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A satellite-based ex post analysis of water management in a blueberry orchard

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ABSTRACT

In the scenario of current water scarcity caused by climate change and increasing water demand for food production, farmers must adapt their water management practices by shifting from supply-driven water management to demand-driven water management, considering trade-offs among quality, quantity and costs. Thus, agricultural practices must take full advantage of technology, research and development and adapt to local requirements. Nowadays, remote sensing is a useful tool for estimating crop water demand (evapotranspiration) as well as mapping their spatial and temporal variability. In this work, we present a new methodology that allows the user to audit (*ex post*) the irrigation strategies of a blueberry field in central Chile using a decision support system for irrigation decision called AquaSat® as the main tool. This tool combines satellite information with field data and provides spatially distributed information on crop water use for managing irrigation at a farm scale. The main contribution of this work is to detail a new approach for irrigation management through the comparison of volume of applied water, against evapotranspiration and potential demand. This procedure allows the user to audit current irrigation management and to determine the impacts on productivity.

From our results, we can conclude that the applied water levels used at the farm during both seasons throughout of the irrigation sector were insufficient to reach the potential blueberries yield.

1. Introduction

Freshwater demand and availability remain as two of the major problems associated with water resources management in agriculture (Grafton et al., 2018; Zhang et al., 2019). According to the Food and Agriculture Organization – FAO – of the United Nations (Food, A. Organization, 2009), world food production will need to increase by 70% to meet the food and nutritional demands of 9 billion people by 2050. In this scenario, agriculture faces critical global challenges: ensuring access to safe, healthy and nutritious food for a growing global population, and also requiring a sustainable use of natural resources to contribute effectively to the adaptation and mitigation of climate change (O. Publishing, Food, A. Organization, 2017).

Under higher climate variability and less available water, farmers must adapt their management practices to maximize yields while reducing water use and environmental impacts. As water demand will continue to increase while water resources become less available (water volume) or suitable (water quality), there is a need to tailor management practices to implement sustainable water management in agriculture, by shifting from supply-driven water management to demand-driven water management. To accomplish this paradigm shift, agricultural practices must take full advantage of available technology, research, and development to adapt to local requirements to estimate crop water needs in time and space as well as potential effects on yields and quality.

Information technologies (*IT*) in agriculture provide information to farmers and advisers to support management decisions, to reduce costs (water, energy, and fertilizers), and to increase crop yields (Schönfeld et al., 2018). *IT*-based tools assist decision-makers in establishing effective agricultural policies that help to reduce greenhouse gas emissions, regulate water rights, and estimate agricultural subsidies and insurances among others (Ciriza et al., 2017; Wolfert et al., 2017; Rivera et al., 2016).

Technological efforts must provide efficient economic solutions that

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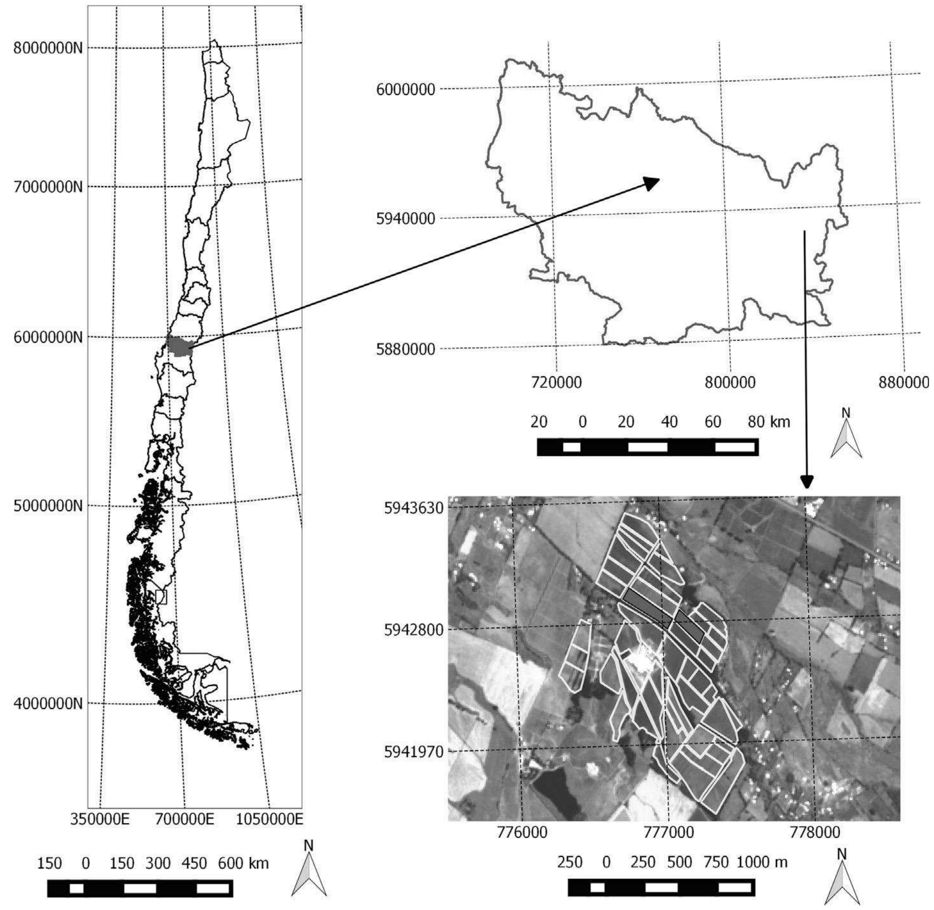


