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Monitoring vineyard water status using Sentinel-2 images: qualitative survey on five wine estates in the south of France

Eve Laroche-Pinel[1,2,3]*, Sylvie Duthoit[1], Anne D. Costard[1], Jacques Rousseau[4], Jérome Hourdel[4], Marie Vidal-Vigneron[5], Véronique Cheret[2,3] and Harold Clenet[2,3]

[1] TerraNIS, 12 Avenue de l'Europe, 31520 Ramonville Saint-Agne, France
[2] Ecole d'Ingénieurs de Purpan, 75 voie du TOEC, 31076 Toulouse, France
[3] University of Toulouse, INRAE, UMR DYNAFOR, 31326 Castanet-Tolosan, France
[4] Groupe Institut Coopératif du Vin, La Jasse de Maurin, 34970 Montpellier, France
[5] Syndicats du cru Minervois, 35 quai des tonneliers, 11200 Homps, France

corresponding author: eve.laroche-pinel@terranis.fr

Associate editor: Luca Brillante

ABSTRACT

The wine industry must face many challenges because of climate change. One of them is the increase in temperatures and droughts events. These changes sometimes lead to yield losses and can also impact the quality of the wine produced (e.g., increased alcohol content). The management of available water is also a sensitive issue as water requirements for vineyard irrigation are quickly increasing in the south of France. In this context, there is a need for a decision tool that can help evaluate the vine water status through the entire growth season at a large scale. To address this issue, we have previously developed a model (see Laroche-Pinel *et al.* 2021a) which predicts the vine Stem Water Potential (Ψstem) using Sentinel-2 (S2) images. This model was developed based on a field campaign over three years. The present study now aims to investigate the feedback of winegrowers on the outputs of our model. Therefore, it was applied on the plots of five wine estates that do not belong to the set used in the initial paper. The qualitative results show interesting spatial and temporal consistency in accordance with winegrower knowledge, irrigation data, and weather forecast. The predicted Ψstem highlights spatial variability in vine fields where a water source emerges and reflects the differences between vine fields with a drip or sparkling irrigation or without an irrigation system. The predicted Ψstem also clearly reacts to a peak in temperature. According to their feedback, three of the five winegrowers would be glad to use this service in the years to come.

KEYWORDS

Water status, Precision viticulture, Sentinel-2 images, temporal and spatial evolutions

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INTRODUCTION

Viticulture is highly affected by climatic conditions, as much for its yield as for the quality of the grapes and therefore the wine produced (Chaves *et al.*, 2007; Costa *et al.*, 2007). According to van Leeuwen and Darriet (2016), this is the main factor affecting plant development and berry composition ahead of the soil or grape variety. The climate of the Mediterranean region was until the end of the 1990s rather favourable to the cultivation of vines with wet winters and warm summers, and balanced rainfall. Since 2000, the scarcity of rainfalls and the increase in evapotranspiration lead to regular and important water deficits during the growing period of vineyards (April–June), and thus the need for irrigation to maintain proper yield and wine quality. This raises the question of water resource management (Parker *et al.*, 2020). At the same time, thoughts are ongoing to find other solutions to water stress based on alternative agronomic practices (soil and inter-row management, vine pruning), variety choice, or plant density for example (Bernardo *et al.*, 2018). To implement these different solutions, it is necessary to first identify and quantify the needs. The first need is to detect the areas that suffer the most from water stress to optimise water use at the territory level. The second is the monitoring of the water status throughout the season to adapt irrigation management or other agricultural practices at the field level and maintain harvest and quality targets. A common, robust, and precise method to measure vine water status is the Ψ_{stem} (Acevedo-Opazo *et al.*, 2008). Thanks to pressure chamber measurements (Scholander *et al.*, 1965), Ψ_{stem} reflects plant transpiration and soil conductivity. It reflects the capacity of the vine to conduct water from the soil to the atmosphere (Choné *et al.*, 2001). However, this method is time-consuming and cannot be applied at a large scale during all the growth season.

Remote sensing could be a relevant tool as it gives spatial information on vegetation with possibly an interesting temporal resolution. Optical images have already been used in several studies about vine water status for irrigation management with UAV multispectral images (Romero *et al.*, 2018), to estimate Ψ_{stem} with Landsat 8 images (Borgogno-Mondino *et al.*, 2018) or with UAV multispectral images (Poblete *et al.*, 2017) and to identify irrigation zones with an aircraft (Bellvert *et al.*, 2012).

Considering S2, its spatial resolution of 10 to 20 m for most of its 13 bands, and its temporal resolution of 5 days make this satellites constellation especially suited for vegetation monitoring (Addabbo *et al.*, 2016; Weiss *et al.*, 2020). Despite the inability of S2 to differentiate the row from the inter-row on the images (Cogato *et al.*, 2019; Di Gennaro *et al.*, 2016; Sozzi *et al.*, 2020), the combination of its spatial, spectral, and temporal resolution makes it a very interesting tool to monitor vineyards at a large scale (Devaux *et al.*, 2019) taking into account spatial variability (Di Gennaro *et al.*, 2019). Moreover, its potential use for vineyard monitoring has already been demonstrated to identify vine water status by Cohen *et al.* (2019) and to quantify the impact of heatwaves on the irrigated vineyard by Cogato *et al.* (2019). The ultimate advantage of S2 for future operational service is that it could be low cost as the access to the acquired images is free and open.

