modified slightly.

For the experiment, three groups were arbitrarily defined, since previously it is known that the images are composed of objects corresponding to shadow, soil, and vegetation pixels. It is important to mention that this method is fast and works well with missing values, however, it has a strong sensitivity to the outlier data (Leiva Valdebenito & Torres Avilés, 2010). To solve this limitation, different methods have been developed to get a better performance by correcting some problems of k-means (Nayini et al., 2018) for example; PAM-algorithm, suitable for small data sets and more resistant to outlier data (Kim & Hamasaki, 2007; Nayini et al., 2018), FCM method for fuzzy clustering (Kim et al., 2006) and CLARA-algorithm made for clustering large datasets (Gentle et al., 1991). In this sense, CLARA draws a sample of the data set, then applies the Partitioning Around Medoids (PAM) algorithm and finds the sample's medoid (Alrabea et al., 2013). In our study, for robustness purposes, the CLARA algorithm was also implemented and compared with k-means by visual analysis. Finally, selected algorithms were run in a personal computer (laptop) with an Intel core I7 processor at 2.6 Ghz and 16 GB RAM. The operating system was Windows 10. The algorithms were implemented in R Studio using the "cluster" library.

Results and discussion

First, the TGI index was calculated from the images obtained from the UAV. In Figure 1, the existence of spatial patterns can be clearly observed. However, as has been pointed out in the literature, the direct identification of objects on the index's images is complex. Therefore, the implementation of an unsupervised classification method is required to identify pixels groups. The k-means algorithm was estimated by defining the existence of three data groups (soil, shadow, and vegetation), shown in Figure 2. Then, masks were created with each of these classes, resulting in three masks corresponding to the soil, shadow, and vegetation (Figure 3).

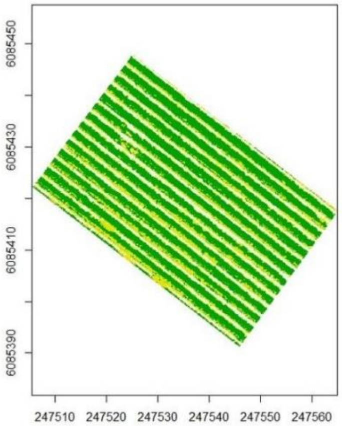

Figure 1 Raster image of groups defined through k-means algorithm

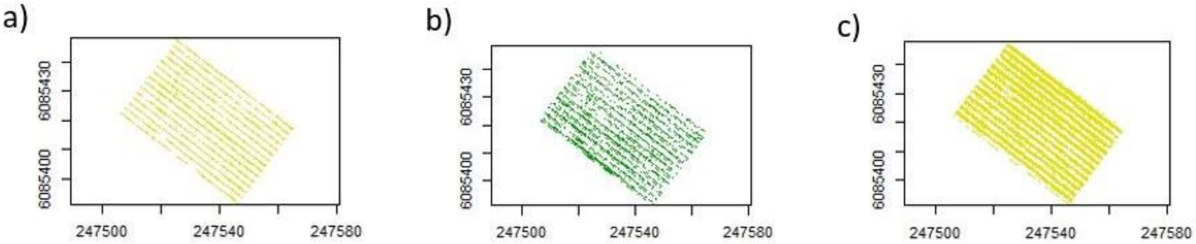

Figure 2, where; a) Area corresponding to crop defined as a class 1 in k-means b) Area corresponding to shadow defined as a class 2 in k-means, and c) Area corresponding to soil defined as a class 3 in k-means

In the second place, segmentation was carried out using the CLARA algorithm, a process for which 3 data classes were previously defined. The results of this estimation are shown in Fig 4. In a similar fashion as k-means, three masks were created from the initial data. In both cases, the masks were developed to identify the pure vegetation pixels.

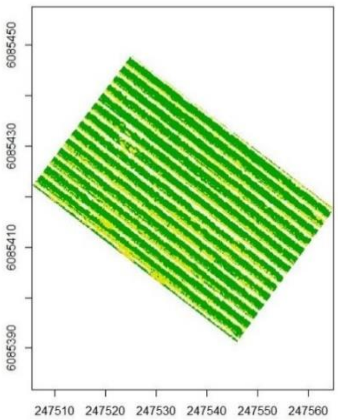

Figure 3 Raster image of groups defined through CLARA algorithm

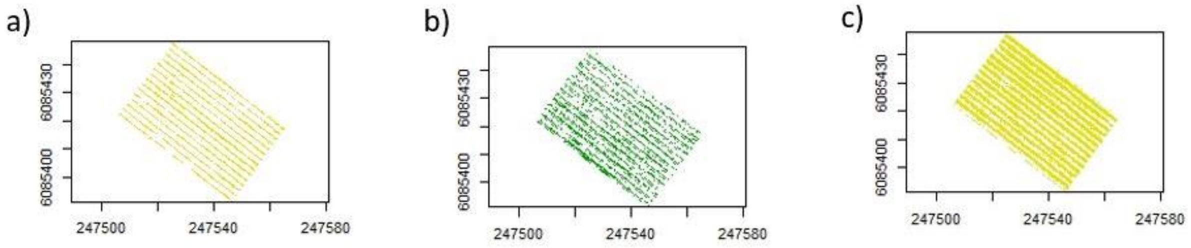

Figure 4 a) Area corresponding to crop defined as a class 1 in using CLARA b) Area corresponding to shadow defined as a class 2 using CLARA, and c) Area corresponding to soil defined as a class 3 using CLARA

Figure 5a an aerial view, which corresponds to a section of the study site where soil, shade, and cultivation are differentiated. Figure 5b shows the same aerial view, however, in this view, the masks developed with k-means (purple) and CLARA (blue) have been superimposed. Our estimations of the CLARA algorithm accurately overlap the area corresponding to the crop. However, k-means has the advantage of identifying pixels in the inter-row and assigned them to the crop group.

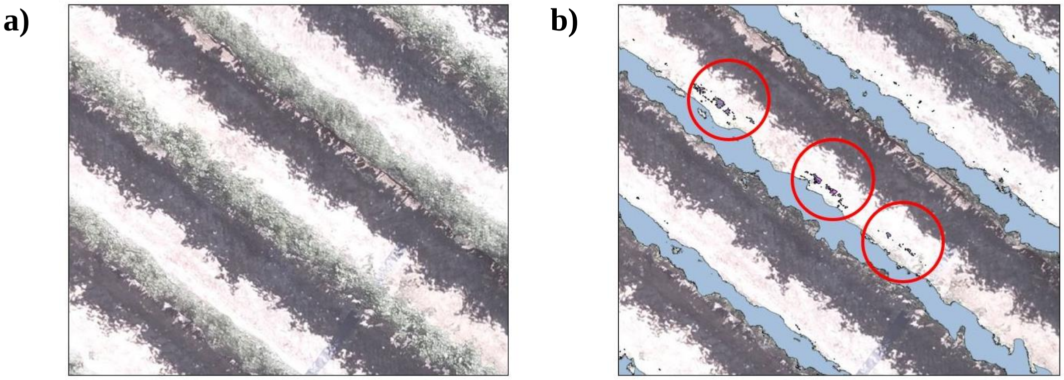

Figure 5, where; a) UAV based image obtained with an RGB sensor b) Raster image of groups defined through k-means (purple) and CLARA (blue) algorithms. Red circles indicate pixels that correspond to crop layer for k-means.

This research's importance lies in the possibility of using the information obtained from low-cost devices (RGB cameras) to create masks that allow the segmentation of images from lower resolution devices (thermal images). The possibility of clearly segmenting the area corresponding to shade and crop will enable the implementation of water consumption estimation algorithms on fruit trees, solving a fundamental problem of carrying out an accurate separation between vegetative and non-vegetative material.

Conclusion

These results allow us to conclude that it is possible to perform a segmentation of soil, shadow, and crop using RGB indices combined with segmentation algorithms through the proposed methodology. Furthermore, the algorithm that showed the best performance was CLARA, since k-means was not precise regarding identifying the area covered by the vegetation.

Acknowledgments

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Chapter 2: UAV-based estimation of actual vineyard evapotranspiration using the Shuttleworth and Wallace model

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Abstract

A field experiment was carried out to implement the Shuttleworth and Wallace (SW) model to estimate actual vineyard evapotranspiration (ET_a) using thermal images from an unmanned aerial vehicle (UAV) and meteorological data. The vineyard (cv. Cabernet Sauvignon) was located in Pencahue Valley, Maule Region, Chile (35°20'33"S, 71°46'41"W, 86 m.a.s.l.). For this study, a UAV was equipped with a thermal infrared camera (FLIR/TAU-2) in order to obtain surface temperatures at a very high resolution (6 cm × 6 cm) during the 2018-2019 growing season. Meteorological variables and surface energy balance (EB) components were measured at the time of the UAV overpass. The SW model's performance was evaluated using measurements of ET_a obtained from an eddy covariance system (EC). In addition, estimated values of latent heat flux (LEi), net radiation (Rni), and soil heat flux (Gi) at the time of the UAV overpass were compared with ground-truth measurements from a four-way net radiometer and flux plates, respectively. Results indicated that SW model estimated ET_a with errors = 5%, root mean squared error (RMSE) = 0.37 mm day^{-1} and mean absolute error (MAE) = 0.27 mm day^{-1}. Finally, instantaneous values of LEi and Rni were computed with errors of less than 10% and with values of RMSE and MAE of less than 34 W m^{-2}. Results demonstrated that a thermal camera placed on an UAV could provide an excellent tool to estimate intra-vineyard spatial variability of Rni, Gi, LEi, and ET_a.

Keywords: Remote sensing, Vineyard water consumption, Unmanned aerial vehicle

Introduction

Due to climate change, it is expected that water availability will decrease significantly in the coming years (IPCC, 2014). In the case of Chile, it is expected that in the central zone, there will be a decrease of up to 20% in precipitation by 2050 (Collins et al., 2013), which will considerably affect the availability of water for irrigation. Due to this, the establishment of techniques that allow the appropriate determination of water consumption becomes relevant. Traditionally, this is done through the actual evapotranspiration ET_a, whose value is obtained by multiplying the reference evapotranspiration (ET_o) by a crop coefficient (Kc). However, in most cases, the values of Kc used are empirical and do not adapt to local conditions (Ortega-Farias et al., 2009). Because of this, several researchers have indicated that the spatial variability of ET_a and Kc can be evaluated using thermal and multispectral sensors placed on satellite and unmanned aerial vehicle (UAV) platforms (Fuentes-Peñailillo et al., 2018; Ortega-Farías et al., 2016). In this case, ET_a is estimated as a residual from the surface energy balance (EB), which considers variables such as net radiation (R_n), soil heat flux (G), and latent heat flux (LE). However, the practical application of satellite platforms for irrigation management is limited by the frequency of the satellite's overpass, cloudiness, and image resolution (each pixel covers 30 m x 30 m). As an alternative, the UAV platform equipped with high-resolution thermal and multispectral cameras has been suggested as an excellent tool to evaluate the intra-field spatial variability of ET_a and Kc (Ortega-Farías et al., 2016). Nevertheless, UAVs' practical use requires developing a Remote sensing energy balance (RSEB) algorithm to estimate the vineyard's actual evapotranspiration properly. Thus, this study aims to evaluate a two-source model to estimate ET_a using UAV-based thermal images and meteorological data.

Materials and methods

Study site

The study was carried out during the 2018-19 growing season, over a vineyard ‘Cabernet Sauvignon’ located in the Pencahue valley, Maule Region, Chile (35°20'33"S, 71°46'41"W, 86 m.a.s.l.), which has a Mediterranean-semiarid climate with an average temperature of 19.3 °C between September and March (spring-summer) and rainfall concentrated in winter with an average of 605 mm year^{-1}. The soil belongs to the “Las Doscientas” series with a sandy loam texture. The volumetric soil water content (θ) at field capacity was 31%, and the wilting point was 10%.

The study covered an area of approximately 1.4 ha. The vineyard was established in 2015 and grafted on 110 Richter rootstock with a spacing of 1 m x 2 m (5000 plants ha^{-1}). Vines at the experimental site were drip-irrigated (2 drippers plant^{-1} with a 2 L h^{-1} flow rate) and trained on a vertical shoot position with a canopy height of 1.85 m.

Physiological measurements

Midday stem water potential (MSWP) measurements were made using a pressure chamber (model 1000, PMS Instrument Co., Corvallis, Oregon, USA). Simultaneously, a LI-COR gas analyzer (Li-6400, LI-COR Inc., Lincoln, NE, USA) was used to measure stomatal resistance (r_{st}) on two leaves that were directly exposed to the sun and were located on the plant's mid-section.

Eddy Covariance measurements

Vineyard evapotranspiration was measured using an eddy covariance system (EC) system installed at 2.2 m above the soil surface. In this case, LE and H were measured using a fast response open-path infrared gas analyzer (LI-7500 IRGA; LI-COR, Inc., Lincoln, Nebraska, USA) and a 3-dimentional sonic anemometer (CSAT3, Campbell Sci., Logan, UT, USA), respectively. Raw data of H and LE were post-processed considering corrections of density (Webb et al., 1980) and sonic temperature (Schotanus et al., 1983). For quality control, the EB closure was computed using the ratio of turbulent fluxes (H+LE) to available energy (R_n-G). When the daily ratios were outside the range between 0.8 and 1.2, the entire day was excluded from the analysis to reduce the uncertainty associated with errors in the LE and H measurements (López-Olivari et al., 2016; Poblete-Echeverría & Ortega-Farias, 2009). Assuming that the measurements of R_n and G were representative of the available energy above the vineyard, the fluxes of H and LE were forced to close the EB using the Bowen ratio approach (B=H/LE) (Carrasco-Benavides et al., 2014).

$$LE_B=\frac{(R_n\text{-}G)}{(1+B)} \qquad (1)$$

$$H_B=\frac{(R_n\text{-}G)}{(1+B^{-1})} \qquad (2)$$

The vineyard evapotranspiration was calculated daily, as follows:

$$ET_{EC}=\frac{\sum_{n=1}^{24} LE_{B\,n}}{\lambda{*}\rho_W}\times 1.8 \qquad (3)$$

where ET_{EC} is the vineyard evapotranspiration (mm d^{-1}), 1.8 is a conversion factor, λ is the latent heat of vaporization (1013 MJ Kg^{-1}), ρ_W is the density of water (1000 kg m^{-3}), and n is the number of measurements in an interval of 24 hours. The subscript $_B$ indicates that turbulent fluxes were recalculated using the Bowen ratio approach.

Thermal and multispectral images acquisition and processing

Images were collected on 7 days from day of year (DOY) 340 to 31 using a UAV equipped with a thermal infrared camera (FLIR TAU-2). Additionally, the UAV had an automatic pilot (PIXHAWK) used to generate a flight route. The flight height was configured at 30 m above ground level, obtaining imagery at a spatial resolution of 6 cm x 6 cm. After each flight, the images were downloaded to a personal computer and processed through the AGISOFT Metashape software (Agisoft LLC, St. Petersburg, Russia) with the objective to generate a thermal Mosaic for each study day. For the two-source model's implementation, a segmentation of the image was carried out based on Fuentes-Penailillo et al. (2018) to differentiate vegetation from the soil.

Implementation of Shuttleworth and Wallace model

A two-source algorithm was implemented to estimate the EB components above the vineyard using input from thermal and climate data. The partitioning of the instantaneous latent heat flux between the soil and canopy is described as follows:

$$\mathrm{LEi=Ti+Ei} \tag{4}$$

$$\mathrm{Ti=Cc}\frac{\Delta\mathrm{Ai}+\left(\frac{\rho_a C_p\, D_i\,-\Delta r_a^c A_{si}}{r_a^a+r_a^c}\right)}{\Delta+\gamma\left(1+\frac{r_s^c}{(r_a^a+r_a^c)}\right)} \tag{5}$$

$$\mathrm{Ei}=C_s\frac{\Delta A_i+\left(\frac{\rho_a+C_p+D_i-\Delta r_a^s(A_i-A_{si})}{r_a^a+r_a^s}\right)}{\Delta+\gamma\left(1+\frac{r_s^s}{(r_a^a+r_a^s)}\right)} \tag{6}$$

where LEi is the instantaneous latent heat flux (LE) computed from the SW model (W m^{-2}), Ti is the instantaneous LE corresponding to the transpiration process computed from the SW model (W m^{-2}), Ei is the instantaneous LE corresponding to the evaporation process computed from the SW model (W m^{-2}), Cc is the canopy resistance coefficient (dimensionless), C_s is the soil surface resistance coefficient (dimensionless), Δ is the slope of the saturation vapor pressure curve at the mean temperature (kPa °C^{-1}), Ai is the available energy leaving the complete canopy (W m^{-2}), A_{si} is the available energy at the soil surface (W m^{-2}), C_p is the specific heat of the air at constant pressure (1013 J kg^{-1} K^{-1}), ρ_a is the air density (kg m^{-3}), D_i is the water vapor pressure deficit at the reference height (kPa), γ is the psychrometric constant (kPa °K^{-1}), r_a^a is the aerodynamic resistance between the canopy source height and reference level (s m^{-1}), r_s^c is the canopy resistance (s m^{-1}), r_a^s is the aerodynamic resistance between the soil and canopy source height (s m^{-1}) and r_s^s is the soil surface resistance (s m^{-1}). The UAV information was used to estimate available energy (Ai) (Fuentes-Peñailillo et al., 2018b).

Finally, soil heat flux (Gi) was estimated using the linear regression proposed by Ortega-Farias et al. (2010):

$$Gi=-38.5+0.25*Rni \tag{7}$$

where Gi represents the estimated values of soil heat flux (Wm^2) and Rni corresponds to estimated values of net radiation (Wm^2).

Statistical analysis

For the model validation, a comparison between the observed and estimated surface EB components' values was carried out using root mean square error (RMSE) and mean absolute error (MAE). Also, the index of agreement (d) and the ratio of the observed to estimated values (b) were computed.

$$RMSE=\sqrt{\frac{\sum_1^N(O_i-E_i)^2}{N}} \tag{8}$$

$$MAE=\frac{1}{N}\sum_{i=1}^N|E_i-O_i| \tag{9}$$

$$d=1-\left[\frac{\sum_{i=1}^N (E_i - O_i)^2}{\sum_{i=1}^N (|E_i - \bar{O}| + |O_i - \bar{O}|)^2}\right] \quad 0\leq d\leq 1 \tag{10}$$

where E_i represents the estimated values by the model, O_i is the observed energy flux, $\bar{O}$ is the mean of the observed values and N is the number of observations.

Results and Discussion

Throughout the study period, the MSWP varied between -0.3 and -0.5 MPa (Table 1), indicating that vines were under no water stress during the study period (Choné et al., 2001;

Williams & Araujo, 2002). Other variables, such as air temperature (°C) and stomatal resistance (s m^{-1}), obtained during the 2018-2019 growing season, can be seen in Table 1.

Table 1. Physiological measurements carried out during the 2018-2019 growing season.

Season	**DOY**	**MSWP**	**Air Temp**	**rst**
		(MPa)	**(°C)**	**(s m^{-1})**
18-19	340	-0.392	25.785	106.897
	348	-0.404	29.888	99.309
	356	-0.496	31.654	87.715
	364	-0.217	31.645	231.200
	10	-0.413	31.426	94.329
	23	-0.300	35.052	235.257
	31	-0.274	34.578	140.601

MSWP = Midday stem water potential and rst = Measured stomatal resistance.

In addition, the ratio of (H+LE) to (R_n-G) at 30 min time interval was 0.91, indicating that the vineyard's EB was underestimated by approximately 9%. In this regard, Spano et al. (2004), in a vineyard, observed EB closure between 0.82 - 0.84, while Sien et al. (2008) observed closure of 0.8.

Figure 1 indicates that estimated and observed energy flux components are distributed close to the 1:1 ratio. In the case of LEi, the linear regression through the origin presents a slope of 0.89. The model validation indicates that the SW model was capable of estimating LEi, Rni, and Gi with an RMSE of 34, 29, and 48 W m^{-2}, respectively (Table 2).

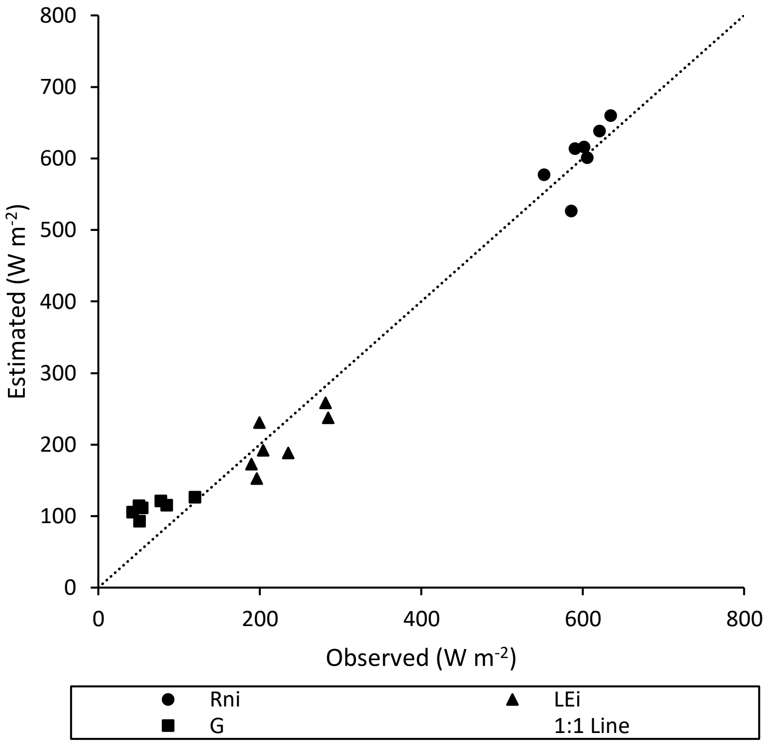

Figure 1. Comparisons at the time of UAV overpass over a commercial vineyard between observed (X axis) and estimated (Y axis) values of: Rni = Instantaneous Net Radiation; Gi = Instantaneous Soil Heat Flux; LEi = Instantaneous Latent Heat Flux.

Table 2. Validation of sub-models that compute LEi = Instantaneous Latent Heat Flux, Rni = Instantaneous Net Radiation, Gi = Instantaneous Soil Heat Flux, ET_a= Daily evapotranspiration, over a commercial vineyard at the time of UAV overpass.

Variable	MAE	RMSE	d	b
LEi	31	34	0.79	0.90
Rni	24	29	0.99	1.01
Gi	44	48	0.50	1.49
ET_a	0.27	0.37	0.88	0.95

MAE = mean absolute error; RMSE = root mean square error; b = ratio of observed to computed values, d = index of agreement.

These results are similar to those observed by Fuentes-Peñailillo et al. (2018a) who estimated LEi, Rni and Gi with RMSE of 26, 39 and 33 W m^{-2}, respectively. In addition, index of agreement (d) for LEi, Rni and ET_a were 0.79, 0.99 and 0.88, respectively. The lowest index of agreement was for Gi (0.50), which could be mainly explained because the model was developed in a different experimental site by Ortega-Farias et al. (2010).

Conclusions

This research indicates that the SW model could be used to estimate spatial variability of ET_a over a vineyard when using UAV-based images and ground-based climate data. In this case, the SW model was able to estimate LEi, Rni, and Gi with an RMSE ranging between 29 and 48 W m^{-2}. Simulated values of ET_a were in good agreement with ground-based measurements where the SW model was able to predict ET_a with an error of 5%.

Acknowledgments

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Third Part

Spatialized wireless sensors

Chapter 3: Spatialized system to monitor vine phenology: Towards a methodology based on a low-cost wireless sensor network

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Abstract

Monitoring grapevine phenology during the agricultural season is one of the most important tasks within the vine field since this is a key input for the proper planning of agricultural labor management. Traditionally, vine growers make very few phenological observations at the field level, which are extrapolated to an entire production unit without considering the field's natural spatial variability. This situation generates a significant loss of agricultural inputs and energy, which makes the vine system less sustainable because this vineyard's natural spatial variability is not usually considered in the field management. In this study, two models were tested using information recollected by a meteorological weather station and a wireless sensor network (WSN) to estimate vineyard phenology in a key period such as flowering. Therefore, this proposal's general objective is to develop a low-cost wireless sensor network (WSN) for monitoring the spatial variability of vine phenology in a commercial vineyard. Results indicated that both models presented a better estimation of vine phenology during the second season, given that the first season was affected by the ENSO "La Niña" climatic effect. However, it can be noted that the Parker model (GPV) presented better phenological estimation than the Monomolecular equation-based model (ME), when using a low-cost wireless sensor network. Based on the results, we can conclude that it is possible to develop and implement a low-cost electronic device to monitor spatialized phenological events in the vineyard.

Keywords: Grapevine phenology, spatial variability, low-cost wireless sensor network, flowering.

Introduction

Vine phenology is the study of the growth stages of the crop, which are repeated during all seasons and are mainly related to climatic and hormonal factors (de Rességuier et al., 2020; Jones & Davis, 2000; Mullins et al., 1992; Prats-Llinàs et al., 2020). The annual cycle of the vine begins with budburst and continues with the vegetative growth, flowering, fruit setting, berry development, veraison, the ripening of the berries (harvest), and ends with the fall of leaves (Schwarz, 2003). The knowledge and monitoring of different vine phenological stages during the season presents multiple applications in viticulture, such as (i) geographical characterization of the vineyard to determine the varieties best adapted to the specific climatic conditions (Ortega-Farías et al., 2002), (ii) planning of agricultural work carried out in the fields (irrigation, fertilization, phytosanitary spraying, and differentiated harvesting) in order to increase the vineyard production efficiency (Mullins et al., 1992; Valdés-Gómez et al., 2017), (iii) study of the synchronism in the development of the vineyard and its pathogens, iv) the study of the effects of phenology over the final quality of the product, in this case, the wine, and v) indicator and predictor of the effects of climate change on plants (Mullins et al., 1992; Valdés-Gómez et al., 2017). Thus, monitoring grapevine phenology is a very relevant task when it comes to decision-making at field level, which is why its study has led to several investigations at different spatial scales of work (Caffarra & Eccel, 2010; Costa et al., 2019; Duchene & Schneider, 2005; Jones & Alves, 2012; Moriondo & Bindi, n.d.; Nendel, 2010; Ortega-Farías et al., 2002; A. K. Parker et al., 2011; Sadras & Petrie, 2012; Tomasi et al., 2011; Urhausen et al., 2011; Verdugo-Vásquez et al., 2016, 2019; Nicolas Verdugo-Vásquez et al., 2017; Webb et al., 2012), for example, at a meso-scale (Falcão et al., 2010; A. Hall & Jones, 2009), where the analysis of the climate of a vine-growing region is often reduced to the analysis of data collected at one site, considered as representative of the whole study area (Hall & Jones, 2009; Jones & Davis, 2000; Tonietto & Carbonneau, 2004). However, it has been observed that there is significant spatial variability in grapevine phenological development at this spatial scale (Hall & Jones, 2009). This scale of work is not useful for vine-growers, whose basic management unit corresponds to the viticultural field (area smaller than 5 ha), which is characterized by presenting the same variety, training system, and management practices.

