ApeX-Vigne: experiences in monitoring vine water status from within-field to regional scales using crowdsourcing data from a free mobile phone application

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Abstract

Monitoring vine water status is a major issue for vineyard management because water constraints impact both the quality and the quantity of the harvest. Existing methods are often costly and complex to implement. ApeX-Vigne is a free mobile application developed to facilitate the collection and geolocation of 50 vine apex observations to characterise vine shoot growth and classify it into 3 growth categories. The application also provides the user with a simple estimate of vine water status based on shoot growth. This paper presents the results obtained over two seasons (2019 and 2020) after the launch of the Apex-Vigne application and its use over a large wine producing region in the south of France. An existing method was adapted for evaluating the interest of the application based on the number of installations and uninstallations. The results showed that the application had more than 1200 downloads and 6000 observations made in the 2020 season. Examples from the commercially collected data showed that ApeX-Vigne can be used as a tool for characterizing water stress at within-field and inter-field scales. Finally, it was also demonstrated that by enabling the massive and centralized collection of spatial field and within-field scale observations of shoot growth, the ApeX-Vigne data was able to characterise the spatial structure of vine water status at the regional scale. Access to this new source of information offers opportunities for the management of water resources at a regional scale as well as for site- and vineyard-specific management. These results also raised new research questions on the joint use of this new source of spatial data with other sources of high spatial resolution information.

Keywords: data sharing, digital agriculture, precision viticulture, smartphone, *Vitis vinifera*,

Introduction

Many authors have demonstrated the significant role of vine water status on vine physiology and berry composition (Van Leeuwen and Seguin 1994; Cifre et al. 2005; Zufferey et al. 2017). Monitoring vine water status is of importance for yield and quality management purposes. The vine water status naturally changes over time according to the climatic characteristics of the season. In addition, many authors have shown that it presents a significant spatial variability at different scales in Mediterranean climate conditions: at the within field level (Tisseyre et al. 2005), at the vineyard level (Taylor et al. 2011) and at the regional scale (Baralon et al. 2012). Characterizing the temporal and the spatial variability of vine water status is of paramount importance at these different scales to provide the industry with relevant decision support tools for various management options, including canopy and irrigation management, fruit maturity and harvest logistics.

Several standard instrumental methods have been proposed to accurately measure plant water status (Rienth and Scholasch 2019). However, these standard methods are not easy to perform as they are manual techniques that require cumbersome equipment and specific skills. As a result, the use of these methods is typically limited to experiments carried out by research or technical institutes and they are rarely adopted by viticulture practitioners (growers or advisors). In order to provide simpler, non-destructive and cost-effective approaches to estimate vine water status, methods to monitor shoot growth have been proposed. When vine access to water becomes limiting, it has been shown that vine growth is affected (Pellegrino et al. 2005). Martinez-De-Toda et al. (2010) proposed a simple and operational method to relate shoot growth to the water restriction experienced by vines. Their method is based on classifying apexes (vine shoot tips) according to three growth levels: i) full growth (FG) when the apex is undergoing active organogenesis, ii) moderate growth (MG) when organogenesis is reduced and iii) stopped growth (SG) when the apex has fallen off or dried out. The authors showed that the observations of apex growth were correlated with stem water potential, a reference measurement of vine water status. The operational implementation of the approach requires counting 50 apexes (Rodriguez Lovelle et al., 2009). The growth of these 50 apexes can be summarised by an indicator S proposed by Martinez-De-Toda et al. (2010) (Eq. 1).

$$S = w_{FG}S_{FG} + w_{MG}S_{MG} + w_{SG}S_{SG} \qquad (1)$$

where w_{FG}, w_{MG}, w_{SG}, correspond respectively to the proportions of full growth, moderate growth and stopped growth apexes. S_{FG}, S_{MG}, S_{SG} are coefficients assigned to each of these growth levels and are adjusted by experts according to the pedo-climatic context.

Although less precise than reference methods, monitoring shoot growth has the advantage of being easily achievable without expensive equipment and by inexperienced operators. Therefore, this method is of interest to monitor temporal and spatial changes in vine water status when several operators (workers, growers, advisors etc.) may be involved in collecting observations. It is of particular interest in regions where the majority of vineyards are managed by small growers, who have limited investment capacities and still carry out many manual in-field operations. However, the monitoring of shoot growth has some limitations that has restricted its adoption until now: i) it requires observers to count the apex of 50 vine shoots, to classify them into three different classes and to carefully record the results of the counts for each class, ii) the final indicator S needs to be calculated based on the apex observations and iii) the observed S value needs to be recorded and transferred to a database with additional information, such as the time and location of the observations. Although simple, these different operations can be cumbersome because they require information to be recorded and a calculation to be made in the field.

In order to tackle this issue and to simplify the use of this operational method for monitoring shoot growth, a dedicated free mobile application (app), called ApeX-Vigne, was developed and launched in 2019 (Brunel et al., 2019). The purpose of the app is to provide a simple tool to growers and advisers to: i) facilitate the collection of apex observations, ii) automatically calculate the S indicator, iii) geo-reference and time-stamp the S indicator values and iv) automatically transfer the S indicator values to a database on a server to facilitate future analysis and sharing of these data.

Two seasons after the launch of the app, it is now possible to evaluate its adoption and appropriation by users. In the literature, the approaches described for this evaluation are either very generic (Liu et al., 2018) or, on the contrary, very specific to a use case (Rahmati and Zhong, 2013). To the authors' knowledge, there is no specific method for understanding user behaviour of an app in a professional agricultural context.

In addition, the use of this app and the collection of observations by a significant number of farmers and advisers paves the way to use this dataset to monitor vine growth at a regional as well as local scale. Characterising vine growth at large spatial scales may be of interest for cooperatives, public services or research for understanding general trends in making common decisions. Using so called 'crowd-sourced' datasets collected by many operators is common in the monitoring of environment conditions (Picaut et al., 2019), biodiversity (Joly et al., 2016) or natural disasters (Rogstadius et al. 2013), but its potential has not been widely studied in agriculture (Minet et al. 2017).

Therefore, the objective of this paper is i) to evaluate how the ApeX-Vigne application is adopted by users, ii) to study whether the application answers the questions that professionals have about monitoring vine water status at the field or within-field scales, and iii) to verify whether the aggregated vineyard data can be used to help address regional-wide monitoring issues by providing a new source of relevant information.

Materials and method

The index of Growing Apex (iG-Apex) for monitoring shoot growth

Based on the equation proposed by Martinez-De-Toda et al. (2010) (Eq. 1), the French Technical Institute of Vine and Wine (Institut Français de la Vigne et du Vin – IFV) recommends that growers set the S_{FG}, S_{MG}, S_{SG} coefficients to respectively 1, 0.5 and 0 to define the index of Growing Apex (iG-Apex) (Payan, 2020). These coefficients have been determined from experiments carried out in the south of France and were selected to best relate the iG-Apex with the occurrence of moderate water restriction (Payan, 2020). These coefficients, as recommended by IFV, have been used to calculate iG-Apex in this study.