In a previous study, we demonstrated the effectiveness of a regression model to predict vine Ψ_{stem} using S2 images (Laroche-Pinel *et al.*, 2021a). The study proposed here aims to check the consistency of the results obtained with the model in a pre-operational context for several new vine fields throughout the 2020 season. The goal is to verify spatial and temporal consistency of the results in a qualitative way based on winegrowers' knowledge and expertise and also using weather forecasts and in-field information. These exchanges with potential end-users also constitute an interesting exploratory step to assess the interest of a potential new decision support tool.

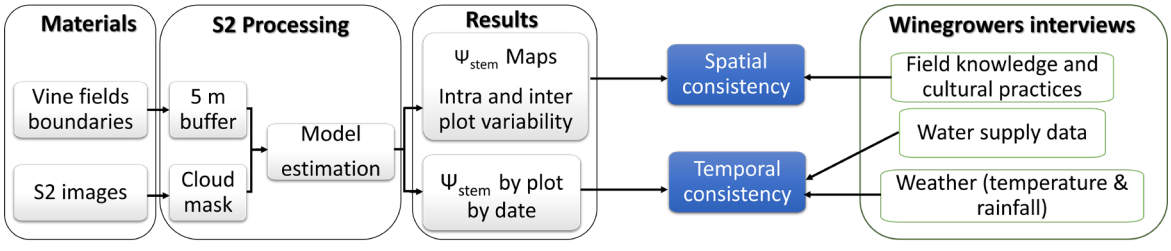


FIGURE 1. Flowchart of the method used in this study (S2: Sentinel-2, Ψ_{stem}, Water Potential).

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Section "Material and method" presents the characteristics of the model and how it has been applied in this study, including the details of the five wine estates' vine fields, the S2 images processing, how Ψ_{stem} are usually interpreted and how the exploitation of the results is made based on winegrowers experience. Section "Results" describes the exploration of the spatial and temporal variability, with few representative results. Section "Discussion" first focus on the consistency of the results according to winegrowers feedbacks, then reports the limitations of the model and discuss how this model could be used in an operational service. Section "Conclusion" resume the goal of the project, the main results, and the future experiments to come.

MATERIAL AND METHOD

1. Model development

The model previously developed and described in Laroche-Pinel *et al.* (2021a) was based on knowledge previously obtained using hyperspectral measurements (Laroche-Pinel *et al.*, 2021b) and was calibrated using in-field Ψ_{stem} measurements. More than 2500 measurements were obtained using a pressure chamber over 3 years (2018, 2019, 2020) on 36 vines fields in the Mediterranean region. In this study, five supervised regression machine learning algorithms were tested to find possible relationships between stem water potential and Sentinel-2 images (bands reflectance values and vegetation indices). The best regression model allows one to predict Ψ_{stem} using Red (B4), NIR (B8), Red-Edge (B6) and SWIR (B11) bands reflectance of S2 images ($R^2 = 0.40$, RMSE = 0.26).

2. Application of the model

For this new study, the model was applied to cloud-free images over 170 new vineyard fields, considering only the pixels fully included in the field. The model processes one image at a time. The results obtained are maps at the pixel level (intra-field variability) and the field level (average of all the pixel values included in the plots). Predicted Ψ_{stem} values are also extracted for each field at each date for temporal monitoring. The goal of the study is to ensure the consistency of this prediction using winegrowers' expertise, weather and water supply data. Figure 1 below shows all the different steps.

2.1. Study sites

In this study, we worked with five wine estates in the south of France whose winegrowers well know their fields and closely monitor their water status. In total, 170 vine fields were monitored near Carcassonne and Beziers (Figure 2).

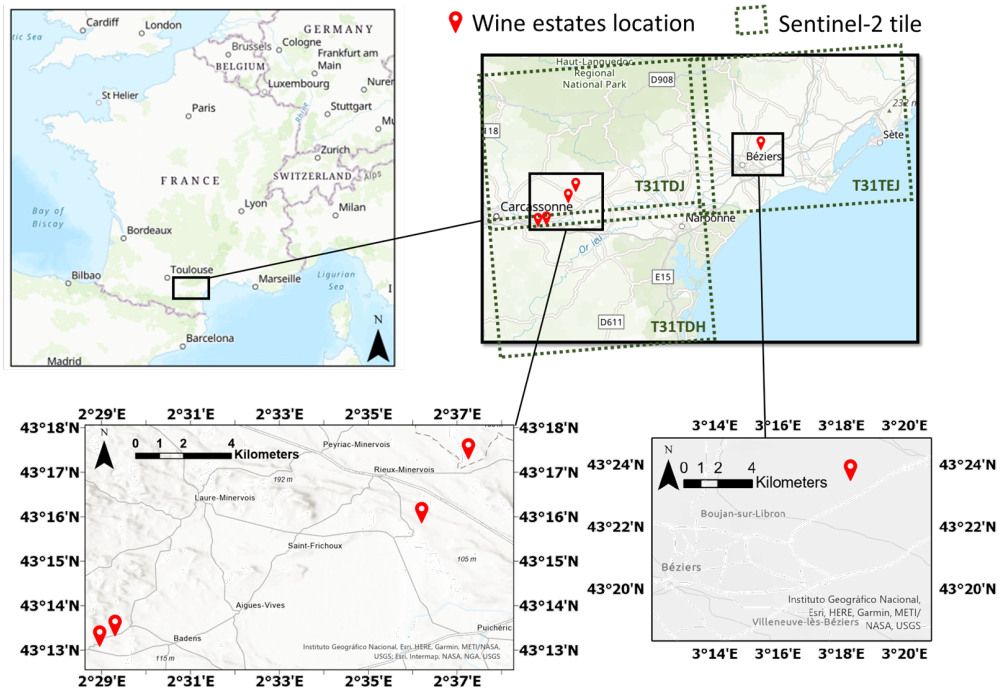


FIGURE 2. Study sites located in the south of France near Carcassonne and Beziers.