Fig. 1. Geographical location (Zone 19, Datum *WGS*84), where the study was carried out, corresponds to the field called Los Abedules, owned by CarSol Fruit S.A. (www.carsolfruit.cl), located in the Central Valley of Chile. The irrigation practices was carried out in sectors C-31 (*Brigitta*) and C-37 (*Legacy*).

are adapted to agriculture and its particularities. In this regard, Liang (2008) pointed out three aspects that should be considered in the design, use, and applicability of *IT*. First, agricultural activities are generally carried out on large areas of land, so field studies for land and soil characterization are time-consuming and, often, costly, especially in landscapes where there exists large spatial variability in soil and topography. Second, most crops have annual patterns with different stages of growth and development in different seasons of the year, so agricultural tasks (*e.g.* irrigation, fertilization, etc.) change over time. Third, human activities and management have strong effects –positively and negatively– on agriculture production.

Consequently, better irrigation management, *i.e.* timely providing the right amount of water to crops and orchards while maintaining water in the root extraction zone of the plant (Holzapfel et al., 2015; Stone et al., 2015), is a cornerstone to achieve sustainable agricultural systems. Technological developments on irrigation systems have made significant advances in recent years. New remote sensors, automation systems, and field sensors allow to reduce the gap between crop water demand and available water, based on data–driven decision making (Holzapfel et al., 2015; Trentacoste et al., 2015; Malik and Dechmi, 2019). Thus, implementing *IT* into agricultural systems allows for assessing irrigation efficiency and effectiveness that requires data of water use, evapotranspiration, soil, and water quality (Holzapfel et al., 1985; Jensen, 2007; Mateos, 2008; Bjornlund et al., 2009; Grafton et al., 2017; Alonso et al., 2019).

Current monitoring systems (both *in situ and remote), as well as increasing computational power for data processing and information management, make it possible to estimate the water demand for crops and orchards in a spatially and temporally distributed manner using satellite images (*Gavilán et al., 2019*;* Souto et al., 2019*;* Gonzalo-Martin et al., 2017*).*

Spatio-temporal estimations of water use allow for identifying homogeneous areas for site–specific irrigation schedules as well as auditing (*ex post* analysis) the irrigation strategies carried out by farmers, which allows for improving the water management in next farming seasons.

Information systems, which are developed to support decision-making, mainly focus on forecasting crop water demand (i.e. *ex ante* analysis). In this regard, Calera et al. (2017) reviewed several works using remote sensing to estimate crop water requirements and pointed out that the way information is provided to users is crucial for (perceived) usefulness. Moreover, they proposed integrating web-based *GIS* methodologies and mobile apps. Chirico et al. (2018) developed a system that forecasts crop potential evapotranspiration with a lead time of up to 5 days by coupling the visible and near-infrared crop imagery with numerical weather prediction outputs. The forecasts are delivered to farmers with a simple and intuitive web app interface which makes daily real-time crop potential evapotranspiration maps accessible from desktop computers, tablets, and smartphones. In Vuolo et al. (2015), the authors developed a satellite-based irrigation advisory system based on dedicated *webGIS*. They concluded that the crop heterogeneity captured by the high resolution images is considered as a valuable add-on information to identify the variability of soil texture and fertility, plant nutrition, or different performance of irrigation systems.

Moreover, satellite-based technologies which are used to estimate crop evapotranspiration could be used to *ex post* analysis to audit used water on crops versus applied water. Therefore, farmers are in positions to identify sectors or time-frames when irrigation quality becomes high or low. That information can be used to tailor irrigation strategies and for further *ex ante* analysis.

In this work, we present a new methodology that allowed to audit (*ex post* analysis) the irrigation strategies using a decision support system for irrigation decisions called AquaSat®.

This system combines satellite information with field data and provides spatio-temporal distributed crop evapotranspiration (ET_c), which is compared with the volume of applied water and potential demand (amount of water to attain maximum yields). A case study on blueberry irrigation in central Chile is presented to illustrate the potential of this novel approach.

2. Material and methods

2.1. Study site

The assessment of the current irrigation practices was carried out in a highbush blueberry (*Vaccinium corymbosum*) field called Los Abedules, owned by CarSol Fruit S.A. (www.carsolfruit.cl), located in the Central Valley of Chile (Fig. 1). The farm is composed of a blueberry orchard planted in 2006 (varieties *Legacy* and *Brigitta*), east–west orientation, with a frame of 3 m between rows and 1 m within the row, summing up to 3333 plants per hectare. Sector C-31 was planted with *Brigitta* and C-37 with *Legacy*. The monitoring period spans the 2011–2012 and 2012–2013 irrigation seasons.

The climate is warm and temperate with a 4-month period (December to March) without rain. The mean annual rainfall is 1025 mm. Pan evaporation reaches 1331 $mm\cdot year^{-1}$ with a monthly maximum of 245 *mm* in January and a minimum of 16 *mm* in June (http://www.inia.cl/zonificacion). The thermal regime of this zone is characterized by an average annual temperature of 14°C with an average maximum in the warmest month (January) of 28.8 °C and an average minimum in the coldest month (July) of 3.5 °C. The frost-free period is 5 months, from November to March. For a base temperature of 5 °C, the annual sum is 3300 $degree - days$; for a base temperature of 10 °C, the annual sum is 1600 $degrees - days$. The cold hours from March to December reach 1400 $degree - days$. The average monthly temperature remains above 8 °C with a variation in the annual thermal amplitude of 11.4 °C (www.meteochile.gob.cl).