The iG-Apex method is used at the field and sometimes at the within-field scale by growers and advisors who measure 50 apexes spread over 10 different vines selected in representative zones of the field (Rodriguez Lovelle et al. 2009). Around full bloom, the iG-Apex is generally close to 1. It then decreases with the occurrence of increasing water restriction to reach values close to 0, generally around veraison.

General technical characteristics of the ApeX-Vigne application

ApeX-Vigne is a free hybrid app combining elements of both native and web applications in order to facilitate its dissemination over several platforms. This application 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 viewed 12/02/2021). The architecture was conditioned to meet operational constraints and functionalities, such as the ability to use the application in areas where network coverage is intermittent or even absent and to safely send and store the data collected on a central database server. Regarding this latter functionality, when users download the ApeX-Vigne application, they explicitly give their consent for the observations they collect to be used in research projects.

For the off-line mode of the application, data storage is performed on the smartphone. Data are automatically synchronized with the central database when the smartphone has a 3G (or greater) signal or a Wi-Fi connection. Communication between the smartphone and the server is provided by a JavaScript API. For geolocation, the application accesses the smartphone's GNSS.

Application interface and publication

The ApeX-Vigne app has two main screens, an input screen for entering observations (Fig. 1a) and an output screen with summarized results (Fig. 1b). The input screen is divided into three areas: i) a list to select the field where the observations were performed, ii) three buttons to select the shoot tip class, and iii) a dynamic counter at the bottom of the screen to inform the user of the number of observations made. The button to calculate the iG-Apex only becomes active once 50 observations have been made. This set of 50 observations is called a survey. The geolocation of each observation is recorded as soon as the accuracy estimated by the smartphone's GNSS receiver is under 10 m. The geolocation of the survey corresponds to the mean coordinates of the 50 observations. Only the survey coordinates are accessible to the users and considered in this study. The output screen (Fig. 1b) provides a summary for each survey of the proportion of each type of apex observed and the corresponding level of water restriction based on the calculated iG-Apex value. A more detailed description of the ApeX-Vigne application's characteristics can be found in Brunel et al. (2019).

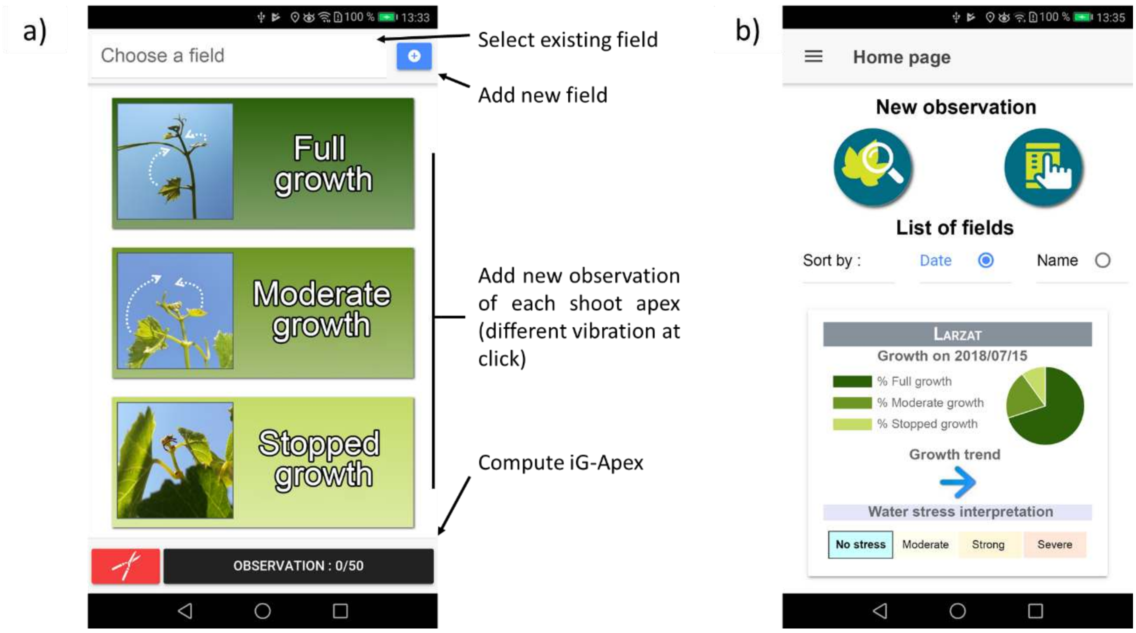

Figure 1: Screenshot of the two main interfaces of the ApeX-Vigne application: the input (a) and output (b) screens.

After a first test campaign in 2018 with approximately 20 beta users, the ApeX-Vigne application was officially launched and widely distributed in late May 2019 (week 21). A new version was released in early June 2020 (week 23). This paper focuses on data obtained from the ApeX-Vigne app over two seasons of use in 2019 and 2020. As the app was designed to assist with management associated with increasing water stress during the growing season, the key period for use in France is considered to be from early June to late August (weeks 23 to 35 in the calendar year)

Study zone:

The approach was tested in the south of France in an area encompassing the vineyards of the Languedoc, Provence and Côtes du Rhone viticulture regions (Fig. 2a). The study zone covers an area of ~49 500 km^2 along the Mediterranean Sea (Fig. 2a) and encompasses 57 different controlled denominations of origin with > 300 000 ha of vines and > 26 000 growers (Agreste, 2010) (Fig. 2.b). It includes a wide range of pedo-climatic conditions. The soils mostly have low soil water storage (< 50 mm) (Fig. 2c) and the mean annual precipitation over the last 30 years varies from relatively low values (500 – 700 mm yr^{-1}) in coastal areas to relatively high values (> 1 300 mm yr^{-1}) in the hinterland (Fig. 2d).

This study zone is of interest because i) it is one of the largest contiguous wine producing areas in France, ii) the majority of the vineyards are non-irrigated and the climate is Mediterranean, i.e. characterized by hot, dry summers, so that the monitoring of vine water status is important for most growers, which should favour the adoption of the ApeX-Vigne application, and iii) the pedo-climatic conditions are diverse and broadly representative of conditions that can be found in many vineyards around the world that are located in regions with a Mediterranean-type climate (e.g. west coast of the USA, southern Australia, western coast of South America and the northern and southern extremities of Africa).