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This region benefits from a Mediterranean climate with hot, dry summers and cool, wet winters. Vine fields are mostly managed by Cordon, with 2 m inter-row, bare soil and cover 220 ha in total. The database was diversified with 18 grape varieties, 11 red (Syrah, Alicante, Cabernet-Sauvignon, Carignan, Cinsault, Grenache, Mourvedre, Marselan, Petit verdot, Pinot n*f*oir, Merlot) and 6 white (Chardonnay, Roussanne, Marsanne, Vermentino, Muscat, Viognier), different types of irrigation (no irrigation, soil and aerial system), and soils (clay or limestone). The planting dates range from 2002 to 2015.

2.2. Sentinel -2 images processing

The S2 sensor takes images with a swath of 290 km and images are then cut into sections of 110 km × 110 km named "tiles". The studied area is covered by three tiles as shown in Figure 2 (T31TDH, T31TDJ and T31TEJ). All available S2 images from June to September 2020 were downloaded from the THEIA platform in L2A format with a cloud mask and an atmospheric correction (CNES, 2021). An average of 20 images could be processed for each field, this means that we had a usable image (without cloud) every 7 days on average (approximately 10 images for each field from June to September). Among the 13 bands of S2, the model developed by Laroche-Pinel *et al*., 2021a estimates Ψ_{stem} from the 4 bands in Red, Red-Edge, NIR and SWIR spectral domains with a spatial resolution of 10 or 20 m.

The 20 m bands are resampled to 10 m and then, the first step of the process consisted in applying a buffer to avoid border effects as done by Devaux *et al.* (2019). A buffer of 5 m is applied inside the field boundary and only the pixels entirely included in the boundaries are kept. In the second step, the model is applied to each image's pixels to have a map of the predicted Ψ_{stem} by pixel for the intra field variability, then values are averaged by field to highlight the inter-field variability. The last step consists of extracting Ψ_{stem} estimation by field for each date for temporal monitoring. These steps are summarised and illustrated in Figure 3.

2.3. Ψ_{stem} interpretation

The model predicts vine water status by predicting Ψ_{stem} from 0 MPa (no water constraint) to -2 MPa (high water constraint). Water stress can occur more or less quickly, depending on climatic conditions (van Leeuwen *et al.*, 2009) and the response speed of the Ψ_{stem} will also differ depending on it. Ψ_{stem} values can be interpreted in terms of water constraint according to the vine development stage and the desired future wine

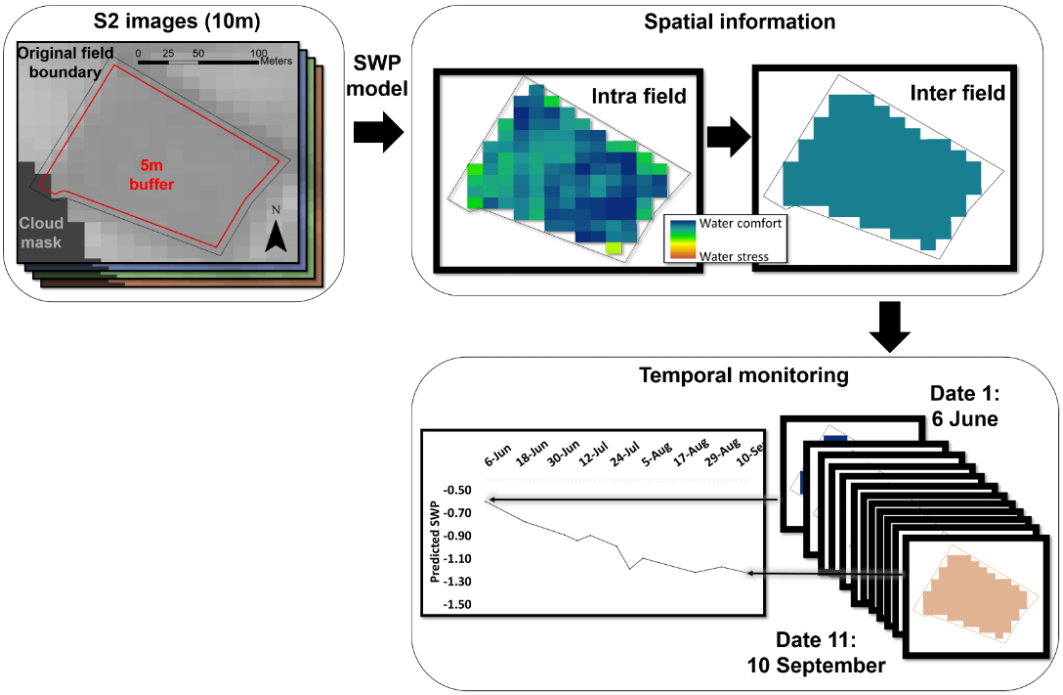


FIGURE 3. Illustration of the process for one field (S2: Sentinel-2). The first step consisted in applying a buffer inside the original field boundary. Then the model is applied in each pixel and Ψ_{stem} predicted values are averaged by field. The mean value of each field is finally extracted by date for temporal monitoring.

