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ORIGINAL RESEARCH ARTICLE

Towards a regional mapping of vine water status based on crowdsourcing observations

Léo Pichon[1*], Guilhem Brunel[1], Yulin Zhang[1] and Bruno Tisseyre[1]

[1] ITAP, Institut Agro Montpellier, INRAE, University of Montpellier, Montpellier, France

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*correspondence: leo.pichon@supagro.fr

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ABSTRACT

Monitoring vine water status is a major challenge for vineyard management because it influences both yield and harvest quality. It is also a challenge at the regional scale for identifying periods of high-water restriction or zones regularly impacted by water stress and changes of these impacts over the years. This information is interesting for defining collective strategies, anticipating harvest logistic issues or applying for irrigation authorisation. At this spatial scale, existing tools and methods for monitoring vine water status are few and often require strong assumptions and/or parameters to be defined exhaustively (e.g. water balance model). This paper proposes to consider a collaborative collection of observations by winegrowers and wine industry stakeholders (crowdsourcing) as an interesting alternative. Indeed, it allows the collection of a large number of field observations while pooling the collection effort. However, the feasibility of such a project and its interest in monitoring vine water status at regional scale has never been tested.

The objective of the article is to explore the possibility of making a regional map of vine water status based on crowdsourcing observations. It is based on the free mobile application ApeX-Vigne, which allows the collection of observations of vine shoot growth. This information is easy to collect and can be considered, under certain conditions, as a proxy for vine water status. Nearly 5,000 observations were collected by winegrowers and wine industry stakeholders during 2019, 2020 and 2021 seasons. Vine shoot growth maps were derived from this dataset at regional scale and its ability to monitor temporal evolution of these maps was studied. This article also proposes an analysis of the factors that favoured the number of observations collected. These results open up new perspectives for monitoring vine water status at the regional scale, they also provide references for other crowdsourcing projects in viticulture.

KEYWORDS: citizen science, crowdsensing, decision support, precision viticulture, smartphone, spatial analysis, *Vitis vinifera*

INTRODUCTION

Water restriction is a major issue in viticulture as it influences vegetative growth (Pellegrino *et al.,* 2005), yield (Medrano *et al.,* 2003) and grape quality (van Leeuwen *et al.,* 2009). Its impact on vineyard performance depends on its intensity, duration and period of occurrence (Mirás-Avalos and Silva Araujo, 2021). Monitoring vine water status allows this water restriction to be characterised. Therefore, it plays a particularly important role in vineyard management and decision support. Consequently, numerous tools have been developed to measure or estimate vine water status at field level (Rienth and Scholasch, 2019).

At regional scale, monitoring vine water status makes it possible to understand and anticipate the major trends at work. It allows the organisations that support growers to identify periods of high-water restriction or zones regularly impacted. At this scale, monitoring vine water status allows cooperative wineries, producers' unions or chambers of agriculture to set up a collective strategy, to anticipate harvest logistic issues, to apply for irrigation authorisation or to define sectors for which irrigation equipment must be set up in priority. In some cases, this monitoring can also be used to broadcast generic and often free advice to the winegrowers of a territory (Bécart *et al.,* 2020). Finally, vine water status is one of the major determinants of terroir effect (Willwerth and Reynolds, 2020). However, effects of climate change have important consequences on vine water status (Mosedale *et al.,* 2016) and should modify our knowledge of vineyard terroirs. It is therefore necessary to have tools to describe vine water status at regional scale and its change over the time as objectively as possible (Brillante *et al.,* 2020).

Tools available to monitor vine water status at a scale larger than the field (i.e. regional scale) are mainly based on the measurement of environmental factors that may influence water status such as soil or meteorology (Bramley *et al.,* 2020). In some cases, these data are also used to feed mechanistic models in order to predict plant behaviour (Naulleau *et al.,* 2022). Remote sensing can also be complementary to these approaches (Laroche-Pinel *et al.,* 2021) as it allows for large-scale measurement of vine characteristics that can be related to plant water status (Pagay and Kidman, 2019). However, the weakness of all these methods lies in the fact that they are not based on direct measurements of the plant. Therefore, they require strong assumptions to be made and present a significant amount of uncertainty that can be detrimental for decision support (Dell'Acqua *et al.,* 2018). Moreover, these methods require to estimate parameters that are difficult to measure exhaustively at this spatial scale (e.g. soil water holding capacity).

Crowdsourcing offers interesting opportunities to collect in situ observations at regional scale (Simoes and Peterson, 2018). This approach consists in carrying out a complex task (i.e. collecting observations on an entire region) by relying on a community of contributors who carry out simpler unit tasks (i.e. collecting observations on a single field) and pool their results (Brabham, 2008). Crowdsourcing is widely used in biodiversity monitoring for the collection of observations on fauna (Prudic *et al.,* 2017) and flora (Marcenò *et al.,* 2021) by enthusiastic amateurs. In this case, participants contribute mainly for altruistic or collectivist motivations, i.e. to be of service to others (e.g. scientists) or to serve the interest of a group (e.g. the botanist community) (Batson *et al.,* 2002). In agriculture this type of project is less developed but initiatives are emerging (Minet *et al.,* 2017). Participants are often professionals who collect observations as part of their daily activity. In this case, the motivations are rather egoist, i.e. the participants contribute to answer a question they have or to serve their own interests (Batson *et al.,* 2002). The collaborative collection project is in this case, only an unintended consequence of their individual action.

The potential of crowdsourcing projects in collecting a significant amount of observations at a regional scale seem to meet the challenges of monitoring vine water status at this spatial scale. Nevertheless, this approach has never been tested. Beyond this potential, the capacity of a crowdsourcing project to motivate enough stakeholders in the wine industry to participate is unknown. The capacity of the collected observations to describe the spatial and temporal evolution of vine water status at different regional scales despite the diversity of cultivars or agricultural practices is not known either. Therefore, the objective of this article is to explore the potential of crowdsourcing observations to carry out temporal and spatial monitoring of vine water status at different regional scales. This article also aims to verify whether an egoist motivation of participants is sufficient to ensure this monitoring.

MATERIALS AND METHODS

1. Collection of crowdsourcing observations

The approach was tested with a crowdsourcing project called ApeX-Vigne. Participants were stakeholders of the wine industry (winegrowers and advisors). Observations about vine water status were made using a method based on the measurement of vine shoot growth. They were collected using a mobile application. The following sections present the observation method and the mobile application.