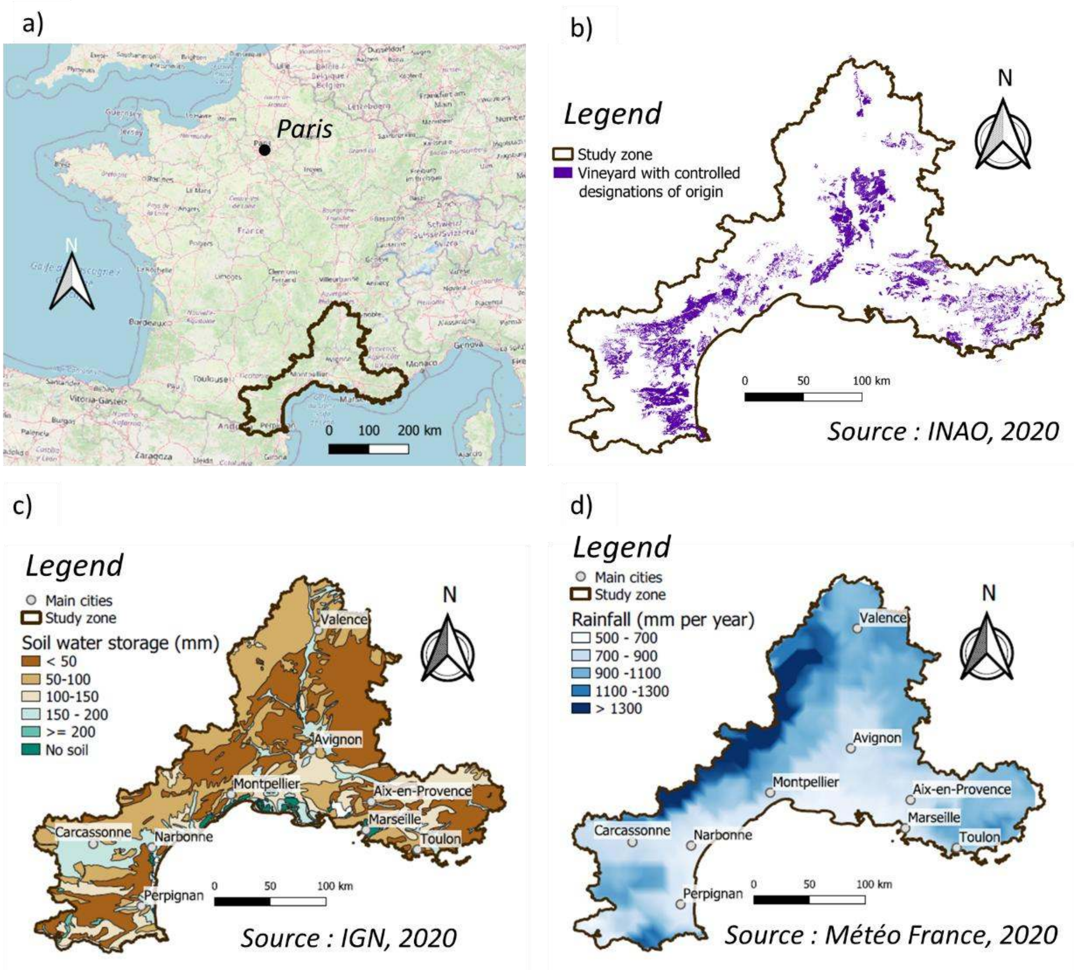

Figure 2: The study zone encompasses several wine-growing regions of importance in southern France with a large variability in soil and climate conditions. (a) The location of the study zone within France, (b) the location of vineyards within the study zone that have a controlled denomination of origin (INAO, 2020). Two principal pedo-climatic characteristics of this zone, (c) soil water storage (IGN, 2020) and (d) mean annual precipitation over the last past 30 years (Météo France, 2020).

Temperatures and rainfall observed during 2019 and 2020 seasons were characteristic of a Mediterranean climate (Météo France, 2020). They are illustrated by the data measured at a meteorological station located in Montpellier in the centre of the study zone (Fig. 3). In 2019, the spring was relatively cold and rainy and the summer hot and dry. Unusual heat waves with extreme high temperatures were observed during a few short episodes (around weeks 27-28) (Fig. 3.a). In 2020, the spring was warm and relatively wet, while the summer was very dry, particularly during the month of July (weeks 26 to 30) (Fig. 3b).

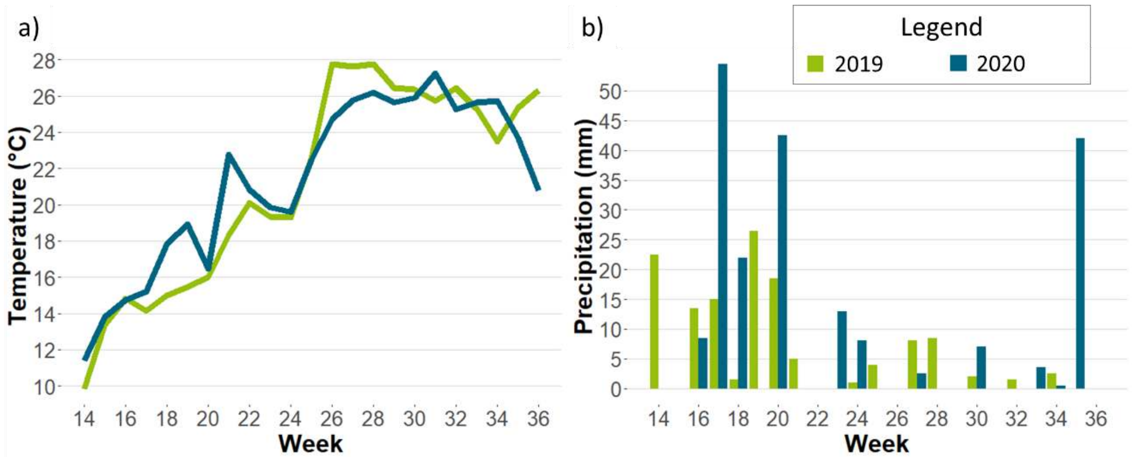

Figure 3: (a) Average weekly temperatures and (b) cumulative weekly rainfall measured during the 2019 and 2020 vintages at a meteorological station located in Montpellier, in the centre of the study zone.

Data Access

The application architecture offers several modes of data access. In its simplest form, each user is able to visualize, on their mobile device, the data collected on their own fields. As well as this individual-level access, the data are collected and centralized on a server database. This also makes it possible for the application administrators to download all the data collected by all users of the application in the form of a CSV file that also includes the user ID, field name, date and geographical coordinates in WGS 84 format.

The two different levels of data access (individual and centralized) permits analyses to be performed at different scales, from the field to the entire region. In both cases, global or local outliers may exist. For these analyses, data were simply filtered to ensure that only surveys collected within the study area and during the relevant time period were considered.

Considered data

The dataset collected during the 2019 and 2020 seasons was considered as a whole. The number and date of installations and uninstallations provided by the Google Play Store platform, in addition to the number and location of surveys provided by the centralized database, were used to characterise the adoption of the ApeX-Vigne application.

In a second step, some example of data were selected from the dataset to illustrate how growers used the ApeX-Vigne application to answer specific questions that they had about the monitoring of vine water status at the within field and inter-field scale.

- The field used to illustrate monitoring at the within-field scale was chosen as it had a large enough number of performed within-field surveys (n) to model a semi-variogram (n > 50) (Kerry and Oliver, 2007), and had surveys made on a frequent and regular basis throughout the season.

- The fields used to illustrate monitoring at the inter-field scale were chosen for being located in contrasting soil and climate conditions and for having regular surveys throughout the season.

In a third step, all the surveys carried out across the study zone in 2019 and 2020 were considered to illustrate the potential of the Apex-Vigne application to monitor vine water status at the regional scale.