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(Payan, 2007; Salva, 2016). Indeed, the required water constraint will differ from a lower constraint at pea-size (to ensure the correct development of the grape) to a higher constraint at the ripening stage (to enhance grape quality by concentrating aromatic compounds). Additionally, for ageing red wine, a high water constraint will be required unlike for a light white wine for example. In all cases, a Ψ_{stem} value below –1.6 MPa is indicative of excessive water stress for vines, which may cause irreversible damage for future production (Deloire *et al.*, 2020).

2.4. Exploration of model application results with winegrowers interviews

At the beginning of the study, vine field boundaries with information about the grape variety and irrigation management were collected from winegrowers. Additional useful information were also collected: weather record with daily mean temperature and rainfalls from June to September, and the irrigation programs reporting dates and quantities of water brought by drip irrigation. Our Ψ_{stem} prediction model has been processed at the end of the summer on all available and usable images. Finally, a meeting with the winegrowers has been organised on 26 November 2020, to present our work and show them the maps and the temporal monitoring of their vine fields. They had to give feedback and discuss the consistency of the model.

The first thing to be evaluated is the spatial consistency of the predicted Ψ_{stem} maps over wine estates fields i.e., to assess if the observed spatial patterns are correlated to the actual vine water status. Maps highlighting intra- or inter-field variability over wine estates were shown to each winegrower to check the model consistency according to their field knowledge (e.g., different soil composition, missing vines, irrigation).

Secondly, to evaluate the temporal consistency of the predicted water status over time, Ψ_{stem} temporal monitoring of vine fields were produced for each field and presented to winegrowers The Ψ_{stem} estimation evolution was then analysed with regards to weather data and irrigation management. As described previously, vine water status evolves from pea-size to harvest. If the decrease is greater or lesser than expected or if a big step is observed between close dates, it could either reflect an alarming change in water status or other agronomical practices (e.g., cover grass destruction, canopy trimming or tying-up).

RESULTS

1. Highlighting Spatial variability

The goal here is to verify that the model gives correct estimation by analysing the predicted Ψ_{stem} variations at the intra-field scale. The following figures show three examples of maps with the feedbacks from winegrowers.

The first example in Figure 4 shows the predicted Ψ_{stem} map on 10 August for several red (red border) and white (yellow border) vineyards of a wine estate. The colour scale of the map ranges from dark blue for no water constraint (0 MPa) to dark orange for severe water stress (–2 MPa).

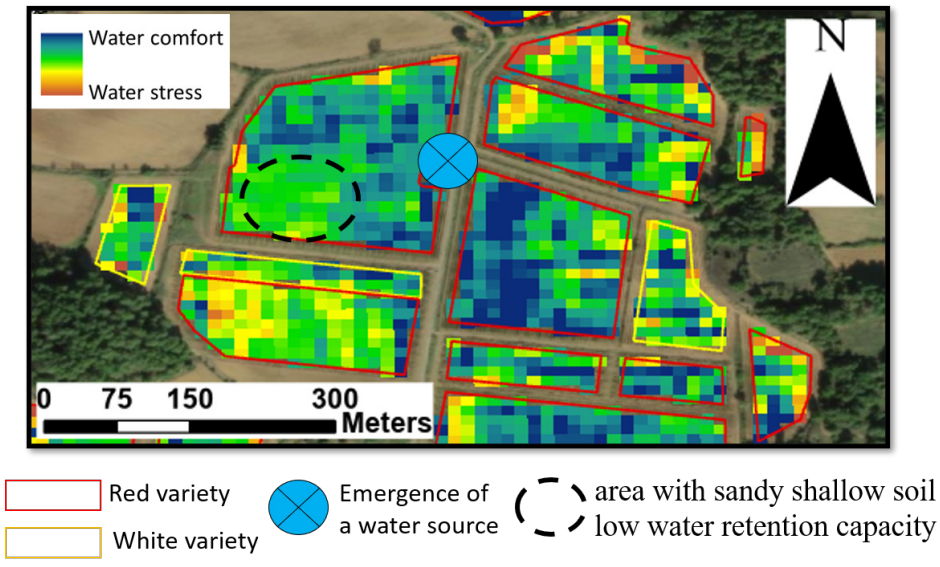


FIGURE 4. Predicted water status map on 10 August 2020.

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Looking at this map, the winegrower explained that there is a water source close to the areas that stand out in blue which may explain why there is less stress in this location. Moreover, he said that the field located in the northwest has a different soil composition in the lower-left corner that does not fix water as well as the rest of the field, and can be seen with a greener colour.

The second example in Figure 5 is a predicted water status map on 14 July. Concerning the white varieties, two fields (1 and 2) of the same variety (Chardonnay) seem to have different water statuses. The second one seems to be less stressed. Moreover, the fields in the east stand out as being less stressed than those from the west. Finally, it can also be noticed that red fields seem to be less stressed than the white ones.

Thanks to the discussion with the winegrower, we learned that fields 1 and 2 have different planting years (field 1: 2012 and field 2: 2003). This makes sense as the older vine, with a deep adult root system, seems to have a better water status than the youngest, with a young and still shallow root system. Moreover, he also described the east area as wetter which can explain the difference between the fields in the east and west. The difference between red and white varieties also makes sense since white varieties do not stand too much water constraint, as outlined in the section "*Materials and Method. 2.3*".