In the previous spatial scale, it is observed that there is an important variability in the vineyard's phenological stages (Verdugo-Vásquez et al., 2016, 2019). This variability can be explained by different factors according to the scale in which it is worked. In literature, it is observed that temperature is the main factor affecting the growth, composition, and quality of grapes (Arrizabalaga et al., 2018; de Rességuier et al., 2020; Jackson & Lombard, 1993; Tonietto & Carbonneau, 2004), for this reason, different studies have been carried out in order to quantify the potential effects of temperature changes on vine phenology in different experimental sites around the world (Fraga et al., 2016; Andrew Hall et al., 2016; Parker et al., 2011; Webb et al., 2012). Due to the relationship between air temperature and the development of grapevine phenology, different predictive phenological models have been proposed using climatic variables (Chuine et al., 2013; Ortega-Farías et al., 2002; Ortega-Farias & Riveros-Burgos, 2019; A. Parker et al., 2013; Parker et al., 2011; Reis et al., 2020). These models have been implemented with relative success in different agricultural applications to facilitate management within the vineyard field, identifying areas with different yield potential and final production quality. This information is obtained, in general, from automatic weather stations (AWS) located at different distances from the vineyards (generally kilometers) (Ortega-Farías et al., 2002; Reis et al., 2020). Therefore, specific weather information is used to generate phenological estimations in the vineyard, and those results are extrapolated to an entire productive unit, assuming that both temperature and phenology are homogeneous across the study vineyard. This methodology has been widely used to predict the vine phenological events, for example, to determine the probable flowering date of a certain variety located at the site where the climatic information was obtained. Thus, the traditional methods used by growers to characterize the vineyard’s phenology (spot measurements or use of predictive models) would not be an adequate methodology to represent the vineyard's spatial variability. In this regard, it can be observed that in the wine industry, field professionals do not perform more than two to three phenological observations per productive unit per season, assuming that these measurements are representative of the entire vineyard (Verdugo-Vásquez et al., 2019). For this, they use AWSs that collect information from a single site, which does not represent the real spatial variability of the vineyard or the plant's micrometeorological condition. Therefore, this traditional method results in inappropriate and inefficient decisions from an agricultural point of view since it does not allow characterizing the vineyard spatial variability in key growth stages to produce high-quality grapes.

In this sense, several authors (Hall & Blackman, 2019; Ortega et al., 2003; Taylor et al., 2005; Tisseyre et al., 2005; Yu et al., 2020) have shown that in viticulture, there is high spatial variability in the fields, understanding this phenomenon as existing differences in a basic productive unit, which can be associated mainly with differences in soil and/or field management (Hall et al., 2003). Recently, the existence of spatial variability in climatic conditions has been studied at intra-predial scale (Matese et al., 2014) and at the level of the valley or productive region, which shows that the recordings made by the AWS do not necessarily represent the micro climatic condition of the vineyard, and therefore, it is not possible to assume that this information represents the entire production unit (Matese et al., 2014). From the above, the following questions arise: What is the representativeness of a weather station? Is it possible to improve the vine phenology's temporal prediction using weather information collected at the plant level (microclimatic condition)?

On the other hand, it has been observed that there is spatial variability in the phenological development within the vineyard (Verdugo-Vásquez et al., 2016, 2019). Recent research shows that the classical methodology used to temporarily predict vine phenology should be used with caution due to the significant spatial variability observed, both in climatic variables and in the vine phenology. The extrapolation of the results of the temporary models obtained from climatic information of a weather station to nearby sites is not trivial since, given the characteristics of viticulture (high heterogeneity observed at the field level), it is not possible to assume climate and plant homogeneity, limiting the results obtained only to the specific site from which the climatic information was obtained. The above poses a new challenge for the modeling of vine phenology: Is it possible to model the spatial and temporal variability of the vineyard's phenology? To answer this question, a probable approach can be the use of climatic information obtained from individual temperature sensors located inside the vineyard canopy, which represents the microclimatic vine condition. However, due to the high cost of implementation, this alternative may be unlikely (N. Verdugo-Vásquez et al., 2019). In this sense, it is important to highlight that in recent years, a series of research initiatives have been carried out in the development of low-cost sensors in agriculture (Polo et al., 2015; Viani et al., 2017). Most of these electronic devices have focused mainly on monitoring micrometeorological variables (Hall et al., 2003; Hall & Blackman, 2019; Ortega et al., 2003; Taylor et al., 2005; Tisseyre et al., 2005; Yu et al., 2020), without considering the many practical applications that could be implemented at the field level in a commercial vineyard, that require accurate phenological estimates for optimal grape production, such as the definition of the optimal moment of phytosanitary spraying for fungal diseases, e.g., powdery mildew (*Erysiphe necator*), which should be applied in precise phenological periods, as flowering. In this way, the correct estimation of the vine phenology becomes a fundamental support system for site-specific management, oriented to the production of high-quality grapes. Based on the aforementioned, it is proposed as a research objective to develop and implement a low-cost wireless microclimatic temperature sensors network at the field level for the spatialized monitoring of vine phenology, specifically flowering, in a commercial vineyard.

Materials and Methods

Experimental site description

The experiment was carried out in a vineyard cv. Cabernet Sauvignon (1.56 ha) located in the Panguilemo Experimental Station of the University of Talca (Maule Valley), Chile (35º22.2' S, 71º35.39' W, WGS84, 121 m.a.s.l.) during the 2011-12 and 2012-13 growing seasons. The vineyard was established in 1998 using ungrafted plants with a spacing of 1.5 m between vines and 3.0 m between rows with E-W orientation. The vines were trained in a vertical shoot positioned system and watered by furrow.

Development of a spatialized phenological sensor

The proposal research consists of developing a system to monitor a key phenological stage (flowering) of the vineyard by implementing a low-cost wireless sensor network (thermo-hygrometers), which will allow characterizing intra-predial spatial variability at the field level.

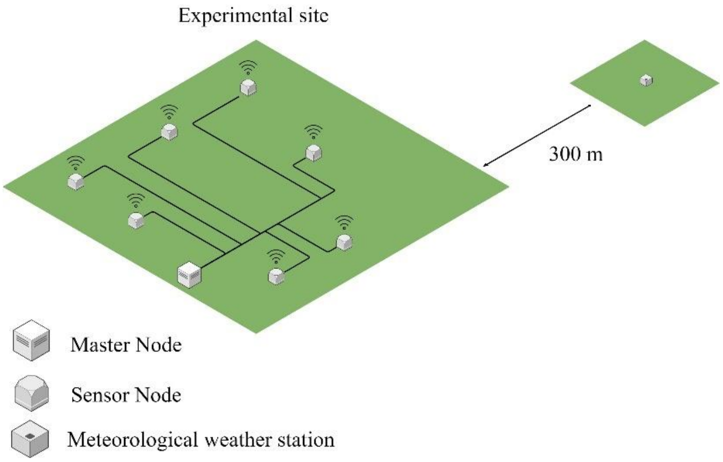


Figure 1. Experimental site and system location

The monitoring network consists of 8 spatialized sensors to monitor the microclimatic temperature of the vineyard canopy (1 central module and 7 slave modules). The distribution of the spatialized sensors and the weather station is shown below (Figure 1). The system was used for mapping the absolute error in days of the estimates of vine phenology during the flowering period

Microcontroller

The microcontroller is responsible for processing all the information generated by the wireless sensors network (WSN) and allows serial communication with the antenna. An Arduino board was implemented only in the central module, given that in this one, the following shields were connected: i) LiPo Power shield to deliver energy, ii) XBee shield to connect the communication antenna, and iii) SD-RTC Shield to store the sensor information in an SD memory card with the date and time. To avoid using Arduino in all modules, a simplified printed circuit board (PCB) that integrates the ATmega328-PU microcontroller, communication card, and sensor was designed. The developed card includes a base for the ATmega328-PU, a 16 MHz oscillator crystal, two 22pF capacitors, one 1K Ω resistor, a 3.3V voltage regulator circuit with two capacitors (to filter both the input voltage and output), and a 3-pin terminal block (to connect the sensor). The electronic board's design was developed with the Software EAGLE and made with a CNC Bungard CCD/2.

Wireless communication systems

Within the wireless communication systems available in the market, there are three types of networks: personal (WPAN), local (WLAN), and global (WWAN). In the case of wireless personal area networks (WPAN), there is a communication protocol called Zigbee, which is based on the IEEE 802.15.4 standard. This is basically a simple type of communication, created in 2004. The main advantages offered by this technology are i) low-cost devices and low power consumption ii) operation under the free band of 2.4 GHz, iii) supports multiple network topologies, iv) AES encryption, blocking the network and prevents other nodes from connecting and v) programming, control, and simple setup.

The ZigBee protocol allows the development of point-to-point network topologies, multipoint, peer-to-peer (all nodes connected to each other), or complex network sensors that interconnect two or more mesh networks. The most used topologies are:

- Star: all modules on the network can connect only to the central one, there is no routing of data between nodes, thus there is low latency. Its configuration is the simplest.
- Cluster Tree: the central module sets the initial network, while routers are responsible for forming the branches with the other routers or end-devices and transmitting messages to the central module. The most significant disadvantage is that if a router fails, most of the network falls.
- Mesh: There is more than one path between nodes and the central module if a route fails. It is the most complex network and has high latency of data when going through multiple nodes.

For this research, the communication board XBee ProS2B was used (features available in Table 1). The used wireless network is based on the star topology, in transparent mode or AT. With this configuration, the central node can send the requested information to each slave node connected to the network. Thus, the network will have a central node programmed as Zigbee coordinator AT and seven remote nodes programmed as Zigbee end device AT, where the central module stores all sensors' information. This type of communication system has a great interest in agricultural applications because it facilitates collecting and storing data.

Table 1. Technical characteristics Xbee Pro 63mW RPSMA - Series 2B

Characteristics	**Specifications**
Power supply	3.3 V - 295 mAh
Range	1200 m
Output power	63Mw (+17 dBm)
Transference rate	250 Kbps
Antenna connector	RPSMA
Serial Data Interface	UART, SPI
Configuration method	Command AT y API
Frequency bands	ISM 2.4 Ghz
Digital I/O	15
Operation Temperature	-40 °C to +85°C

Temperature sensor

The DHT22 sensor was used due to its low cost and high accuracy. It is important to consider that this sensor works using a digital input port of the microcontroller and does not require a pull-up resistor. In the central module, the sensor is connected to digital pin D5, and all remote modules are connected to digital pin D4, corresponding to the physical number 6 of the ATmega328-PU.

Data storage

Data loggers are devices that allow to store information (usually as a text file) measured by any sensor in a memory. When a specific sensor retrieves data, it is especially important to know when it was collected. Arduino has a function called millis () to carry out this task, which allows the use of delay function. So, if Arduino has a feature that allows time to be recorded, why should a Real-Time external Clock (RTC) be used? This is because the function millis () only takes the notion of time by being turned on, and when turned off, it completely unconfigures. The RTC used corresponds to DS1307, which uses a CR1225 battery, allowing Arduino to maintain the date or time when the system is turned off. Considering the above, the monitoring system was configured to generate a text file that stores the temperature data at time intervals of 60 minutes.

Charging source and power supply

The wireless sensor network has an individual power system whose main energy source is a mono crystalline photovoltaic panel that delivers a voltage of 9V and a power of 5W. The panel is connected to a voltage regulator board (Figure 2), also developed for this prototype. The regulator chosen for the circuit design is a linear regulator (LM7805) that delivers a maximum current of 1A (with input voltages ranging from 7V to 25V). Then the voltage regulator card is connected via micro-USB cable to the LiPo power shield. Finally, the LiPo power shield is connected directly to the central node and the remote nodes using the 5V and GND pins.

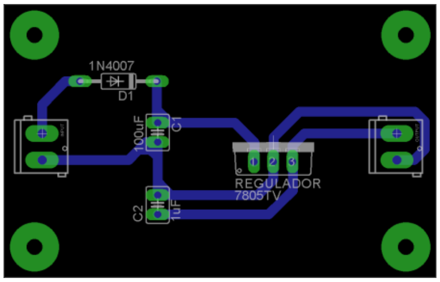


Figure 2. Voltage regulator board.

Operation and prototyping of the modules

The central module is responsible for controlling the entire wireless network and requesting the data collected by the slave modules. The first action executed by the central module is to send a "0" through the serial port, to wake up all the slave modules, and collect the temperature measurements of the entire network (Figure 3). Subsequently, it sends the sensor the number from which it will collect the information through the serial port to receive and store the data generated by this one. The same procedure is repeated for each of the slave modules installed in the field. Finally, the boards' encapsulation was performed in a sealed container resistant to adverse environmental conditions, and its elaboration was made using a 3D printer model Prusa I3 Hephestos using ABS filament.

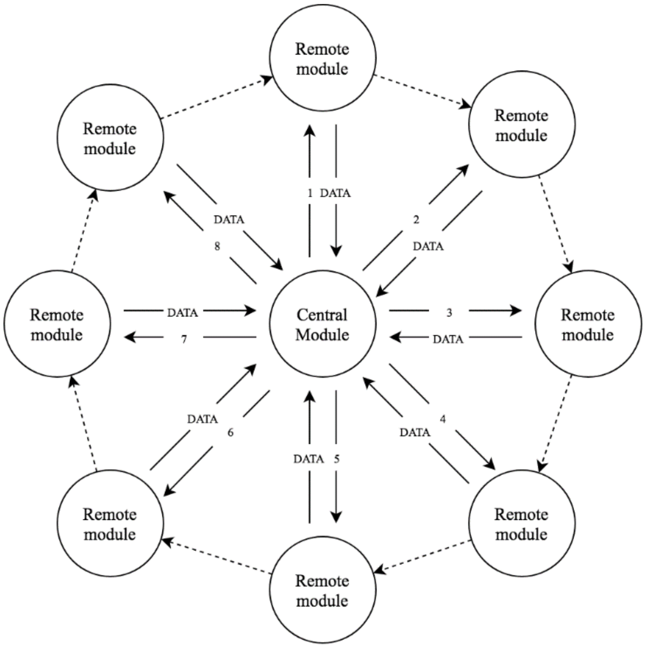


Figure 3. Schematic model of data transfer

Climatic Model description

Two models to estimate phenological stage were considered to predict the flowering event (phenological stage PS = 23 of the Coombe Scale (Coombe, 1995).

1. Monomolecular equation-based model (ME): The first model corresponds to the formulation developed by (Ortega-Farías et al., 2002) on a Cabernet Sauvignon vineyard. This methodology is based on the monomolecular equation of Mitscherlich proposed by (Thornley & Jhonson, 1990) (eq. 1).This model estimates the phenological stage using the accumulated Growing Degree Days (GDD) as a basis from the date of the budburst (phenological stage PS = 4 of the Coombe Scale (Coombe, 1995) until the harvest event (phenological stage PS = 38 of the Coombe Scale (Coombe, 1995), based on 10°C.

$$PS = Psf - (Psf - Psi) * exp^{-k*GDD} \tag{1}$$

where: PS = current phenological stage, Psf = last phenological stage corresponding to PS = 38, Psi = first phenological stage corresponding to PS = 4, k = rate of phenological development and GDD = sum of Growing Degree Days (heat units) from the date corresponding to Psi to the date of PS.

According to the above, the model calibrated by (Ortega-Farías et al., 2002) is shown in eq. 2:

$$PS = 39 - 28.81 * exp^{-0.00204*GDD} \tag{2}$$

2. Parker model (GPV): The second model was proposed by (Parker et al., 2013), and it was based on the methodology proposed by (Hunter & Lechowicz, 1992; Robertson, 1968; Wang, 1960). In this model, a specific phenological stage occurs when a critical forcing state S_f, which is defined as a the sum of Growing Degree Days from a start date t_0, reaches a particular value F^*(Eq. 3).

$$S_f(t_s) = \Sigma_{\mathrm{t_0}}^{\mathrm{t_s}} R_f(x_t) \geq F^* \tag{3}$$

The state of forcing is described as a daily sum of the rate of forcing, R_f, which starts at t_0, defined as the DOY 241 (southern hemisphere) for (Parker et al., 2013) (Eq. 4). Flowering is therefore simulated independently of prior developmental stages.

$$R_f(x_t) = GDD(x_t) = \left\{ \begin{matrix} 0 & if \;\; x_t \leq T_b \\ x_t - T_b & if \;\; x_t > T_b \end{matrix} \right\} \tag{4}$$

where: T_b corresponds to a base temperature set at 0°C for (Parker et al., 2011), above which the thermal summation is calculated, x_t is the daily arithmetical means temperature (the sum daily minimum and maximum temperature divided by two). Thus, the $F*$ value for the Cabernet Sauvignon cultivar corresponds to 1299 heat units.

Observed values corresponding to dates (expressed in days of the year) of phenology (from pre-budburst to flowering) for each site of the vineyard were recorded during two consecutive seasons, using the phenological scale. For this purpose, phenological observations were performed every 5-7 days systematically for each selected site.

It is important to consider that wireless sensors were installed inside de plant's canopy at the height of 1.5 m above the soil (recording data at intervals of 60 minutes). On the other hand, climatic data (air temperature) obtained from an automatic weather station (Adcon Telemetric, A730, Klosterneuburg, Austria), installed on a grass surface located 300 m from the vineyard under study, was also collected. The information recorded by these electronic devices (spatialized sensors and automatic weather station) was used to model the phenological events of the vineyard through the methodologies proposed by (Ortega-Farías et al., 2002; Parker et al., 2013). The results obtained from these simulations were used to study the spatial behavior of both models during the flowering phenological event.

Statistical analysis

For sensor data validation, a comparison between the observed and estimated values was carried out using the root mean square error (RMSE) and mean absolute error (MAE) (Mayer & Butler, 1993; Willmott, 1981; Willmott et al., 1985). Likewise, the evaluation of the behavior of both models was carried out by comparing the absolute value of the differences in days between the measured value and the estimates made during both study seasons. In this regard, 4 days was defined as the criterion of maximum error allowed by growers to make an adequate phenological estimation when using predictive models during the flowering phenological event.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{1}^{N}(\mathrm{O_i} - \mathrm{E_i})^2}{\mathrm{N}}} \tag{5}$$

$$\mathrm{MAE} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} |\mathrm{E_i} - \mathrm{O_i}| \tag{6}$$

where E_i represents the estimated values by the model and O_i is the observed flowering date and N is the number of observations.

Results

Climatic characterization of the experimental site

The two seasons evaluated during the experiment showed different climate behavior. The first season (S1) was strongly influenced by the ENSO "La Niña” climatic phenomenon. Due to the occurrence of this phenomenon, higher average temperatures were observed during this season, registering an average increase of 0.56 ºC compared to the second season (S2). On the other hand, rainfall registered during the summer of the first season (September to March) was scarce, reaching 44.6 mm, which is considered normal for a Mediterranean climate, under the influence of “La Niña” event. For the second season, the situation changes drastically due to the influence of normal weather conditions for Mediterranean climates. In this sense, rainfall increases considerably during the summer period, reaching 138.7 mm (three times more than the previous season). When observing the reference evapotranspiration (ETo) recorded during both seasons, the first season presented a higher evaporative demand (ETo: 1010.02 mm) compared to the second season (ETo: 921.6 mm), observing a difference of 9.6 % with higher water consumption during the first season. Finally, it is important to highlight that the climatic differences observed between both study seasons had a significant effect on the predictive behavior of the two proposed phenological models, which is explained below.

Validation process of the low-cost wireless sensors network

To evaluate the differences between the real and estimated values using the proposed models, the RMSE and MAE statistics were used. The results obtained are shown in Table 2, where, for the first study season, the ME showed RMSE and MAE values of 5.98 and 5.71 days, respectively, when using the spatialized sensors. However, during the second season, an improvement in error estimates was observed between the estimated and observed values when using the spatialized sensors, showing an RMSE and MAE values of 4.07 and 3.43 days, respectively, values a 50% lower than the statistical values obtained with the Automatic Weather Station (AWS), which were of 8.36 and 7.86 for RMSE and MAE, respectively. The previous results question using the AWS as a tool for predicting phenological events, such as flowering, especially in seasons where climatic conditions are atypical, as observed during the first study season.

Table 2. Error estimators for estimates made during the two study seasons.

Statistic parameters (days)	SEN-ME	AWS-ME	SEN-GPV	AWS-GPV
S1: 2011-12				
MAE	5.71	3.57	3.57	9.57
RMSE	5.98	4.23	3.95	10.13
S2: 2012-13				
MAE	3.43	7.86	1.71	6.86
RMSE	4.07	8.36	1.93	7.11

were; SEN-ME corresponds to the estimation of phenology made using (Ortega-Farías et al., 2002) model in combination with spatialized sensors, AWS-ME is the estimation of phenology made using (Ortega-Farías et al., 2002) and meteorological weather station (AWS) data, SEN-GPV is the estimation of phenology made using (Parker et al., 2013) model in combination with spatialized sensors and AWS-GPV is the estimation of phenology made using (Parker et al., 2013) and meteorological weather station (AWS) data

On the other hand, the GPV showed consistent results during both study seasons. For the 2011-12 and 2012-13 seasons, the RMSE values were 3.95 and 1.93 days, respectively, for the estimates performed with the spatialized sensors. For the case of measurements made with the AWS, RMSE values were 10.13 and 7.11 for 2011-12, 2012-13 seasons, respectively. The above shows stable and better behavioral results for the phenology data estimated with the spatialized sensors during both study seasons when using GPV. In this regard, it is important to note that a maximum tolerable error criterion (<4 days) was defined to make an adequate estimate of the phenological conditions in the vineyard. This criterion is based on the maximum period of tolerance that a vinegrower would have to carry out an opportune work in the field considered as key for the vine production, such as phytosanitary spraying during the flowering event.

Regarding the higher error estimates obtained with the AWS, (Verdugo-Vásquez et al., 2016, 2019) showed the existence of high spatial variability of the vine's phenology at the field level. In this sense, it is important to highlight that using an AWS to characterize the variability of the phenology is insufficient to adequately model the spatial structure of phenology in the flowering period at the level of the agricultural field. For this reason, the present investigations raise the need to model this variability. At present, there are no commercial sensors that allow the establishment of wireless monitoring networks at the entire field level due to the high cost of implementation and maintenance of these monitoring systems, therefore, their use at the small farmer's level is impracticable. In this sense, if we consider the existing technology in the market, it is impossible to model the spatial behavior of the productive variables associated with the plant's microclimate. Therefore, the alternative proposed in this work is a viable solution to model the phenology considering the spatial variability of the vineyard in the flowering period. The adequate performance of this task would allow adequate management of productive resources within the vineyard.

After calculating the error estimators, the difference in days was estimated between the values observed in the field and the values estimated by the proposed models, and they are presented in Table 3. In this regard, it is observed that ME shows estimation results that are below the maximum tolerable error by the farmer (4 days) when using spatialized sensors, obtaining average values of 3.7 and 2.9 days for the first and second season, respectively. For the case of using AWS, average values of 5.7 and 8.3 days were obtained for the first and second seasons, respectively. As in the previous table, these results cast doubt on the stability of the first model, especially in the case of using an AWS, given the erratic results observed in this study.

Table 3. Absolute value of the differences in days, with respect to the measured value for estimates made during two study seasons.

Season	Site	SEN-ME	AWS-ME	SEN-GPV	AWS-GPV
1	1	4	9	6	14
	2	5	8	5	13
	3	4	7	5	12
	4	6	2	3	4
	5	4	4	2	8

	6	3	5	3	9
	7	0	5	1	7
	MEAN	3.7	5.7	3.6	9.6
	SD	1.9	2.4	1.8	3.6
2	1	4	7	2	9
	2	0	8	2	9
	3	3	6	1	7
	4	2	14	0	6
	5	5	2	3	3
	6	1	6	2	7
	7	5	15	2	7
	MEAN	2.9	8.3	1.7	6.9
	SD	2.0	4.6	1.0	2.0

were; SD corresponds to Standard Deviation (in days), SEN-ME corresponds to the estimation of phenology made using (Ortega-Farías et al., 2002) model in combination with spatialized sensors, AWS-ME is the estimation of phenology made using (Ortega-Farías et al., 2002) and meteorological weather station (AWS) data, SEN-GPV is the estimation of phenology made using (Parker et al., 2013) model in combination with spatialized sensors and AWS-GPV is the estimation of phenology made using (Parker et al., 2013) and meteorological weather station (AWS) data.

On the other hand, the GPV showed consistent results during both study seasons. For the 2011-12 and 2012-13 seasons, the estimated mean error values were 3.6 and 1.7 days, respectively, for the evaluation of the spatialized sensors. Meanwhile, measurements made with the AWS presented error values of 9.6 y 6.9 days, respectively. The above shows stable results and better behavior for the phenological data estimated with the spatialized sensors during both study seasons. In this sense, it is important to point out that the spatialized sensors, when using the GPV, never exceeded the maximum tolerance criterion defined by the vine-growers, as a practical threshold for scheduling agricultural activities in which the correct estimation of phenology in the flowering period is key information for making decisions in the vineyard.

Spatialized study of phenology.

To assess the coincidence between the values measured in the field and those estimated by both models, the absolute errors were mapped in days (Figures 4-5). Thus, it can be observed that the estimates made by the evaluated models are consistently better when the climatic information from the low-cost spatialized sensors is used instead of the information captured by the AWS. In this regard, the ME and GPV showed a greater coincidence with the real date measured in 64.0% and 78.5% of the sites evaluated in the field, respectively, compared to the 14% observed when using climate information recorded with the AWS for both evaluated models (Table 4). On the other hand, when comparing the results obtained during both seasons, it is observed that the first season shows slightly worse results than those recorded during the second season. This may be due to different weather conditions between both seasons. Notwithstanding the foregoing, spatialized sensors always presented consistently better results than those recorded by the AWS. Regarding the results obtained by the spatialized sensors, it can be pointed out that GPV was the one that presented the best estimation results in the phenological period of flowering in the vineyard during the second season, with an average error of less than 3 days in 100% of the evaluated sites (Figure 5). Finally, it can be indicated that the predictions made with climatic information obtained from the AWS are unable to correctly model the spatial variability of the phenology observed within a vine-growing field.