1.1. Monitoring vine water status with shoot growth observations

Observations were collected using vine shoot growth observation method described by Martinez-De-Toda *et al.* (2010). Hereafter is a short description of the approach. The reader will find more details on its implementation in the context of southern France in Pichon *et al.* (2021).

Pellegrino *et al.* (2005) demonstrated that when water access becomes a limiting factor, vine shoot growth slows down and then stops. Martinez-De-Toda *et al.* (2010) proposed an operational method based on this principle by demonstrating that observations of vine shoot growth were correlated with stem water potential, a reference measurement of vine water status. The method of vine shoot growth observation consists in observing 50 apexes (i.e. vine shoot tips) and classifying them according to three levels: i) full growth (FG), ii) moderate growth (MG) and iii) stopped growth (SG). Observations are summarized by an index *S* calculated using the equation proposed by Martinez-De-Toda *et al.* (2010) (Eq.1).

▸ Equation 1: $S = w_{FG}S_{FG} + w_{MG}S_{MG} + w_{SG}S_{SG}$

where w_{FG}, w_{MG}, w_{FG}, correspond to the proportions of full growth, moderate growth and stopped growth apexes respectively and S_{FG}, S_{MG}, S_{SG}, correspond to coefficients assigned to each of these growth levels. In the south of France, the French Technical Institute of Vine and Wine (Institut Français de la Vigne et du Vin – IFV) recommends that growers set these coefficients to respectively 1, 0.5 and 0 to define the index of Growing Apex (iG-Apex) (Payan, 2020). These coefficients were considered to be the most adapted to the context of this study.

To better characterise the water status of their vineyards, users generally carry out weekly monitoring of vine shoot growth during the summer period. iG-Apex is generally close to 1 around full bloom and then decreases down to 0 around veraison, as water restriction increases.

1.2. ApeX-Vigne mobile application

ApeX-Vine is a free mobile application that facilitates the observation, calculation and interpretation of iG-Apex index. This application is hybrid, which offers the possibility to deploy it on several platforms. It is currently only available on the Android platform via the Google Play Store (https://play.google.com/store/apps/details?id=ag.GB.apex&hl=fr last seen 23/02/2022). It was officially launched in June 2019. A more detailed description of the application's technical features can be found in Brunel *et al.* (2019).

ApeX-Vigne has two main screens for collecting an observation (Figure 1.a) and interpreting the corresponding vine water status (Figure 1.c). When the user starts a new observation, he chooses a field and then observes and classifies each apex by clicking on one of the three corresponding buttons (Figure 1.a). Then, the user can calculate iG-Apex index in order to interpret the observation (Figure 1.c).

ApeX-Vigne application records the date and position for each observation. The position is determined using the smartphone's GNSS receiver. The collected data is automatically synchronised with a central database when the smartphone has a 3G signal (or better) or a Wi-Fi connection. In the event that an observation is collected in an area without network coverage, it is stored on the smartphone and then synchronised when a network connection is available. When users download the application, they explicitly give their consent for their observations to be used in research projects.

The data analysed in this article correspond to observations from the centralised database that were collected during the three seasons 2019, 2020 and 2021. Only observations collected during the summer period (June, July and August in our conditions) were taken into account. It was considered that observations collected outside this period did not correspond to a monitoring of vine water status and could be classified as outliers. Within the summer period of time, all collected observations were therefore considered as relevant.

1.3. Participation strategy

Identified participants were the stakeholders of wine industry who contribute as part of their professional activity. From the

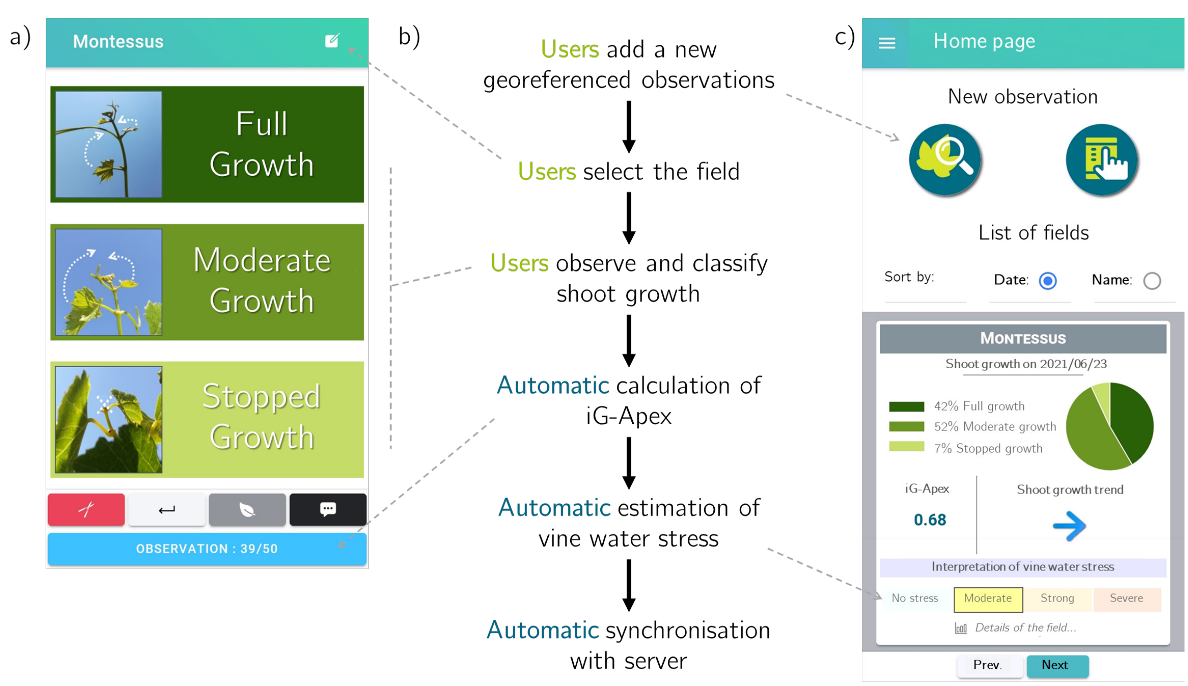

FIGURE 1. Presentation of the ApeX-Vigne mobile application: (b) Main process for collecting and synchronizing observations using (a) the input screen and (c) the summary screen.

crowdsourcing projects in agriculture as described by Minet *et al.* (2017), it was hypothesised that egoist motivation was the most appropriate to foster the contribution of these potential participants. It was also hypothesised that monitoring water constraint was a strong issue for them. Therefore, ApeX-Vigne application was designed to activate this lever by giving them access to a free and simple tool for assessing and monitoring vine water status of their own fields.