Approach for evaluating the adoption of ApeX-Vigne

Four experts participated in six development cycles by providing feed-back and improving the application step by step. Previous research work has shown that the ApeX-Vigne application met the users' needs and that the proposed interface was appropriate (Brunel et al. 2019). The objective of this work was to go a step further and to characterise the adoption and uses of the application on the study zone using relevant indicators.

The first indicators were derived from the usage statistics provided by Google for any application uploaded to the Play Store and compared to references established by Liu et al. (2018) based on an analysis of 280 000 applications:

- An application with more than 50 downloads is part of what Liu et al. (2018) called the "popular app set", i.e. the most popular 3500 applications among the 280 000 studied.
- For applications that were part of this "popular app set", Liu et al. (2018) proposed the I/U ratio (Installed/Uninstalled) that represents the number of devices on which the app has been installed divided by the number of devices on which it has been uninstalled. In the Liu et al. (2018) study, the mean I/U ratio was 5.875. Applications with an I/U ratio > 6 were considered to be well adopted.

Although these values were established in a different country (China) and with another application store, Wandoujia (Wandoujia, China), they were assumed to be a reference due to the very large number of applications considered. No equivalent metric was found based on apps delivered via the Google Play or Apple stores.

The second indicator was the evolution of the number of surveys collected per week by all users. This indicator was calculated directly from the database on the ApeX-Vigne server. Its objective was to evaluate the actual use of the application. Finally, spatial distribution of the surveys was mapped to identify whether adoption (and usage) was consistent across the region or possible zones of preferred adoption (and usage).

Approach for illustrating the uses of ApeX-Vigne

Use cases of ApeX-Vigne were illustrated differently at within-field, inter-field and regional scales.

- At the within-field scale, the data were aggregated over time according to the week number in which they were collected. The mean and standard deviation of iG-Apex per week were calculated and their evolution over time was represented. For the week with the highest iG-Apex standard deviation, the experimental semi-variogram was computed and an exponential model fitted (see Oliver and Webster (2015) for details of modelling and fitting variograms). A map of the iG-Apex interpolated by ordinary kriging was then produced in order to assess the potential interest of ApeX-Vigne app to delineate within-field zones of vine water restriction.

- At the inter-field scale, the evolution of iG-Apex over time for three selected fields were compared. The objective was to assess the potential interest of the ApeX-Vigne app to highlight potential differences in water restriction dynamics within a farm or a region and the potential to use the app data for benchmarking vineyards.
- At the regional scale, the data were also aggregated over time on a per week basis. The mean and standard deviation iG-Apex per week were calculated for both seasons 2019 and 2020. The iG-Apex of each week was compared between the two seasons with the Wilcoxon test (Rey and Neuhäuser, 2011). The spatial structure was again assessed for every week by calculating the experimental semi-variogram and fitting an exponential model. There were ~ 94 – 451 surveys for a given week to compute the semi-variogram. These values were reasonably close or larger than the limit ($n > 100$) usually reported in the literature to perform this kind of analysis (Kerry and Oliver, 2007). The semi-variogram at a regional scale was assumed to be relevant to highlight meso-scale auto-correlation (tens – hundreds of kilometres). It is commonly used at this spatial scale in soil science (Mishra et al. 2010) and climate studies (Vieira et al. 1997). Depending on the average distance between the surveys' sites, this scale may not highlight any auto-correlation phenomena at short distances, as is commonly used in precision agriculture. However, it remains an interesting approach to study the spatial auto-correlation of data at scales greater than the vineyard (meso- and macro-scale). The objective was to assess the suitability of the iG-Apex to highlight possible zones of different water restriction across the entire study zone.

The different analyses were performed using R 3.6.1 (R Core Team, 2020). The semi-variograms were fitted with the gstat package using REML (Pebesma, 2004) and maps were produced using Qgis 3.4.8-Madeira (QGIS Development Team, 2020).

Results and discussion

ApeX-Vigne application adoption - downloads and surveys

In 2019, no applications were installed until week 21, corresponding to the official launch date (Fig. 4a). A peak in the number of installations was observed in week 24 with more than 100 installations and then a gradual decrease to a value close to 0 around week 35, corresponding to the end of the observation period. The same seasonal dynamic was observed in 2020, with only a few installations per week until week 22, then a strong increase at the beginning of the observation period and finally a decrease to reach values close to 0 around week 35 again. This period corresponded to mid-late summer when collection of this information is most relevant for decision-making. In total, the ApeX-Vigne app was downloaded 581 and 650 times during the 2019 and 2020 seasons respectively. This total of 1231 downloads (~5% of growers) was well above the threshold of 50 downloads set by Liu et al. (2018), indicating that the app was ‘popular’. Note that between the end of the key period for use in 2019 and the beginning of the same period in 2020, the app was still downloaded (around 300 downloads). This result illustrated the curiosity of users for the application outside the target time period of use.

The number of uninstallations was relatively stable over the entire period with ~10 uninstallations per week (Fig. 4a). A higher number of uninstallations was observed between weeks 18 to 22 of the 2020 season. This result is certainly explained by the release of a new version of the application that may have triggered uninstallations. The I/U ratio was close to 1 between the two key periods of use (from week 34 of the 2019 season to week 18 of the 2020 season). It was highest at the beginning of the two key period of use (weeks 18 to 26 in 2019 and 2020 seasons) ranging from two to > 10.