Table 4. Coincidence expressed in percentage between the values measured in the field and those estimated using both models

Model	**Season 1**	**Season 2**	**Mean**
AWS-ME	14.0 %	14.0 %	14.0 %
AWS-GPV	7.0 %	17.0 %	12.0 %
SEN-ME	57.0 %	71.0 %	64.0 %
SEN-GPV	57.0 %	100 %	78.5 %

were; SEN-ME corresponds to the estimation of phenology made using (Ortega-Farías et al., 2002) model in combination with spatialized sensors, AWS-ME is the estimation of phenology made using (Ortega-Farías et al., 2002) and meteorological weather station (AWS) data, SEN-

GPV is the estimation of phenology made using (Parker et al., 2013) model in combination with spatialized sensors and AWS-GPV is the estimation of phenology made using (Parker et al., 2013) and meteorological weather station (AWS) data

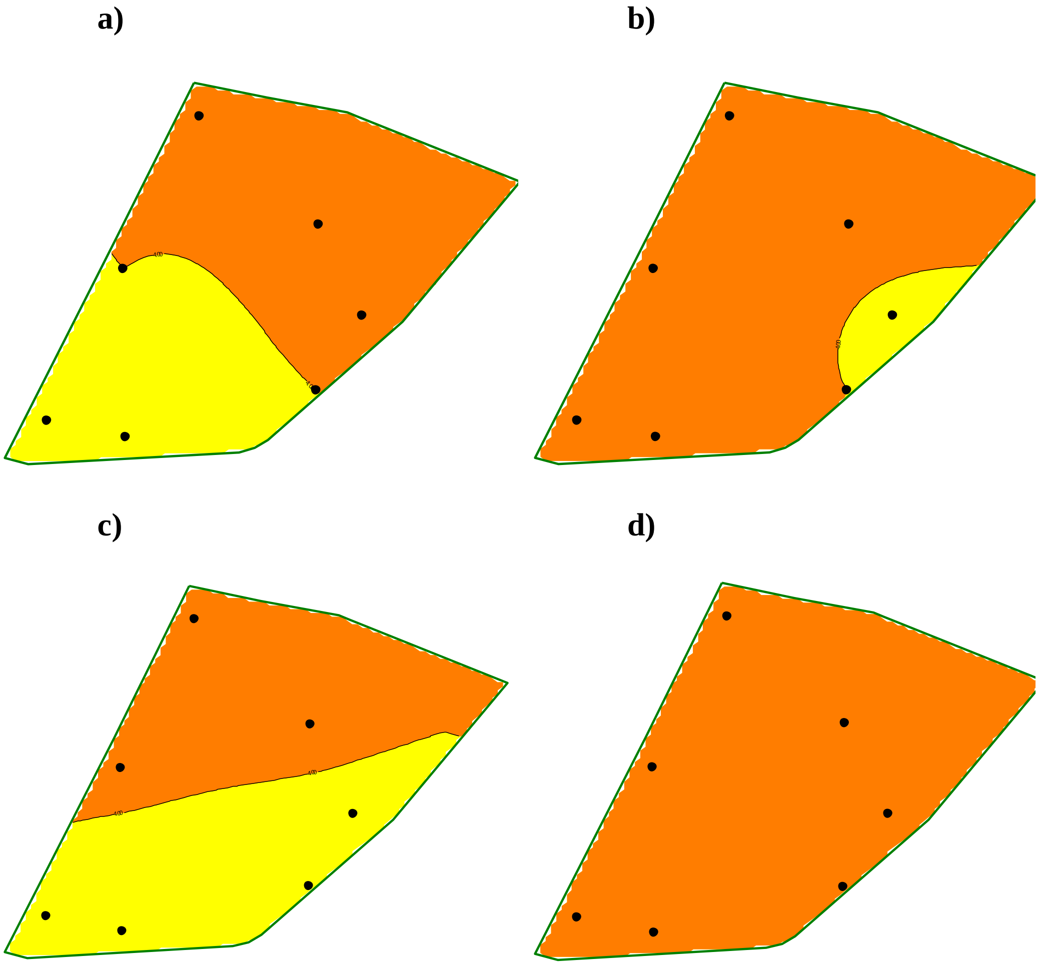


Figure 4. Absolute value of the differences in days, with respect to the measured value for estimates made during season 1 (2011-12). The orange color indicates the measurement points at which values greater than 4 days were observed, on the other hand, the points indicated with yellow indicate differences less than 4 days between observed values versus estimated. a): corresponds to the estimation of phenology made using (Ortega-Farías et al., 2002) model in combination with spatialized sensors (SEN-ME), b): is the estimation of phenology made using (Ortega-Farías et al., 2002) and meteorological weather station (AWS) data (AWS-ME), c): is the estimation of phenology made using (Parker et al., 2013) model in combination with spatialized sensors (SEN-

GPV) and d): is the estimation of phenology made using (Parker et al., 2013) and meteorological weather station (AWS) data (AWS-GPV).

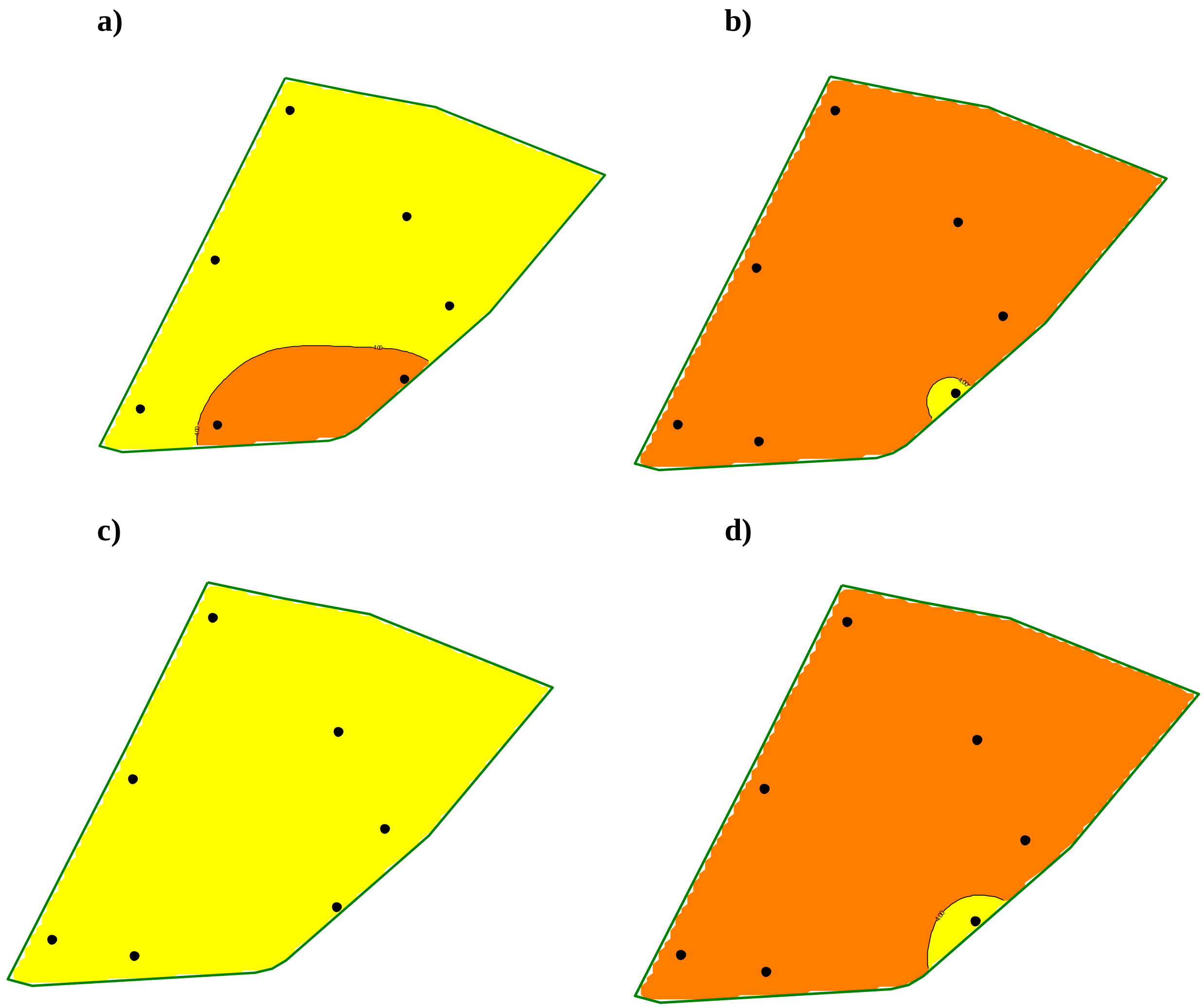
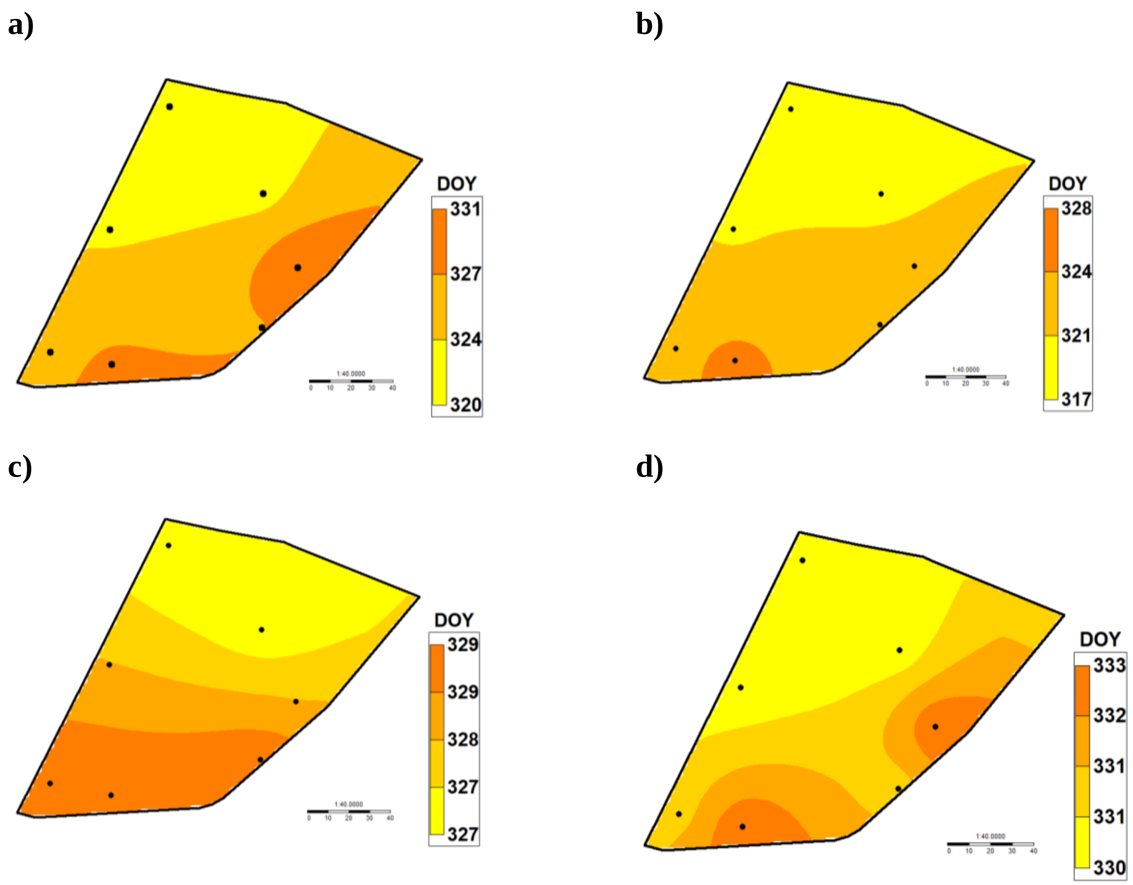


Figure 5. Absolute value of the differences in days, with respect to the measured value for estimates made during season 2 (2012-13). The orange color indicates the measurement points at which values greater than 4 days were observed, on the other hand, the points indicated with yellow indicate differences of less than 4 days between observed values versus estimated. a): corresponds to the estimation of phenology made using (Ortega-Farías et al., 2002) model in combination with spatialized sensors (SEN-ME), b): is the estimation of phenology made using (Ortega-Farías et al., 2002) and meteorological weather station (AWS) data (AWS-ME), c): is the estimation of phenology made using (Parker et al., 2013) model in combination with spatialized sensors (SEN-

GPV) and d): is the estimation of phenology made using (Parker et al., 2013) and meteorological weather station (AWS) data (AWS-GPV).

Cartographies corresponding to the simulations carried out for the flowering phenological event during seasons 1 and 2 are presented in Figures 6 and 7. In these, a similarity of the spatial patterns between the values measured in the field and those simulated by the sensors can be seen. It is also important to note that a relative scale has been used for the cartographies to preserve the spatial variability patterns observed in the phenological flowering event analyzed in this work.



e)

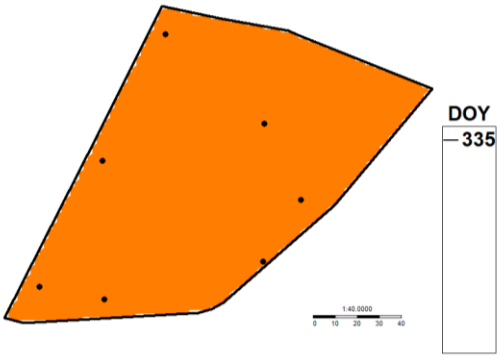
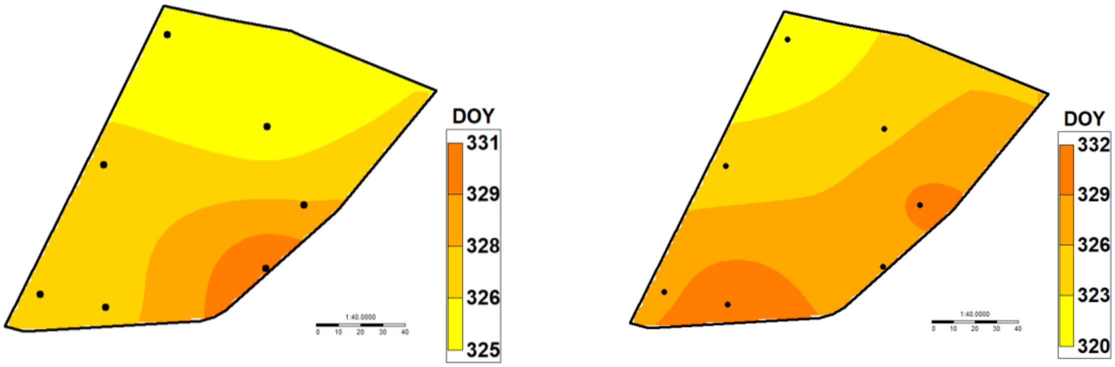


Figure 6. Cartographies corresponding to season 1 were, a): Measured values of phenology, b): is the estimation of phenology made using (Ortega-Farías et al., 2002) and spatialized sensors (SEN-ME), c): is the estimation of phenology made using (Parker et al., 2013) model in combination with spatialized sensors (SEN-GPV) d): is the estimation of phenology made using (Ortega-Farías et al., 2002) and meteorological weather station (AWS) data (AWS-ME) and d): is the estimation of phenology made using (Parker et al., 2013) and meteorological weather station (AWS) data (AWS-GPV).

a) **b)**



c) **d)**

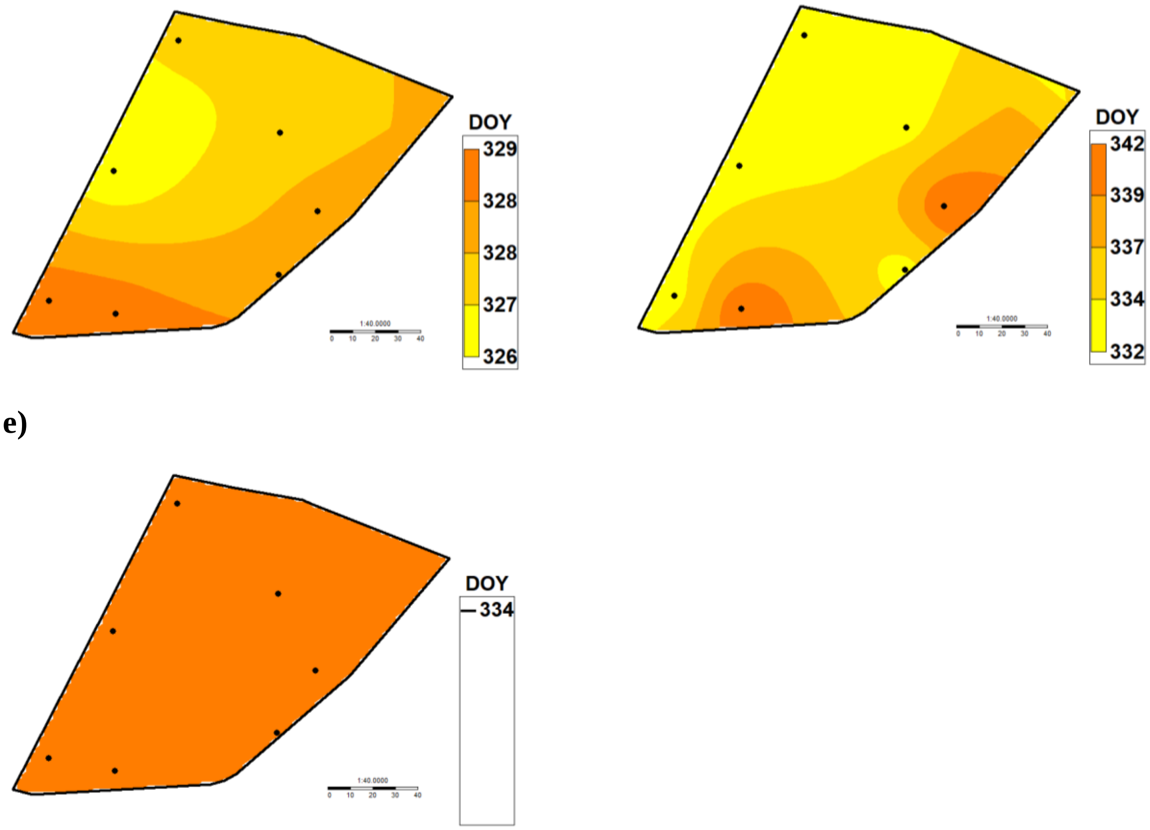


Figure 7. Cartographies corresponding to season 2 were, a): Measured values of phenology, b): is the estimation of phenology made using (Ortega-Farías et al., 2002) and spatialized sensors (SEN-ME), c): is the estimation of phenology made using (Parker et al., 2013) model in combination with spatialized sensors (SEN-GPV) d): is the estimation of phenology made using (Ortega-Farías et al., 2002) and meteorological weather station (AWS) data (AWS-ME) and e): is the estimation of phenology made using (Parker et al., 2013) and meteorological weather station (AWS) data (AWS-GPV).

Finally, Figure 7 shows a remarkably interesting result for the reader. Even though GPV model presents a superior behavior in estimating the flowering phenological event, we can observe in Figures 6c and 7c than the ME model, despite incorporating only specific information from an AWS, allows to obtain a map with spatial patterns of phenology variability. This could sound contradictory; however, this methodology incorporates into the model the observation of the phenological event of the sprouting, from which it allows to obtain for each site measured within the agricultural plot a value with a phenological scale that can be spatially modeled. On the other hand, the Parker model, when implemented using only a weather station, does not allow generating spatial patterns due to its formulation. In this way, each of the evaluated models presents advantages in its implementation that must be taken into account considering the weather data available at the field level and the management objective to be implemented with these predictive models for the phenological event of vineyard flowering.

Discussions

This study shows the implementation of a spatialized system for estimating of grapevine phenology using a field sensor network. The advantage of this approach lies in the ability to measure with high detail the spatial variability within the vineyard, minimizing the cost of monitoring and collecting plant information through the implementation of a low-cost wireless sensor network. This tool would allow phenological observations of the vineyard with high accuracy during the growing season, including the harvest date (Chmielewski, 2013). Numerous models have been evaluated in the literature, which has placed special emphasis on the phenological state of flowering since this growth stage presents a high degree of correlation with the harvest date (Reis Pereira et al., 2018). In literature, Models such as the Thermal Time model (Cannell & Smith, 1983) also known as the Spring Warming model (Hunter & Lechowicz, 1992), the Parallel model (Kramer, 1994), the Sequential model (Kramer, 1994), and the Unified model (Chuine, 2000), have been used to monitor vineyard phenology. However, these models have been developed for large productive areas and do not consider the natural spatial variability of the vineyard, therefore, the implementation of site-specific models that consider this variability could become key information for the decision-making of winegrowers in function of the spatial variability detected at the field level (Caffarra & Eccel, 2010; Parker et al., 2011). Precise modeling of the stages of vineyard development requires very detailed work consisting mainly of four stages: i) data collection, ii) model definition, iii) adjustments and iv) model testing (Chuine et al., 1999). As a result of the extensive work required to develop new phenological models, some authors have adapted the original formulations to suit their local environments. Using this method, accurate results have been observed. However, the spatial variability of vineyard phenology has been little studied, due to the limitations in the sensing tools normally used for the precise estimation of phenological events. Taking this into consideration, the present work incorporates the ME model developed for local conditions, and the GPV model, which was developed considering a wide variety of vineyard located in different geographic locations. The results show that both models are consistent with what is observed in the literature; however, when it comes to predicting phenological development in detail, the GPV and ME models perform better when they are incorporated into a network of spatialized sensors strategically distributed within a vineyard. On the other hand, the results obtained from the meteorological station were the ones that showed the worst performance, a situation that had been originally contemplated since the station was located outside the vineyard. The previous results also allow us to conclude that models developed under other conditions are available to be used under different environmental conditions from those in which they were originally calibrated.

On the other hand, it is important to note that although these models are quick and easy to implement when using information collected from a meteorological station. However, the specific local conditions of this information present important limitations that are related to its inability to account for the specific conditions of the field and its spatial variability. Therefore, the most convenient solution at a commercial level consists of the implementation of a low-cost sensors network, which will allow the farmer to accurately determine the spatial variability of phenological development within his vineyard.

The results observed in the present work show that the use of a spatialized microclimatic device (low-cost electronics) could be an interesting alternative to be implemented at the field level. However, for this technology to be implemented successfully, adequate isolation of the sensors must be carried out during its construction. This is especially relevant at the level of the microcontroller, which should ideally be insulated with resin to avoid conduction electricity. Additionally, it is important to mention that when it is desired to incorporate a wireless communication system to the devices, the tests must be carried out under real operating conditions. In this case, a significant reduction in the data transmission range of the evaluated communication system was observed due to the wire structure that supports the vineyard’s canopy. This vineyards trained structure reduced the communication distance of the devices at the field level by up to 50%. To face this situation, we suggest placing the communication antennas on the crop using cables that allow the antennas to be extended so that they have a direct line of sight between the devices installed in the vineyard. At the field level, this turned out to be an effective strategy to recover a large percentage of the communication range reported by the manufacturer. Another important factor that must be considered in the development of these devices is their electrical energy consumption. Several authors have used microcontrollers from different manufacturers; however, we recommend using simple field-level processing units that consume much less energy than traditional units used (microcomputers). The previous topic is important, since it will allow the development of more economically sustainable devices since the processing and power modules must meet some minimum requirements, thus optimizing the electricity consumption of the proposed system.

Finally, this study shows that the use of phenological models at specific moments in the vineyard (in this case, flowering) in combination with a low-cost wireless sensor network is essential information for modern vineyard production, which aims to produce very high-quality fruit. Given the results obtained in this work, this proposal could become a tool for field viticultural procedures by knowing the stage of advance or delay in the vine growth during the season and its relationship with the vineyard historical information. However, the model calibration requires an extensive historical database that could present a significant drawback for the commercial implementation of this proposal.

Ongoing and future work

During the development of this study, a recompilation of information regarding possible improvements in further studies was made. In this sense, it was noted that some elements of the prototype must be improved to increase the robustness and usefulness of the proposed system. In this research, it was possible to identify some environmental and technical factors to consider in a new, improved version of the prototype:

i) *Improve antenna position in the field*: the main factor that affects the data transmission is the irregular field topography, a situation that is usual in commercial viticultural systems. This condition does not allow direct vision between the antennas of the devices; therefore, a possible solution would be to add extension cables between the XBee and the 2.4GHz antenna to place the transmitter above the vine canopy.

ii) *Improve the power supply system*: it is important to consider that the wireless measuring modules are installed during the summer, when the highest solar radiation values of the years are recorded, which ensures efficient operation of the solar panels for recharge the wireless measuring system. However, if the device is intended to measure field information throughout the year, a modification to the power system should be considered. These modifications should be aimed at reducing energy consumption at times of the day in which the sensor is not taking measurements (sleep mode).

iii) *Integration of other sensors into the spatialized monitoring system*: for example, foliage temperature sensors; for the calculation of water stress indexes, which is a fundamental variable for crops in which deficit irrigation applications are required.

iv) *Cloud storage*: Implementing a GSM or GPRS system to send information stored in the central node to a server or mobile phone to display in real-time processed information (mapping of agricultural variables of interest) for making more efficient decisions.

Conclusions

This proposal presents a practical example of the use of weather information (temperature) for the prediction of phenological events (flowering) in a vineyard. This type of information is highly relevant for decision-making in various practical applications of agricultural interest, such as phytosanitary spraying, fertilization, and irrigation management. This information, along with the development of a wireless acquisition data system presented in this document, corresponds to an initial prototype that, given the promising results shown in this study, serves as the basis for further development of new electronic devices that expand the possible applications of new technologies to be performed in the agricultural sector, adding new features to the system, which will be proposed for future research. Based on the results, we can conclude that it is possible to develop and implement low-cost electronic devices for monitoring spatialized phenological events in the vineyard, which can be used in other agricultural species of economic interest (such as fruit trees of high commercial value). In the case of the present study, both the Ortega and Parker models presented better phenological estimates when using a low-cost wireless sensor network compared to the estimate made with the Automatic Weather Station (AWS). However, both models presented a better estimate during the second season, due to the Enso "La Niña" climatic effect observed during the first season, which presented three times less rainfall and 9.6% more water consumption than the second season. Finally, it can be noted that the GPV presented better phenological estimates than the ME with errors of less than 4 days in both study seasons when using a low-cost wireless sensor network. In the case of the ME, only during the second season errors of less than 4 days were observed when using the spatialized sensors network. Finally, having low-cost spatialized sensors not only consider the temporal dimension in the intrapredial data analysis, but also the spatial dimension, which would allow generating differential managements areas, increasing the sustainability of modern viticultural systems, which are characterized by presenting an important spatial variability in various productive variables of interest.

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Chapter 4: Low-cost wireless sensor networks for monitoring spatial variability of plant water status in a commercial vineyard

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Abstract

Under the current climate change scenario, the water available for agriculture will be drastically limited by the effects of climate change, therefore, an adequate determination of the water status of crops becomes a critical task. Traditionally, techniques associated with the physiological monitoring of the plant have been developed, which have been widely accepted within the scientific community because they allow the integration of soil, climate, and crop conditions. Within the traditional techniques, the stem water potential (SWP) measurement stands out as the most used tool in crops such as vines. However, the limited number of sampling points makes it difficult to monitor large areas, which is why this technique is unable to consider the spatial variability of the measurements made. In this sense, tools such as thermometry become relevant since its combination with thermal indices such as the Crop Water Stress Index (CWSI) allow constant monitoring of variables of agronomic interest, however, the cost of these devices has been an important limitation in their massive use. In the present study, a low-cost device (aSIMOV) has been developed, seeking to solve this limitation by building an autonomous spatialized sampling network based on infrared radiometers (IRT). To achieve the abovean evaluation of the IRT was carried out against a Blackbody (BB) under controlled temperature conditions. In addition to this, an evaluation was also carried out under real conditions over a grass surface to verify the accuracy of the device. This test presented root mean square error (RMSE) and mean absolute error (MAE) values that ranged between 0.10 and 0.79 °C. Subsequently, the device was installed in a commercial vineyard under study in which the temperatures obtained by the spatialized network of thermometers and manual measurements were simultaneously sampled to estimate the CWSI using both sources of information. The results of these tests showed that the data obtained simultaneously by both devices were similar in terms of temperature measurement and in obtaining the CWSI. The above demonstrates the potential of these wireless prototypes to collect accurate radiometric temperature readings that can be integrated in thermal indices, to estimate vine water status.

Keywords: Vine water consumption, Crop water stress index, Irrigation spatial variability, low-cost wireless sensor networks.