The soil of the study area corresponds to an *Andisol Arrayan Phase II* series of silty soil. The average soil physical characteristics are 0.485 $m^3\cdot m^{-3}$ for field capacity, 0.255 $m^3\cdot m^{-3}$ for permanent wilting point, and 1.05 $Mg\cdot m^{-3}$ for soil bulk density. The main characteristic of this type of soil, which is derived from volcanic ash, is its high water retention capacity and the high infiltration rate (Valdivia-Cea et al., 2017; Holzapfel et al., 1988). The soil depth considered for the irrigation scheduling was the depth of effective root water extraction of 0.4 m, based on previous studies (Holzapfel et al., 2015) as well as the data collected by CarSol Fruit S.A.

The blueberries were irrigated by drip lines with two emitters per plant and a flow rate of 2.2 $L\cdot hr^{-1}$ each. Irrigation usually begins in the first week of October and ends in the last week of April. Daily irrigation was carried out in several pulses per day to meet the requirements of plant water based on the farm's experience.

2.2. Estimating water demands by AquaSat®

The AquaSat® is a decision support system developed by our research group during the last 5 years, which allows estimating crop evapotranspiration (ET_c) and their water requirements, according to irrigation programs. It is also a useful tool for auditing a farmer's irrigation strategies *ex post* (Lillo-Saavedra, 2019). Fig. 2 shows the architecture and tools used to implement it. The inputs correspond to multispectral images captured by the *LandSat 7 ETM+* satellite with meteorological data from the National Agrometeorological Network, Chile (https://www.agromet.inia.cl/) to estimate of reference evapotranspiration (ET_o) and shape–files that delimite the sites. In particular, for this research, AquaSat® selected a National Agro-meteorological Network weather station which located at the study site. The satellite images that were used to generate the ET_c maps correspond to those captured by the *Landsat 7 ETM+* satellite during the 2011–2012 and 2012–2013 irrigation seasons. Table 1 shows the dates when the images were captured. For water demand estimates, AquaSat® uses a Surface Energy Balance (*SEB*) model to determine ET_c by using satellite images (Gavilán et al., 2019; Allen et al., 2007; Bastiaanssen et al., 1998), following the protocol proposed by Fonseca-Luengo et al. (2017). *SEB* model is used to estimate biophysical variables such as net solar radiation, vegetation indices, and surface temperature, among others.

Once the ET_c estimation has been carried out for each of the areas under analysis, these data will be stored in a structured way in a *PostgreSQL* and *PostGIS* database. The information is then displayed to the users through a web platform.

In addition, the system allows the storage of free annotations in an unstructured database ($Mongo - DB$). Finally, the web server uses $Node - js$ as a tool for the asynchronous execution of the *JAVA* code that manages the data. *NGINX*, which is a web/proxy server, is used for the management of communication protocols between the platform and the end user.

2.3. Methods

Adequate water management in crops and fruit trees requires the consideration of a series of factors when establishing irrigation programs. Among these considerations, the most relevant ones are the crop water demand, the root water extraction pattern, the irrigation system on use, the contribution of rainfall or other external sources of water, and the soil type that affect the frequency of irrigation (Arumí and Holzapfel, 2010; Holzapfel et al., 2004).

To perform an audit (*ex post* analysis) of the irrigation strategies carried out by farmer in study site, it is needed to have data regarding the amount of water applied to each sector (irrigation schedule), as well as the plant water use and potential water demand. The water applied at each sector (*IR*) was provided by the farm's records associated with the number of irrigation cycles and water application rates.

It is important to note that the farm's managers did not use AquaSat® to adjust their irrigation schedule during the season under analysis because the schedule was based on his criteria.

The ET_o was estimated from the meteorological data of the station at the study site using the FAO-56 (Penman–Monteith) model (Allen et al., 2006). The ET_c was calculated using the *SEB* model and implemented in AquaSat®. ET_c values are spatial averages for each site (C-31 and C-37).

The following ratios were calculated:

- The crop factor (*CF*) as the ratio of ET_c to ET_o, for each sector (Eq. (1)). ET_o ($mm\cdot day^{-1}$) was calculated for the same day that the satellite image was captured on. The *CF* represents the plant's response to the current water management regime, whether associated with irrigation or rainfall. Values less than 1 imply that field evapotranspiration is less than potential evapotranspiration:

$$CF = \frac{ET_c}{ET_o} \tag{1}$$

  By considering the *CF* constant until the next satellite passes, it is possible to determine the orchard evapotranspiration (ET_c) at specific sites for dates without images as the product $ET_c = CF \times ET_o$.
- The iii rrigation factor (*IF*) as the ratio of water applied at each sector (*IR*) to ET_o (Eq. (2)). This ratio gives a measure of how much water is being applied related to reference evapotranspiration. Values greater than 1 imply that the irrigation schedule is delivering more water than the reference evapotranspiration.