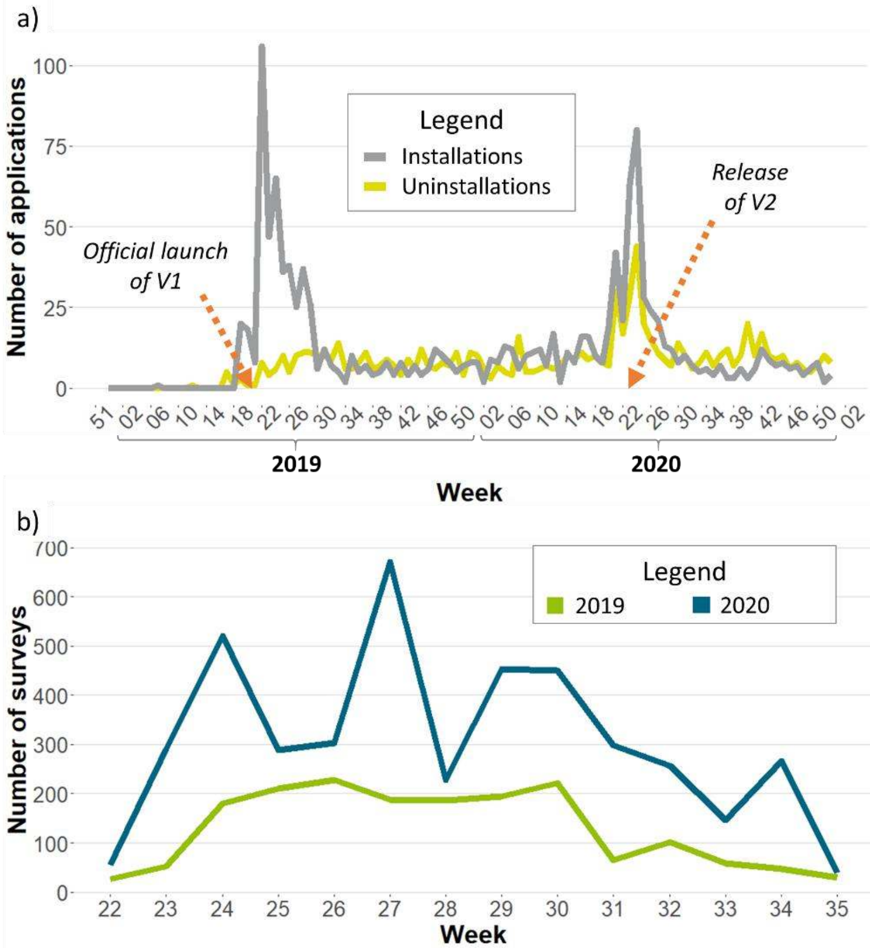

Figure 4: Basic statistics of the use of the ApeX-Vigne application. (a) Evolution of the number of installations and uninstallations during the 2019 and 2020 seasons (launched in week 21, 2019) and (b) number of surveys carried out per week over the key usage period (Weeks 22 – 35) of these two seasons.

The number of surveys per week (Fig. 4b) increased as the expected period of water stress began (week 22) and remained fairly high during the key period from weeks 24/25 to weeks 30/31. Moreover, while the trend was similar between the two years, the number of surveys per week increased significantly between 2019 and 2020, with a respective total of ~2000 and 4500 surveys. The total number of fields (608 in 2019 and 902 in 2020) and the average number of surveys per field (3.3 and 4.9 respectively) also increased between the 2019 and 2020 seasons. Comparison of ApeX-Vigne's I/U ratio to standards established by Liu et al. (2018) suggested that the application was not well adopted by users (I/U < 6). On the contrary, the number of surveys collected showed a relatively high and growing interest from users. This contradiction can be explained by two characteristics of ApeX-Vigne that existing metrics do not take into account.

The first is that ApeX-Vigne is an application used in a professional setting. Therefore, potential users are much less numerous than for the mainstream applications studied by Liu et al. (2018). Also, although there are still very few studies on this subject, it seems that the drivers of adoption for mobile applications are not the same in the agricultural sector as in the general population (Michels et al. 2020). Users expect a professional application, such as ApeX-Vigne, to save them time or to improve confidence in their decision making. These expectations are higher than for those of a mainstream application. It is possible that these differences in target audience and expectations may influence installation and uninstallation dynamics and induce I/U ratio values different from the standards set by Liu et al. (2018). The second characteristic of ApeX-Vigne that is not taken into account by existing methods is its periodic nature. The period during which the iG-Apex method is relevant for decision support is limited to two months in the year. Considering a single threshold valid for the whole season does not take this into account.

These two characteristics of ApeX-Vigne may be common for a lot of mobile applications in agriculture. They are guided on the one hand by the stakeholders of the agricultural world who are mainly professionals, and on the other hand by the seasonality of agricultural production, which leads to a periodicity in the use of many agricultural applications. The poor consideration of these characteristics by existing reference metrics illustrates the need for a detailed and specific study to monitor adoption of agricultural applications accounting for specificities like seasonality, spatial distribution, etc.

ApeX-Vigne application adoption – Location of surveys

Figure 5a shows the number and spatial distribution of surveys performed by the users over the study zone in 2019 and 2020. It should be analysed in relation to Fig. 2. The surveys were spread across all the winegrowing areas of the region, showing the interest in the app from a large range of viticulture stakeholders, whatever the region or controlled denomination of origin the vineyards belonged to. The density of surveys was higher closer to the Mediterranean Sea and on locations where annual mean precipitation was lower (Fig. 2d), showing that the app seems logically more adopted in zones where the risk of having significant water restriction is the higher according to climatic characteristics. The density of surveys was particularly high in the northern part of the study zone and in several locations in the south-eastern part. It appeared that when the use of the app was recommended locally by early adopters, including private or cooperative advisors, the use of the ApeX-Vigne app appeared to be higher. The spatial disparity in adoption may also be explained by the fact that in some areas the iG-Apex method has already been adopted by local professionals (before the launch of the ApeX-Vigne application), and this may have facilitated adoption of the app.

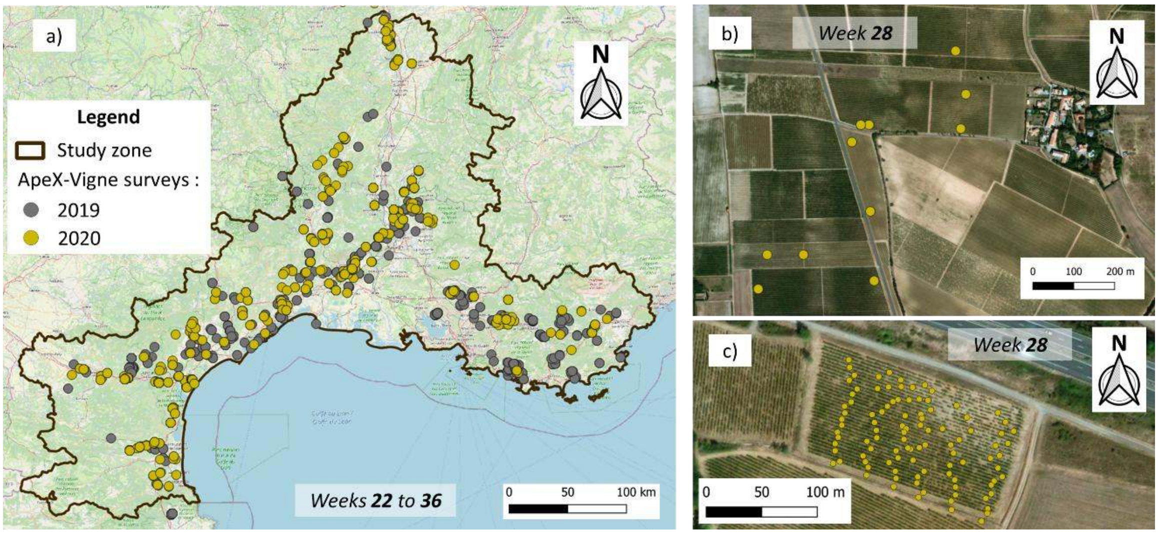

Figure 5: (a) Location of surveys made in the study zone using the ApeX-Vigne mobile application during weeks 22 to 36 of the 2019 and 2020 growing season. Local examples of (b) surveys made for a field scale monitoring and (c) for a within-field scale monitoring in week 28 of the 2020 growing season.

In most cases, users only made one survey (50+ observations) per field and per date (Fig. 5b). This common sampling strategy aimed at monitoring the average of the field and characterizing inter-field differences. However, in some cases, several surveys for the same date were carried out within the same field (Fig. 5c). The case highlighted here was rare, but indicated an interest among some users to use the application to characterize within field variability and to define potential within-field vine water status zones.