Introduction

The future availability of water for agriculture will be strongly affected by the negative effects of climate change (DeNicola et al., 2015; Kumar & Ilango, 2018). This situation is especially relevant in a context in which agricultural production must double in the near future in order to meet global demand for food (Martínez et al., 2017). The knowledge and monitoring of the plant water status during the growing season would allow proper planning of irrigation (time and frequency of irrigation). In recent years, countless methods have been developed to carry out adequate irrigation scheduling. The most widely used is the approach proposed by FAO-56 (Bornhofen et al., 2015), where vineyard water consumption can be determined by multiplying the actual evapotranspiration of the crop (ETa) by a crop coefficient (Kc). However, this method has some important issues since Kc values must be calibrated locally for adequate use in viticultural systems (Fuentes-Peñailillo et al., 2018). Other traditional approaches correspond to measuring the soil water balance (Andreu et al., 1997; Lebon et al., 2003; Ramos & Martínez-Casasnovas, 2010), soil moisture sensing and monitoring (Smith et al., 2012), and several approaches based on plant physiology used as indicators of plant water status, such as stem water potential (SWP) (Acevedo-Opazo et al., 2010; Choné, 2001; Delrot et al., 2010; Girona et al., 2006; Santesteban et al., 2011), sap flow sensor (Braun & Schmid, 1999; Fernández et al., 2008; Ferreira et al., 2012; Poblete-Echeverría & Ortega-Farias, 2013; Zhang et al., 2011), stomatal conductance (Naor et al., 1997; Williams et al., 2012; Winkel & Rambal, 1990) and canopy temperature (Jones et al., 2009; Van Zyl, 1986; Wang et al., 2010). Taking into account the methods mentioned above, SWP measurement has traditionally been the preferred method to determine the plant water status in agriculture (Choné, 2001; Jones, 2006; Leeuwen et al., 2006). However, this technique is characterized for presenting a low spatial representation at the field level due to a limited number of possible measurements to be taken per day. The aforementioned limitation makes it difficult to propose an irrigation strategy that considers the spatial variability of a complete vineyard (Dhillon et al., 2018; Jones, 2004; Romero et al., 2018). Despite this, it is important to emphasize that the approaches based on direct measurements of the plant provide significant advantages in the monitoring of water status since the plant is the best water indicator in the soil-plant-atmosphere continuum.

Among the approaches based on plant measurement to determine water status, canopy temperature has received much attention over the last two decades, especially with the emergence of portable infrared radiometers and thermal imaging cameras (Meron et al., 2013). These sensors have been used at several observation scales. The largest observation scale corresponds to satellite platforms, where, together with information on vegetation indices and meteorological data, allow the study of water status and water consumption of crops in more extensive areas. The main limitation to this observation scale is related to the pixel size or spatial resolution (Ribeiro-Gomes et al., 2017) (which includes varying proportions of vegetation, soil, and shade), the temporary frequency of revisit (Xiang & Tian, 2011), image fusion methods (Al-Wassai & Kalyankar, 2013) and presence of clouds or other atmospheric disturbances. The following observation scale is represented by infrared sensors mounted on airplanes or unmanned aerial vehicles (UAV), where the frequency of visits can be programmed more easily according to the key phenological events of the vineyard (Ballesteros et al., 2015; Gago et al., 2015; Gomez-Candon et al., 2014; Hoffmann et al., 2016; Santesteban & Di Gennaro, Herrero-Langreo, Miranda, Royo, 2017; Turner et al., 2010; Zhao et al., 2016), overcoming the main limitation of satellite platforms. However, these technologies also present some difficulties in their implementation at the field level, such as instrumentation cost (Huang et al., 2013), the logistics of flight programming (Gago et al., 2015), battery life (Gómez-Candón et al., 2014), a very limited payload capacity (Martínez et al., 2017) and data interpretation, particularly how the information observed in the images is related to the plant's water status. The last scale of water status measurement corresponds to the so-called "proxidetection," in which temperature records are made at the plant level. Through sensors installed in the field, it is possible to accurately monitor the surface temperature of the canopy, which would be related to the measurement of the SWP, through the computation of thermal-based indices such as the Crop Water Stress Index (CWSI). This index has been widely used as a crop water status indicator and provides the crop stress level based on canopy-air temperature differences. This index has proven to be a useful methodology to evaluate the plant water status of different agricultural species such as; bermudagrass (Emekli et al., 2007), winter wheat (Alderfasi & Nielsen, 2001) (Yuan et al., 2004), corn (Yazar et al., 1999), sorghum (Shaughnessy et al., 2012), alfalfa (Hutmacher et al., 1991), tall fescue (Al-Faraj et al., 2001), cotton (Howell et al., 1984), sunflower (Erdem et al., 2006), broccoli (Erdem et al., 2010), red pepper (Sezen et al., 2014), watermelon (Orta et al., 2003) olive orchards (Agam et al., 2013), citrus (Gonzalez-Dugo et al., 2014) and vineyards (Bellvert et al., 2014).

However, the traditional methodology proposed by (Idso, Jackson, Pinter, Reginato & Hatfield, 1981) has as main limitations the following:

i) Cost and complexity of traditional infrared thermometers
ii) Difficulty of implementing spatially distributed sensors to characterizes natural variability of temperature or plant water status.

To solve these limitations, the industry has developed new communication devices and systems. In the case of infrared radiometers, traditional devices can reach a cost of $ 1500 (USD) sensor that additionally requires other peripherals for its operation (data logger, batteries, solar panel, etc.).
It is because of the above that devices such as MLX90614 sensor has received special attention, having a wide range of applications, among which consumer electronics and industrial monitoring stand out. Due to the precision and robustness of these devices, some authors have proposed their use to replace high-cost devices due to their accuracy (± 0.5 °C), affordable prices in comparison to conventional sensors, and the possibility of being easily integrated into other systems. A single infrared point sensor's cost may represent 1 %, or even lower of the cost of conventional devices, making this technology better suited for small to medium-sized farms that cannot afford costly equipment.
In the case of communication systems, new technologies have also been developed that would make it possible to solve the traditional limitations in the deployment of sensors at the field level. A clear example of this is the development of Wireless Sensor Networks (WSN), which are presented as a type of ad-hoc network which is autonomous, self-organized and composed of tens, hundreds or thousands of smart low-rate devices, which are generally battery-powered (López Riquelme et al., 2009) and have many useful features for applications in precision agriculture (PA).

Due to these and other technological advances, a series of research initiatives have been carried out in the development of low-cost sensors for agriculture (Polo et al., 2015; Viani et al., 2017). Most of these electronic devices have focused mainly on monitoring micrometeorological variables of the plant (air temperature and relative humidity) and some others in the estimation of soil moisture variables. However, there are very few sensors developed for monitoring plant water status. This initiative seeks to evaluate and develop an inexpensive WSN-based system (aSIMOV), suitable for monitoring CWSI to predict spatially distributed measurements of SWP in a commercial vineyard, oriented to the production of high-quality grapes. Additionally, the authors propose comparing vineyard canopy temperature measurements collected using low-cost infrared radiometers with those obtained from a conventional infrared radiometer and identifying the main factors that will limit the implementation of this technology field level.

Materials and Methods

General description of aSIMOV system

aSIMOV system consists of a series of nodes spatially distributed at the field allowing site-specific monitoring of the vineyard's infrared temperature. Each node retrieves data and then sends the information to a coordinator node using Zigbee protocol. Additionally, this unit is connected through General Packet Radio Service (GPRS) to internet.

Experimental site

aSIMOV system was evaluated during 2017-18 growing season on a commercial vineyard (*Vitis vinifera* L., cv Cabernet sauvignon) with drip irrigation located in the Pencahue valley, Maule Region, Chile (35°20'32.70"S, 71°46'47.52"O, 86 m.a.s.l.). This valley has a Mediterranean climate, with a medium average temperature of 14.8 º C and an accumulated ETo of 968.18 mm from September to March. The average annual rainfall on the region is approximately 602 mm, distributed mainly during winter. The summer period is generally hot and dry with high atmospherical demand. The soil of the vineyard is classified into Quepo series with a clay loam texture. Finally, the vineyard was established on 2015, with 2,5 m x 1,5 m of spacing trained on a vertical shoot positioned system (VSP).

Experimental design

The experimental design consisted of four different irrigation regimes, where four stem water potential (SWP) thresholds were applied whit the aim of inducing different levels of SWP over the experimental plot.

SWP thresholds were determined according to Choné et al., (2001) and are detailed below:

- Level 1 (L1): Non-water stress (SWP > -0.8 MPa),
- Level 2 (L2): moderate water stress (SWP between -0.9 and -1.1 MPa),
- Level 3 (L3) strong water stress (SWP between -1.2 and -1.4 MPa),
- Level 4 (L4) Severe water stress (SWP < -1.4 MPa).

Measurement of micrometeorological variables

Additionally, to monitor environmental conditions, a meteorological tower was installed over the experimental plot corresponding to 1.4 ha of a vineyard with the objective to measure micrometeorological variables on a 30-minute interval. The air temperature (Ta) and relative humidity (RH) were monitored using a Vaisala probe (HMP45C Campbell Scientific Inc., Logan, Utah, USA). The speed (u) and direction of the wind (w) were monitored with an anemometer (YOUNG, 03101-5, Michigan, USA). Precipitation (Pp) was measured with a pluviometer (A730RAIN, Adcon Telemetry, Klosterneuburg, Austria). The solar radiation (Rs) was measured with a Silicon Pyranometer (LI200X, Campbell Scientific Inc., Logan, UT, USA). The sensors that measured u, w, Pp, Ta, RH, and Rs, were installed 1.9 m above the vineyard.

aSIMOV Node

Each Node was developed integrating different types of sensors, the first of them corresponds to an infrared thermometer MLX90614 (Melexis, Ypres, Belgium). This sensor was chosen because of its low cost (10 $USD), narrow FOV (restricted to 10° by the manufacturer), and capability for non-contact radiometric surface temperature measurements. The sensor package is composed of a long-wave filter that passes radiation from 5.5 to 14µm. Sensor voltage outputs were converted to temperature readings using the equation, $Ti=Vj\times0.02$ in K and later converted to ◦C. This sensor is factory calibrated over a wide temperature range: -40 to 85 ° C for ambient temperature and -70 to 382 ° C for object temperature. The standard precision is 0.5 ° C relative to room temperature, although medical versions offer a resolution of 0.1ºC in temperatures between 35-38ºC. However is important to consider that for any radiometric sensor, the accuracy of the thermometer can be influenced by thermal gradients induced across the sensor package (Melexis Data Sheet, 2009). All these characteristics make this technology better suited for small to medium-sized farmers who cannot finance costly equipment.

For the development of each electronic board, the microcontroller Arduino FIO was used. This card was selected due to the following advantages that help reduce the operating cost of the system:

i) It has a port that allows to connect an Xbee communication card (Xbee S2B)
ii) It has a port that allows to connect directly a LiPo battery
iii) It has an internal regulator that allows to connect a power supply directly to the card.

Finally, all the components were integrated into the electronic board.

aSIMOV Coordinator Unit

For the construction of the coordinator unit, the Arduino Mega microcontroller was used. This device receives and stores information from all the nodes installed in the field. If the user requires it, the information can be sent through a text message or uploaded directly to a web platform. The coordinating node is composed of an Arduino Mega microcontroller (Atmega2560) that has 54 digital pins, 16 analog inputs and 4 serial ports by hardware. Its working frequency is 16MHz and it has a flash memory of 256KB. Another important component of the central node is the datalogger, which has a Real-Time Clock (RTC), composed of an integrated circuit DS1307Z, a quartz crystal and a 3V CR1220 battery. The datalogger also includes a slot for a microSD card, in which the information received from the nodes can be stored. The communication of the central node with the remote nodes is carried out through an Xbee PRO S2B configured to work in a network of star topology. Finally, the coordinator unit has the ability to send via GPRS the information received from the nodes using a GPRSBee card, that provides GPRS and GSM connectivity, thanks to an M95 module. In this way, by request, it sends the information to a database mounted on a Virtual Private Server (VPS). For the protection of electronic elements under field conditions, ABS components have been designed and printed on a Creality Ender 3 3D printer. Nodes and central units have encapsulations adapted to the size of each board.

Communication protocol

The system considers two types of communication protocols. For the transmission of data from the node unit to the coordinator unit the system employs Xbee modules Series 2B that use the IEEE 802.15.4 networking protocol. Once data is received from the coordinator unit, it is transmitted to VPS database trough GPRS. with Wi-Fi technology based on IEEE 802.11 or 3G mobile telecommunications technology protocols. Finally, data is stored in a MySQL database, which can be queried by many clients to provide data tables, graphical visualization plots and export data (in .csv format). The user could view data remotely via a browser or a dedicated App.

Evaluation of the reference sensor and the low-cost thermometers

To verify the accuracy indicated by the manufacturer, a radiometric evaluation of the reference sensor (Portable infrared radiometer model MI-2H0, Apogee Instruments, North Logan, UT, USA) and the 8 low-cost thermometers (MLX90614) mounted on the aSIMOV system were conducted using a Black Blackbody (Isothermal Technology Limited, Pine Grove, Southport, Merseyside, UK). The evaluation was carried out in a Climatic Chamber (CC) located in CITRA-University of Talca, where the environmental conditions during the experiment were monitored and controlled. For the evaluations, each sensor was installed in a fixed position in front of the BBS at 0.01 m, then the temperature measured by the sensor was recorded. Blackbody temperatures used in the calibration process ranged from 5 to 65 °C in steps of 5 °C, which covers the range of temperatures found in agricultural applications. To obtain different temperature values of the sensor, the temperature in the CC was modified from high to low using a cooling/heater system. Therefore, a wide sensor temperature range was achieved to evaluate the sensor`s performance.

However, some authors suggest that the accuracy of the sensors varies when they are subject to field conditions in which they are exposed to different conditions of temperature and solar radiation and humidity. To evaluate the quality of the information under field condition, a second test was carried out in which the measurements of infrared temperature was compared with commercial sensors under field condition. The MLX90614 sensor was compared to an MI-2H0 following a similar methodology to proposed by (Mahan & Yeater, 2008). To carry out this test, the sensors were placed on a reference grass surface, where continuous measurements were carried out during a week.

Temperature and physiological measurements

The vineyard water status was monitored by means of the stem water potential (SWP) technique. To carry out this measurement, healthy leaves and completely exposed to the sun were selected, which were covered first with a plastic film, and later with an aluminum film to avoid transpiration, exposure to light and overheating of the plant tissue. After 1 hour, the SWP measurement was carried with a Scholander type pressure chamber.

On the other hand, the canopy temperature measurement was performed with two instruments simultaneously: the aSIMOV system and an MI-2H0 infrared radiometer. The aSIMOV was programmed with a measurement frequency of 1 minute to obtain the instantaneous temperature values. Subsequently, considering the moment of each measurement, the temperature values collected by the different sensors was compared and analyzed.

Crop Water Stress Index (CWSI) computation

The CWSI was calculated based on *Leaf Reference Methodology (LRM*):

$$CWSI=\frac{T_c-T_{wet}}{T_{dry}-T_{wet}} \tag{1}$$

where, T_c = canopy temperature (°C), T_{wet}=temperature of a fully transpiring leaf (°C) and T_{dry} = a leaf with fully closed stomata (°C).

This methodology is based on the equation proposed by (Jones, 1999), where T_{wet} and T_{dry} were obtained from an infrared radiometer, choosing the highest canopy temperature as T_{dry} and the lowest as T_{wet}. Additionally, for the computation of the CWSI it was considered the proposed by (Testi et al., 2008) who indicated that more repeatable and effective estimations for evaluating tree water status for irrigation purposes were obtained from 1200 to 1500 h (local time). Due to the above, the evaluations made at the field level considered the manual recording of the temperatures evaluated with the MI-2H0 to later extract the temperatures measured by aSIMOV at the same time.

Statistical analysis

For sensor data validation, a comparison between the observed and estimated values was carried out using the root mean square error (RMSE) and mean absolute error (MAE). Also, the ratio of the observed and estimated values was computed as the slope of the linear regression between them.

$$RMSE = \sqrt{\frac{\sum_1^N (O_i - E_i)^2}{N}} \tag{Eq. 3}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|E_i - O_i| \tag{Eq. 4}$$

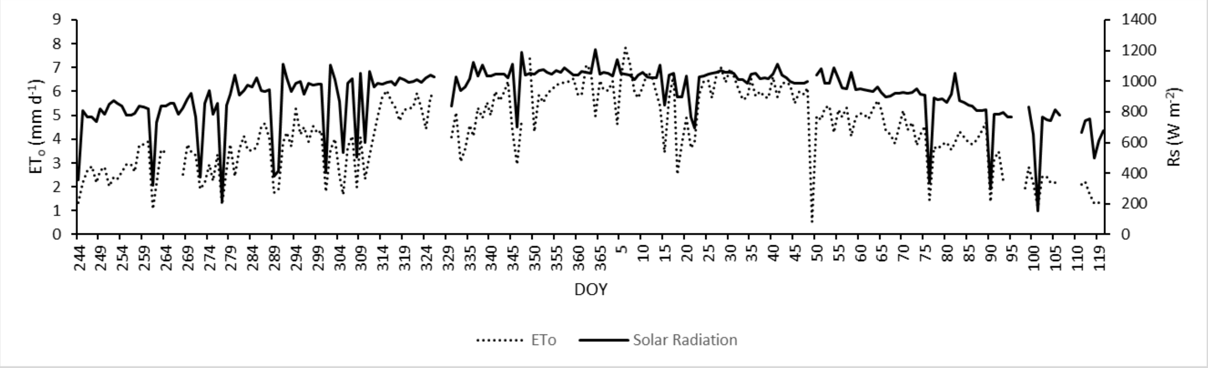
where E_i represents the estimated values by the model and O_i is the observed energy flux and N is the number of observations.

Finally, the t test was used to check whether the ratio was significantly different from unity at the 95 % confidence level.

Results

Figure 1 presents the climatic characterization for the main stages of crop development (budburst to veraison). At the experimental site, maximum atmospheric demand was observed between December (DOY 335) and January (DOY 31) with cumulative ETo ranging between 1-7.8 mm (Figure 1). During the growing seasons, the rainfall events were minimum, showing the highest effective rainfall during 2017 (10 mm). Daily values of solar radiation (Rs) were between 180 - 1200 W m^{-2} day presenting peaks in December and February. In this study, irrigations were applied from 25 October 2017 (DOY 268) to 15 April 2018 (DOY 105). These results indicate that there were no abnormal climatic events during the study period.

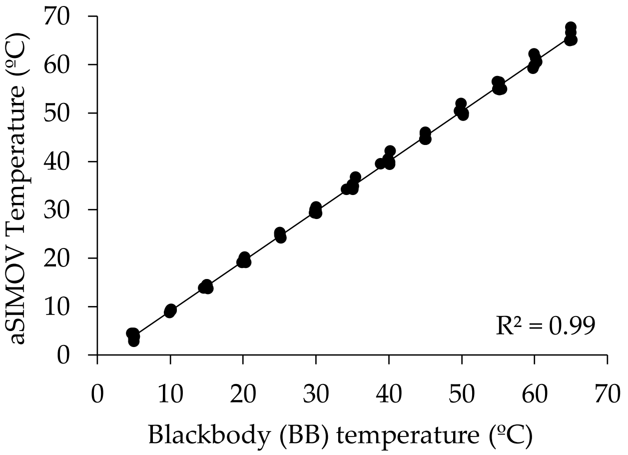
Figure 1. Meteorological conditions for season 2017-18 (September 1 to March 30), where ETo corresponds to reference evapotranspiration (mm d-1), Rs is solar radiation (W m-2) and DOY is day of year.



where, ETo corresponds to reference evapotranspiration (mm d^{-1}), Rs is solar radiation (W m^{-2}) and DOY is day of year.

To verify the precision of the low-cost infrared radiometers, a test was carried out in which each of the devices was evaluated against a BB at different temperature ranges. The results for all the evaluated sensors were similar, yielding R^2 values that varied between 0.97.5 and 0.98, thus demonstrating the robustness of these devices. In figure 2 a representative test of one of the devices is attached, where the high degree of adjustment between the BB temperature and the temperature detected by the low-cost sensor can be observed. However, of the 8 devices evaluated, 1 gave erratic measurements, which corresponded to a factory defect. This shows the importance of evaluating before integrating these sensors to more sophisticated devices to avoid obtaining anomalous data.

Figure 2. Calibration of the Apogee sensor and low-cost thermal sensor integrated in aSIMOV using a Blackbody (BB) at different temperature levels



Subsequently, a test was carried out under controlled environmental conditions in which a aSIMOV was installed on a grass surface together with MI-2H0 to verify possible deviations in the measurement product of environmental conditions such as temperature, relative humidity, or solar radiation. To validate the results of the low-cost sensors, a comparison was made between aSIMOV sensors and the MI-2H0. The results of this comparison showed an RMSE and MAE of 0.83 and 0.99°C, respectively, similar to the error indicated by the manufacturer, which corresponds to ± 0.5° C. Additionally, the slope and the coefficient of determination of the regression were estimated, finding values of 0.98 and 0.99, respectively. The ratio between aSIMOV and MI-2H0 was significant at 95% confidence level indicating that aSIMOV estimates temperature with a high degree of accuracy. Finally, in the case all evaluations made, it was observed that the ratio between the expected and observed values was significantly equal to the unit, which would indicate that the low-cost sensors are equivalent to the reference sensors.

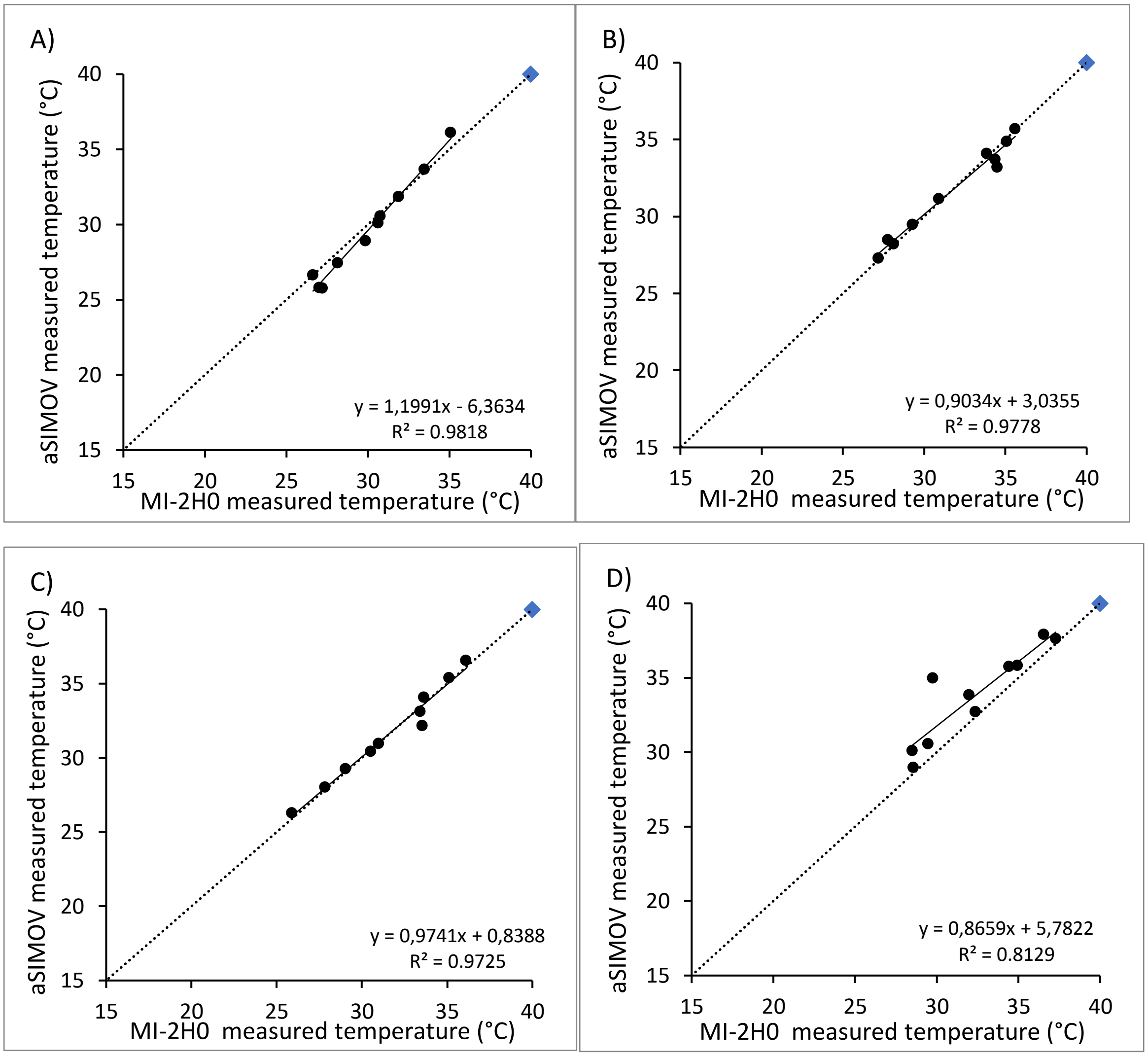
Table 1. Validation of dataset obtained from MI-2H0 and low-cost aSIMOV sensors

Deviances measures	**aSIMOV vs MI-2H0** **Object Temperature (°C)**
MAE	0.83
RMSE	0.99
b	0.98
R^2	0.99
t-test	T

MAE = mean absolute error; RMSE = root mean square error; b = ratio of observed to computed values and R^2= coefficient of determination, T null hypothesis (b = 1) true, F alternative hypothesis (b ≠ 1) false

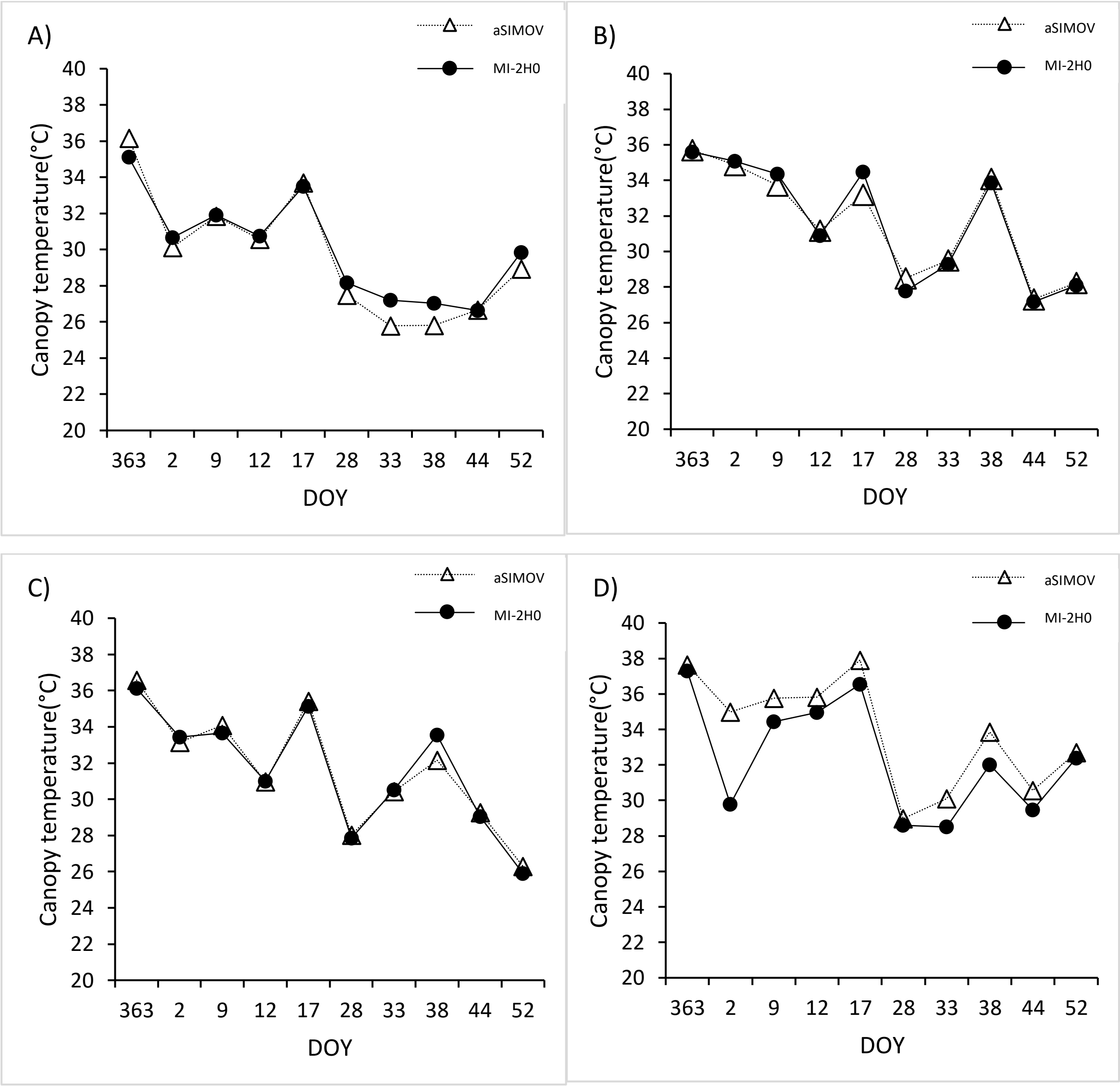
Afterwards, a test was carried out under real operating conditions where the infrared radiometers had already been integrated into the aSIMOV device. In this test, the devices were installed in different sites of the vineyard that had different levels of water replacement. To detect differences at the field level between the measurements made by the prototype, the devices were configured to take measurements at one-minute intervals during noon (1200-1500 hrs). Then, for each experimental site, a commercial infrared thermometer was measured, recording the time and the measurement manually in a field notebook. The results of the comparisons between the estimated and observed values of foliage temperatures are shown in Figure 3 where it can be seen that L1 had an R^2 of 0.98, L2 a 0.98, L3 0.97 and finally L4 reported an R^2 value of 0.81. In general terms, there was a good agreement between the estimated and observed values at the field level.