The third example shown with the map in Figure 6 highlights two fields in the middle that seem to have a more stressed area in their northern parts.

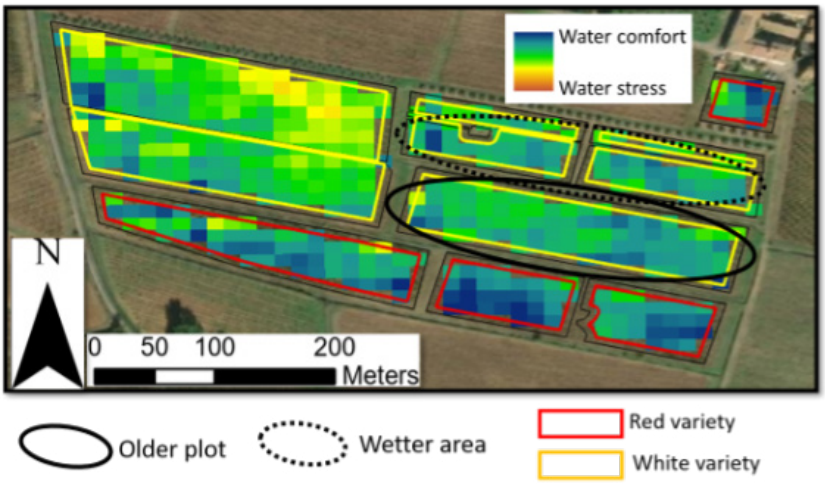


FIGURE 5. Predicted water status map on 14 July 2020 (field 1: chardonnay of 8 years old, field 2: chardonnay of 17 years old).

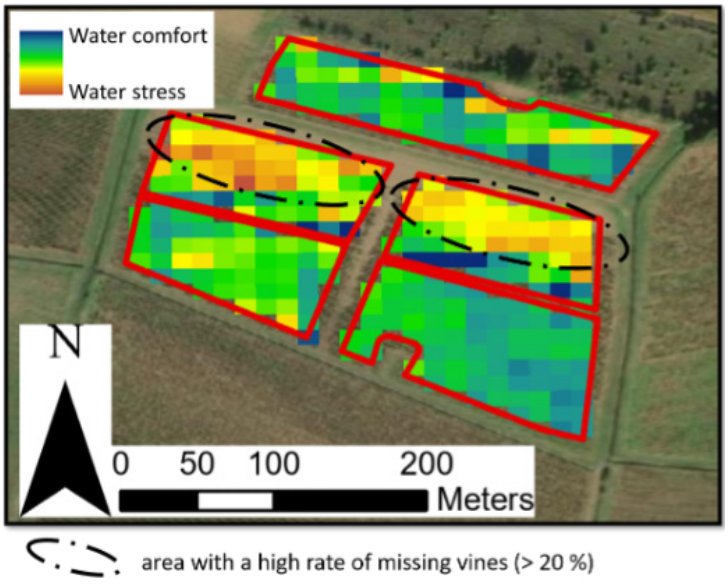


FIGURE 6. Predicted water status map on 31 July 2020.

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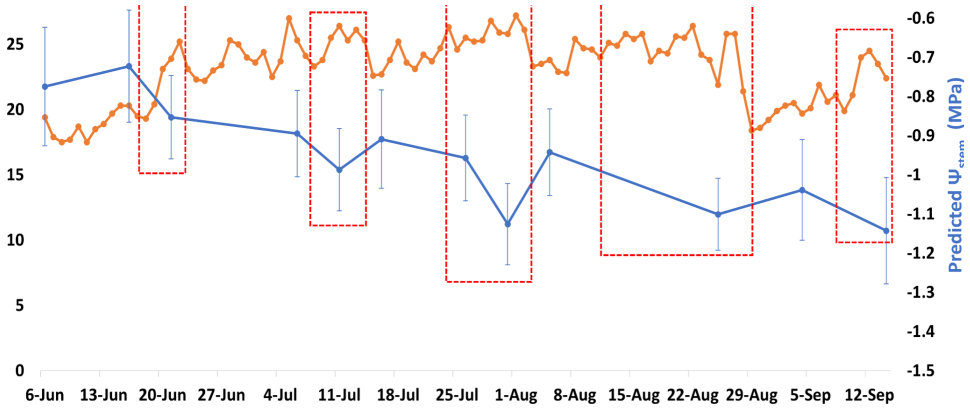


FIGURE 7. Temporal monitoring of predicted Ψ_{stem} averaged and standard deviation for 32 vine fields with red varieties of one wine estate according to mean temperature for 2020.