Opportunities for using the application at the within-field, field and study zone scales

Examples taken from ApeX-Vigne's centralized database illustrated how the application was used at different scales to address vineyard management issues.

The first example is the result of within-field scale vineyard monitoring. At this scale, the iG-Apex decreased from a value close to 1 in week 24 to a value approaching 0 in week 33 (Fig. 6a). The standard deviation observed was initially very low, then increased between weeks 27 to 30 and become very low again at the end of the observation period. The standard deviation of the within field surveys was the highest around week 28, suggesting that at this time, water availability becomes limiting for the most sensitive zones in the field. The variogram and mapping of iG-Apex at week 28 (Fig. 6b-c) showed that shoot growth within the vineyard was spatially structured. Analysis of the variogram indicated that the spatially structured variance was about twice the observed nugget (stochastic) variance (respectively 0.002 and 0.001). According to Martinez-De-Toda et al. (2010), a difference in iG-Apex results in differences in water restriction experienced by the vines. As a result, the characterization of this spatial structure made it possible to understand the spatial distribution of vine's response to water restriction at the within-field scale and provided information to the grower or their advisor for decision making at this scale.

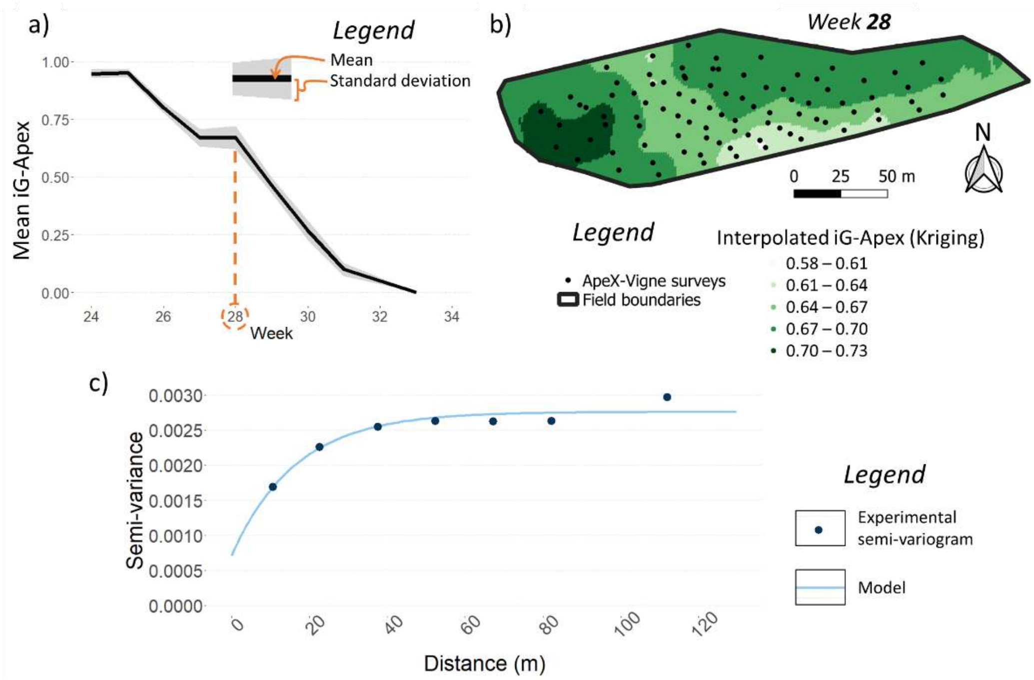

Figure 6: The ApeX-Vigne application was used by farmers and advisers for monitoring vines at the within-field scale: (a) Mean and standard deviation evolutions for the index of Growing Apex (iG-Apex) collected at the within-field scale in 2020 by a user of the ApeX-Vigne application, (b) example of an iG-Apex kriged map obtained from data collected in week 28, 2020 and, (c) the corresponding iG-Apex semi-variogram at this stage.

The second example illustrated vineyard monitoring at an inter-field scale. At this scale the temporal data collected permitted the 2020 season's shoot growth dynamics to be observed and compared for three selected fields (Fig. 7). Field 1 had the latest and slowest decrease in iG-Apex, indicating that water restriction may have been less severe in this vineyard or at least that the water restriction occurred more slowly over the season. For Field 2, the iG-Apex started decreasing very early in the season, highlighting a very early water restriction. Field 3 had an intermediate behaviour, iG-Apex started decreasing later than Field 2; however, it showed the sharpest slope of decrease in iG-Apex indicating that once water restriction started, it proceeded at a very fast rate.

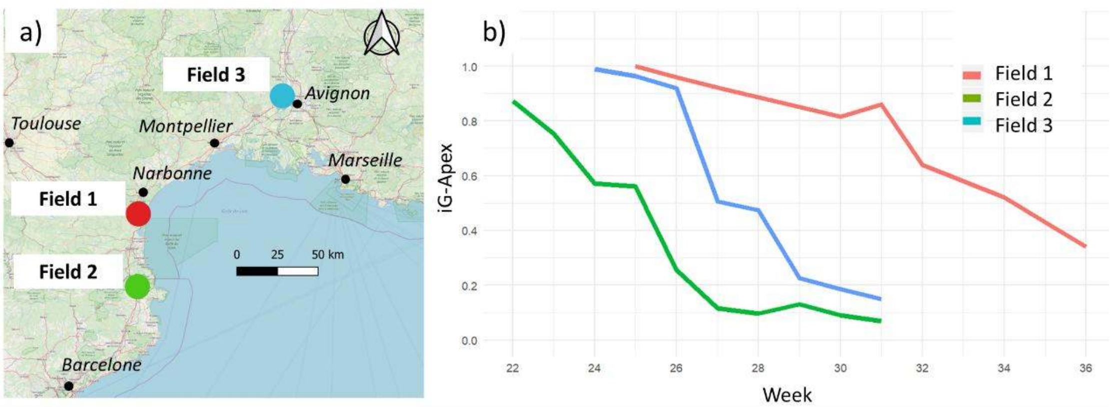

Figure 7: The ApeX-Vigne application as used by farmers and advisers for monitoring the evolution of vine water status at the field scale. (a) Examples from three individual fields in different wine-growing regions of the study zone (b) showing the evolution of the index of Growing Apex (iG-Apex) score from week 22 to week 36 in 2020.

In these Mediterranean climate conditions, and according to Martinez-De-Toda et al. (2010), the differences in Fig. 7 indicated a greater or lesser sensitivity of the three fields to water restriction. It illustrated a potential to establish a benchmarking option for the app so that this information could be used by a farmer or an advisor to understand different fields dynamics at the vineyard, the denomination or the region scale. This information would be useful for operational decision support, for example by identifying groups of homogeneously functioning fields. During the season, analyses such as these will make it possible for growers to target vineyards or within-vineyard zones where observations need to be made with more spatial and temporal precision. This may permit them to better deploy more precise but expensive and laborious measurements, e.g. on sap flow or leaf water potentials, to monitor more precisely the vine water status and to target management interventions.