According to Rechenberger *et al.* (2015), a simple data collection process favours the collection of a large number of observations. The iG-Apex approach was chosen in this study for this purpose, as it is simple to collect and to interpret.

For the communication about ApeX-Vigne mobile application, emphasis was placed on the interest of this tool to answer to the individual challenges of wine sector's stakeholders. Information on the application was disseminated during technical days and in the specialised press.

2. Study zones

2.1. Characteristics of the study zones

The approach was tested in southern France where two study zones were defined (Figure 2.a):

- The Large Regional Scale (LRS) study zone covers an area of approximately 49,500 km² encompassing the vineyards of the Languedoc, Provence and Côtes du Rhône wine regions. Its shape has been defined on the basis of nine French administrative departments. The area encompasses 57 different controlled designation of origin with > 300,000 ha of vineyards and > 26,000 winegrowers (Agreste, 2020) (Figure 2.b). The soils of the region are diverse and the majority of them have a low water holding capacity (Figure 2.c).

- The Small Regional Scale (SRS) study zone covers an area of approximately 4,750 km², encompassing the vineyards of several wine regions, including two main controlled designation of origin: Côtes du Rhône and Costières de Nîmes. Its shape has been defined from a 5 km buffer around the controlled designation of origin (Figure 2.b). Most of the soils have a low water holding capacity (< 50 mm) (Figure 2.c).

The two study scales illustrate two different regional scales at which the wine industry stakeholders monitor vine water

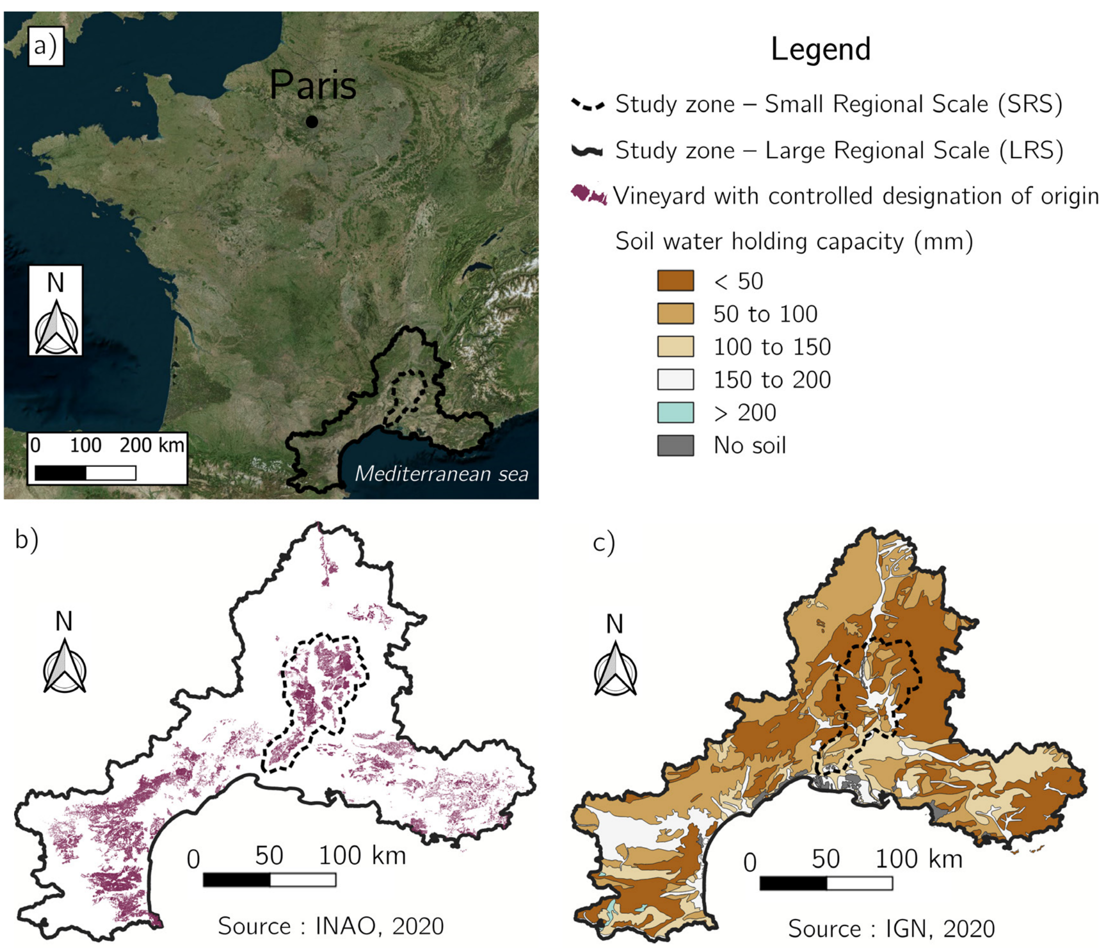

FIGURE 2. Presentation of Small Regional Scale (SRS) and Large Regional Scale (LRS) study zones: (a) location of the study zones in France, (b) location of vineyards having a controlled designation of origin over the study zones (INAO, 2020) and (c) soil water holding capacity (in mm) over the study zones (IGN, 2020).

status and take decisions. For LRS, the main involved stakeholder is generally the administration (i.e. state, region, etc.) which seeks for example to define land use policies or the research for climate change monitoring issues. For SRS, pedoclimatic and socio-economic conditions are often more homogeneous and the wine industry is often more organised (e.g. controlled designation of origin syndicate). In this case, vine water status is often monitored to ensure a collective use of water resource and possibly to justify irrigation requests.

2.2. Climatic conditions

Both LRS and SRS study zones are located in a Mediterranean climate with a high annual water deficit. The Climatic Water Balance index (CWB) is a simple but synthetic index to characterise the drought of a region or a vintage (Bandoc and Pravalie, 2015). It corresponds to the sum of daily precipitation minus the sum of daily potential evapotranspiration. When integrated over a period of time, it represents the water deficit (or excess) of a region. In this study, the drought of a given year was assessed by integrating this index from January 1st to August 31st from SAFRAN weather data provided by Météo France on an 8x8km grid (Météo France, 2022).

At the LRS scale, CWB values showed a large magnitude of variation as well as spatial patterns over the three years studied (Figure 3). 2019 was a particularly dry year. CWB was closed to -800 mm for the majority of the LRS (Figure 3.a).