Figure 3. Comparison per treatment of the temperature measured by MI-2H0 and aSIMOV at same time of physiological measurements. Dotted line corresponds to 1:1.



were, A = corresponds to Level 1; B = Level 2; C = Level 3, D =Level 4, and DOY = Day of Year.

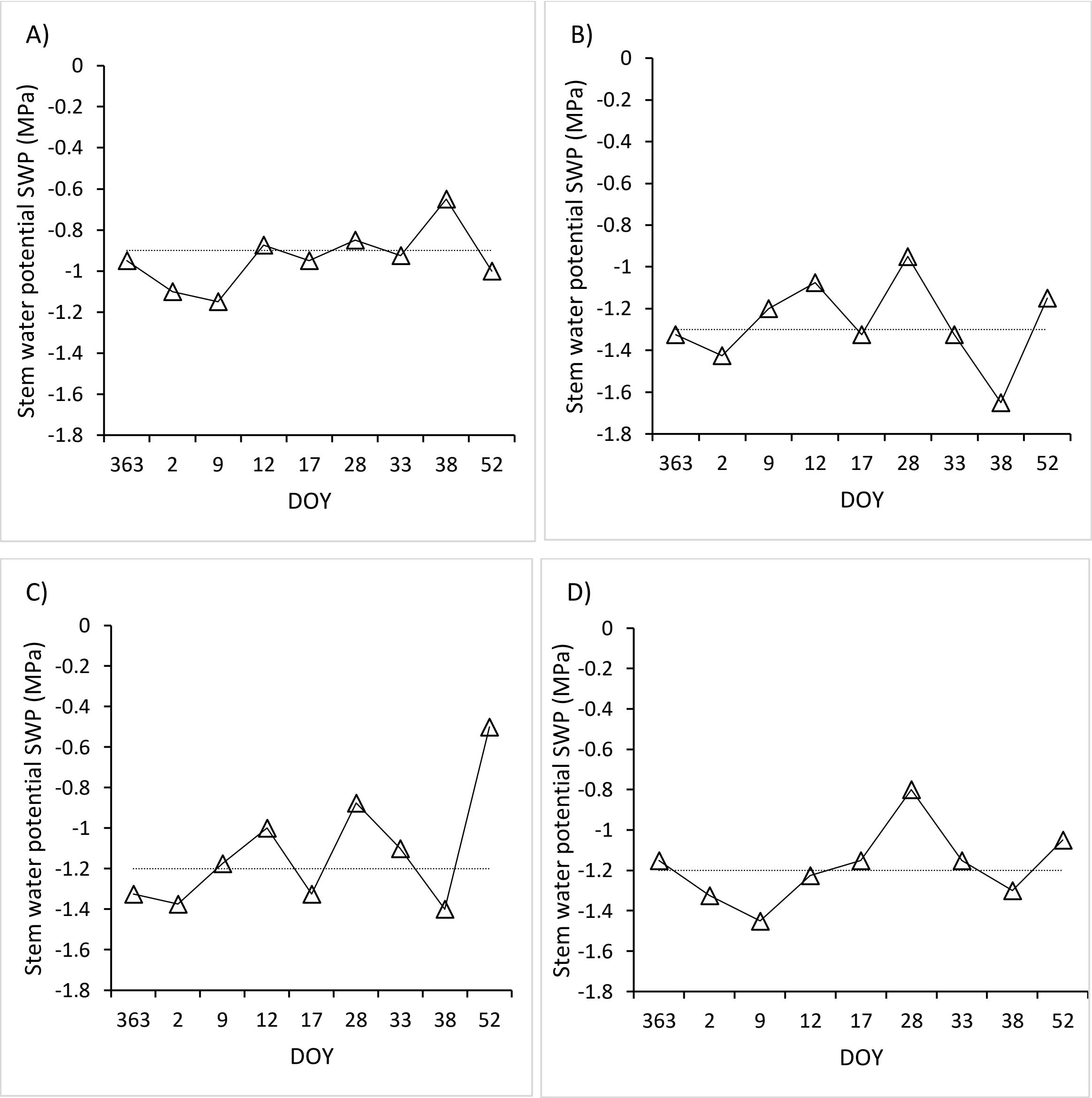
Figure 4. Comparison between temperatures per Level and day of year (DOY) measured by aSIMOV and MI-2H0.



were, A = corresponds to Level 1; B = Level 2; C = Level 3, D =Level 4, and DOY = Day of Year.

On the other hand, simultaneously with the temperature measurements, SWP measurements were made in each of the treatments with the aim of reaching the proposed thresholds. In Figure 5 the behavior of the treatments can be observed throughout the study period. It is interesting to note that the edaphic conditions of the trial did not allow reaching the desired thresholds. Reporting finally only two levels of stress. The final stress levels when the average reached values were analyzed corresponded to moderate water stress (SWP between −0.9 and −1.1 MPa) for Level 1 and strong water stress (SWP between −1.2 and −1.4 MPa) for Levels 2, 3 and 4. However, it is important to note that when the measurement points were observed, all stress levels were reached at some point. The above also allowed to induce maximum and minimum values of leaf temperature and SWP, a situation that allowed estimating the CWSI through the empirical method.

Figure 5. Stem water potential (SWP) measurements per treatment obtained with a pressure chamber.



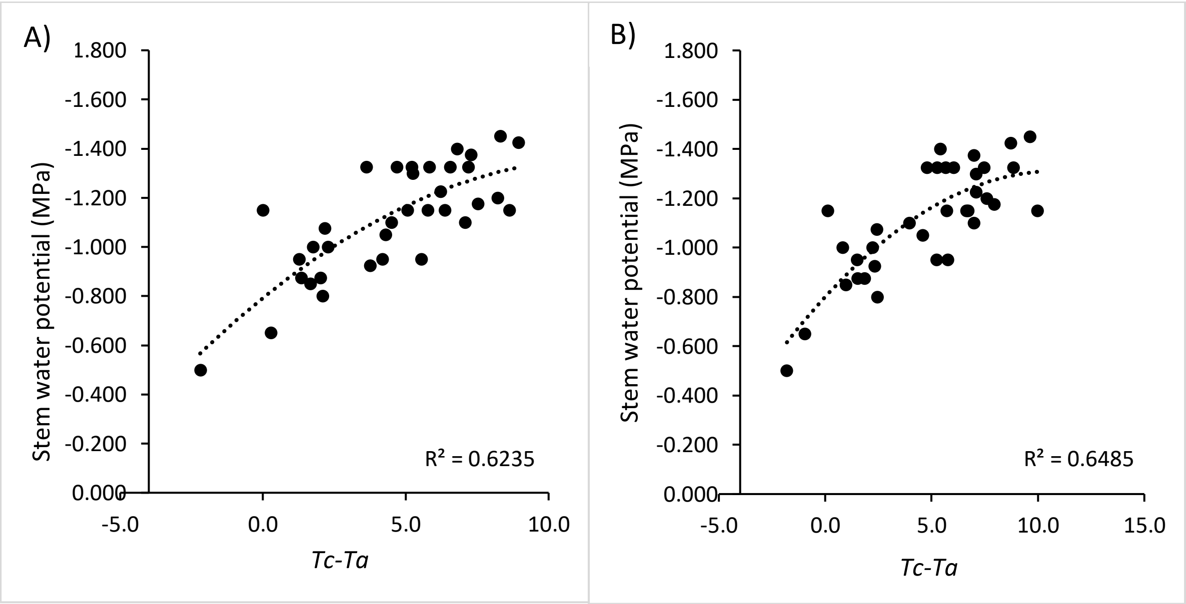
were, A = corresponds to Level 1; B = Level 2; C = Level 3 and D =Level 4 and DOY = Day of year. Dotted line corresponds to average value for all study days

At the beginning of the experiment, there were significant differences among stress levels for the SWP with global values < -0.90 MPa during the last week of December (DOY 365) in the

2017/18 growing season (Figure 65). The lowest values of SWP (-1.40 MPa > Ψstem MPa) were observed in plants at severe water stress (L4) and moderate water stress (L2) conditions on DOY 9 and DOY 38, respectively, but the water stress was more sustained in the strong water stress (L3). In addition, the lowest water stress levels were associated with the highest values of ETo during the seasons (Figure 1). At the beginning of the irrigation experiment (DOY 362), the SWP values in all Levels were lower than -0.90 MPa. After 2 and 3 weeks, SWP values significantly decreased until reaching minimum values (safe for L2) on DOY 2 and DOY 9, respectively. After that, SWP values increased until reaching mean values of -1.20 MPa during all seasons. As expected, plants in L2-L4 were under strong water stress during the experiment with SWP values ranging between -1.20 and -1.40 MPa (Figure 5).

After establishing the similarities between commercial sensors and low-cost sensors, the SWP data was used to establish the simple relationship reported in the literature for monitoring water stress. This relationship corresponds to the difference of Tc-Ta / SWP. The results of these estimates are shown in Figure 6. To evaluate the performance of the prototype, this calculation was performed using both data sources. On the one hand, commercial sensors reported an R^2 value of 0.62. For the case of our prototype, a slightly higher value was reported, corresponding to 0.65.

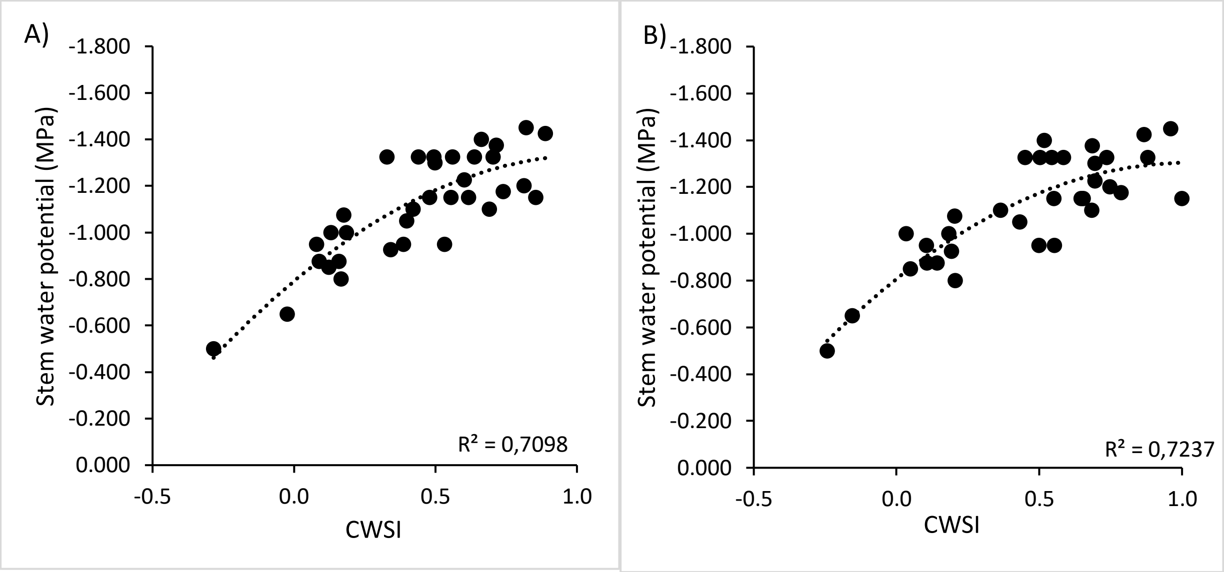
Figure 6. Difference of Tc-Ta versus Stem Water Potential (SWP) estimated using a) MI-2H0 sensors and b) Asimov sensor



were; A): difference of *Tc-Ta* versus Stem Water Potential estimated using MI-2H0 sensor and B): difference of *Tc-Ta* versus Stem Water Potential estimated using aSIMOV sensors.

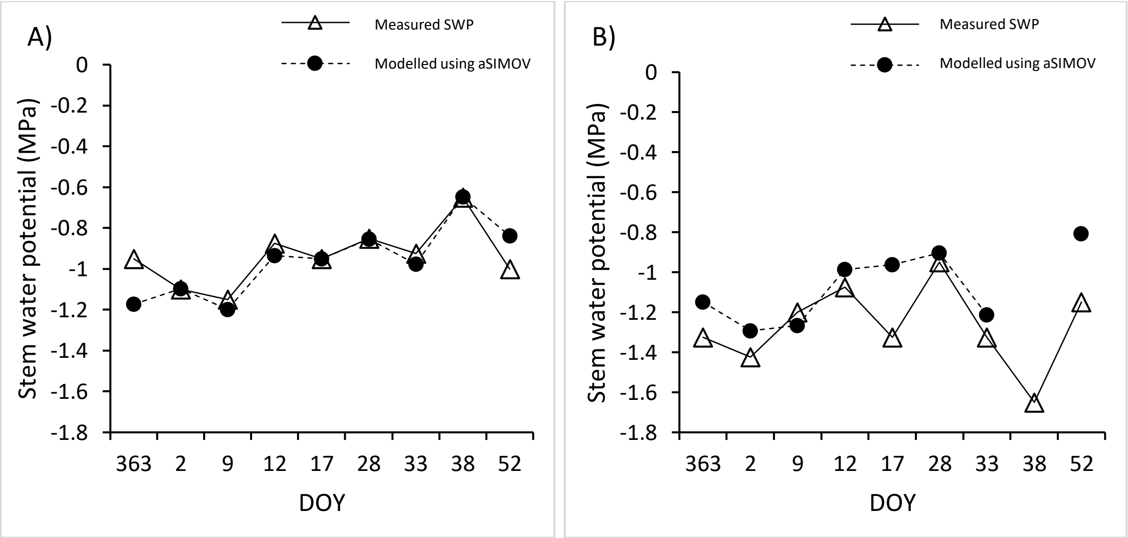
Once this was done, the same procedure was repeated to calculate the CWSI using the methodology proposed by (Jones, 1999). Where the results for commercial sensors showed an R^2 of 0.71, significantly increasing its value regarding the use of the Tc-Ta / SWP relationship. In the case of aSIMOV, the value reported for the CWSI was 0.72, being almost identical to the value obtained by using commercial sensors. The relationship obtained between CWSI / SWP for both cases is shown in Figure 7. From the relationships established above, two models were generated that allow predicting the SWP based on the temperatures measured by the device, for commercial sensors the determined model corresponded to Predicted SWP_Apogee = 0.48 * (CWSI) ^ 2-1.0216 * CWSI-0.7908, on the other hand for our prototype the generated model corresponded to Predicted SWP_Asimov = 0.4756 *(CWSI) ^ 2-0.9721 * CWSI-0.8067. The model generated for the low-cost device was finally used to simulate the SWP based on the field-measured leaf temperature data for aSIMOV. The results of this modeling are shown in Figure 8, where the high degree of correspondence can be observed for all levels of water replacement. However, exceptions in the agreement of the estimates were observed for DOY 17 for treatment 2 and 3.

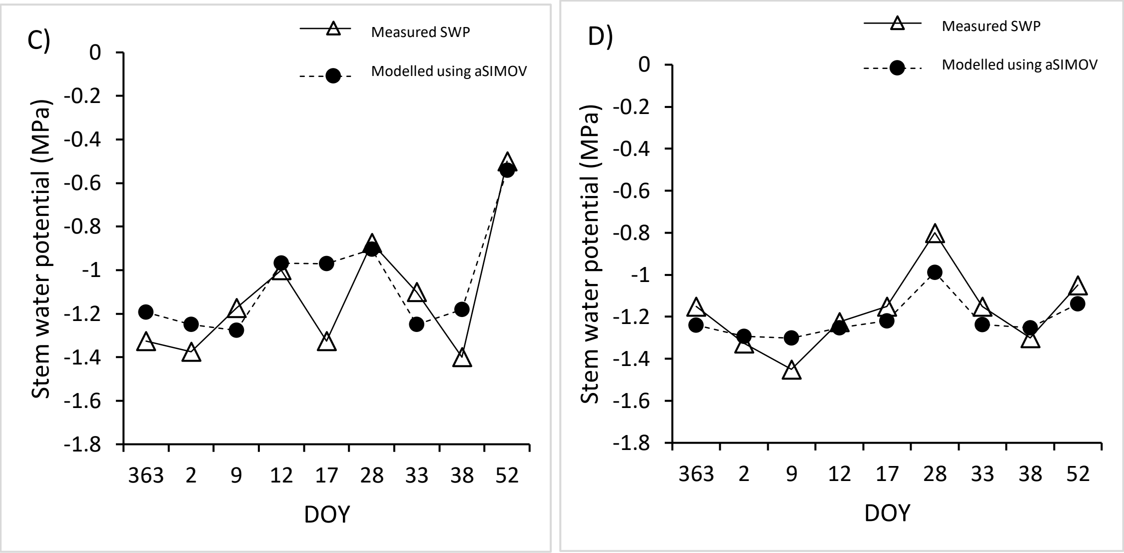
Figure 7. Relation determined between Crop Water Stres Index (CWSI) and Stem water potential (SWP).



were: were; A) MI-2H0, B) Asimov-based data to predict Stem water potential (SWP) and CWSI: Crop Water Stress Index

Figure 8. Stem water potential (SWP) measured and modeled with aSIMOV





were, A = corresponds to Level 1; B = Level 2; C = Level 3 and D =Level 4. Dotted line corresponds to average value for all study days

Discussion

General Considerations: Some indications based on literature

Numerous investigations have reported the use of low-cost sensors for monitoring and automating measurements that are traditionally performed by humans. The experiences evaluated address a wide range of possibilities to enhance productivity, especially considering the alarming climate change and scarcity of water (Bouwer, 2000; Falloon & Betts, 2010; Jury & Vaux, 2007; Mueller et al., 2012; Postel, 2000; Saleth & Dinar, 2000). This context has demanded new and improved methods for modern agricultural practices based on automation and intelligent decision-making systems such as wireless ad-hoc and sensor networks (Karim et al., 2013; Mirabella & Brischetto, 2011; Ojha et al., 2015; Priyadarshi et al., 2020; Srbinovska et al., 2015; Venkata Krishna et al., 2012; L. Zhao et al., 2013). Moreover, the improvements shown by the development of sensors oriented to establish precision agriculture strategies to increase the efficiency of agro-industrial processes, has enabled rapid adoption of these technologies (Jawad et al., 2017). Most of the WSN low-cost applications in agriculture have been oriented to the automation of processes (Christin et al., 2010; Ratnakar & Rao, 2018) as well as the development of sensors that carry out direct measurements of temperature, luminosity, gases, soil moisture etc. (Al Rasyid et al., 2017;

Hamouda & Elhabil, 2017; Mat et al., 2017). In this sense, thermal sensors have received special attention (Moribe et al., 2018; O'Shaughnessy & Evett, 2010) due to their effectiveness in detecting crop water status, providing the crop stress level based on canopy-air temperature differences (Mahan et al., 2010; Mahan & Yeater, 2008). However, the handling of thermal sensors is not trivial because they require exhaustive tests that demonstrate the precision of the measurement being made, before being integrated into mobile devices (O'Shaughnessy et al., 2011). To carry out this research work, the integration of multiple methodologies found in the literature was considered, which allowed the establishment of a quality control system that ensured that the sensors that reached the field appropriately measured radiometric surface temperature (Bugbee et al., 1998; Kalma et al., 1988). In relation to the above, the first step that must be taken into consideration is the verification of the measurement made by the thermal sensor, a measurement that is verified by using a BB (O'Shaughnessy et al., 2011). However, this device is insufficient, because the ambient temperature must also be varied, thus simulating the final variations that the sensor will face under field conditions. This methodology is also applied to non-refrigerated thermal cameras to evaluate the effectiveness of their measurements (Ribeiro-Gomes et al., 2017). Secondly, the literature suggests conducting tests under real operating conditions, and this in contrast to reference devices will allow obtaining greater certainty of the quality of the measurements that are being made. For our research, it was extremely important to evaluate each of the integrated thermometers in the nodes deployed in the field because for the eight sensors evaluated, one presented manufacturing problems. This fault was detected in time and the thermometer was replaced thanks to the strict protocol that was followed. Once these actions have been carried out, the thermal sensor is ready to be integrated into a field device, considering of course an appropriate isolation to the environmental conditions so that the housing does not interfere with the sensor's field of vision.

Specific indications: Communications and power consumption

Another factor that must be taken into consideration corresponds to wireless communications; in our case we use the Zigbee Wireless Protocol, which is considered one of the best candidate technologies for the agriculture applications (Jawad et al., 2017). Some of the most important advantages of the ZigBee wireless protocol corresponds to its capacity to preserve energy by switching between active and sleep states (Xiao & Li, 2020), reason why power consumption can be minimized, and the battery lifetime of sensor nodes can be extended. On the other hand, this system allows to establish different communication topologies in a simple way, which allows any user with a medium training level to program a network. Therefore, it was decided to integrate this communication system to the sensor developed to provide the system with the ability to simultaneously establish communication between its components. In our investigation we used the module Xbee S2B because of its adequate range/price ratio. Numerous experiences using these devices can be found in the literature, especially in applications oriented to precision agriculture (Mueller et al., 2012). Despite the positive comments reported in the literature, in this particular case it is important to note that the Xbee S2B can significantly vary its communication range due to local operating conditions (Usha Rani & Kamalesh, 2015), therefore it is extremely important that communication antennas have a direct line of sight with respect to each other, otherwise the range can be reduced up to 30% according to our communication tests (data not shown), being affected by the metallic structure that supports the vineyard as well as the plant's own canopy. Additionally, it is important for the reader to consider that due to the rapid advancement of technology there are other alternatives to establish wireless communication systems. An example of this is Narrow band (NB) IoT technologies, such as Long Range radio (LoRa), due to low power consumption and preferably used when the agricultural information are to be transmitted over long distances (Jawad et al., 2017). This technology offers the opportunity to improve this sensor or other future developments by integrating this receiver, which costs a fraction of the Zigbee antennas. Regarding GPRS communication, it is important to point out that during the performance of this work, a high intermittence was obtained in sending data, with the system being disconnected from the network most of the time. This was due to the low coverage that telephone companies have in rural sectors, a situation that has systematically hindered the implementation of these technologies at the field level in the central area of our country. Therefore, it is suggested to resort to other technologies and network topologies that allow direct access to local routers that upload the information through home networks that have a much more stable connection over time, in order to have a constant stream of information without interruptions. Another critical factor reported in the literature for the development of wireless sensor networks corresponds to current consumption. In this sense, our work suggests the use of simple low-consumption microcontrollers to prioritize the energy efficiency of the device. In the same way, it is suggested (whenever possible) the integration of solar charging systems that significantly increase the autonomy of the devices (Sharma et al., 2019). However, it is recommended to be careful in sizing the electrical needs of the device because solar energy is not constant and has a very intermittent nature at field level. If the above is rigorously evaluated, solar energy corresponds to an attractive alternative to provide autonomy to sensors deployed in the field.

Stress index computations

For the calculation of the CWSI this study had initially considered the original formulations of this index that required data from T, HR and To. This analysis was possible because in a complementary way the sensor was originally equipped with a thermohygrometer that was located inside the foliage. However, after analyzing the results, the direct estimation of the CWSI was chosen using only the infrared temperatures measured at the foliage level. Although the temperatures were able to respond to the different ranges of potential stem water, the same did not happen with the air temperature or with the relative humidity at the canopy level, values that were erratic and did not show any relationship with the applied water treatments. According to what was observed in the field, the authors of this study observed that the high number of sulfur applications with nebulizers carried out in all the water replacement treatments affected the microclimate behavior at the foliage level and were also a continuous source of damage for the thermo-hygrometers installed at the canopy level, which is why their use was discarded.

However, despite the difficulties indicated, the results obtained by this research are similar to those obtained in the literature when the CWSI was used to determine the water status.

Final considerations

Finally, is important to highlight that an appropriate crop monitoring requires sophisticated approaches to integrate information across temporal and spatial scales. The advances of technology in automated data collection have enabled higher spatial, spectral, and temporal resolution at a geometrically declining cost per unit area (Akyildiz et al., 2002). Satellite and airborne sensors are also useful in observing large areas, however, for massive use, its high cost is still a limitation, as well as the need to have specialized personnel for its operation. For this reason, despite the difficulties in the implementation of low-cost devices, their application on a farm scale would allow addressing the problem of cost and allow considering spatial variability, making this solution more attractive than conventional remote sensing techniques

Conclusions

This research was developed with the objective of evaluating the effectiveness of a spatialized network of low-cost infrared thermometers to calculate the Crop Water Stress Index (CWSI) to monitor in a spatialized way the water status of the vine. First, the MLX90614 inexpensive infrared thermometers were evaluated under controlled conditions using a black body. The tests carried out demonstrated the precision of these devices, however, this study emphasizes that the use of low-cost sensors must be carefully evaluated before their implementation in the field. Additionally, as suggested by the literature, a test was carried out under real operating conditions on a grass surface for a period of one week, comparing low-cost sensors versus an Apogee Instruments brand infrared thermometer. In this situation, similar results were also obtained, which is why the subsequent stage consisted in the integration of these thermometers to the spatialized devices that would be installed in a commercial vineyard. Once the thermometers were integrated into the autonomous devices that were mounted in the field, a test was carried out that simultaneously evaluated the temperatures obtained by the spatially distributed devices, as well as the measurements obtained from a commercial infrared radiometer. For the above, different ranges of water replacement were carried out in small plots at the field level with the objective of obtaining measurements of canopy temperature in plants with different water status to allow the estimation of the CWSI. However, due to the local conditions of the vineyard, the more restrictive treatments could not be differentiated when their water potential values were analyzed. Subsequently, the Tc-Ta / water potential relationship was evaluated both for the temperatures obtained from the spatialized device, as well as for the manual radiometer. The results showed that for the commercial sensor an R^2 of 0.62 was observed. On the other hand, in the case of low-cost sensors, the observed result was 0.65. Then we proceeded to calculate the CWSI / Potential relationship. In the case of the commercial sensor, an R^2 of 0.71 was observed, while for the low-cost sensor, an R^2 of 0.72 was observed. Finally, taking into consideration the model developed for the low-cost CWSI / water potential sensors (Predicted SWP_Asimov = 0.4756 * (CWSI) ^ 2-0.9721 * CWSI-0.8067), a simulation of the SWP was performed, which was compared with the real measurements obtained at the field level. Given the above, it can be concluded that it is posible to estimate vine water status through the use of low-cost temperature sensors.