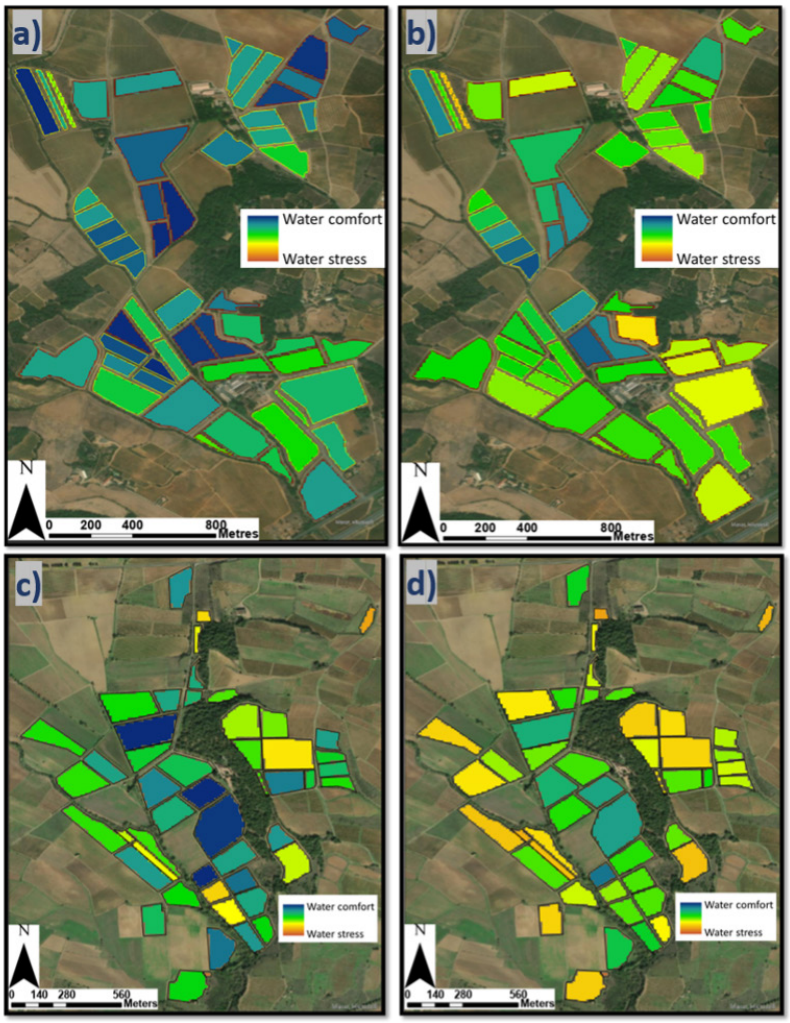


FIGURE 8. Water status maps averaged by field for two wine estates at two dates, a) and c) after the rain on 26 July 2020 and b) and d) during a temperature peak on 31 July 2020. Figures a) and b) represent a well-irrigated wine estate and Figures c) and d) represent a wine estate with non-irrigated plots.

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According to the winegrower, these areas have many missing vines (a rate higher than 20 %). Such an abnormal level of missing vines may affect the model of Ψ_{stem} estimation by increasing the soil fraction seen by the satellite.

2. Monitoring temporal evolution

The second objective is to verify the relevance of the temporal monitoring. It is important to know whether the model reacts correctly throughout the season and if the variations observed are actually due to changes in the water status of the vines. Four examples are detailed below to illustrate how the relevance of the model monitoring was verified.

2.1. Link with weather data

Figure 7 emphasises the link between the mean temperature recorded in a wine estate during summer 2020 and the predicted Ψ_{stem} of its 32 vine fields (mean and standard deviation). Indeed, Ψ_{stem} evolution is inversely proportional to the mean temperature which means that the model reacts in the right way throughout the season. According to the intensity and the duration of the temperature increase, the answer of the vine to a temperature increase is more or less quick, but as shown with the red boxes in Figure 7, the Ψ_{stem} estimation is always impacted by high or long temperature increases. For example, in the first box, it can be clearly seen that the predicted Ψ_{stem} is inversely proportional to the temperature increase. For the others, the correlation depends on the intensity and duration of the temperature increase. In the third box, the predicted Ψ_{stem} considerably decreases after several days of high temperatures.

2.2. Evaluation of the Ψ_{stem} prediction over a whole wine estate after a rain and during a heatwave

Figure 8 shows two water status maps at a field scale for two wine estates on 26 July and 31 July. Figure 8a,c displays water status three days after rain (66.4 mm on 23 July) and Figure 8b,d highlights the water status during a temperature peak (mean temperature between 25 °C and 27 °C). As expected, the majority of the fields tend to be more stressed in Figure 8b,d but their levels remain reasonable for the first wine estate (Figure 8b). The winegrower explained to us that it is not surprising from his point of view because he tries to irrigate all his vineyard as soon as they require it with a drip irrigation system. On the contrary, for the second estate (Figure 8d), the colour of the plots tend to be more orange for some fields indicating that there is a big decrease in predicted Ψ_{stem} values. The winegrower of this second estate explained to us that it is logical as he cannot irrigate all these fields in the same way, and some are never irrigated.

2.3. Impact of irrigation management

To follow and compare different vine fields with an interesting range of water statuses, it was particularly interesting to have access to a wine estate having a different irrigation system installed