2020 was a less dry year with contrasting CWB values between north and south of the LRS study zone (Figure 3.b). 2021 was a moderately dry year with a CWB gradient that decreases when approaching the Mediterranean coast (Figure 3.c).

LRS and SRS study zones are of interest because they are located in regions with many vineyards and winegrowers. They encompass a wide diversity of soils and socio-economic contexts. Their Mediterranean climate corresponds to that of many other vineyards in the world (California, South Africa, Southern Australia, etc.). Finally, low CWB values indicate that water resources are limited and therefore that monitoring vine water status in time and space is a major issue in these regions both at LRS and SRS.

3. Approach to assess potential of crowdsourcing observations

3.1. Characterisation of temporal dynamic

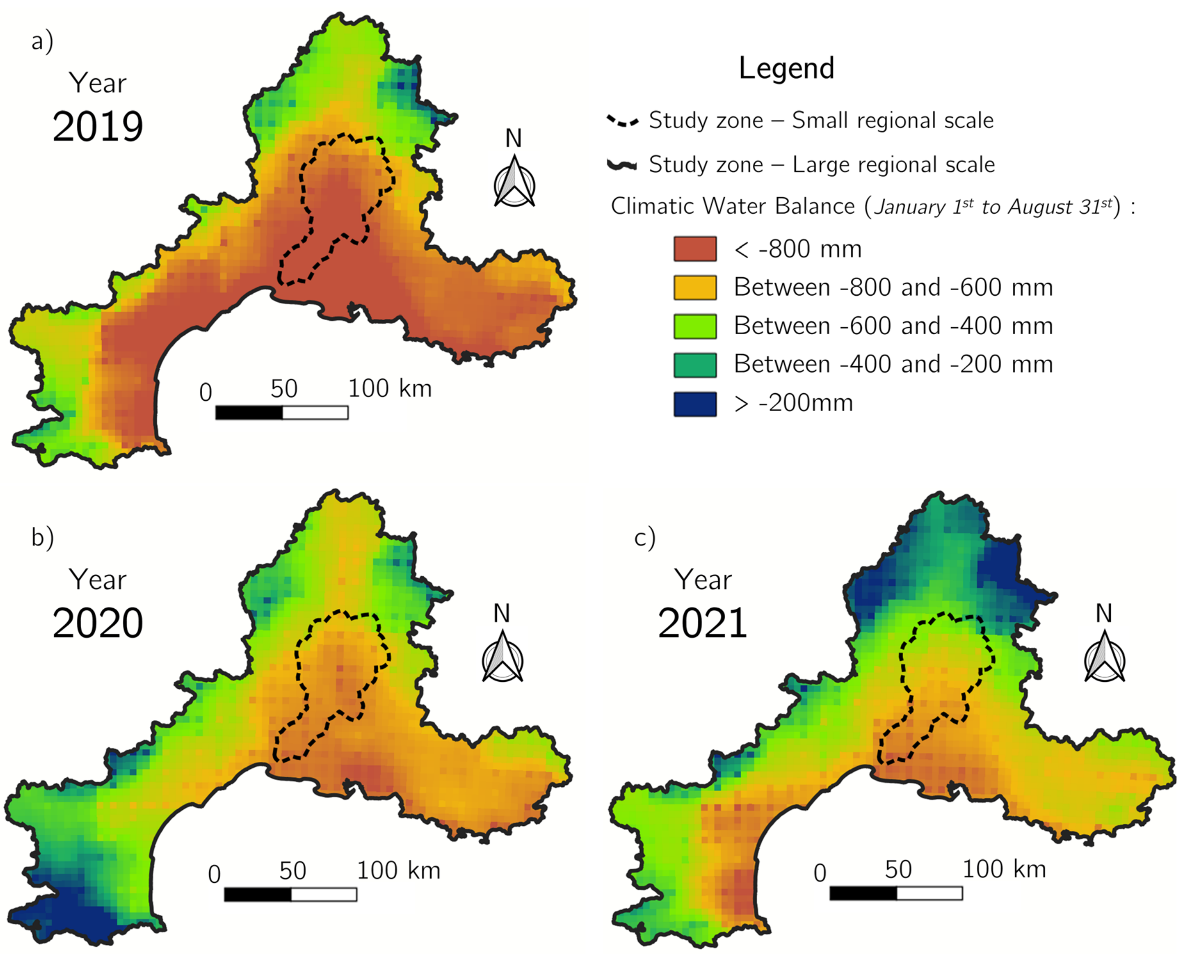

FIGURE 3. Climatic Water Balance (Bandoc and Pravalie, 2015) over the study zones calculated from January 1st to August 31st for (a) 2019, (b) 2020 and (c) 2021 seasons.

The ability of crowdsourcing data to characterise the temporal dynamics of vine water status at the scale of LRS study zone was assessed by studying the evolution of the daily mean value of iG-Apex. This evolution was modelled by a logistic regression often used in the literature to describe the relationship between vegetative growth and vine water status (Lebon *et al.,* 2006). This logistic regression was based on the following sigmoid function (Eq. 2):

▸ Equation 2: $y(t) = \frac{1}{1+e^{-\lambda(a-t)}}$

Where α is the inflection point and λ is the slope at inflexion point. The Root Mean Square Error (RMSE) was used to assess the quality of the logistic regression.

3.2. Mapping and characterisation of spatial structure dynamic

When it comes to the description and measure of the spatial variability, many indicators have been proposed in the literature (Leroux and Tisseyre, 2019). In this study, testing if and how crowdsourcing data was spatially organised was performed with a classical geostatistic approach aiming at characterising the spatial auto-correlation of the data through a semi-variogram analysis (Leroux and Tisseyre, 2019). Provided stationarity assumptions are verified, this approach provides a decomposition of the variance in two components: i) random variance or nugget effect (c_0) and ii) spatially structured variance or the partial Sill (c_1). These two components are derived from a semi-variogram model fitted to the observed data. This approach was used at both scales, LRS and SRS and the proportion corresponding of variance corresponding to a spatial phenomenon was derived from the ratio inspired by the Cambardella index (Cambardella *et al*., 1994). Finally, semi-variogram models were used to interpolate iG-Apex observations by kriging (Willwerth and Reynolds, 2020).

3.3 Tools and software

Analyses and graphs were performed using R 3.6.0 (R Core Team, 2022). Semi-variograms were fitted with gstat package using REML (Pebesma, 2004) and maps were produced using Qgis 3.16.16-Hannover (QGIS Development Team, 2022).