Author Contributions: Fernando Fuentes-Peñailillo and Samuel Ortega-Farias conceived and designed the experiments and wrote the original manuscript draft., Cesar Acevedo-Opazo, Miguel Araya and Marco Rivera contributed extensively to results interpretation and discussions and editing of the manuscript. All co-authors contributed valuable information to the final version.

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Fourth Part

Discussion, perspectives and general conclusions

General discussion and future perspectives

Answer to the general problem of the thesis

The main objective of this thesis aimed to determining actual water consumption (ETa) and water status over a drip-irrigated vineyard, using information obtained from remote sensing and spatialized wireless sensor networks (WSN). For this, the hypothesis was proposed according to the knowledge of the spatial variability of water consumption and water status of the vineyard.

To analyze whether the problem addressed in this thesis has been effectively answered, it is worth mentioning the scientific questions that were posed at the beginning of this document.

I) Is it possible to use traditional image segmentation algorithms to identify objects of agricultural interest in digital images?
II) Is it possible to accurately estimate the water consumption of the vine using the Shuttleworth and Wallace model and thermal images?
III) Are inexpensive spatialized sensors an effective tool for determining grapevine phenology stages?
IV) Are inexpensive spatialized sensors an effective tool to determine the water status of the vine?

In the first place, it is important to mention that the research questions were segmented by spatial scale to give an adequate structure to the development of this work. While research questions I and II corresponded to the analysis of data obtained from remote sensing, questions III and IV corresponded to the development and implementation of low-cost sensors sensor networks in order to predict phenological development and plant water status.

The question addressed in the first chapter of this research work is of great relevance for this and future research. As mentioned above, digital images are becoming more and more relevant in the study of the characteristics of crops. In this sense, various sensors are used to carry out this task, such as multispectral, thermal and RGB sensors located on aerial platforms. However, in discontinuous crops such as vineyard, it is extremely important to be able to carry out an adequate segmentation of the objects in order to extract the pixels corresponding only to the canopy of the vineyard. Conventional sensors such as thermal cameras do not allow an adequate segmentation of the vineyard canopy due to the spatial resolution of the sampling (which in our case corresponded to a pixel of 6 x 6 cm). This is a problem when it is desired to establish precision experimental devices that require a thorough process of extraction of temperatures from the foliage for calculations of indices such as the CWSI. Phenomena such as the porosity of the canopy are continuous sources of error since the mixture of pixels does not allow to obtain precise results from the experimental plots. Therefore, the literature has proposed the combination of sensors, for example, thermal cameras along with RGB sensors. RGB sensors have a higher spatial resolution at a much lower cost, which would eventually allow the generation of masks that can be used to accurately extract information from other layers of information. The RGB sensors used in our study were able to deliver information with a pixel size of 0.8 x 0.8 cm. Based on the RGB data obtained, this work also suggested the use of the Triangular Greenness Index (TGI) as well as two segmentation methods; k-means and Clustering Large Applications (CLARA) to accurately differentiate objects corresponding to ground shade and vegetation within the image.

The second research question tries to elucidate whether it is possible to know the water consumption of the vineyard using thermal images obtained from an unmanned aerial vehicle. In this chapter, once again, the knowledge generated in chapter I is used to segment thermal images in order to extract the information corresponding to soil and crop, eliminating information the corresponding to shade to implement the Shuttleworth and Wallace (SW) model to determine the water consumption of vineyard. The results of this chapter indicated that the method is capable of predicting with high precision the water consumption of the vineyard considering spatial variability.

The third research question in this work tries to resolve the question related to the possibility of accurately predicting the phenological development of the vineyard. As mentioned above, phenology is closely related to the water consumption of the vineyard, however traditional methods do not allow us to observe in detail the spatial variability at the farm level. Therefore, in this chapter the development of a low-cost spatialized network of temperature sensors was proposed that, by integrating two models obtained from the literature, was able to accurately predict the intrapredial spatial variability of the vineyard phenology.

The fourth research question is related to the prediction of the water status of the vineyard using low-cost sensors. As in chapter IV we know that the monitoring of the spatialized water status can be a highly demanding task for personnel and equipment, therefore, using the knowledge generated in the previous chapter, the design and implementation of a device based on temperature measurement was proposed to estimate the SWP of the vineyard by calculating the CWSI. The results of this investigation indicated that it is possible to use low-cost spatialized sensors to preset the foliage temperature with a high degree of precision and therefore achieve an appropriate SWP modeling.

Scientific originality of the work

This thesis proposed different types of original methodologies in the field of precision viticulture. The first contribution corresponded to the use of RGB images together with simple spectral indices and traditional segmentation methodologies to accurately identify the classes of objects corresponding to shady ground and vegetation, opening the possibility of using this information to mask more complex products such as data obtained from sensors multispectral and thermal. The second scientific contribution corresponded to the use of the Shuttleworth and Wallace model, which in combination with information from high-resolution thermal sensors allowed the vineyard's water consumption to be accurately determined considering spatial variability. Finally, the most relevant contribution of this work consisted in the development and implementation of low-cost spatialized sense sensor networks to predict the phenological development and the water status of the vineyard (SWP)

Ongoing and future work

The techniques and methods developed in this doctoral thesis made it possible to determine the consumption and water status of the vineyard using information obtained through remote sensors mounted on UAVs and low-cost sensors considering spatial variability. This was done by combining traditional analysis techniques together with new sensing and wireless communication technologies. It is also important to highlight that the integration of technologies and methods carried out in this work allowed the generation of two prototypes that are in the process of intellectual protection due to their impact and novelty and whose invention reports can be found in the Annex section.

The knowledge generated in this doctoral thesis can be used transversally in a wide range of crops and situations. In the first place, the proposed segmentation technique can be used for the isolation of objects in studies oriented to fruit trees where it is desired to isolate the individual canopies. In the same way, the SW model can be used in other row crops, however, an appropriate determination of the critical parameters to which the model is highly sensitive, such as leaf area index, stomatal conductance and available energy. Future developments oriented in this line will aim to develop models to predict these variables using information obtained from remote sensing, eliminating the dependence of this model on measurements that must be carried out at the field level. On the other hand, the greatest impact of this study could perhaps be reported in the use of low-cost spatialized networks to monitor variables of agronomic interest, where future technology will allow the integration of any sensor to determine spatially distributed variables. To achieve this, the implementation of new models, a greater number of sensors, higher capacity batteries, more robust communication systems and operator training must be taken into consideration. These mentioned points were identified by this research as the critical factors that currently limit the implementation of this new and attractive technology at the field level.

Fifth Part

General Conclusion

General Conclusion

The development of this doctoral thesis revealed that estimating the water consumption and water status of the vineyard using new technological tools is not trivial. In this sense, the main objective of this work was to determine the actual water consumption (ETa) and water status of a commercial vineyard, using information obtained from low-cost wireless sensor networks (WSN) and remote sensing (RS). Both techniques correspond to useful tools, however, they require important scientific contributions to enable their use at the field level, especially when the spatial component is incorporated. For this reason, the study of this variables requires the development of new methods and technologies to precisely study the different factors that affect the water behavior in vineyards. In this way, this doctoral thesis contributes to achieving the above through the implementation of remote sensing techniques and the development of new devices. Initially, this study explored different mathematical methods that, in combination with images obtained from remote sensing, allowed segmenting objects into digital images. The above presented a great utility for this research since it made it possible to use traditional uncooled thermal sensors to determine the water consumption of the vineyard. In this sense, the same segmentation used initially was used to separate soil and canopy to implement the Shuttleworth and Wallace (SW) model in order to determine vineyard actual evapotranspiration. The parameterization of the SW model indicated that model was able to estimate ETa with errors = 5%, root mean squared error (RMSE) = 0.37 mm day^{-1} and mean absolute error (MAE) = 0.27 mm day^{-1}. Also, values of LEi and Rni were computed with errors of less than 10% and with values of RMSE and MAE of less than 34 W m^{-2}. These results suggest that it is possible to directly estimate ETa using remote sensing information in combination with biomathematical modeling techniques. Additionally, this study explored the development of low-cost spatialized wireless sensors to study the water status of the vineyard. This was done due to the high cost of conventional techniques and the promising results reported in the literature by studies that have carried out technological integration of low-cost components. In the first place, a low cost WSN was developed to predict the phenology of the vineyard (parameter that was considered critical due to its relationship with water consumption). The results indicated that it is possible to accurately predict the spatial variability of grapevine phenology, however the integrated model within the device corresponds to the critical factor to make a good estimation of phenological development. The authors suggested the use of the GPV model because its formulation considers a wide database, which makes the model more robust compared to others. After validating the effectiveness of the WSN a second device was developed to predict the SPW. The device called aSIMOV made it possible to determine vineyard water status (SWP) with an R^2 equal to 0.72. The results of our research indicated that the low-cost WSN represents a new and innovative tool to study any phenomenon at the field level when it is desired to consider spatial variability. Finally, implementation of the remote sensing techniques and low-cost spatialized sensor networks could be a reliable tool for estimating the intraorchard spatial variability in vineyard water requirements and the factors that affect it.

Appendix

Appendix 1

INVENTION REPORT FORM: aSIMOV, Spatialized wireless system for monitoring the Vineyard (**S**istema **I**nalambrico Espacializado para el **M**onitoreo de la **V**id)

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1. **TITLE OF THE INVENTION**
   Enter a short, but technically accurate and descriptive title so that anyone with some experience in the field can train.

aSIMOV, Spatialized wireless system for monitoring the Vineyard (**S**istema **I**nalambrico Espacializado para el **M**onitoreo de la **V**id)

Brief Description:

The information needs to maximize productive factors in agriculture have not yet been fully covered. Visual observations of plant growth are traditionally carried out, which are extrapolated to the entire productive unit without considering the spatial variability of their crops. Some producers use high-cost sensors that measure a point on the farm and provide little information. Today, there is no solution that allows generating information at low cost and spatially distributed. aSIMOV aims to commercialize low-cost sensors that provide reliable and trustworthy information on the climatic variables that affect the quality and yields of fruit in a spatialized way in the fields. Trough the use of this system sampling times is reduced by more than 80% and agricultural management costs by 30%.

2. **STATE OF THE ART**
   To guide future background searches of your invention and thus, to be able to evaluate the patentability of your innovation, include those references that you know from works, documents, papers, technologies, or others, which contain relevant information; we ask you to include a brief description of this background.

An adequate water supply is as essential for the successful growth of plants as photosynthesis and other biochemical processes in carbohydrate synthesis and transformation into new tissues. An essential factor is the maintenance of a sufficient amount of water to sustain cell turgor and to allow the normal functioning of physiological processes involved in plant growth (Pallardy and Kozlowski, 2010). But these changes related to the water status depend on the species under study and on the severity, duration, and moment in which the stress occurs (Bradford and Hsiao, 1982). Water deficit is one of the most important factors that can potentially limit vegetative development, and when it becomes severe it reduces the foliar area, which reduces the interception of light and that, combined with stomatal closure, limits photosynthesis and the production of assimilates (Anne et al., 2008; Cifre et al., 2005; Herrero-Langreo et al., 2013). However, the use of controlled deficit irrigation requires constant monitoring of the water status of the soil or the plant to minimize risks (Williams et al., 2012). Irrigation scheduling is a methodology that allows defining the optimal level of irrigation to apply to a crop according to the water content in the soil, climate conditions and evolution of the vegetative growth of plants. Irrigation programming considers 3 stages, which include knowing the properties of the soil, observation and analysis of the plant and study of the climate. Irrigation control is commonly done through techniques that determine soil water content and estimates of atmospheric demand. However, currently it is also preferred to evaluate the water status of the plant through different physiological indicators because the plant considers all the conditions of its environment, that is, it integrates demand from the atmosphere and content of soil water. Usually, the evaluation of water requirements is carried out by estimating the evapotranspiration of the crop (ETa), whose methodology is standardized and defined in the FAO-56 Manual (FAO, 2006). For this, the reference evapotranspiration values (ETo) must be known, which is estimated from meteorological data obtained in a certain location; a value that is adjusted by the crop coefficient (Kc) that considers the growth cycle of the plant and its variation over time (Ellena et al., 2013; INIA, 2017). With this information, it is possible to calculate the amount of water that must be replaced by irrigation. ETo is usually obtained by daily meteorological variables (wind speed, solar radiation, air temperature and relative humidity) recorded by an automatic weather station (AWS) under reference conditions equipped with a thermometer, hygrometer, anemometer and pyranometer (Allen et al., 1998a; Campos et al., 2016).

The water status of the plant can also be evaluated by means of physiological indicators such as basal water potential, leaf water potential, stem water potential, stomatal conductance, sap flow and trunk diameter. These have the advantage of integrating climatic and soil conditions. Of those mentioned above, the one with the greatest sensitivity is the stem potential (Ψs), which is determined by means of a pressure chamber in leaves that are covered with a plastic sheet and aluminum foil, to balance the water potential of the plant with that of the leaf (Gálvez et al., 2011; Williams and Araujo, 2002). However, acquiring these indicators is an intensive work that consumes time and money and requires intrusive equipment and labor (Jones, 2004).

The third way to estimate irrigation needs is by determining the physical water parameters of the soil, which considers estimating the water content in the soil or soil moisture. The amount of water a soil can store will depend on its texture and structure. Water in this way is retained in the ground by an energy or tension and its value can be associated with the amount of water present in it. The plant in turn must overcome this tension to extract the water (Ellena et al., 2013).

In this regard, Table 2 summarizes the main advantages and disadvantages of the different methodologies for monitoring the water needs of plants.

Table 1. Main advantages and disadvantages of measuring water in the soil, water balance, plant water status and stomatal conductance for the programming of vine irrigation. Adapted from Jones (2004).

	Advantages	Disadvantages
I. Measurement of soil water Soil water content (e.g. TDR, FDR)	Easy to apply in the field; can be very precise; water content measurement indicates how much water to apply; many commercial systems available; some sensors already automated	Soil heterogeneity requires many (sometimes expensive) sensors or extensive monitoring programs; Difficulty selecting positions that are representative of the root zone; the sensors generally do not measure the water status at the surface level of the roots (which depends on the evaporative demand)
II. Calculation of the water balance (requires estimation of evaporation and precipitation)	In principle easy to apply; indicates how much water to apply	Not as accurate as direct measurements: you need accurate information on local rainfall; the calculation of evapotranspiration requires a good estimation of the crop coefficients (which depend on the development of the crop, depth of roots, etc.); Errors are cumulative, so regular calibration is required.
III. Detection of plant "stress"	Directly measures the plant's response to stress;	In general, it does not indicate "how much water"

	integrates environmental effects; potentially sensitive	to apply; requires calibration to determine "control thresholds"; still largely in the research / development stage and little used yet routinely in agronomy (except for thermal sensing)
(a) Water status of tissues (e.g., pressure chamber)	Widely accepted reference technique; more useful if stem water potential is estimated, using covered leaves	Slow and laborious (therefore expensive, especially pre-dawn measurements; unsuitable for automation
(b) Physiological response (e.g., stomatal conductance)	Potentially more sensitive than measurements of the water status of tissues (especially leaves)	Usually requires sophisticated or complex equipment; requires calibration to determine "control thresholds"
		Large sheet-to-sheet variation requires many replications to obtain reliable data

The FAO Penman-Monteith method is now recommended as the only standard method for the definition and calculation of reference evapotranspiration. This method requires data on radiation, air temperature, atmospheric humidity, and wind speed (Allen et al., 1998b).

The evaporation of water requires relatively high amounts of energy, either in the form of sensible heat or radiant energy. Therefore, the evapotranspiration process is controlled by the exchange of energy on the surface of the vegetation and is limited by the amount of energy available. To determine Evapotranspiration experimentally, specific equipmnet and precise measurements of various physical parameters or soil water balance are required. Field experimental methods are generally expensive, demanding precision in measurements, and can be fully performed and properly analyzed only by sufficiently trained research personnel (FAO, 2006).

Another widely used methodology to determine the water status of plants corresponds to the determination of the water potential, which involves measuring the pressure of the sap inside the xylem through a pressure chamber (Rodríguez-Pérez et al., 2018; Williams et al., 2012). This physiological variable can be obtained through leaf water potential (Ψleaf), stem water potential (Ψstem) and water potential before sunrise (ΨPD) (Acevedo-Opazo et al., 2010). However, under irrigation conditions it is preferred to use stem water potential, because it presents less variation between individual vine canopies compared to the leaf potential (Rodríguez-Pérez et al., 2007). In this regard, De Bei *et al.* (2011) mentions that the stem is considered a more stable and integrating measure of the water status of the plant compared to the leaf.

However, the measurement of water potential is tedious, slow, time consuming, destructive, and requires trained personnel (Acevedo-Opazo et al., 2008; Fang et al., 2017; González-Fernández et al., 2015; Rodríguez-Pérez et al., 2018).. Furthermore, this technique is characterized by presenting a low special representation at the field level, due to the limited number of possible measurements that can be taken per day. The limitations make it difficult to propose irrigation strategies that consider the special variability of an entire farm (Dhillon et al., 2018; Jones, 2004; Romero et al., 2018). Despite the foregoing, it is important to note that the approaches based on direct measurements of the plants provide significant advantages in monitoring the water status, since the plant is the best water indicator of the conditions of the soil-plant-atmosphere continuum.

Therefore, methodologies are required that allow evaluating any type of surface at lower investment costs. It is here where different alternatives arise that are based on the use of sensors to determine physical variables related to the water status of the plants. In recent years, a series of investigations have been carried out in order to develop low-cost sensors for agriculture. (Polo et al., 2015; Viani et al., 2017). Many of these electronic devices have focused mainly on the monitoring of micrometeorological variables of the plants (such as air temperature and relative humidity) and some others on the estimation of soil humidity variables. However, there are only a few sensors that have been developed for monitoring variables related to the water status of plants.

Among plant measurement-based approaches to determining water status, canopy temperature has received a lot of attention over the past two decades, especially with the advent of portable infrared radiometers and thermal imaging cameras. (Candogan et al., 2013; Meron et al., 2013; 2008). These sensors have been used at various scales of observation. The largest observation scale corresponds to satellite platforms, where, together with information on vegetation indices and meteorological data, they allow the study of the water status and water consumption of crops in larger areas. The main limitations of this observation scale are related to the size of the pixels or the spatial resolution.

The following scale of observation is represented by infrared sensors mounted on airplanes or unmanned aerial vehicles (UAV) where the frequency of visits can be more easily programmed according to the key phenological events of the vineyard. (Ballesteros et al., 2015; Gago et al., 2015; Gomez-candon et al., 2014; Hoffmann et al., 2016; Santesteban and S.F. Di Gennaro, A. Herrero-Langreo, C. Miranda, J.B. Royo, 2017; Turner et al., 2010; Zhao et al., 2016), thus overcoming the main limitation of satellite platforms. However, these technologies also present some limitations in their implementation at the field level, such as: cost of instrumentation (Huang et al., 2013), the logistics of the flight schedule (Gago et al., 2015), battery duration (Gómez-Candón et al., 2014), limited load capacity (Martínez et al., 2017) and data interpretation, in particular, how the information observed in the images is related to the water status of the plants and can be used as information for irrigation decision-making at the field level.

The last scale of measurement of the water status corresponds to the so-called "proxidetection" in which temperature records are made at the foliage level of the plant in the field. Through these sensors it is possible to precisely monitor the temperature of the canopy surface, which would be related to the measurement of the water potential, through the calculation of the so-called Crop Water Stess Index (CWSI) proposed by Idso, Jackson, Pinter, Reginato, & Hatfield, (1981); Jones, (2004).

This index has proven to be a useful methodology for evaluating the water status of plants of different agricultural species. Proof of the above is that it has been used in a wide variety of crops, such as: bermuda grass (Emekli et al., 2007), winter wheat (Yuan et al., 2004), corn (Irmak et al., 2000), sorghum (O'Shaughnessy et al., 2012), alfalfa (Hutmacher et al., 1991), tal fescue (Al-Faraj et al., 2001), cotton (Howell et al., 1984), sunflower (Erdem et al., 2006), broccoli (Erdem et al., 2010), red pepper (Sezen et al., 2014), watermelon (Orta et al., 2003), pistachio, olive trees (Agam et al., 2013), cítrus (Gonzalez-Dugo et al., 2014) and Vineyard (Bellvert et al., 2014). However, the traditional methodology proposed by Idso et al., (1981) has the following main limitations: i) for the calculation of the CWSI, the development of two baselines is required (baseline without water stress and baseline top) that are specific to each crop (Veysi et al., 2017) and ii) the difficulty of implementing a sensor network that adequately characterizes the spatial variability of the vineyard's water status with a high degree of precision at a reasonable economic and operating cost for the vine grower. To solve the last limitation, advances in new sensor technology have made it possible to implement low-cost wireless sensor networks (WSN)(Akyildiz et al., 2002), presented as a type of ad-hoc network that is autonomous, self-organizing, and comprised of tens, hundreds, or thousands of low-activity smart devices, generally powered by batteries (López Riquelme et al., 2009), which have many useful features for precision agriculture applications, such as: i) nodes can be arbitrarily deployed and adapted to the specific needs of each field, ii) fault tolerance, iii) they can be powered only by batteries or based systems in renewable energy and iv) relatively low cost (López Riquelme et al., 2009).

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López Riquelme, J.A.; Soto, F.; Suardíaz, J.; Sánchez, P.; Iborra, A.; Vera, J.A. Wireless Sensor Networks for precision horticulture in Southern Spain. *Comput. Electron. Agric.* **2009**, *68*, 25–35, doi:10.1016/j.compag.2009.04.006.

3. DESCRIPTION OF THE INVENTION (product or process) AND PROBLEM THAT IT SOLVES

Describe the characteristics of the invention that you consider to be “new”, the aspects that make it unique and not obvious, and how it can be applied in society or in the market. emphasizes those elements that make it different from known technologies in the state of the art; use drawings, diagrams, photographs and whatever means you deem pertinent to improve the description; be as long as you like.

aSIMOV consists of a mobile device of low-cost wireless sensors that are installed in agricultural fields and that send specialized information on water consumption and crop development status through radio frequency during the season. Through its software it generates automatic reports in the form of maps and interactive graphs, easy to read and with which the farmer can make productive decisions that help reduce costs, maximize resources, improve quality, and increase yields.

The device has 3 versions:

Version 1: This version is considered as the local version of the device which is capable of measuring variables such as: humidity, temperature, and infrared temperature. These measurements are stored on a microSD card in the same device.

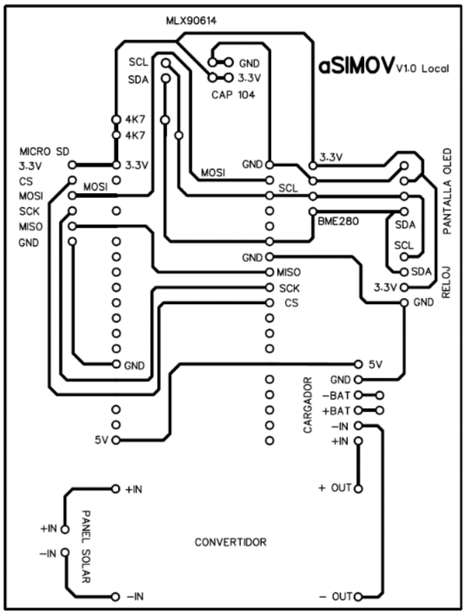


Figure 1. Electronic diagram of Version 1.

Version 2: This version is considered as the remote version of the device which is capable of measuring variables such as: humidity, temperature, and infrared temperature. These measurements, like version 1, are stored on a microSD card in the same device and are sent using the radio frequency using the 915Mhz band to another receiving device which connects to Wifi to upload the received data to the cloud.

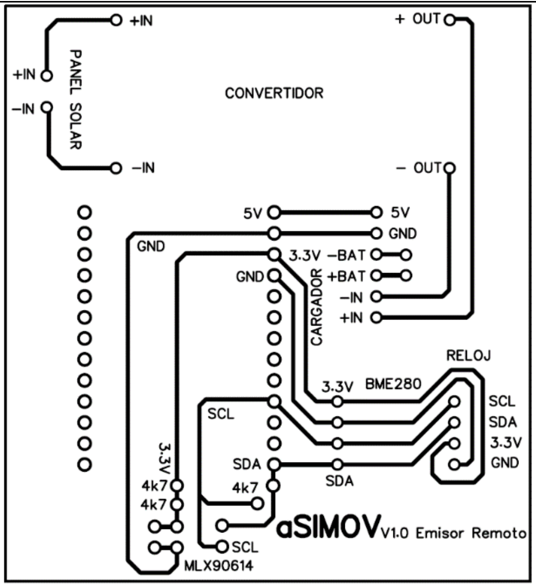


Figure 2. Electronic diagram of the remote transmitter

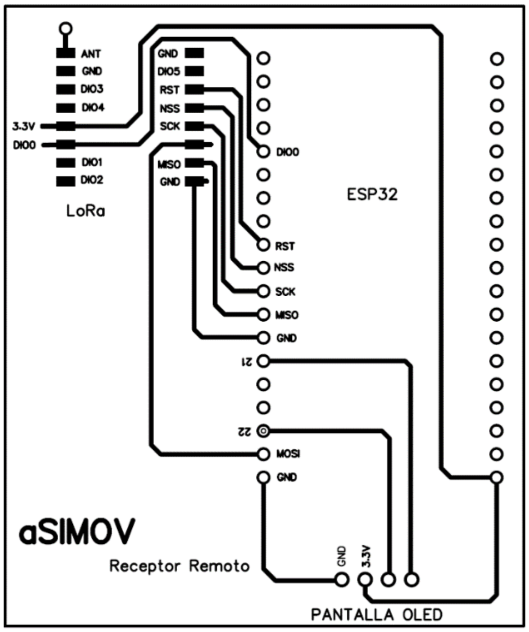


Figure 3. Electronic diagram of the remote receiver

Version 3: This version is considered as the GPRS version of the device which is capable of measuring variables such as: humidity, temperature, and infrared temperature. These measurements, like version 1 and 2, are stored on a microSD card in the same device and are sent using the GPRS signal directly to the cloud.