At the study zone scale, the collection of a large number of surveys and their synchronization on a centralized server made it possible to consider the understanding of the phenomenon over a large scale. As an illustration, the results presented in Fig. 8 consider the changes of mean and standard deviation for the whole study zone dataset over the 2019 and 2020 seasons.

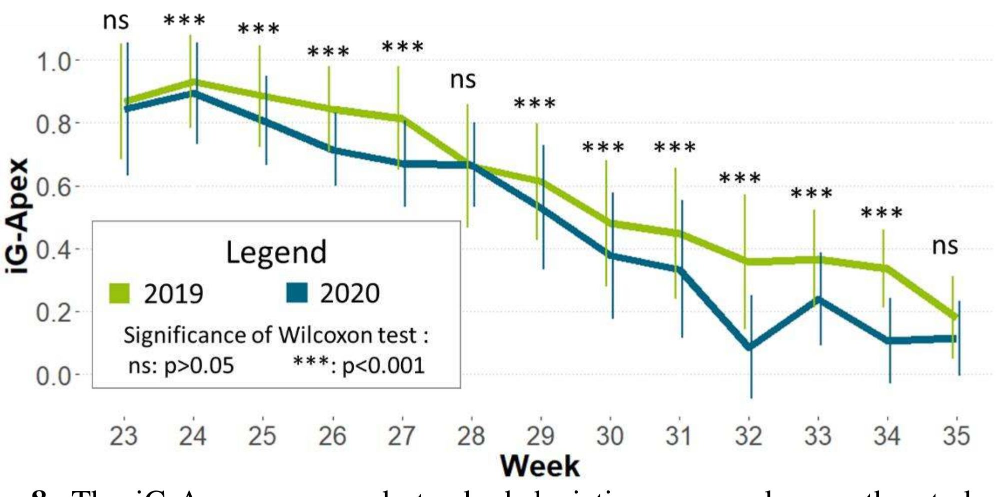

Figure 8: The iG-Apex mean and standard deviation per week over the study zone during the 2019 and 2020 seasons.

At the beginning of the period of interest (week 24), the iG-Apex was high over the entire study zone in both seasons (Fig. 8). The iG-Apex then decreased towards values close to 0 around week 35. From week 24 to week 27 and from week 29 to week 35 the average iG-Apex was significantly lower in 2020 than in 2019. It is worth noting that week 28 was an exception in this global dynamic with the same average iG-Apex for both seasons (Fig. 8). An event interfering with the shoot growth stop dynamics had apparently occurred around this period during one or both of the seasons.

These results indicated that between weeks 24 and 35, shoot growth gradually stopped over the study area. Over the same period, very little rainfall and relatively high temperatures were observed. This shoot growth stop dynamic can be explained by the gradual appearance of water restriction. These results are consistent with the Mediterranean climate of the study zone that Schultz (2017) characterized as a water-limited region. According to Schultz (2017), during the summer period, water constraints appear progressively because the evaporative demand largely exceeds precipitation. These results were also consistent with other research that have studied the shoot growth stop when the vine is exposed to water restriction, in both experimental (Pellegrino et al. 2005) and real conditions (Martinez-De-Toda et al. 2010)

The results here also indicated that the shoot growth stop was earlier in the 2020 season. Numerous papers have shown that high temperatures tend to accelerate vine phenology (Yzarra et al. 2015; Parker et al. 2020). Even though the design of this work did not allow for a formal interpretation of these results, it is possible that the higher temperatures in the spring of the 2020 season accelerated phenology and favoured earlier shoot growth stop that year. The particularly hot temperatures observed around weeks 27-28 of the 2019 season may have played a role in the same values of iG-Apex observed in week 28 for both seasons. Although the consequences on vine physiology of such temperatures observed so early in the season are still poorly documented, Ben Salem-Fnayou et al. (2011) showed that they have consequences on cell structure and photosynthesis that could be equivalent to those of a drought. Therefore, it is possible that these phenomena caused a sudden shoot growth stop in part of the study zone and that this resulted in a general decrease of iG-Apex.

At the study zone scale, the data collected with the ApeX-Vigne application helped to understand the evolution of the variance in iG-Apex values (Fig. 9). In both seasons, the total variance was at first relatively small (around 0.02 for weeks 24-26), then it increased (around 0.04 to 0.06 for weeks 28-30) and remained at relatively high levels (around 0.04 for weeks 30-32). The spatial structure of this variance also evolved throughout the period of interest for both seasons but with a time lag of around two weeks between 2019 and 2020. Figure 9 shows the four semi-variograms that best illustrate this evolution of the spatial structure for each season. Considering the time lag, weeks 24 to 30 and 26 to 32 were chosen for the 2019 and 2020 seasons respectively. The spatial structure was initially relatively low, then increased to reach its highest level at weeks 28 and 30 in 2019 and 2020 respectively, and then decreased again at the end of the period of interest. The semi-variograms computed for week 28 of 2019 season and for week 30 of 2020 season showed the strongest spatial auto-correlation in the iG-Apex data (Fig. 9). Both phenomena were second order stationary and had exponential semi-variogram models with respective ranges of 21.8 km and 14.9 km and a nugget-to-sill ratio of ~0.13.