RESULTS

1. Participants contributions

During each of the 2019 to 2021 seasons, between 1,000 and 2,000 observations were collected on the LRS study zone. Contributors were between 60 and 90 depending on the season and they collected observations on several hundred different fields (Table 1). The number of observations collected during the first season (1,849 observations) increased slightly in 2020 (2,072 observations) and then decreased the following year (1,294 observations). The number of users decreased slightly between 2019 and 2021 from 87 to 65. Apart from the launch year (2019) when the ApeX-Vigne application probably benefited from a curiosity effect, the annual number of new users remained relatively stable between 2020 and 2021, at around 50 (Table 1). On the other hand, the number of people who collected observations even though they had already collected them the previous year decreased between 2020 and 2021 (23 versus 15).

The number of fields on which observations have been collected went from 1,659 in 2019 to 582 in 2021. However, the number of fields on which temporal monitoring (temporal series of observations) has been carried out is 10 times higher in 2021 than in 2019 (158 versus 12). The rate of fields on which only a single observation was collected also decreased from 89.6 % in 2019 to only 48.3 % in 2021.

The ApeX-Vigne application is used by stakeholders of the wine industry. The important share of new users compared to people who use the application several years in a row can be interpreted by the profile of participants. In experimentation or observation networks, tasks of regular observation of the vineyard are often entrusted to seasonal workers or trainees. These people install the application and then use it during one season. The following season, a new trainee or seasonal worker carries out the observations and then installs the application. Then, they are considered as a new user by the ApeX-Vigne application although same fields are monitored over two subsequent years.

These results also show that users have changed the way they use the mobile application between the launch season in

TABLE 1. Figures on observations collected with ApeX-Vigne mobile application during 2019 to 2021 seasons over the Large Regional Scale (LRS) study zone.

	Year		
	2019	2020	2021
Total number of observations	1,849	2,072	1,294
Total number of users, including	87	70	65
▸ New users	87	47	50
▸ Users of previous years	0	23	15
Total number of fields, including	1,659	1,445	582
▸ Fields with only 1 observation	1,486	1,168	281
▸ Fields with temporal series of observations	12	143	158

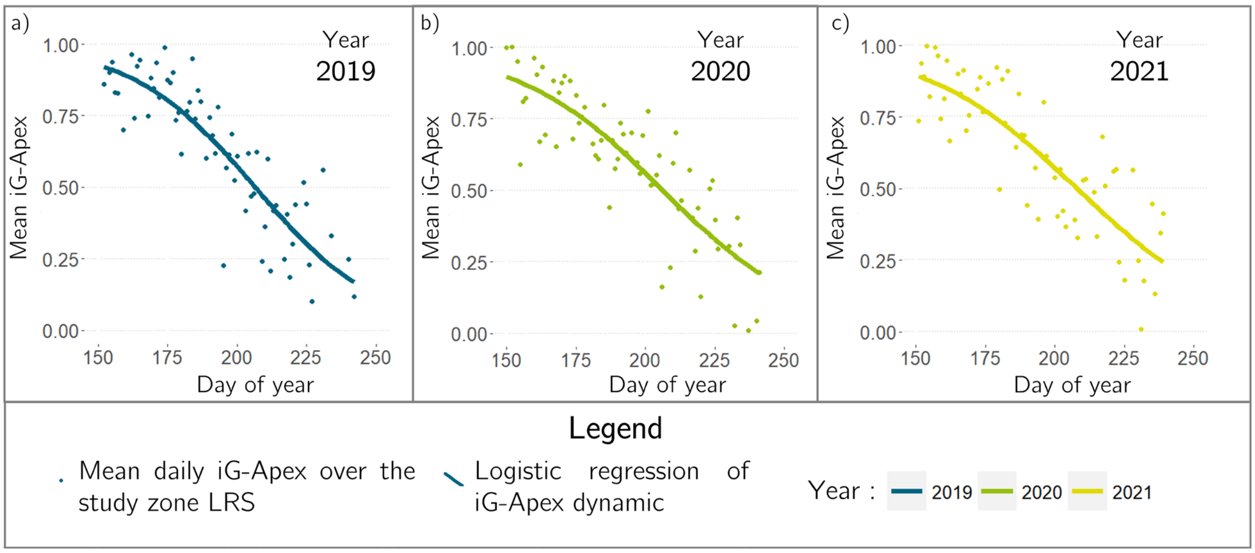

FIGURE 4. Evolution of mean iG-Apex during the season over the LRS study zone during years (a) 2019,(b) 2020 and (c) 2021.