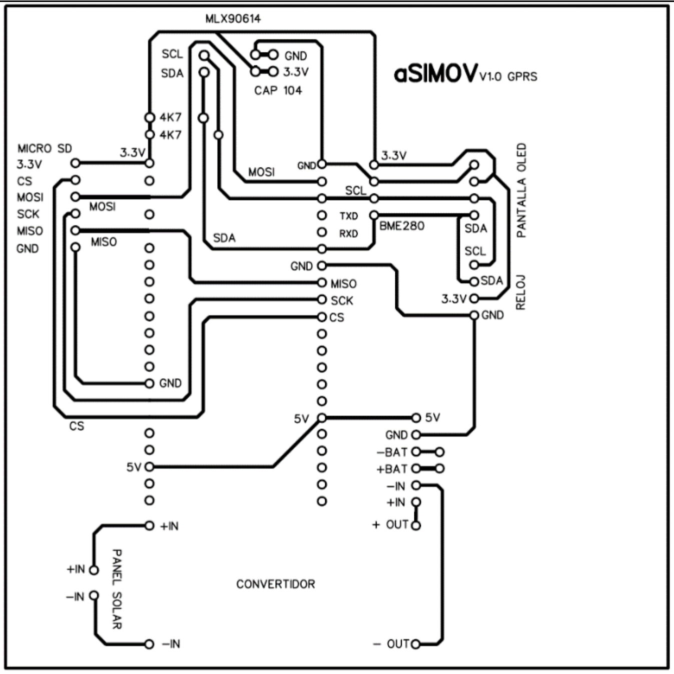


Figure 4. GPRS version electronic diagram

Description of the most relevant parts and components

BME280: Is a temperature, humidity and atmospheric pressure sensor specially developed for mobile applications and where size and low power consumption are key design parameters. It is a device with high precision and is perfectly feasible for low current consumption, long-term stability, and high robustness.

RTC DS3231 Real Time Clock: Allows obtaining time measurements in the time units (seconds, minutes, hours, days, weeks, months and years). It has an internal temperature compensated oscillator, which makes its precision remarkably high. The DS3231 incorporates measurement and temperature compensation guaranteeing an accuracy of at least 2ppm, which is equivalent to a maximum lag 172ms/day or one second every 6 days. Although our controller board has built-in an internal clock, it requires a Wi-Fi connection to be able to synchronize it with the local time, due to this, that is why it is chosen to incorporate an external clock since in the field where the station is installed it will be little feasible to have an internet connection.

Charger: It is a module that allows us to simultaneously load and unload the station together with the use of a solar panel.

Voltage regulator: Allows us to regulate the voltage delivered by the panel transforming its variable voltage into a constant one. For this case, the voltage is fixed at 5V.

TTGO LORA32 V2.1.1.6: It is a board that has the ESP32 microcontroller, the LoRa SX1276 chip and a 0.96-inch OLED screen integrated. In addition, it has a locker available to add a MicroSD card to it. The board allows us to communicate in different ways such as: Wifi, Bluetooth and LoRa (LoRaWan). For the development of this project, two boards will be used: a transmitter who will be in charge of collecting all the measurements from the connected sensors and then sending them through the LoraWan communication protocol which will be read by the receiver who will be using Wifi. the one in charge of uploading the collected medicines directly to the cloud. In order to save energy, thanks to the different configuration parameters of the board, it can be programmed in such a way that it only performs measurements of the data every x time when required and while not, it goes into deep sleep mode sent the plate to a state of hibernation which allows to reduce its consumption to only 10 uA.

4. ADVANTAGES OF THE INVENTION.

Identify, in comparison with the references given in point 2 above, which are the advantages and / or differences of the invention compared to the existing alternatives, or the deficiencies that it overcomes. identify, if any, the limitations your invention has.

aSIMOV will make it possible to identify problem areas within the field to manage them efficiently. Sampling times and costs can be reduced by more than 80% and the costs of excessive use of irrigation equipment, pesticides, and fertilizers by 40%. In addition, it will improve yield and quality at harvest. Traditionally, the irrigation status and phenological condition of the crop is analyzed with visual observations or plant-by-plant measurements, which means a high cost in time and labor, which makes it is impossible to monitor the entire field to characterize its productivity. Companies that have similar sensors, have high costs per equipment ($ 3,000,000 each) with equipments that offer less benefits than those delivered by aSIMOV.

5. TECHNICAL ASPECTS

a. STATE OF DEVELOPMENT OF THE INVENTION

Describe the state of development of the invention, including the current state of research:

☐ **LAB TEST**
☒ **PROTOTYPE**
☐ **PILOT PLANT**
☐ **IN VITRO TESTS**
☐ **IN VIVO TESTS**
☐ **OTHERS (Explain)**

b. EQUIVALENT, ALTERNATIVE OR REPLACEMENT TECHNOLOGIES.

Identify alternatives that develop the same features as those of your invention or solve similar technical problems

There are two companies that distribute and commercialize sensors, Wiseconn and Morpho, both correspond to the precision agriculture segment, but they serve less needs than those that our product covers. Their sensors have a high cost (3 million CLP each) and do not consider the variability of the field (they measure in a single point). Other companies offer satellite images or images from airplanes which have a high cost, complex logistics associated with flight scheduling, low sampling frequency and great difficulty in interpreting the information by the end user. Both Morpho and Wiseconn comprise about 12% of the national market. Morpho has its market focused on sensors for monitoring fruit trees in the V, VI and R. M. While Wiseconn focuses on the sale of meteorological stations in the national territory.

6. FINANCING ASPECTS

a. Indicate the sources of financing you used for the development of your invention. If it corresponds to public funds, indicate institution, date, assigned project and amount of the subsidy. If it corresponds to private funds, investors, or loans, identify, if possible, organization or person, date and amount of the funds committed.

Private funds and CORFO project Awarded by Doctoral Student

b. Is there an agreement or commitment regarding the participation in the benefits, profits, or intellectual property rights with third parties who have participated in the financing of the invention?

☒ NO
☐ YES. Identify the commitments and characteristics of it.

N/A

7. REGULATORY ASPECTS

Indicate if your invention is subject to any type of sanitary, safeguard, registration or other restriction that is necessary to identify and obtain as a requirement for the production or commercial exploitation of the invention.

Protection of the layout scheme or topographies of integrated circuits

8. COMMERCIAL ASPECTS

a. Indicate if there are previous agreements for the exploitation, commercialization or licensing of the ipr, with investors or project participants, or with organizations or companies interested in your invention; also, indicate if there are previous, developing or planned contacts to offer or transfer the invention.

There are no prior exploitation agreements

b. If possible, indicate the potential market -sized in money, demand and / or users- for your invention and the production or service capacity that you or whoever is interested in your invention have; if there is no production capacity, indicate the estimated time and money necessary to start the commercialization of the invention.

The focus will be on small farmers (<20 hectares defined by the INE agricultural census), who currently do not have tools for climate monitoring and the resources to invest in high-cost systems. They are located throughout the entire country, but are concentrated in agricultural regions, such as Maule. Small farmers are characterized by having low access to technology, either due to financial or cultural barriers, solving their production problems with their own knowledge. The market for small producers is then targeted. According to the National File prepared by ODEPA, of the total number of agricultural producers in the country, more than 74% fall into the category of small, being the Maule Region the third in terms of quantity, with about 31,000 small farms, which represents a surface area of almost 160,000 hectares. At the country level, the potential market would be around 221,000 small farmers, representing more than 1 million hectares (ODEPA, 2019). Worldwide, according to estimates using information from the FAO, it is estimated that there are 450 million farms of less than 20 hectares, which represents 98% of all agricultural holdings (Lowder, Skoet and Raney, 2016).

c. If possible, identify those companies that are or could be interested in your invention and those that produce or market equivalent technologies

This invention aims to target private companies (wine, fruit, and horticultural companies), mainly concentrated in the central valley. Then to small and medium farmers, through collaborative ties with government institutions (PROCESAL and INDAP). A second phase expects to expand sales nationwide and access other markets of interest. In the long term, it is expected to reach Latin American countries that need to improve water efficiency and productive management of crops.

9. PUBLICATIONS.

A. Has any aspect of the invention been published, presented at a scientific conference, fair or other?

☒ NO
☐ YES. Identify the dates and reasons for the posts.

Date	**Reason for publication**
27-08-2016	Fuentes-Peñailillo, F., Guerrero-Rivas J., Acevedo-Opazo C., Rivera-Abarca M., Ortega-Farías, S., Verdugo-Vasquez N., Fonseca-Luengo D., and Arraztio M. Development of a wireless spatialized system to monitor vine phenology. University of Talca research conference
29 Nov – 2 Dic 2016	Development of a wireless spatialized system to monitor vine phenology. 67º Congreso Agronomico http://67congreso.agronomia.uchile.cl/index.asp

b. Are there any plans to publish the invention in the future?

☐ NO
☒ YES. Identify the dates and reasons for the posts

Date	Reason for publication
30-12-20	Doctoral Thesis Fernando Fuentes, Article titled "Spatialized system to monitor vine phenology: Towards a methodology based on a low-cost wireless sensor network"

10. PROPERTY ASPECTS

a. The present invention was developed by the signatory inventor (s) listed below:

Full Name Inventor	Date	Participation percentage	Signature
Fernando Fuentes-Peñailillo	13-12-20	N/D	
Samuel Ortega-Farias	13-12-20	N/D	
Cesar Acevedo-Opazo	13-12-20	N/D	
Marco Rivera Abarca	13-12-20	N/D	
Ricardo Vega Ibañez	13-12-20	N/D	
Fabian Oyarce Valenzuela	13-12-20	N/D	

b. The present invention will be owned together with the University of him or the signatories indicated below *

Full name	Profession and Position	Company	Signature
Fernando Fuentes-Peñailillo	Ing. Agr. Dr. - Professor	Independent	
Samuel Ortega-Farias	Ing. Agr. Dr. - Professor	UTAL	
Cesar Acevedo-Opazo	Ing. Agr. Dr. - Professor	UTAL	
Marco Rivera Abarca	Ing. Elec. Dr. - Professor	UTAL	
Ricardo Vega Ibañez	Ing. Agr.	Independent	
Fabian Oyarce Valenzuela	Student	Independent	

*** Consider that the owners can be companies or people, including himself or the inventors, investors, employers, or others**

*** If shared ownership occurs, authorization must be requested from the Intellectual Property Committee**

This REPORT OF INVENTION was prepared by the signatory (s) indicated below. It is understood that all the information provided in this report is absolutely true, belongs to those who declare themselves as natural or legal persons who own the invention and includes all relevant data of the innovation, being responsible (s) who (is)) has (have) prepared this document, for all the information that they have voluntarily omitted and that may influence the final result of the evaluation that results from the analysis of this report.

(firmar aquí)---	**(firmar aquí)--**
Name: **Fernando Pablo Fuentes Peñailillo**	Name: **Marco Rivera Abarca**
Position: **PhD Student**	Position: **Professor PhD**
Profession: Agricultural Engineer, Mg. education, Mg. Horticulture, Dr (c)	Profession: Electrical Engineer Doctor Date: 13-12-20
Date: 13-12-20	

Appendix 2

INVENTION REPORT FORM: TELEMAP: "Computer platform for monitoring the water consumption of fruit trees and vines"

1. TITLE OF THE INVENTION

Enter a short, but technically accurate and descriptive title so that anyone with some experience in the field can train.

TELEMAP: "Computer platform for monitoring the water consumption of fruit trees and vines"

Brief Description:

Web service platform that allows clients and users to view variables and productive recommendations related to water management, based on the integration of complex bio-mathematical models in combination with the analysis of satellite images.

2. STATE OF THE ART

To guide future background searches of your invention and thus, to be able to evaluate the patentability of your innovation, include those references that you know from works, documents, papers, technologies, or others, which contain relevant information; we ask you to include a brief description of this background.

The scientific-technological basis of this proposal is the result obtained from the master's thesis “Implementation of a Two-Source Model for Estimating the Spatial Variability of Olive Evapotranspiration Using Satellite Images and Ground-Based Climate Data”. The novelty of this work lies mainly in its innovative methodology, which makes it possible to value free satellite images, obtaining from them a complex product of agricultural interest, through the implementation of validated and calibrated algorithms in Chile. In simple terms, we can say that this technique allows establishing site-specific management strategies to assess vigor and water requirements to improve the productive efficiency of orchards and vineyards. The previous work is carried out because a series of studies have indicated that the availability of water in the world will be reduced significantly and there will be strong competition between agriculture, industry, and urban areas (Ortega-Farías et al., 2009). In central Chile, a decrease in the level of rainfall has been projected that could vary from 20 to 40%, a problem that is accentuated periodically due to the "La Niña" phenomenon limiting the growth of the olive industry. For this reason, in the production of fruit trees there is a need to optimize the use of water and energy without affecting quality and yield. For this reason, the thesis proposed the use of the Shuttleworth and Wallace (SW) model to estimate the evapotranspiration (ETa) of an olive orchard, incorporating the use of climatic and satellite information, where the latter was used to calculate the parameters Net radiation (Rn) and soil heat (G), which, in combination with climatic measurements, allowed obtaining more precise estimates of ETa (also considering the effect of spatial variability). Additionally, it is important to mention that the model was technically validated in the USA, Spain, and Chile. For this, the performance of the implementation of the model on the use of satellite images was evaluated, the results of which were compared with high-precision meteorological stations (for each analysis area). To establish the feasibility of applying at the field level, the percentage of error was estimated for each analysis area, reaching levels no higher than 10%. This result can be considered optimal, since according to Allen et al., (2011): "For a methodology for estimating water consumption to be implemented at a practical level, its error must be less than 20% compared to a system of reference". Therefore, in the following project it is proposed that the current challenge consists of developing a computer system that integrates the analysis of free satellite images using the model proposed in this thesis, to prototype a service platform that allows to establish curves of water consumption for irrigation efficiently and thus be able to market it as a validated business model, capable of adjusting to the productive capacities of customers.

3. DESCRIPTION OF THE INVENTION (product or process) AND PROBLEM THAT IT SOLVES

Describe the characteristics of the invention that you consider to be "new", the aspects that make it unique and not obvious, and how it can be applied in society or in the market. emphasizes those elements that make it different from known technologies in the state of the art; use drawings, diagrams, photographs and whatever means you deem pertinent to improve the description; be as long as you like.

The service consists of offering farmers in the fruit sector a tool that allows them to know the water demand of their crops, in order to maximize irrigation efficiency and thereby reduce energy costs for water collection and distribution, as well as reducing costs in phytosanitary supplies due to the effect of reducing the risks triggered by excessive and inefficient irrigation, which increases the probability of proliferation of phytosanitary threats to fruit trees, considering that it reduces the available moisture on the surface, a critical factor for the development of infections in conjunction with temperature. The service will be packaged as a web platform that will allow segmenting the customer's area (s) of interest and adding reference points that facilitate their spatial location in the reading of satellite images obtained for free and processed with the bio-mathematical two-source model developed from the reference thesis and subsequently validated in Latin America, Europe, and North America. The computer system that supports the service is based on the processing and interpretation of free-access satellite images (Landsat 7 and Landsat 8) using the bio-mathematical model described above, technically validated in fruit trees located in various areas. The results of the application of this model were compared with the measurements of high precision meteorological stations near each evaluation point, obtaining results with error percentages that allow the model to be declared as validated, which guarantees the effectiveness of its use for the elaboration of Evapotranspiration curves (associated with water consumption) and vigor (associated with the condition of the plants). The main value proposition of the use of the platform that is sought to be prototyped is that it allows democratizing access to precision agriculture, since from small to large fruit producers they will be able to take advantage of a complex model of efficient estimation of water consumption, without investing in high-cost weather stations or in highly technological services that often involve excessive costs. The use of this platform is not only based on visualizing data but also allows access to an applied analysis of it and indications for their correct use through a system of automatic recommendations, which means that the farmer or his advisor will not only be able to have the data, but will also receive guidance to get the most out of them, in order to effectively maximize the efficiency of the water resource, with all the positive externalities that this entails at the environmental and social level, and the positive effects that this generates on the internal operation of each orchard by reducing energy and input costs. The fact of packaging the service as a platform allows projecting a scalable and replicable marketing model not only in Chile, but also anywhere in the world, so it is expected that once the platform has been commercially validated in Chile, it can be exported to other latitudes, first in Latin America and then the rest of the world, taking advantage of the promotion instruments for the export of services that today are available to national companies.

In addition, a brief description of the models on which this platform is based is attached.

Model 1: Shuttleworth and Wallace model

The partitioning of the instantaneous latent heat flux between the soil and canopy is described as follows:

$$LEi=Ti+Ei$$

$$Ti=Cc\,\frac{\Delta Ai+\left(\frac{\rho_a C_p\, D_i\, -\Delta r_a^c A_{si}}{r_a^a+r_a^c}\right)}{\Delta+\gamma\left(1+\frac{r_s^c}{(r_a^a+r_a^c)}\right)}$$

$$Ei=C_s\,\frac{\Delta A_i+\left(\frac{\rho_a+C_p+D_i-\Delta r_a^s(A_i-A_{si})}{r_a^a+r_a^s}\right)}{\Delta+\gamma\left(1+\frac{r_s^s}{(r_a^a+r_a^s)}\right)}$$

where LEi is the instantaneous latent heat flux (LE) computed from the SW model (W m^{-2}), Ti is the instantaneous LE corresponding to transpiration process computed from the SW model (W m^{-2}), Ei is the instantaneous LE corresponding to evaporation process computed from the SW model (W m^{-2}), Cc is the canopy resistance coefficient (dimensionless), C_s is the soil surface resistance coefficient (dimensionless), Δ is the slope of the saturation vapor pressure curve at the mean temperature (kPa $°C^{-1}$), Ai is the available energy leaving the complete canopy (W m^{-2}), A_{si} is the available energy at soil surface (W m^{-2}), C_p is the specific heat of the air at constant pressure (1013 J kg^{-1} K^{-1}), ρ_a is the air density (kg m^{-3}), D_i is the water vapor pressure deficit at the reference height (kPa), γ is the psychrometric constant (kPa $°K^{-1}$), r_a^a is the aerodynamic resistance between the canopy source height and reference level (s m^{-1}), r_s^c is the canopy resistance (s m^{-1}), r_a^s is the aerodynamic resistance between the soil and canopy source height (s m^{-1}) and r_s^s is the soil surface resistance (s m^{-1}).

Therefore soil heat flux (Gi) was estimated using the linear regression proposed by Ortega-Farias et al. (2010):

$$Gi=-38.5+0.25*Rni$$

where Gi represents the estimated values of soil heat flux (Wm^2) and Rni corresponds to estimated values of net radiation (Wm^2).

Model 2: METRIC Model

METRIC estimates ETa as a residual of energy balance applied to the land surface, where ETa is expressed in terms of net radiation, heat flux to soil and sensitive heat flux to the air.

$$\lambda \mathrm{ETa} = \mathrm{LE} = \mathrm{Rn} - \mathrm{H} - \mathrm{G}$$

where, ETa is actual evapotranspiration (mm d^{-1}); λ is latent heat of vaporization (J kg^{-1}); LE is latent heat flux (W m^{-2}); Rn is net radiation (W m^{-2}); H is sensible heat flux (W m^{-2}); G is soil heat flux (W m^{-2}); all values are instantaneous at the time of satellite overpass (11:30h local time).

Rn is estimated from albedo, surface temperature and information of image capture, considering basic radiometric and atmospheric corrections because the METRIC model is not largely affected by errors in these processes. G is estimated by empirical equations from the surface temperature, Rn, NDVI (Normalized Difference Vegetation Index) and albedo. H is determined from the general equation of heat transference (Equation 2).

$$\mathrm{H} = \frac{\rho * C_p * dT}{r_{ah}}$$

where, ρ is air density (Kg·m^{-3}); C_p is specific heat of air at constant pressure (1,004·J·kg^{-1}·K^{-1}); dT is the near-surface air temperature gradient; r_{ah} is the aerodynamic resistance to heat transport (s·m^{-1}).

LE is estimated as a residual of energy balance (Equation 1) and taken to instant evapotranspiration ($\mathrm{ETa}_{\mathrm{ins}}$) in units of mm h^{-1} (Equation 3), where λ (J kg^{-1}) corresponds to latent heat of vaporization.

$$\mathrm{ETa}_{\mathrm{ins}} = 3{,}600 * \frac{\mathrm{LE}}{\lambda}$$

To transform the instantaneous values of evapotranspiration to daily values (mm day^{-1}), the concept of evaporation fraction ($\mathrm{ET_rF}$) was used (Allen et al., 2007).

$$\mathrm{ET_rF} = \frac{\mathrm{ETa}_{\mathrm{ins}}}{\mathrm{ETr}_{\mathrm{ins}}}$$

Crop evaporation extrapolated to daily period $\mathrm{ETa}_{\mathrm{d}}$ is estimated through Equation 5, where $\mathrm{ETr}_{\mathrm{d}}$ is the reference evapotranspiration for the daily period obtained from the automatic weather station.

$$\mathrm{ETa}_{\mathrm{d}} = \mathrm{ET_rF} * \mathrm{ETr}_{\mathrm{d}} \qquad (5)$$

In practice, the ET_rF parameter it can be used in the same way as the classic crop coefficient, meaning it can be multiplied by ETr_d to obtain ETa_d in other time scales, in this study, by the entire season. The first step to integrate daily values of ETa to values per season (ETa_{season}) is interpolate each pixel-values of ET_rF for days of satellite overpass to generate values for every day in the season, not considering null-values due to the presence of clouds or out of range values of ET_rF.

This interpolation was done using a cubic spline which ensures a better fit to ET_rF curves. Finally, the sum of the all days of interpolated ETa maps (pixel by pixel), generates the ETa_{season} in mm season^{-1} (Fig. 1).

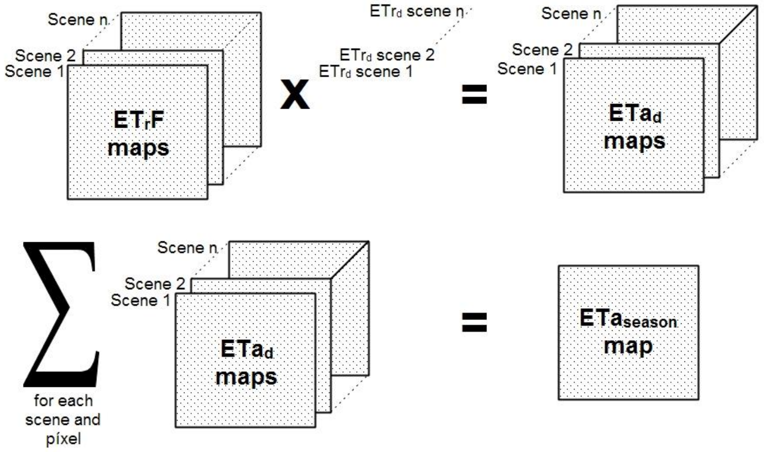


Figure 1. Conceptual diagram of ETa_{season} computational process.

4. ADVANTAGES OF THE INVENTION.

Identify, in comparison with the references given in point 2 above, which are the advantages and / or differences of the invention compared to the existing alternatives, or the deficiencies that it overcomes. identify, if any, the limitations your invention has.

The main technological advantage of the proposed service is that it delivers benefits that nowadays can only be achieved by assuming high investment amounts or by canceling services that require a technological deployment that makes them economically inaccessible to all farmers.

By doing the exercise of identifying and classifying competitors and substitutes, we can establish that there are:

Digital web or desktop platforms

Provision of services in the field

Specialized professional advice; and that on the other hand we can identify internal capacities based on high precision technological infrastructure and traditional methods for estimating agronomic parameters.

By comparing the benefits of the platform proposed in this project with each of the identified competitors and substitutes, we can establish as a central advantage the cost / efficiency ratio provided by the use of this platform, since if we group the lower cost alternatives (professional advice specialized and traditional estimation methods) we can affirm that the level of efficiency of these competitors and substitutes is considerably lower, since they use factors that increase the probability of error such as the Crop Coefficient (Kc). Unlike these alternatives, the proposed platform does not use any of these factors, since it is based on a bio-mathematical model (Shuttleworth-Wallace) that analyzes images obtained from the Landsat 7 and 8 satellites, which allows obtaining updated images every 7 days and considering fundamental factors that reduce the error rate, validating the practical application of its estimates; These factors are for example:

Net radiation (Rn)
Soil heat (G)
Field variables (Leaf area index), among others.

Regarding to platforms specifically, we can describe 2 of the highest diffusion in Chile: on the one hand, the SPIDER platform of CAPRA, dependent of INIA, which bases its model on the relationship of NDVI and Evapotranspiration, which increases its probability of error, further accentuated by the fact that it feeds on images that are updated every 16 days. On the other hand, we find the Satellite Agricultural Platform for the Monitoring of the Determination of the Water Requirements of the Main Crops of the Country, financed by FIA and a national FIC, which bases its model on the METRIC process, which has limitations in its commercial application. Regarding the most efficient alternatives (provision of services in the field and high precision technological infrastructure), these require costly and repetitive technological deployments during the season or high investments in physical assets, calibrations, and maintenance, which makes them economically unviable for most of the farmers in the fruit sector. Other relevant aspects to differentiate the value proposition are that the proposed platform is not designed only to display numerical data, but also considers a specialized technical assistance component through a system of recommendations based on the data obtained for each client, which allows to maximize the use of the service and not depend on external agents to analyze the information and design the associated action plan. This differentiation component must be based on a specialized technical support model dedicated to the operation of the platform and the correct implementation of the after-sales model.

5. TECHNICAL ASPECTS

a. STATE OF DEVELOPMENT OF THE INVENTION

Describe the state of development of the invention, including the current state of research:

☐ **LAB TEST**
☒ **PROTOTYPE**
☐ **PILOT PLANT**
☐ **IN VITRO TESTS**
☐ **IN VIVO TESTS**
☐ **OTHERS (Explain)**

b. EQUIVALENT, ALTERNATIVE OR REPLACEMENT TECHNOLOGIES.

Identify alternatives that develop the same features as those of your invention or solve similar technical problems

To facilitate understanding of the background, we have prepared a table that contemplates the main similar developments, considering the impact on the project, the rationale and observations made by the competing team:

Table: Main developments or similar publications

Document type	Basis	Impact on this report (+ or -)	APPOINTMENT OR WEB LINK	Observation
Publication ISI	Clumped model	+ since it can be incorporated as a complementary methodology	Poblete-Echeverría, Carlos & **Ortega-Farias, Samuel**. (2009). Estimation of actual evapotranspiration for a drip-irrigated Merlot vineyard using a three-source model. Irrigation Science. 28. 65-78. 10.1007/s00271-009-0183-y.	Scientific publication without commercial application to date Complex model, but interesting

				contributions to our proposal can be derived from it
Publication ISI	METRIC	+ since it can be incorporated as a complementary methodology	Carrasco-Benavides, Marcos & **Ortega-Farias, Samuel** & Octavio Lagos, Luis & Kleissl, Jan & Morales-Salinas, Luis & Kilic, Ayse. (2014). Parameterization of the Satellite-Based Model (METRIC) for the Estimation of Instantaneous Surface Energy Balance Components over a Drip-Irrigated Vineyard. Remote Sensing. 6. 11342-11371. 10.3390/rs61111342.	Scientific publication without commercial application to date
Proyecto: Irrigation SAT	METRIC	+ since it generates knowledge that can be incorporated into the project	http://www.citrautalca.cl/irrigationsat/	Research project with no commercial application to date. It is also important to indicate that to date it is not operational
Platform INIA: SPIDER-CAPRA	Based on NDVI-ET Ratio	-Direct competitor	http://maps.spiderwebgis.org/login/?custom=capra&lang=es	Direct competitor, however, NDVI does not properly

				explain water consumption (Platform not commercially developed, in the process of validation). Application on annual crops.
Platform: OPIA	METRIC	- Direct competitor	https://www.opia.cl/601/w3-article-89961.html	Direct competitor, however, METRIC is commercially restricted (Platform not commercially developed). Currently used to advise on annual crops.

***The members who have participated in the completion of this doctoral work are highlighted in bold**

6. FINANCING ASPECTS

a. Indicate the sources of financing you used for the development of your invention. If it corresponds to public funds, indicate institution, date, assigned project and amount of the subsidy. If it corresponds to private funds, investors, or loans, identify, if possible, organization or person, date and amount of the funds committed.