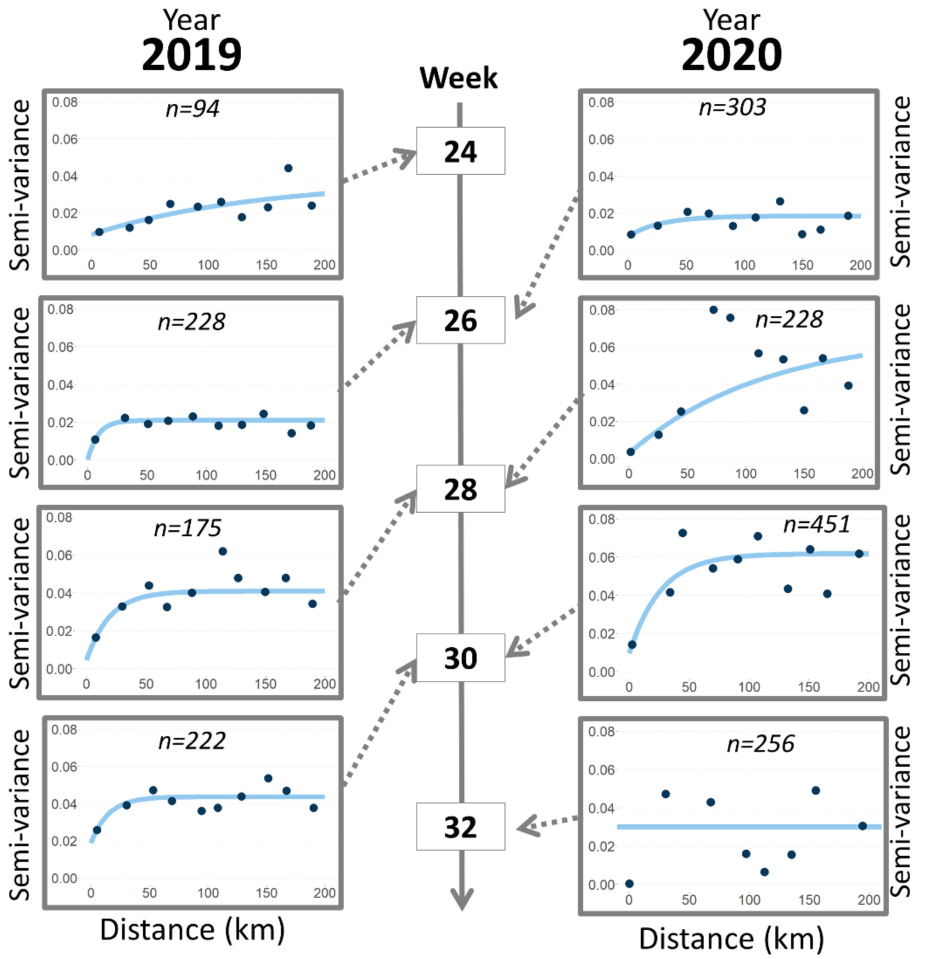

Figure 9: Fitted variograms of weekly iG-Apex data illustrating the evolution over time of the spatial structure in these data for the 2019 and 2020 seasons. Arrows indicate the shift associated with an apparent two-week time-lag in response between the two seasons.

Available data did not allow a detailed interpretation of these dynamics, but some hypotheses for interpreting them may be formulated based on the different known sources of variation in the vine water status:

- At the beginning of the period of interest (weeks 24-26), iG-Apex data ranged from 0.8 and 1 (Fig. 9) indicating that all vineyards were still actively growing. The low spatial structure at these dates may be interpreted by the fact that no spatially organised factor was limiting shoot growth.
- The stronger spatial structure observed in weeks 28 (2019 season) and 30 (2020 season) corresponded to a period where mean iG-Apex was between 0.4 and 0.6 for both years. These iG-Apex mean values indicated that there was a factor(s) limiting shoot growth and the observed spatial structure indicated that this limiting factor was spatially organised with a range of 15 to 20 km. Factors that may limit shoot growth and that are spatially organised include soil (Van Leeuwen et al. 2018), topography (Santesteban et al. 2012) or local climate conditions (Deloire et al. 2004). It can be hypothesised that the spatial structure observed in the iG-Apex data at these dates was related to the spatial structure of

one or a combination of several of these factors. Note that nugget effects at regional scale were respectively around 0.006 and 0.007. Most of the surveys collected using the ApeX-Vigne application corresponded to the sampling of 50 observations spread over a field. The observed nugget effect may be partly explained by the within-field variability of shoot growth. According to the example shown in Fig. 6c, this within-field variability is ~0.003. The rest of the nugget effect, ~0.003 to 0.004, can be explained by factors that may influence shoot growth at the inter-field scale over very short distances, such as cultivar (Bota et al. 2001), row orientation (Hunter et al. 2020) or short range variability of soil characteristics (Willwerth and Reynolds, 2020).

- At the end of the period of interest (weeks 30-32), the spatial structure exhibited a lower nugget-to-sill ratio (0.52) in 2019 and had almost disappeared in 2020 (Fig. 9). During this period, mean iG-Apex ranged from 0.1 to 0.4 (Fig. 9). This result may be interpreted by the saturation of the iG-Apex. When this index reached a value of 0, it did not evolve anymore, even if the water restriction kept on increasing because of summer water deficit. This limitation in the iG-Apex itself may have masked partially or totally the observed spatial structure of the phenomenon.

These results showed that the aggregation of observations collected by ApeX-Vigne may provide access to a new source of spatially structured information at regional scales. It is likely that in the coming years, with the high level of smartphone equipment among farmers (Michels et al. 2020) and their interest in collective monitoring approaches (Dehnen-Schmutz et al. 2016), the ApeX-Vigne application will be adopted more widely. A wider adoption of the ApeX-Vigne application should make it possible to study the spatial variability of vine water status at even more scales, including intermediate scales of a few kilometres to a few tens of kilometres. This spatial scale is particularly interesting because it corresponds to a scale of collective vineyard management (cooperatives, organisations of controlled denomination of origin, etc.) (Leibar et al., 2018). The proposed approach may be relevant as it would make it possible to identify areas with homogeneous behaviour and areas that are particularly prone to high water restriction. Studying the temporal evolution of a simple indicator based on the nugget-to-sill ratio seems relevant to define the best date to meet this objective. This information may be important to support the logistics of agriculture water supply across a whole region. In the longer term, this information could also support vineyard adaptation strategies to climate change at regional scale, such as the choice of the most suitable sites or cultivars (Naulleau et al. 2021).

Nevertheless, the use of ApeX-Vigne data for decision making may raise issues of data quality as reported in literature for projects involving a wide variety of operators in gathering observations (Senaratne et al. 2016). The first major issue is data quality evaluation (Touya et al., 2017). This challenge will be all the more important since, at these scales, finding reference data may be an issue (Severinsen et al. 2019). To assess its quality, it will be necessary to propose approaches that rely solely on the characteristics of the Apex-Vigne data, such as the spatio-temporal consistency of the collected data (Senaratne et al. 2016) or the trustworthiness of the operator (Fogliaroni et al. 2018). The second issue is data quality improvement (Goodchild and Li, 2012). Ancillary data, such as sources of reference information (e.g. sap flow or pressure chamber) or high spatial resolution information (e.g. Sentinel 2 satellite imagery), may offer an opportunity to improve the quality of the collected data. However, this will require new approaches to be defined for the conjoint use of these sources of information with various characteristics (quality, spatial and temporal resolution). Both issues should benefit from further research.

Conclusion

The ApeX-Vigne mobile application was developed to monitor shoot growth and estimate vine water restriction using a simple and robust method that can be used by stakeholders with very different skills. This study presented the results obtained after two seasons of use of this application in the south of France. It showed that the ApeX-Vigne application was downloaded and used on a seasonal basis. The number of downloads indicated that it was a rather popular application in southern France with a growing number of users and an increasing number of surveys from 2019 and 2020. The study also highlighted the limitations of metrics as proposed in the literature to assess mobile application adoption in a seasonal context, as is often encountered in agriculture. The development of metrics that account for the seasonality of use and the specific behaviour of professional users is still an issue and may be the subject for future research. Through real examples, the study has shown the different scales that the ApeX-Vigne application can be applied to: i) at the within-field scale to identify potential management zones with differences in vine water restriction and ii) at the inter-field scale to compare and benchmark shoot growth dynamics and vine water restriction within the same farm or region. Although the use of the ApeX-Vine application at both scales is possible, inter-field use is the most frequently implemented by farmers and their advisers. This study has also shown that the regional aggregation of observations collected by ApeX-Vigne provided access to spatially structured information. It is likely that this may provide information on pedo-climatic phenomena influencing water restriction at this regional scale.

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Conflicts of interest/Competing interest: The authors declare that they have no conflict of interest

Availability of data and material: The data collected in this project is not available. Please contact the corresponding author to access the data.

Code availability: The code of the ApeX-Vigne application is available online at: https://github.com/Agrotic-Supagro/ApexV3

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