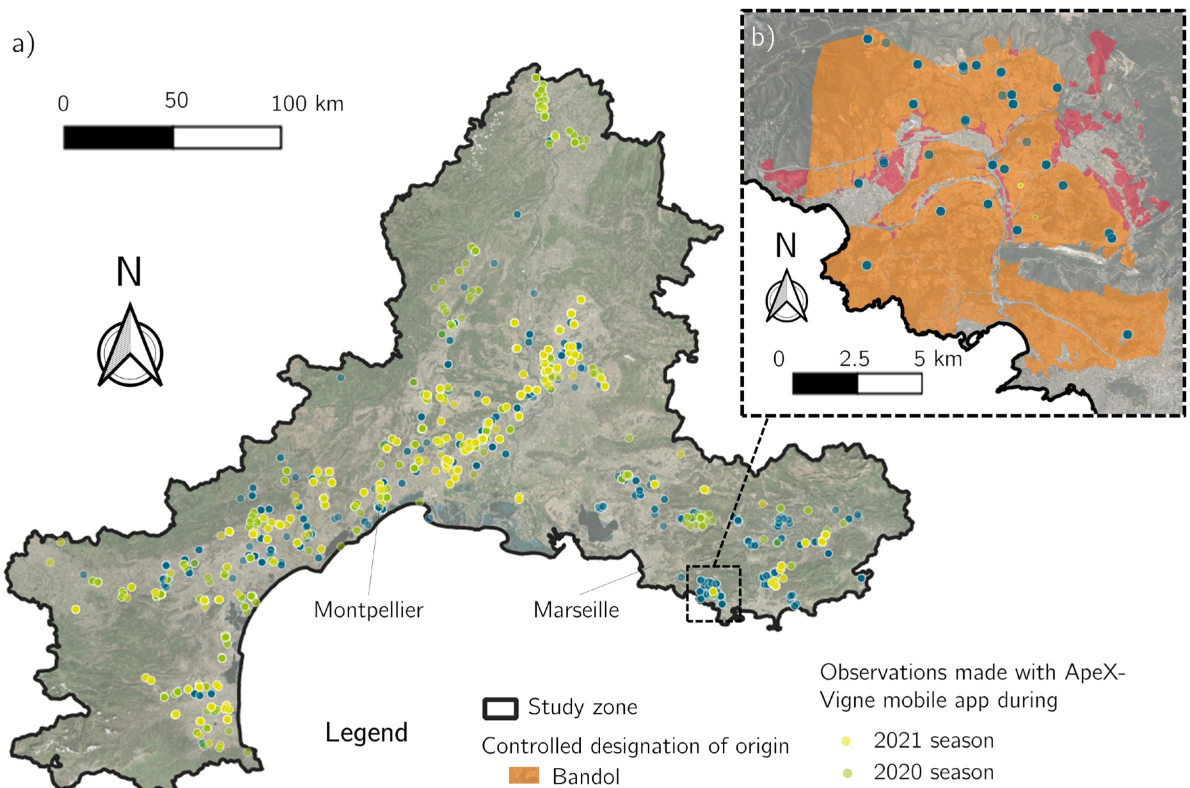

FIGURE 5. Location of observations collected with ApeX-Vigne mobile application during 2019 to 2021 seasons: a) overview of the Large Regional Scale (LRS) study zone and b) zoom on a location with particularly high density of observations.

2019 and the 2021 season. Their use seems to have evolved from exploratory use aiming at just testing the potential of the application to a more regular use with fewer fields observed but with a real monitoring based on time series of observations throughout the season. This evolution highlights how ApeX-Vigne application is adopted and used in a more rational way by stakeholders of the wine industry.

2. Evolution of vine water status at Large Regional Scale: general trends

The pooling of crowdsourcing observations allows average iG-Apex values to be studied across the entire LRS study zone for the three years of the study. Whatever the year under consideration, average iG-Apex values were close to 1 around day 150 and then gradually decreased to values close to 0 around days 225 to 250 (Figure 4). This trend of generalised cessation of shoot growth across the LRS study zone was observed in all three years studied. Given the Mediterranean climate, this trend can be explained by a progressive installation of water restriction becoming gradually a limiting factor of shoot growth. The dynamics of this cessation of shoot growth is relatively well modelled by a logistic regression with RMSE ranging from $1.20*10^{-1}$ to $1.33*10^{-1}$ for the three years.

The slope at inflexion point λ is lower in 2021 than in 2019 (λ = $3.67*10^{-2}$ versus $4.49*10^{-2}$). These results can be interpreted in relation to the maps of CWB (Figure 3). In 2019, CWB was more negative overall than in 2021 illustrating a more severe drought. This may have led to a quicker cessation of shoot growth in the LRS study zone than in 2021, resulting in higher slope at inflexion point.

3. Spatial repartition at Large Regional Scale of crowdsourcing ApeX-Vigne observations

Geolocation of crowdsourcing observations allows the general description of these trends at the scale of the LRS study zone to be complemented by a spatial analysis. Observations were collected throughout the LRS study zone during the three studied seasons (Figure 5.a). Comparison of the map of collected observations with the map of vineyards within controlled designation of origin areas (Figure 2.b) indicates that observations were found in most vineyards of the LRS study zone. The density of observations is highest in the southern part of the LRS (i.e. close to the Mediterranean Sea). Particularly high densities of observations occurred locally in several sectors of the LRS study zone. In some cases, this density has been observed every year (e.g. sector near Montpellier). In other cases, the high density was observed only for one year (e.g. sector near Marseille) (Figure 5.b). These high-density areas often correspond to a geographical unit as is the case for example in figure 5.b. All observations in the dense zone were collected within the same controlled designation of origin area. This result can be interpreted by a local dynamic supported by the farmers or the controlled designation of origin syndicate that favours participation in this specific zone.

4. Mapping vine water status at Large Regional Scale

The relatively dense spatial distribution of collected observations makes it possible to produce interpolated maps of iG-Apex at the scale of the LRS study zone for a given date. For example, during week 29 of year 2020, 250 observations were collected. The rest of the analysis focuses on this example because many observations were collected that week. Note however that similar results were observed in 2019 (194) and 2021 (157 observations).

Table 2 presents the results for these two years for illustrative purposes. The semi-variograms model of iG-Apex values observed over the week 29 of year 2020 shows that the nugget effect (c_0) was $1.94*10^{-2}$ and the spatially structured variance (c_1) was $8.83*10^{-2}$ (Table 2). 82 % of the variability observed at this date was therefore not random but strongly organised spatially which highlights the relevance to map iG-Apex at the LRS scale.

The spatial organisation of iG-Apex values is confirmed by the analysis of the kriged map at the scale of the LRS study zone (Figure 6). To facilitate the visualisation of iG-Apex spatial organisation, this kriged map is represented over the whole LRS study zone. However, interpretation should be done considering that an estimation of iG-Apex only makes sense in areas where vineyards are present.

The imprecision associated to these estimates is of the nugget effect's order (c_0 = $1.94*10^{-2}$) close to the observations and of sill's order (c_1+ c_0 = $1.07*10^{-1}$) for estimates at a distance of any observation higher than the range (~ 100 km). On week 29 of year 2020, the central zone shows iG-Apex values globally lower than 0.4 while the South-western zone shows higher iG-Apex values, in some cases above 0.6. The map highlights several gradients of iG-Apex values among which the South-Western vs North eastern one is the most significant. Considering the CWB map for the year 2020 (Figure 3.b), there is a correspondence between zones with the lowest iG-Apex values in week 29 and the lowest CWB in 2020.

TABLE 2. Parameters from the semi-variogram model resulting from iG-Apex observations collected with ApeX-Vigne mobile application over the Large Regional Scale (LRS) study zone during week 29 of years 2019, 2020 and 2021.

Year	Nugget effect (c_0)	Spatially structured variance (c_1)	$\frac{c_1}{(c_1+c_0)}$
2019	$1.00*10^{-2}$	$3.29*10^{-1}$	97 %
2020	$1.94*10^{-2}$	$8.83*10^{-2}$	82 %
2021	$1.25*10^{-2}$	$2.10*10^{-1}$	94 %

TABLE 3. Parameters from the semi-variogram model derived from iG-Apex observations collected with ApeX-Vigne mobile application over the Small Regional Scale (SRS) study zone during weeks 25 and 29 of year 2020.