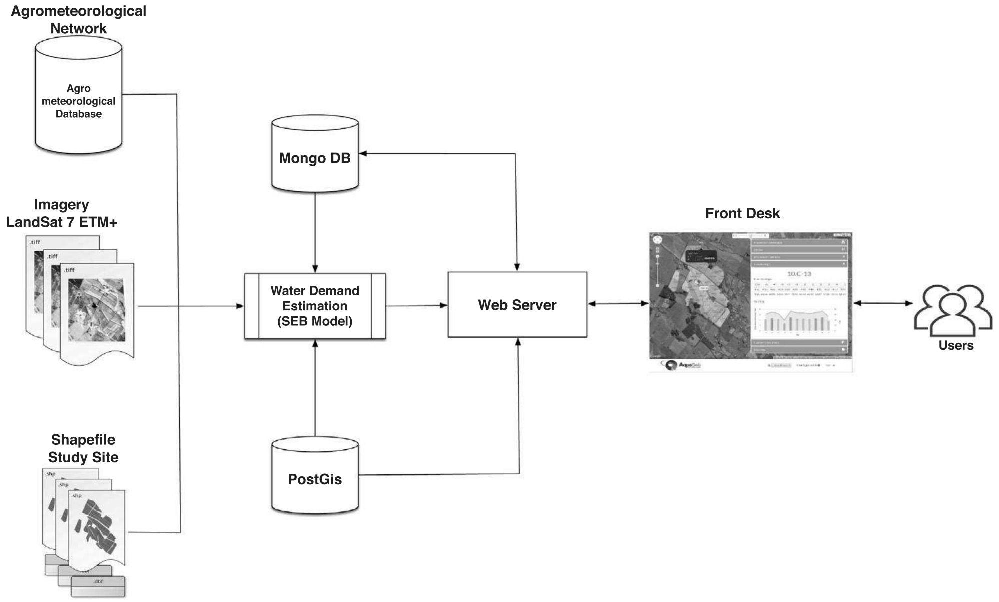


Fig. 2. AquaSat® architecture and its tools.

Table 1
Satellite image dates used to determine crop evapotranspiration (ET_c) by AquaSat® on the study sites.

Landsat 7 ETM + Imagery	
Season 2011–2012	Season 2012–2013
–	Oct. 10, 2012 (DOY 283)
Nov. 25, 2011 (DOY 329)	Nov. 11, 2012 (DOY 315)
Dec. 11, 2011 (DOY 345)	–
Dec. 27, 2011 (DOY 361)	Dec. 29, 2012 (DOY 363)
Jan. 12, 2012 (DOY 012)	–
Jan. 28, 2012 (DOY 028)	Jan. 30, 2013 (DOY 030)
–	Feb. 15, 2013 (DOY 046)
–	Mar. 03, 2013 (DOY 062)
–	Mar. 19, 2013 (DOY 078)

$$IF = \frac{IR}{ET_o} \tag{2}$$

- The relative water supply (*RWS*) as the ratio of the total amount of water received by crops (irrigation, rain or other) to water demand associated with crops grown with cultural practices and for the irrigated area (Eq. (3)). This ratio is a critical factor for irrigation planning, design, and operation that considers the available water supply and water demand by defining a relationship between supply and demand (Jensen, 2007). In this case, daily and space-averaged values for each sector are considered. Unlike *IF*, the ratio *RWS* considers rainfall.

$$RWS(\%) = \frac{IR + ER}{ET_{opt} + SP} \times 100 \tag{3}$$

where *ER* is rainfall; ET_{opt} is the crop evapotranspiration that matches the optimal crop growth on time, by using the potential crop factor (*PCF*) (Eq. (4)), and *SP* is the percolation loss, which was considered to be negligible, given the conditions of the crop as well as the soil water store capacity. The *PCF* is based on the percent coverage model or Leaf Area Index (*LAI*) for blueberries (Eqs. (5) and (6)) (Holzapfel et al., 2004, 2015). All variables are in $mm{\cdot}day^{-1}$.

$$ET_{opt} = PCF \times ET_o \tag{4}$$

$$PCF = F_1 \times P + F_2 \tag{5}$$

$$P = \frac{SA}{H \times L} \tag{6}$$

where *P* corresponds to plant canopy coverage ($0.2 < P < 0.7$), *SA* is the shaded area at noon (m^2) determined by measuring the shadow projected on the soil by the plant, in several directions; *H* is the distance between rows (*m*) and *L* is the distance between plants within the row (*m*). The coefficients F_1 and F_2 are empirical coefficients from a series of field experiments on blueberries that allows to estimate optimal water allocation as a function of the orchard growing (Fereres et al., 1981). For blueberries and orchards under drip irrigation, F_1 and F_2 take the values of 1.28 and 0.11 respectively (Holzapfel et al., 2015).

The *RWS* concept has been proven to be a powerful tool for understanding the behavior of irrigation systems and the impact of major actors in the irrigation process. In Amin et al. (2011), the authors claim that *RWS* is a useful concept in the analysis and interpretation of the operation and management of the irrigation system under different annual, seasonal, monthly or daily time intervals. The calculation flexibility, in terms of time and space, is incorporated into the *RWS* concept which makes it easy to use this measure in monitoring and comparing irrigation system behaviors.

The analysis of the *RWS* index allows for knowing if the total amount of water (irrigation and rainfall) that the crop has received during its growth cycle has been excessive, sufficient, or scarce. In this study based on previous research carried out by Holzapfel et al. (2004), it proposes that values of *RWS* in the range $115\% \geqslant RWS \geqslant 85\%$ indicate that the amount of water needs by the crop has been adequately met; values $RWS < 85\%$ indicate that water has been insufficient and values of $RWS > 115\%$ indicate that the crop has had more than enough water to meet its requirements.