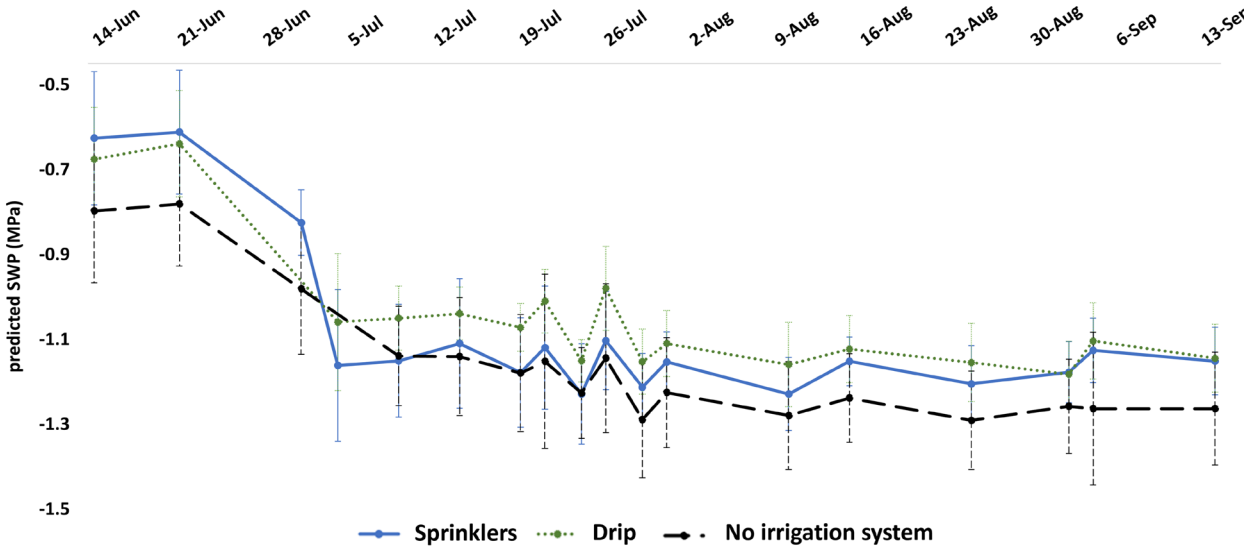


FIGURE 9. Temporal monitoring of predicted Ψ_{stem} for fields according to irrigation system type for a wine estate in summer 2020. The red box highlights a complication with the sparkling irrigation system at the beginning of July.

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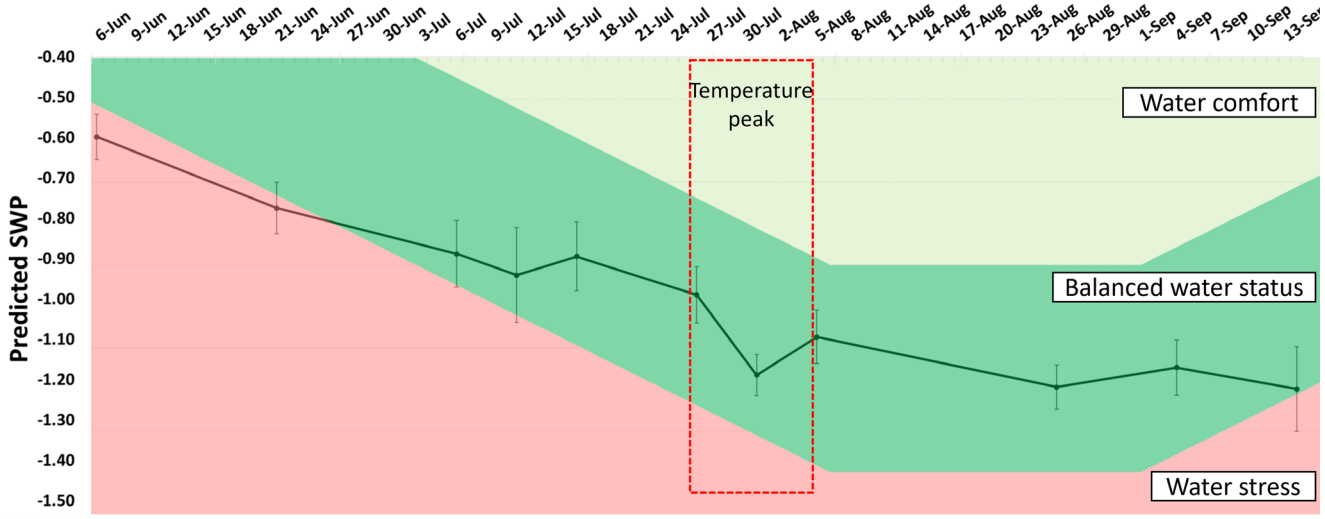


FIGURE 10. Mean value of the Ψ_{stem} temporal monitoring for red fields of one wine estate according to three thresholds from water comfort to water stress for a red concentrated wine (adapted from Ojeda & Saurin, 2014).

on their fields: 15 vine fields have no irrigation system, 15 benefit from an overhead sprinkler irrigation system and 19 have a drip irrigation system. Figure 9 shows the temporal monitoring of predicted stem water potential for these fields according to their irrigation systems. As expected, fields without irrigation systems tend to be more stressed than fields with soil or aerial systems. Fields with a drip irrigation system tend to be less stressed than the others: drip irrigation allows a better spatial and temporal regularity of irrigation, with fewer losses than sparkling irrigation. Furthermore, the aerial irrigation system was broken in early July. The fields may then not have received the right amount of water and this is visible on the predicted Ψ_{stem} value as a rapid decrease is observed at these dates for fields with aerial irrigation system (red box in Figure 9).

2.4. Verification of watercourse according to the objective of an ageing red wine

In Figure 10, Ψ_{stem} thresholds were reported on temporal monitoring according to a watercourse adapted for an ageing red wine (Ojeda and Saurin, 2014). Proper management of the whole estate is highlighted as predicted Ψ_{stem} are almost always in the optimal range, i.e., in "Balanced water status". This estate is the same as the one shown in Figure 8 and the winegrower well manages the water status of its fields by having a global vision of its entire estate and by being able to irrigate each of its fields when they need it with a drip system. In this figure, the temperature peak at the end of July can also be noticed with a decrease of the predicted Ψ_{stem} at the end of July.