Private funds and CORFO project Awarded by Doctoral Student

b. Is there an agreement or commitment regarding the participation in the benefits, profits, or intellectual property rights with third parties who have participated in the financing of the invention?

☒ NO
☐ YES. Identify the commitments and characteristics of it.

N/A

7. REGULATORY ASPECTS

Indicate if your invention is subject to any type of sanitary, safeguard, registration or other restriction that is necessary to identify and obtain as a requirement for the production or commercial exploitation of the invention.

Invention patent

8. COMMERCIAL ASPECTS

a. Indicate if there are previous agreements for the exploitation, commercialization or licensing of the ipr, with investors or project participants, or with organizations or companies interested in your invention; also, indicate if there are previous, developing or planned contacts to offer or transfer the invention.

There are no prior exploitation agreements

b. If possible, indicate the potential market -sized in money, demand and / or users- for your invention and the production or service capacity that you or whoever is interested in your invention have; if there is no production capacity, indicate the estimated time and money necessary to start the commercialization of the invention.

More and more markets can enjoy Chilean fruit, and with this, new challenges are presented for producers and exporters. Fifty years ago, Chile had 52 thousand hectares of fruits, which have increased, currently reaching 310 thousand hectares. Now, if we refer to the surface occupied by crop, we can point out that the panorama is changing. Although table grapes are still an important crop, with around 48 thousand hectares, the cultivated area is decreasing since it reached almost 54 thousand hectares. The same has happened with apples, also in decline, with 36 thousand hectares, although both are the main export fruits of Chile. However, the surface of other crops, such as walnut trees, with 31 thousand hectares, avocado, with 30 thousand hectares, cherry trees, 25 thousand hectares, blueberries, 16 thousand hectares and European hazelnut, with 14 thousand hectares, is growing rapidly. In 2000, Chile exported 1.44 million tons of fruit with returns to the country of the order of USD 1.35 billion. In 2014-2015 there was a sharp drop in volumes of exported fruit, mainly due to weather issues, and in 2015 there was a drop in returns, reaching USD 4,400 million, which were later recovered in 2016 and 2017, reaching 2, 84 million tons this last year, with a 5% growth and returns in foreign currency to the country of the order of 5,280-5,300 million dollars with growth of 4-5%. Regarding the vineyards, in Chile there are almost 400 vineyards that are dedicated to the production of wine, of the most different varieties and qualities. It is an increasingly sophisticated industry, where making profits is not easy. But the high number of competitors is not synonymous with low concentration. In fact, only eight economic groups concentrate more than 60% of the production of wine that is exported abroad, that is, without considering domestic consumption. These are the families: Guilisasti, Luksic, Claro, Solari, Chadwick, Larraín, Montes and Edwards, whose total sales exceeded US $ 940 million in 2014. In the first half of 2017, 54% of the 100 most important wineries in the country decreased their average value. Industry leader Concha y Toro showed a drop in both value and volume. This mainly because the world outlook has not been stable and relevant markets for Chilean musts have contracted. Such is the case in the United Kingdom, where Brexit and the consequent depreciation of the pound, knocked income down, and the average value per box fell 7% in the first half of 2017. In fact, of the 50 The vineyards that exported the most to Great Britain in this period, 27 showed a decrease in export value and 36 showed a drop in the average price. In this market, the value per box today is around US $ 22, well below the industry average. Chile, within the framework of work with the Ministry of Agriculture in 2010 (Fundación Chile, 2010), analyzed the Water Footprint (HH) indicator and established its estimation methodology as a possible future requirement by our export destination markets. Finally, regarding production trends, climate change, the lack of regulation of water rights in Chile and the drought that the country and the entire world is experiencing, make the agricultural sector begin to look for alternatives that reduce the high consumption of this raw material, without affecting its production.

c. If possible, identify those companies that are or could be interested in your invention and those that produce or market equivalent technologies

Previously, research studies have been carried out with companies of national relevance and government technology centers such as:

Viña Concha y Toro, through its research center (the most important vineyard in the country), Previous relationship: Execution of a FONDECYT project (in progress)

Viña San Pedro (Pencahue, Maule, Chile), Previous relationship: Execution of a FONDECYT project (in progress)

Agrícola Daniel Rojas e Hijos Limitada, Previous relationship: Irrigation programming

9. PUBLICATIONS.

a. Has any aspect of the invention been published, presented at a scientific conference, fair or other?

☒ NO
☐ YES. Identify the dates and reasons for the posts.

Date	Reason for publication
-	-

b. Are there any plans to publish the invention in the future?

☐ NO
☒ YES. Identify the dates and reasons for the posts

Date	**Reason for publication**
30-12-20	Doctoral Thesis Fernando Fuentes

10. PROPERTY ASPECTS

a. The present invention was developed by the signatory inventor (s) listed below:

Full Name Inventor	**Date**	**Participation percentage**	**Signature**
Fernando Fuentes-Peñailillo	13-12-20	N/D	
Samuel Ortega-Farias	13-12-20	N/D	
Alvaro Elgueda Labra	13-12-20	N/D	

b. The present invention will be owned together with the University of him or the signatories indicated below *

Full name	**Profession and Position**	**Company**	**Signature**
Fernando Fuentes-Peñailillo	Ing. Agr. Dr. - Profesor	Independiente	
Samuel Ortega-Farias	Ing. Agr. Dr. - Profesor	UTAL	
Alvaro Elgueda Labra	Estudiante	Independiente	

*** Consider that the owners can be companies or people, including himself or the inventors, investors, employers, or others**

*** If shared ownership occurs, authorization must be requested from the Intellectual Property Committee**

This REPORT OF INVENTION was prepared by the signatory (s) indicated below. It is understood that all the information provided in this report is absolutely true, belongs to those who declare themselves as natural or legal persons who own the invention and includes all relevant data of the innovation, being responsible (s) who (is)) has (have) prepared this document, for all the information that they have voluntarily omitted and that may influence the final result of the evaluation that results from the analysis of this report.

(firmar aquí)---	**(firmar aquí)---**
Name: **Fernando Pablo Fuentes Peñailillo** Position: **PhD Student**	Name: **Samuel Orlando Ortega Farias** Position: **Professor PhD**

Profession: Agricultural Engineer, Mg. Education, Mg. Horticulture, Dr (c) Date: 13-12-20	Profession: Agricultural Engineer, Doctor Date: 13-12-20

Appendix 3

Participation in other events not reported in the document during the completion of the Doctoral thesis.

https://www.scopus.com/authid/detail.uri?authorId=57193341909

Participacion en Congresos

Date	Activity	Title
November 17 - 20, Valdivia, Chile.	66º Congreso SACH y 13º SOCHIFRUT	Estimation of the evapotranspiration of an olive orchard using a double layer model integrating climate and satellite information
November 17 - 20, Valdivia, Chile.	66º Congreso SACH y 13º SOCHIFRUT	Analysis of the space-time variability of evapotranspiration on a regional scale.
24-26 October 2016. Concepcion, Chile.	CRHIAM INOVAGRI International Meeting	Analysis of the spatial and temporal variability of water consumption in a drip-irrigated vineyard and its dependence of different trellis system
24-26 October 2016. Concepcion, Chile.	CRHIAM INOVAGRI International Meeting	Hierarchical classification of different crops using medium and high spatial resolution images
29 Nov - 2 Dec 2016	67º Congreso Agronomico http://67congreso.agronomia.uchile.cl/index.asp	Development of a wireless spatialized system to monitor vine phenology
11-5-17	V Simposio de Energías Renovables Ener 17. https://www.youtube.com/watch?v=sZTFG4JsUQM&feature=em-upload_owner	Spatial variability of the water status of the plant
August 12-16, 2018. Istanbul (Turkey)	International Symposium on Water and Nutrient Relations and Management of Horticultural Crops. https://www.ishs.org/symposium/675	Estimation of vineyard evapotranspiration using multispectral and thermal sensors

		placed aboard an unmanned aerial vehicle
June 23 - 28, Thessaloniki, Greece, 2019	GiESCO	Evaluation of metric model to generate maps with spatial distribution of vineyard evapotranspiration

***The members who have participated in the completion of this doctoral work are highlighted in bold**

Participation in Seminars

Date	Activity	Exhibitor
15-10-15	Using temperature as an indicator of water stress	Carlos Poblete Echeverria
22-10-15	Experiences in the use of ICT in the agricultural sector: Situation in Latin America and Chile	Francine Brossard Leiva Oficial de Asuntos Económicos, Unidad de Desarrollo Agrícola de la CEPAL
27-10-15	Technology-management and markets for efficient and sustainable agriculture. "@SIMOV, System for specialized monitoring of vine development: practical tool for sustainable vineyard management"	**Fernando Fuentes-Peñailillo**, Ing Agr. Mg Educación, Mg Horticultura
27-10-15	Spectral Imaging: Theory and Practice	Mathieu Marmion, Spectral Imaging (SPECIM), Finland.
27-11-15	Carbon sequesting in the soil: sustainable management and mitigation of climate change	Dr. Erick Zagal (University of Concepcion)
10-12-15	Agrophysiological behavior of two crops adapted to severe conditions of salinity and excess boron	Dr. Elizabeth Bastias (University of Tarapaca)
8-3-16		
4-5-16	Ecophysiology and genetic improvement of crops before the paradigms of agriculture of the 21st century	Dr. Daniel Calderini (Austral University)
28-4-16	Climate change scenarios in the Maule region	**Dr. Luis Morales** (University of Chile)
10-5-16	Table Grape Berry Firmness: Questions and Challenges	Dr. Reinaldo Campos, U. Andrés Bello

17-5-16	Use of sensors and irrigation management in agriculture	Chris Lund, Ph.D. Stanford University
18-5-16	Transformation of landscapes into a biodiversity hotspot: Chile's contribution to global environmental change	Dr. Cristian Echeverría (University of Concepcion)
21-7-16	Evaluation of the carbon footprint in organic berry production	Dr. Alfredo Iriarte (University of Talca)
2-8-16	Irrigation technology: deep drop system	John Yates, (Deeproot distribution)
11-8-16	The study of transitions towards sustainability: perspectives and options for agricultural sciences	Dr. Laurens Klerkx (University of Wageningen)
21-10-16	Genetic analysis related to rice vigor traits in California-USA	Dra. Karla Cordero (INIA, Chile).
27-10-16	Towards aridization resilient fruit growing	Dr. Nicolás Franck (University of Chile)
4-11-16	Agricultural productivity and international trade	Dr. David Fleming, (SCIRO-Australia)
11-11-16	The chemistry of food	Dr. Ryan Elias, Penn State Universit-USA
17-11-16	Challenges and opportunities of global change in agriculture	Dr. José Luis Araus, (Barcelona University)
25-1-17	Capture of agricultural variables: technologies and applications	Dr. Dongryeol Ryu, (University of Melbourne)
26-1-17	Technology for gathering agricultural information and its applications	Dr. Matt Barden, (University of Talca)
3-5-17	Use of Semiochemicals for the management of fruit moths	Dr. Eduardo Fuentes, (University of Talca)
11-5-17	Etiology, epidemiology, and sustainable control of the main diseases that affect fruit trees and grapevines in Canada	Dr. José Ramón Úrbez-Torres (Summerland-Canadá)
6-7-17	Application of satellite and meteorological information for the management of water resources in agriculture	Dr. José Maria Tarjuelo (University of Castilla la Mancha) **Dr. Samuel Ortega** (University of Talca)

21-7-17	Foliar Application Strategies in Vines and their impact on their quality "and" Chemical Analysis of Musts and Wines	Dra. Teresa Garde Cerdán, Institute of Vine and Wine Sciences Logroño (La Rioja)
5-10-17	Protection of plant varieties	Dr. Hermine Vogel (University of Talca)
24-10-17	Regulation of atmospheric nitrogen fixation in legumes	Dr. Joachim Schulze (Göttingen University)
16-11-17	Israelite Weed Control Experience	Dr. Hanan Eizenberg y Dr. Yaakov Goldwasser, Universidad Hebrea de Jerusalén (Israel)
8-3-18	Productivity and Innovation at Farm Level	Johannes Sauer, Universidad Técnica de München, Alemania.

***The members who have participated in the completion of this doctoral work are highlighted in bold**

National-international competitions

Contest	Project title	Team	Status
Brain UC	Design of a wireless monitoring system for the spatialized study of crop phenology	**Fernando Fuentes-Peñailillo** Cesar Acevedo Samuel Ortega Marco Rivera Jorge Guerrero Martin Arraztio	Finalists (02-09-2015)

***The members who have participated in the completion of this doctoral work are highlighted in bold**

Diffusion and technology transfer

Date	Activity	Team	Status
11-09-2015	Institutional broadcast video recording aSIMOV	**Fernando Fuentes-Peñailillo** **Marco Rivera Abarca** Jorge Guerrero	Available in: https://www.dropbox.com/s/qtigt4aza1fv8ec/aSIMOV.mov?dl=0
08-10-2015	Workshop Doctorate program in Agricultural Sciences	**Fernando Fuentes-Peñailillo**	-
April 3-15, 2016	IFT Agro Fair 2016	**Fernando Fuentes-Peñailillo**	-

-	Irrigation Bulletin; Review of the main methods for control irrigation in agriculture	**César Acevedo Opazo** **Fernando Fuentes Peñailillo** Héctor Valdés Gómez	-
16-11-16	XII research and postgraduate conference	**Fernando Fuentes Peñailillo**	-
15-11-17	XIII research and postgraduate conference	**Fernando Fuentes Peñailillo**	-

***The members who have participated in the completion of this doctoral work are highlighted in bold**

Articles

Journal	Titulo del trabajo	Autores
R Journal. https://www.scimagojr.com/journalsearch.php?q=21100255423&tip=sid	water: Tools and Functions to estimate CropEvapotranspiration using Land Surface EnergyBalance Models incR. https://journal.r-project.org/archive/accepted/olmedo-ortegafarias-delafuentesaiz-etal.pdf	Federico Olmedo **Samuel Ortega-Farias** **Fernando Fuentes-Peñailillo** David Fonseca
Water. 5-year Impact Factor: 2.709. https://www.scimagojr.com/journalsearch.php?q=21100255400&tip=sid&clean=0	Evaluation of a two-layer model to estimate olive evapotranspiration using satellite images and ground-based weather data	**Fernando Fuentes-Peñailillo** Samuel Ortega-Farias Cesar Acevedo-Opazo David Fonseca-Luengo

***The members who have participated in the completion of this doctoral work are highlighted in bold**

Training

Training Agency	Topic
IDETEC	-Multicopter Operation

	-Processing and operation of data obtained from Multispectral and Thermal camera
Faculty of Agricultural Sciences	Introduction to programming in Matlab.
Faculty of Agricultural Sciences	Training in the use of Licor-6400. (Dr. Nicolás Franck, University of Chile)
Pix4D Training	Pix4D User Workshops SANTIAGO - CHILE
Dr. Miguel Angel Moreno (University of Castilla la Mancha)	- Geometric and radiometric calibration of the sensors (Special case of thermal cameras), - Products in 2D and 3D web environments - Correlations between the geomatic product and the earthly reality - Calculation of volume and biomass using high resolution images - Agisoft Metashape mosaicking software.

***The members who have participated in the completion of this doctoral work are highlighted in bold**

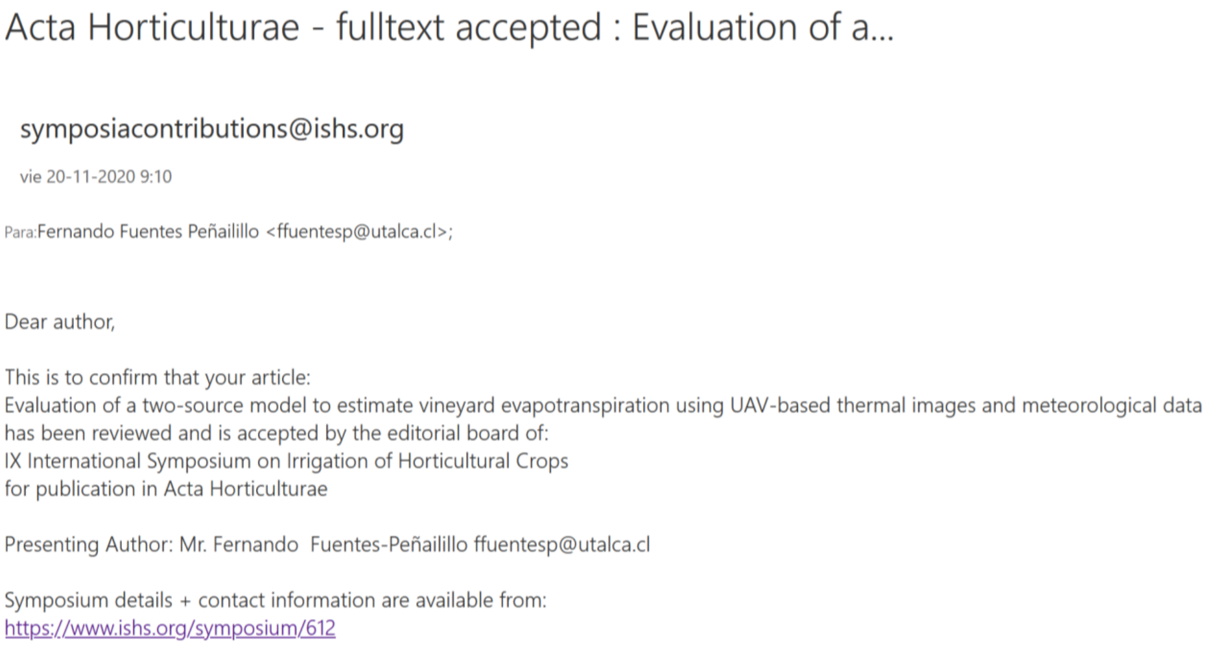
Software Creation

Name	Description	Objective
ANDES	Hyperspectral data analyzer. Program that includes computation of 334 spectral indices and has the ability to work automatically with SVC and ASD spectroradiometers	Processing of large volumes of hyperspectral information

Reviewer

Journal name	Organization	Sponsor
Journal of Unmanned Vehicle Systems Editorial Office	Canadian Science Publishing/NRC Research Press	Dr. Rocio Ballesteros

Appendix 4



Acta Horticulturae - fulltext accepted : Evaluation of a...

symposiacontributions@ishs.org

vie 20-11-2020 9:10

Para:Fernando Fuentes Peñailillo <ffuentesp@utalca.cl>;

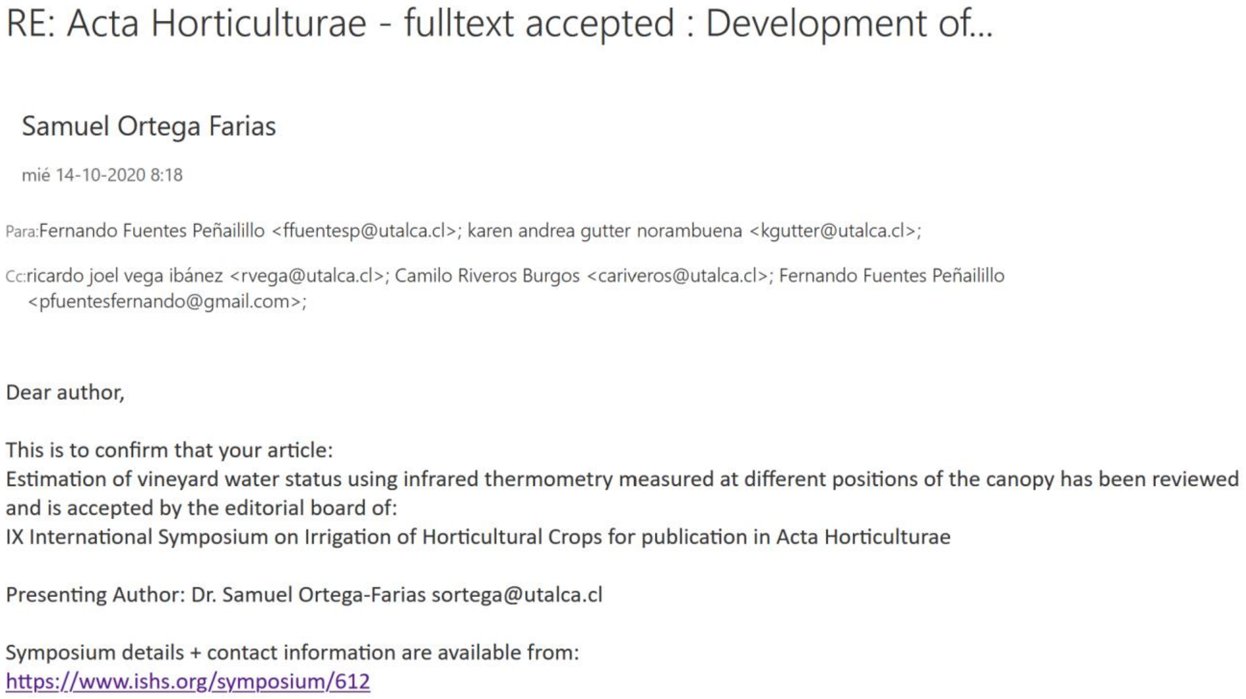
Dear author,

This is to confirm that your article:
Evaluation of a two-source model to estimate vineyard evapotranspiration using UAV-based thermal images and meteorological data
has been reviewed and is accepted by the editorial board of:
IX International Symposium on Irrigation of Horticultural Crops
for publication in Acta Horticulturae

Presenting Author: Mr. Fernando Fuentes-Peñailillo ffuentesp@utalca.cl

Symposium details + contact information are available from:
https://www.ishs.org/symposium/612

Appendix 5



RE: Acta Horticulturae - fulltext accepted : Development of...

Samuel Ortega Farias

mié 14-10-2020 8:18

Para:Fernando Fuentes Peñailillo <ffuentesp@utalca.cl>; karen andrea gutter norambuena <kgutter@utalca.cl>;

Cc:ricardo joel vega ibánez <rvega@utalca.cl>; Camilo Riveros Burgos <cariveros@utalca.cl>; Fernando Fuentes Peñailillo <pfuentesfernando@gmail.com>;

Dear author,

This is to confirm that your article:
Estimation of vineyard water status using infrared thermometry measured at different positions of the canopy has been reviewed and is accepted by the editorial board of:
IX International Symposium on Irrigation of Horticultural Crops for publication in Acta Horticulturae

Presenting Author: Dr. Samuel Ortega-Farias sortega@utalca.cl

Symposium details + contact information are available from:
https://www.ishs.org/symposium/612

Appendix 6

De: symposiacontributions@ishs.org
Asunto: Acta Horticulturae - fulltext accepted : Development of...
Fecha: 9 de octubre de 2020 a las 17:13
Para: rvega@utalca.cl, ffuentesp@utalca.cl, Karengutter@gmail.com, Albornoz.ignacio.gonzalez@gmail.com

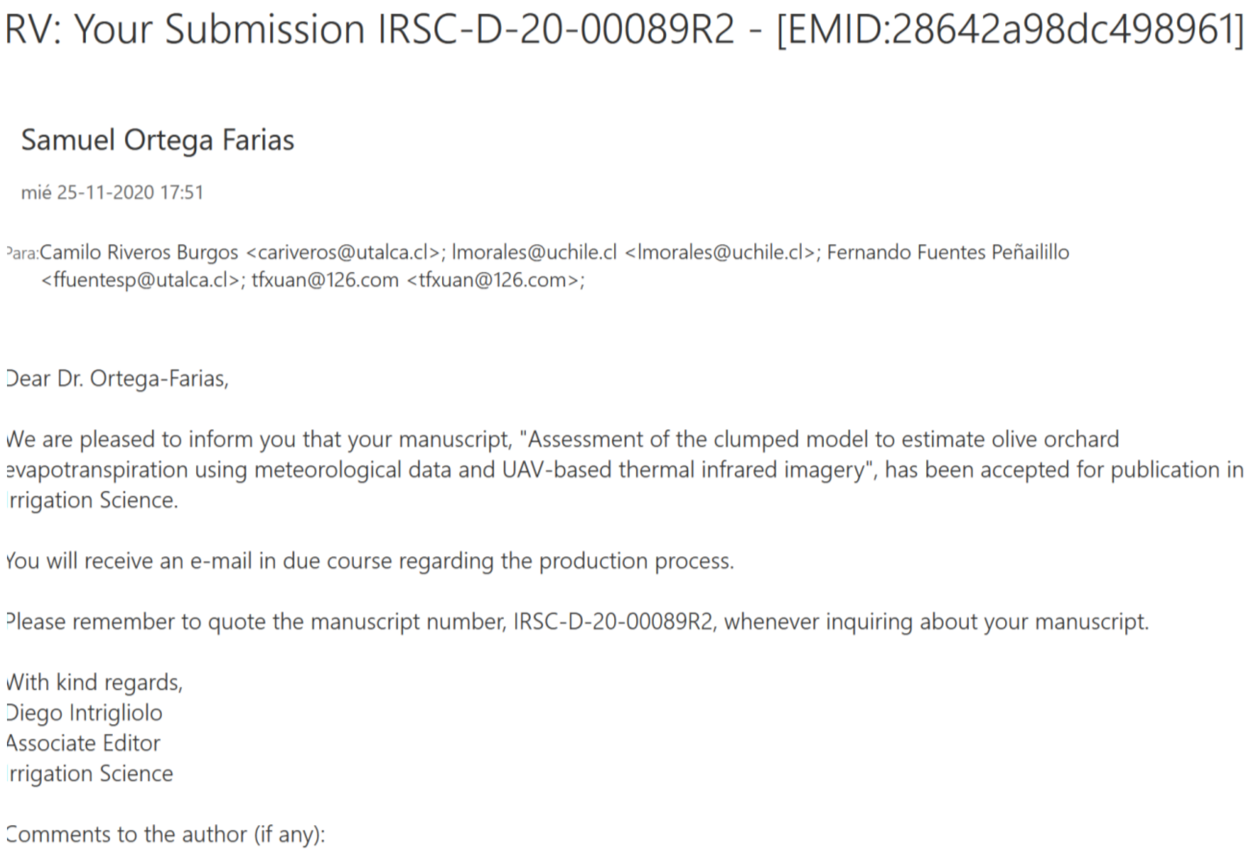
Dear co-author,

This is to confirm that the article:
Development of linear models to estimate vine water status using spectral indices
has been reviewed and is accepted by the editorial board of:
IX International Symposium on Irrigation of Horticultural Crops
for publication in Acta Horticulturae

Presenting Author: Dr. Samuel Ortega-Farias sortega@utalca.cl

Symposium details + contact information are available from:
https://www.ishs.org/symposium/612

Appendix 7



RV: Your Submission IRSC-D-20-00089R2 - [EMID:28642a98dc498961]

Samuel Ortega Farias

mié 25-11-2020 17:51

Para:Camilo Riveros Burgos <cariveros@utalca.cl>; lmorales@uchile.cl <lmorales@uchile.cl>; Fernando Fuentes Peñailillo <ffuentesp@utalca.cl>; tfxuan@126.com <tfxuan@126.com>;

Dear Dr. Ortega-Farias,

We are pleased to inform you that your manuscript, "Assessment of the clumped model to estimate olive orchard evapotranspiration using meteorological data and UAV-based thermal infrared imagery", has been accepted for publication in Irrigation Science.

You will receive an e-mail in due course regarding the production process.

Please remember to quote the manuscript number, IRSC-D-20-00089R2, whenever inquiring about your manuscript.

With kind regards,
Diego Intrigliolo
Associate Editor
Irrigation Science

Comments to the author (if any):