3. Results and discussion

3.1. Water applied

Fig. 3 shows applied monthly water and rainfall for each season,

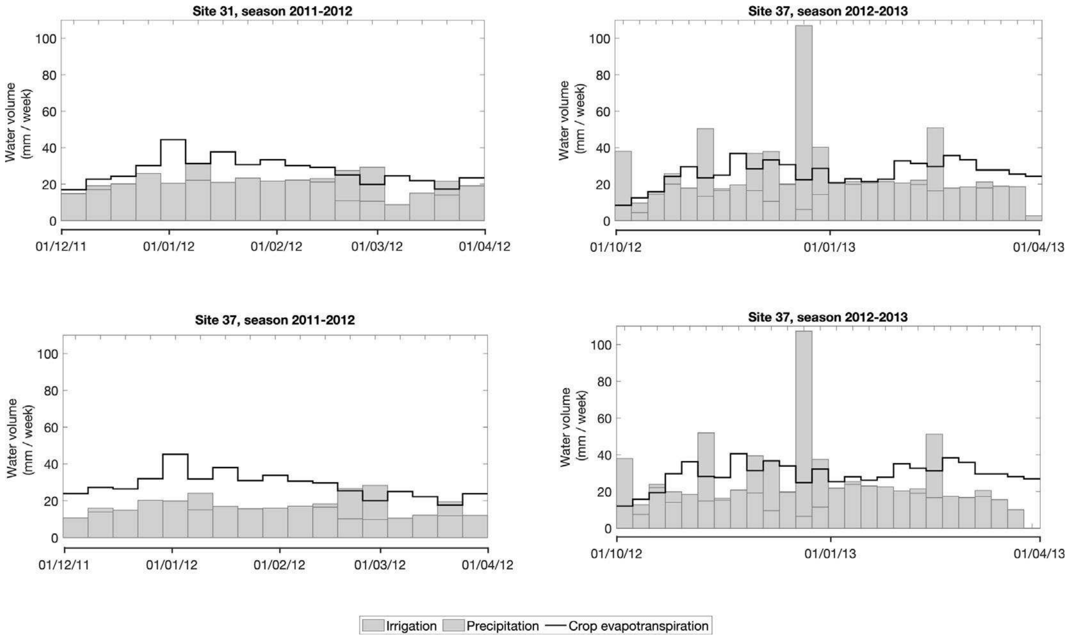


Fig. 3. Irrigation, precipitation and crop evapotranspiration for the 2011–2012 (Dec–Mar) and 2012–2013 (Oct–Mar) irrigation seasons, in blueberry crops at sites 31 and 37.

which reflects the water received by the crop (*IR*), as well as the crop evapotranspiration (ET_c), estimated from the AquaSat®. The contribution of rainfall helped to maintain a good water supply to the crop as well as the water store in the soil in both seasons. In particular, the contribution of the rainfall all long the 2012–2013 season helped to maintain an adequate water supply to the crop during the spring period (October-December). During those months, the demand for the crops is greater, given that the fruits are growing at this time. In contrast, during the period of 2011–2012, rains supplied less water to plants, leaving the crop largely dependent on irrigation. It is important to note that during the 2011–2012 season, the largest contributions of rain occurred in March, which is at the end of the season when crop demand was lower.

3.2. Determining ET_c using AquaSat®

Fig. 4 shows the spatially distribution of the ET_c estimates (at a resolution of 15 m) for sector C–31, with *Brigitta* and sector 37, with *Legacy*, for the 2011–2012 (Fig. 4a) and 2012–2013 (Fig. 4b) seasons using AquaSat®. Fig. 4a shows a low level of evapotranspiration for blueberry crops during November and December in the 2011–2012 season, which should be around 4 to 5 $mm{\cdot}day$, which evidence a water deficit for the crops during a relatively critical period when flowering and fruiting occurs. However, during the month of November of the 2012–2013 season, the results showed reasonable values of evapotranspiration and maintained this condition from January to February. Still, a small decrease was observed in December.

Fig. 4 also shows the irregular water management scheme applied to the crops and how deficit conditions were reached. This implies that the parameters and criteria used for irrigation management are not suitable.

3.3. Determining the Crop Factor for Blueberry

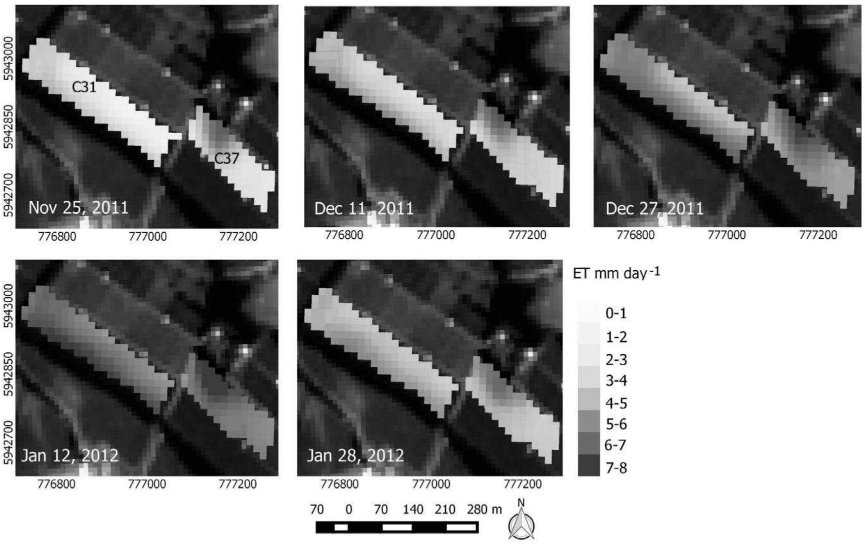
Fig. 5 shows the *CF* values obtained from Eq. (1) for each sector under study during the seasons 2011–2012 and 2012–2013 and compare them to the results delivered by AquaSat®. It also shows the *IF* (Eq. (2)) values used to define the company's irrigation criteria and the *PCF* (Eq. (5)) estimated by the percentage of plant canopy coverage model. The optimal condition is obtained when the *IF* and *CF* curves approach *PCF*, which implies that the water applied by the farmer is approaching the expected values of evapotranspiration and that the crop evapotranspiration is supplemented by irrigation and/or rainfall.