DISCUSSION

1. Winegrowers feedback

Among the five solicited winegrowers, three were enthusiastic about the model's results on their vine fields. Among these three, two would even like to use a service based on this model to help them better choose the fields to irrigate and the third one would rather rely on both the Ψ_{stem} prediction and a vigour estimation to improve the management of their fields (pruning, harvest date and allotments). Another winegrower would like to test the model for several years to check the consistency of the results over several vintages, and the last one considers that he knows his plots well enough to avoid using this kind of service. In fact, his wine estate is smaller than the others (less than 50 ha) and he can visit these fields very regularly during the season.

1. 1. Consistency of spatial variabilities

The feedback from winegrowers was positive with the right correlation between the predicted water status at an intra-field level and the knowledge provided by the winegrower. Moreover, differences between red and white cultivars have also been highlighted which seems logical as they do not require the same water constraints, and are planted in deeper soils, or more irrigated (van Leeuwen *et al*., 2009). Our Ψ_{stem} predictions have also highlighted that older vine fields seem to be less stressed than young and this makes sense

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as they are generally less sensitive to water deficit because of their deeper root system (Bou Nader *et al*., 2019).

1.2. Consistency of temporal evolutions

The first positive aspect of the temporal monitoring with our model is the good relationship with the weather in relation to heatwaves (Figure 7) and rain (Figure 8) events. The second is the distinction between irrigated and non-irrigated vine fields of an entire vine estate (Figure 9), this means that the model can reasonably be used to distinguish fields with a lack of water. This also proves the robustness of the model over a whole wine estate even with several water supply practices. Finally, as the future service will provide Ψ_{stem} estimation during the season in real-time, it could also be possible to verify and adjust the water management of a vine estate with water status thresholds according to the development stage and desired future wine (Figure 10).

2. Limitations of the model

To take into account the risk of water stress overestimation due to a high missing rate or a low vine vigour, it is necessary to measure the vine vigour as a complement with vegetation indices or biophysical parameters, for example. A threshold could be determined below which the water stress level would not be calculated because there would not be enough vegetation. Moreover, to avoid underestimating stress, the vegetation in the inter-row can be useful information to better interpret the Ψ_{stem} prediction. In fact, in Mediterranean region, the grass is not very vigorous in summer, so in our studies, the presence of grass between the vine rows was not a problem.

This model is based on the prediction of Ψ_{stem} which is a commonly used precise vine water status assessment, however, recent studies have highlighted some limits of this measurement under certain climatic conditions (Santesteban *et al*., 2019, Suter *et al*., 2019) or for isohydric behaviour (Blanco-Cipollone *et al*., 2017).

New field campaigns are needed to go further with the exploration and validation of the model on vine fields in other regions with different varieties, hydric behaviour, inter-row management or vine pruning, for example, that could lead to signal differences or/and could impact the vineyard signature in 10 or 20 m pixels.

A way to enhance the precision of the model could be to make some Ψ_{stem} calibration measurements each year at strategic locations to adjust the prediction of the model. More information like rain or average temperatures could also be used as additional predictors in the model.

Finally, the model used in this study combines four bands of an optical multispectral satellite (S2) while the arrival and development of thermal, radar or hyperspectral satellites could be interesting to explore to improve the accuracy of the vine water status prediction models as they allow one to assess other characteristic links to vegetation water status (e.g., temperature, complete vegetation spectrum) (Das *et al*., 2020, Pagay & Kidman, 2019) or soil moisture (El Hajj *et al*., 2018, Balenzano *et al*., 2021). However, most of these tools are not yet available to use from an operational point of view at an affordable price for customers.

3. Towards an operational service

To operate a future service, two levels seem to emerge, one to help winegrowers to manage their vine fields at a vine estate scale and one for winegrowers unions to have an entire view of a region for example. In both cases, spatial and temporal information will be needed. Yearly temporal monitoring will help to know where to start watering for example. Maps can help in designing irrigation plans, with irrigation blocks corresponding to areas with the same water requirements. Pluriannual monitoring would give a better idea of the characteristics of each vintage, terroir, and region. Both can contribute to justifying applications for irrigation authorisation adapted to each area and year climatic characteristics, and also to long term policies concerning water and vineyard management. Finally, it would be interesting to add the weather information (historical and forecast) to have an overview of all available data. This would allow to complete the comparisons between years or terroir and to be able to act according to the predictions of the model and the weather forecast. The major advantage of a service like this one is that it can allow one to monitor the vine water status in near-real-time (possibly every 5 days) on a large scale and at an affordable cost as the images are free.

CONCLUSION

The goal of this study was to verify the consistency of spatial and temporal monitoring of vine water status obtained with a model using S2 images. Images of vine fields of five wine estates have

been processed with a previously developed model to predict their water status during the 2020 season. The feedback from winegrowers has been very positive according to their knowledge of their vine fields, the type of irrigation used or the weather data. Some limits have been highlighted like the necessity to well know the cultural practices and the vigour of the studied vine fields. The results obtained here are promising for future operational service in the Mediterranean region and further investigations will be done in other regions with different agronomic practices (e.g., grass, inter-row). The next step is to test this model systematically on many vine fields in real-time and asking winegrowers to go on the field and check the consistency of the water status estimation by measuring Ψ_{stem} or using a within-field notation with a mobile application like ApeX-Vigne (Pichon *et al.*, 2021), for example.

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