Week	Number of observations	Nugget effect (c_0)	Spatially structured variance (c_1)	$\frac{c_1}{(c_1+c_0)}$
25	145	$2.02*10^{-2}$	$3.91*10^{-2}$	66 %
29	61	$1.69*10^{-2}$	$1.83*10^{-2}$	48 %

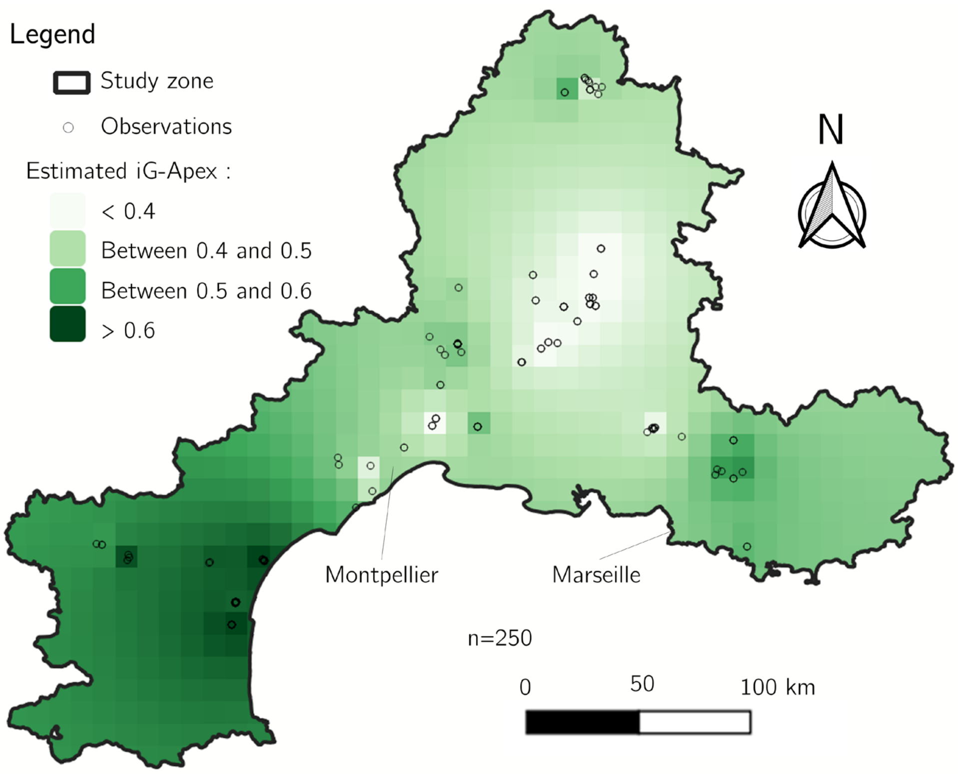

FIGURE 6. Kriged iG-Apex values over the Large Regional Scale (LRS) study zone. Map made from observations collected with ApeX-Vigne mobile application during week 29 of year 2020.

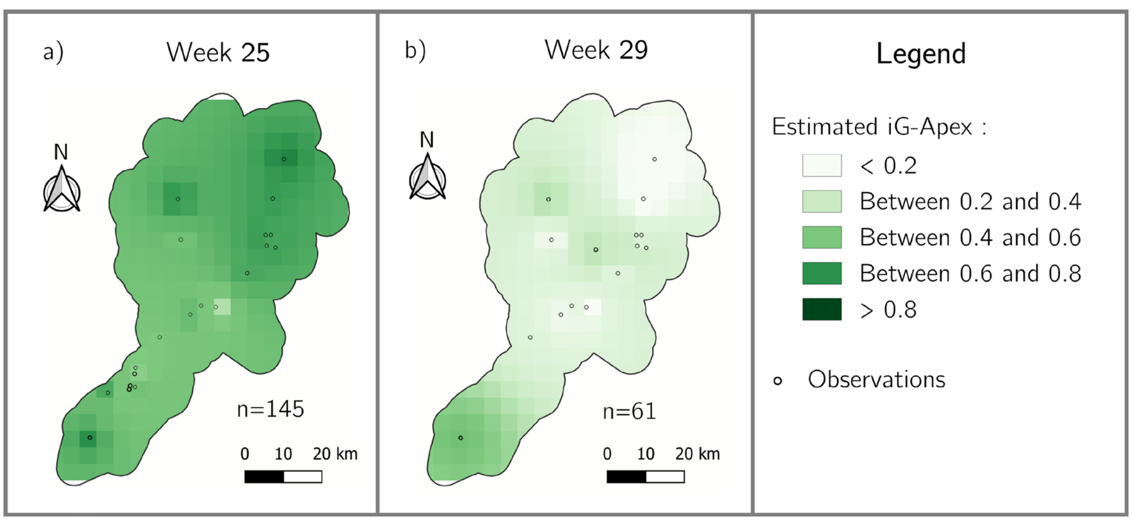

FIGURE 7. Example of interpolated iG-Apex maps over the Small Regional Scale (SRS) study zone made from observations collected with ApeX-Vigne mobile application during (a) week 25 and (b) week 29 for year 2020.

These results show the potential of crowdsourced iG-Apex at the scale of the LRS to highlight spatial variability. The high density of observations collected in certain areas makes it possible to consider going further by producing maps of this same index at smaller spatial scales.

5. Mapping vine water status at Small Regional Scale

At the SRS study zone scale, 145 observations were collected in week 25 and 61 in week 29 of year 2020 (Table 3).

The semi-variograms model of iG-Apex values show that the nugget effect (c_0) was 2.02*10^{-2} in week 25 and 1.69*10^{-2} in week 29. The spatially structured variance (c_1) was 3.91*10^{-2} and 1.83*10^{-2} respectively. The share of spatially structured variance thus decreased from 66 % in week 25 to 48 % in week 29.

These results are confirmed by the two corresponding maps. In some regions of the SRS study zone, observations were collected in week 25 but not in week 29 (Figure 7). Spatial organisation of iG-Apex values is generally weaker than maps of the LRS study zone. At this scale, values of iG-Apex which differed significantly from those of their neighbourhood are clearly highlighted. These differences may be due to specificities of the considered field (cultivar, farming practices, etc.) or to outliers. Given the information collected with the mobile application, it is difficult to analyse further these results. However, it is worth mentioning that despite the small number of observations available at this scale of work, it is possible to identify spatial phenomena, temporal dynamics and also surprising observations.