This information allowed to establish that, for the 2011–2012 season, the *IF* values derived from the irrigation schedule done by the farm and the *CF* are relatively similar, reflecting the adequate water management criteria of the farm in terms of crop evapotranspiration. However, the values are notoriously lower than the *PCF* associated with the plant canopy coverage model (potential demand). This indicates a deficient application of water throughout the season. For the beginning of the 2012–2013 season, there was an important difference between the values of *CF* and *IF* that was fundamentally associated with the contribution of rainfall during that period. Later in this season, *CF* values were more similar to those of *IF*.

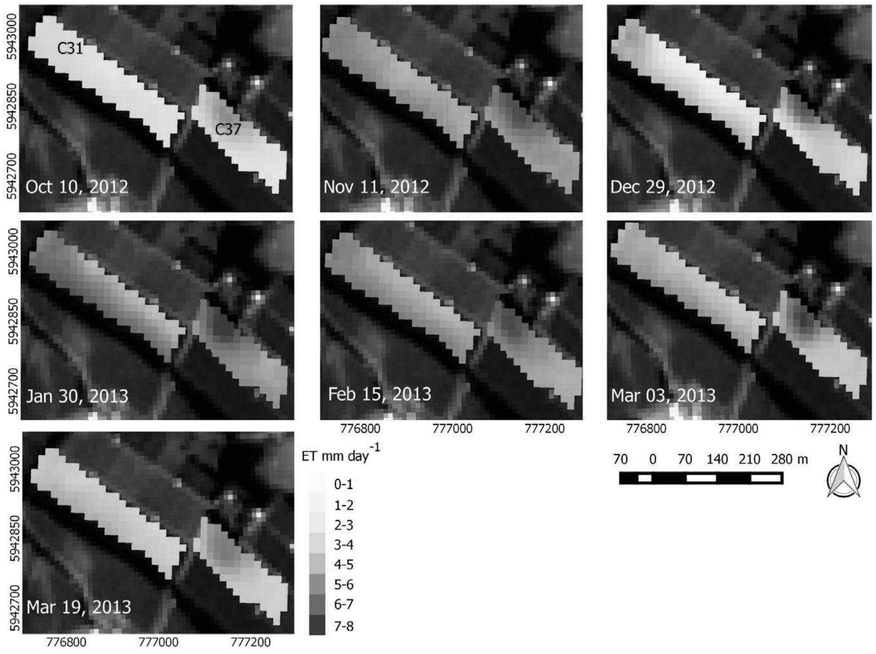
The above shows that the ET_c estimates obtained by AquaSat® are valuable inputs to estimate *CF* and the response of the blueberry crop to its water status, either by the contribution of irrigation or rainfall. There is no doubt that having a reference model of the water requirements allows to compare with of what is taking place on the ground is a great support for making adjustments and establishing effective irrigation management.

From the obtained results, it is possible to deduce that the irrigation management associated with the criteria used by the farm led to a deficit in water application levels. This situation reveals the need for systematic monitoring of the irrigation process. It is important to point out that the results obtained through AquaSat® adequately represent the response of the crop to current management and that it allows for comparisons against the estimated potential water demand by the crop, serving as an audit instrument for irrigation management.

The development of tools, such as those examined in this study, are relevant to establishing an adequate level of control over the management of irrigation systems in order to achieve optimal levels of production under the seasonal and spatial variations of demand. It is important to consider that it is necessary to have base-values of potential demand associated with the percentage of crop coverage to have a clear correlation with demand as shown in several past investigations (Bryla and Strik, 2007; Holzapfel et al., 2015). Thus, it is necessary to know the value of the potential factor of crops and orchards to assess the



(a) Season 2011–2012



(b) Season 2012–2013

Fig. 4. Crop evapotranspiration (ET_c) spatially distributed over blueberry crops for both sectors (C-31 and C-37) for 2011–2012 and 2012–2013 irrigation seasons. Each bar correspond to total weekly water volumes, aggregated from daily values.

irrigation management in place.

AquaSat® makes it possible to reveal the total contributions of water to the plant, which are expressed both in terms of water come from irrigation and what come from rainfall. Table 2 provides a comparison of the total values of contributed water, including irrigation and precipitation, with the estimate made by AquaSat® and water demand estimated by the coverage model. The production levels associated with such management systems in each irrigation period are also shown.

Given the previous information, it can be established that the first season had a greater deficit considering that there is a contribution of water stored in the soil and that the rain in the second season made an important contribution to the water requirements of the blueberry orchard, reducing the lack of water caused by insufficient irrigation. Previous studies established that the demand for water from drip irrigation in the blueberry orchard fluctuates between 6000 and 7000 $m^3 \cdot ha^{-1}$ (Holzapfel et al., 2004), which indicates that the orchard requires a higher level of water application than that used by the farm for both seasons of the study. As rainfall amounts are not subject to control of farm's managers, it allowed us to test qualitatively whether more water than scheduled irrigation volumes led to higher yields by 44 % (Site 31) and 26 % (Site 37). Also, it is important to note the timing of rainfall as it occurred during water-demanding periods. For season

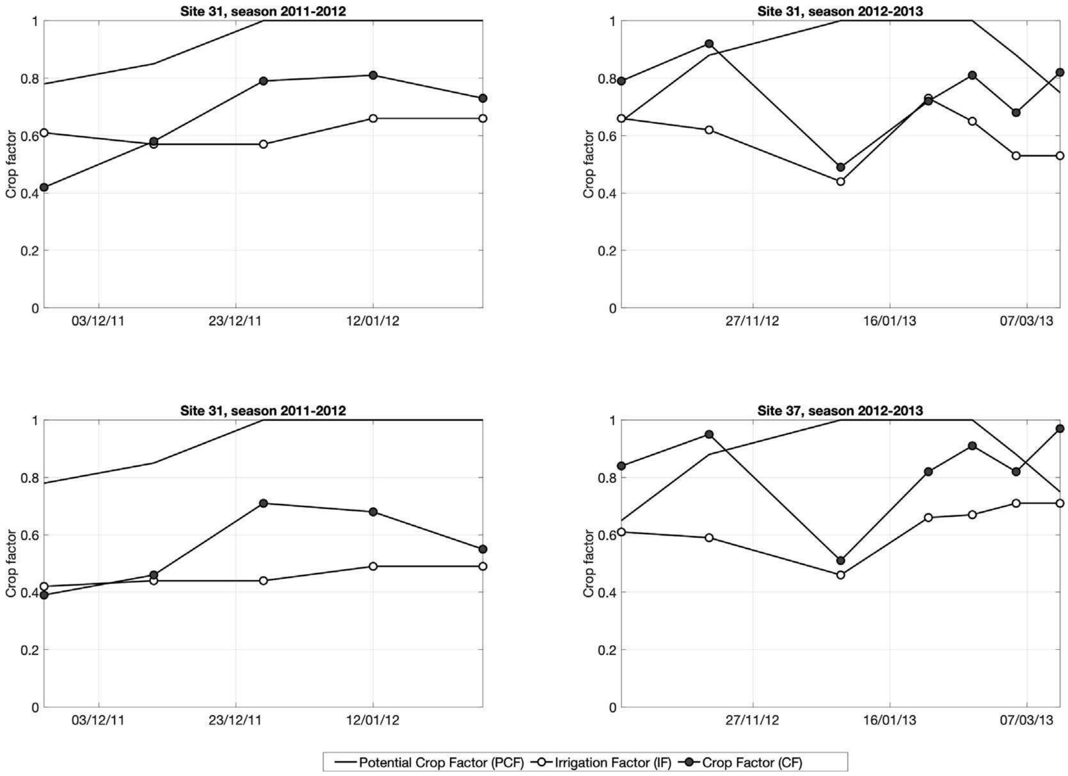


Fig. 5. Crop factor (*CF*) estimated by AquaSat®, irrigation crop factor (*IF*) from water applied by farm and the potential crop factor (*PCF*) estimated by the percentage coverage model for both site (31, *Brigitta* and 37 *Legacy*), during the 2011–2012 and 2012–2013 irrigation seasons.

Table 2
Water level applied, rainfall contribution, values delivered by the AquaSat® platform, the estimated by the plant canopy coverage model and production for blueberry cultivation for both sites during the 2011–2012 and 2012–2013 irrigation seasons.

	Site 31		Site 37	
	2011–2012	2012–2013	2011–2012	2012–2013
Water applied ($m^3 \cdot ha^{-1}$)	3175	4082	2511	4046
Precipitation ($m^3 \cdot ha^{-1}$)	406	2509	406	2509
Total applied water ($m^3 \cdot ha^{-1}$)	3581	6591	2917	6555
AquaSat® Estimate ($m^3 \cdot ha^{-1}$)	4537	6783	3566	7517
Estimated Potential ($m^3 \cdot ha^{-1}$)	6286	7244	7933	6774
Production ($Kg^3 \cdot ha^{-1}$)	17.074	24.595	25.977	32.848

2011–2012, data show that the farm's manager applied 57 % (Site 31) and 37 % (Site 37) of estimated potential water needs. During season 2012–2013, applied water was 91 % (Site 31) and 97 % (Site 37), but the increasing amount of water entering to the systems was due to rainfall. Also, it is worth to note that rainfall occurred at the beginning of the growing season, so it had larger effect on yields.

Records of applied water for both seasons supports that more applied water translates into higher production for both varieties. The increase in production during the second season in both sites was due more water volumes, mainly from rainfall, reaching close values to potential demand.

It is necessary to emphasize that, during the second season, the contribution of water from rainfall was important and is reflected in the values of the *CF* obtained from AquaSat® as well as in the production. For this reason, the monitoring of the crop with the use of remote sensors (satellite images) appears as an important source of support for an adequate management of irrigation and water levels applied.