DISCUSSION

Firstly, this study shows that egoist motivation implemented in the ApeX-Vigne project has made it possible to collect between 1,000 and 2,000 observations per year in the LRS study zone. This motivation factor was adequate to collect observations in all the wine-producing regions of the study zone. The use of the mobile application by wine industry stakeholders has evolved over the three years studied. It is therefore likely that the motivations have also evolved over time. For example, in 2021, the CWB was globally higher than the two previous years indicating a globally lower water stress. The monitoring of vine water status was therefore less important for the wine industry stakeholders than in the previous years. It seems reasonable to hypothesise that the egoist motivation lever was less powerful in 2021, resulting in a lower number of observations collected. This limitation of egoist motivation in crowdsourcing projects has already been observed and described in the literature (Batson *et al.,* 2002). One way of limiting this versatility is to activate other motivational levers. Altruism and collectivism are particularly interesting because they promote participation and commitment over time (Asingizwe *et al.,* 2020). In this case, what motivates the participant to contribute is the desire to belong to a group and to carry out a task collectively. This lever seems interesting to explore for the future of the ApeX-Vigne project and more broadly for crowdsourcing projects in viticulture. It is likely that it cannot be activated in the same way at the SRS, where there is often an identified and coherent collective (e.g. cooperative, controlled designation of origin syndicate, etc.), as at the LRS scale, where the collectives are larger and less formally structured in the wine industry (e.g. administrative region). Considering crowdsourced iG-Apex values are relevant to be monitored at this scale in relation to vine water restriction, future research should be conducted on the implementation of this lever and its capacity to reinforce the quantity and quality of crowdsourcing data collected.

Secondly, results of this study show that observations collected by crowdsourcing using ApeX-Vigne application allow to characterize the cessation of growth trend at the LRS study zone scale. The number of observations collected over the study period seems to be large enough to characterise this trend despite variations in the density and location of observations over time. Considering a similar contribution and even if the location changes from year to year, this result shows that relevant maps at this spatial scale can be obtained from one year to another. A limitation to be considered, however, is the spatial dispersion of the contributions. Indeed, in the (extreme) case where all contributions are concentrated in a small area of the LRS, the resulting map would be of poor relevance over zones where no contributions are made. The approach therefore assumes that the contributions are distributed in a regular or random manner over the study area. Crowdsourcing observations from ApeX-Vigne application also allow to collect spatially structured information and to produce interpolated iG-Apex maps at this scale. Observations collected in the SRS study zone can also be interpolated but are less spatially structured. At this scale, the quality of collected data seems to be too limited to describe satisfactorily vine water status. This issue of quality of crowdsourcing data has already been widely addressed in the literature (Goodchild and Li, 2012). In the case of this study, the quality of the data could be influenced by several factors with a different impact depending on the spatial scale considered:

- Other factors than water constraint may have influenced the vine shoot growth. This is the case, for example, for cultivar and rootstock (Bota *et al.,* 2016), cover cropping (Delpuech and Metay, 2018) or farming practices (Reynolds, 2010). In the ApeX-Vigne data, this information about the field was unknown. This uncertainty may potentially limit the ability of iG-Apex to correctly describe vine water status. However, the results of this study showed that despite this limitation, collected observations allowed the mapping and the identification of major trends in the evolution of vine water status at LRS. At SRS, the potential of these data is also important but the spatially structured part of the variance in iG-Apex observations is lower. This study does not allow to explain whether this result is due to too few observations or to a too strong impact of other factors influencing vine shoot growth at this scale. Future research should be conducted specifically at the SRS to answer this question.

- It is possible that outliers may have been collected into the ApeX-Vigne application. The purpose of this study was not to identify these outliers but it can be considered that their number was relatively low. In the literature, crowdsourcing projects generally have around 1 to 3 % of outliers (Mehdipoor *et al.,* 2015). However, maps at the SRS have highlighted observations having attribute values different from their neighbourhood. These observations deserve special attention because they may correspond to outliers to be eliminated (i.e. malicious operators, data entry or location errors, etc.) but they may also correspond to surprising observations (Senaratne *et al.,* 2016) due for example, to different (and maybe interesting) agricultural practices. The development of methods to automatically identify these observations is an interesting area to explore. Some authors have, for example, used the autocorrelation of the phenomenon studied to identify these observations (Simoes and Peterson, 2018). This approach seems interesting to explore in the case of ApeX-Vigne data, given the spatial structure of soil and climatic conditions that may influence vine water status at regional scale (Ruffault *et al.,* 2013).

▸ Results showed that observations were collected over the entire LRS study zone. The higher density of observations in the south of this study zone can be explained by a lower CWB in this area, which leads to a higher overall water restriction and therefore a higher need for its monitoring. This influence of the studied phenomenon on the spatial and temporal distribution of observations is relatively classic in crowdsourcing projects (Sullivan *et al.,* 2009). At the SRS, the number and spatial distribution of observations varies between weeks 25 and 29. This phenomenon illustrates the difficulty of maintaining a large number of observations and spatial completeness throughout the season at this scale. It raises the question of the motivation of participants to collect observations and to keep on contributing over time. This issue is central to crowdsourcing projects (Asingizwe *et al.,* 2020) and deserves to be studied in detail.

Finally, these results illustrate the potential of this crowdsourcing project to characterise and spatialize a vineyard characteristic at this scale. According to Brillante *et al*. (2020), this characterisation is a major challenge because climate change will modify our knowledge and understanding of vineyards at regional scale. According to these authors, it is necessary to build objective means to describe the heterogeneity of vineyards at these spatial scales. To meet this challenge, the potential of crowdsourcing data collected by the ApeX-Vigne application seems to be complementary to other existing approaches such as meteorological data (Bramley *et al.,* 2020), remote sensing (Laroche-Pinel *et al.,* 2021) or modelling (Naulleau *et al.,* 2022).

CONCLUSION

ApeX-Vigne mobile application has been developed to collect data on vine water status by making observations on vine shoot growth. This application allows the gathering, geolocation and pooling of these observations. It makes it possible to consider a collaborative collection of observations (crowdsourcing) at a regional scale. This study explored the potential of crowdsourcing observations collected by ApeX-Vigne application for temporal and spatial monitoring of vine water status at two regional scales. It also tested the hypothesis that an egoist motivation of participants is sufficient to ensure this monitoring. According to the results, the amount of collected data was large enough to describe the trend of cessation of vine shoot growth at a large regional scale during the three studied years. At this spatial scale, it was also possible to spatialize and to capture the spatial structure of an index that may be linked, in Mediterranean conditions, to vine water status. At a smaller regional scale, crowdsourcing data has stronger limitations. Motivation of participants by other levers than only selfish ones seem to be an avenue to explore.

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