3.4. Irrigation assessment using the relative water supply criterion

In order to evaluate the characteristics of the irrigation system employed by the farm, the relative water supply (*RWS*) values were used following the previously mentioned criteria with margins of 15% above and below their optimum values. Fig. 6 shows the results for both sectors associated with the information obtained by AquaSat®, with respect to the management and applied water level at the two sites.

In general, it can be observed that the water management regime used at the farm during both seasons delivered *RSW* values outside of the range established for adequate irrigation conditions and that, throughout most of the irrigation sector the applied water levels were insufficient when compared to what the crop requirements estimated by AquaSat®

There is no doubt that this kind of technology is useful to support decision-making to improve the irrigation strategies, improving the farmer profit. It is also important to mention that it is necessary to have a clear knowledge of the potential requirements of the plant, especially during the different stages throughout the irrigation season with the support for crops associated with the percentage of canopy coverage (Holzapfel et al., 2004).

4. Conclusions

AquaSat® allowed for auditing the irrigation management followed by the blueberry company. By using satellite images and demand models considering the percentage of coverage, it was established that the applied water level had an important effect on blueberry yields. Values around 6000 to 7000 $m^3 \cdot ha^{-1}$ showed the highest yield levels for both varieties (*Brigitta* and *Legacy*), but there was a strong influence on rainfall that was not accounted by the company's irrigation strategy. In fact, the audit using AquaSat® showed that the relative water supply

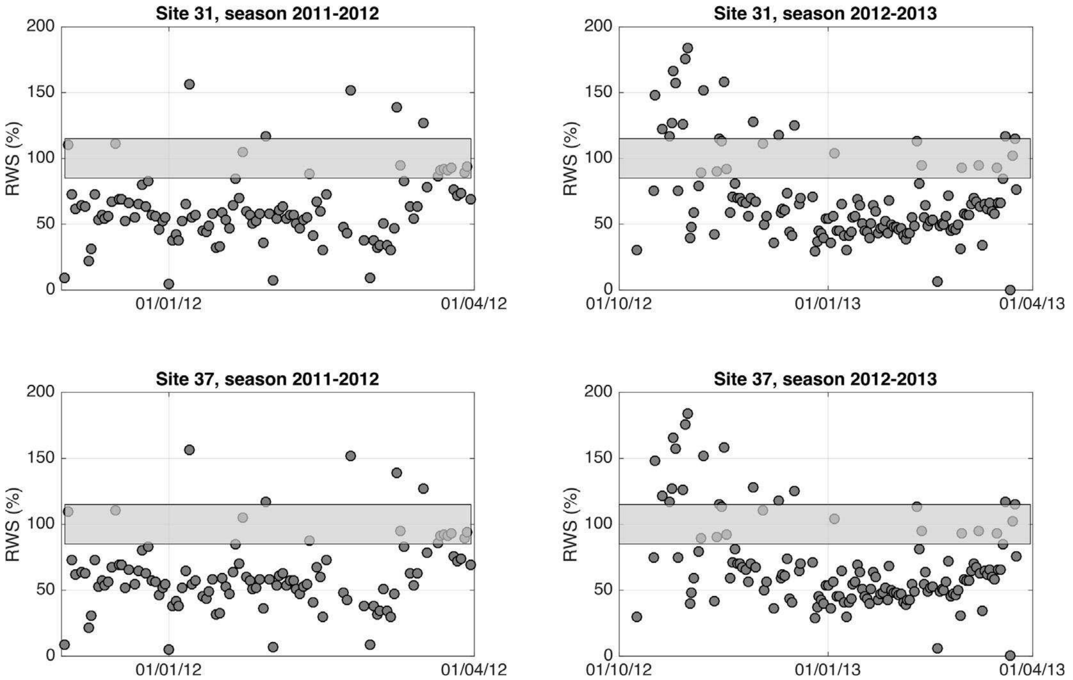


Fig. 6. Relative water supply (*RWS*) with a daily frequency for the blueberry crop for both sites (31, *Brigitta* and 37, *Legacy*) for the 2011–2012 (Dec-Mar) and 2012–2013 (Oct-Mar) irrigation seasons, using the crop evapotranspiration (ET_{opt}).

(*RWS*) for the drip irrigation system was consistently delivering less water than needed. Therefore, the criteria used in the management of irrigation by the farm's manager were inadequate, so improving the applied water level and water management can have important effects on crop production by using water more effectively.

The proposed method simplifies some aspects of the problem. In this sense, AquaSat® is a reliable and low-resource using approach to audit larger farms, making it possible to adequately monitor the water conditions of the blueberry crop and its relationship to water management.

Its use is associated with the potential demand model of the crop based on the percentage of coverage, which allows for adequate control over the behavior and management of irrigation systems. In addition, AquaSat® might support the decision to rearrange the sectors of irrigation.

CRediT authorship contribution statement

Eduardo Holzapfel: Conceptualization, Methodology, Software, Writing - original draft. **Mario Lillo-Saavedra:** Conceptualization, Methodology, Software, Writing - original draft. **Diego Rivera:** Conceptualization, Methodology, Software, Writing - original draft. **Viviana Gavilán:** Data curation, Visualization. **Angel García-Pedrero:** Writing - review & editing. **Consuelo Gonzalo-Martín:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.compag.2020.105635.

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