



# Can we detect the damage of a heatwave on vineyards using Sentinel-2 optical remote sensing data?

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## ABSTRACT

Climate change will exacerbate environmental threats, which will, in turn, affect agricultural production patterns. This study addresses the feasibility of using Sentinel-2 (S2) optical remote sensing data to map the consequences of heatwaves on vineyard plots. The proposed method to map damaged and undamaged vineyards is based on the use of an inter-annual (C1) and an intra-annual (C2) criterion derived from the Normalized Difference Vegetation Index (NDVI) calculated on S2 data. While the inter-annual criterion compares the NDVI of the heatwave year to the average NDVI of the previous years with no heatwave, the intra-annual criterion compares the NDVI values before and after the heatwave in the same year. Predictions from either criteria or both combined were tested against two datasets collected during two field surveys performed in 2020 and 2021, with different ways of recording the damage caused on the grapevine by the 2019 heatwave in southeastern France. Results showed that within the reference vineyard plots with heat damage, 46 %, 62 % and 40 % of the S2 pixels were correctly predicted as damaged using C1, C2 and their combination, respectively. Within undamaged plots, 91 %, 88 % and 99 % of the S2 pixels were correctly predicted as undamaged using C1, C2 and the combination, respectively. Results also showed that only severe leaf damage was detected using the S2 NDVI. The combination of C1 and C2 provides the most accurate detection of heatwave consequences on vineyards.

**KEYWORDS:** Vineyards, Sentinel-2, heatwave, France



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## INTRODUCTION

Anthropogenic effects have discernibly influenced the global climate. Instrument observations and reconstruction of global hemispheric temperature evolution have revealed pronounced warming of 0.7 °C in global mean since the second half of the 19th century (Frich *et al.*, 2002). One of the results of global warming is the observed increase in the occurrence of heatwaves leading to significant reductions in crop yields and threatening food security (Rosenzweig *et al.*, 2001). Heatwaves correspond to abnormally high temperatures observed for several consecutive days. There is no universal definition of the phenomenon. The temperature levels and the duration characterising a heatwave episode vary according to the region of the world (Robinson, 2001).

Climate change projections suggest that summer heatwaves in Europe will become more frequent and severe during this century (Meehl and Tebaldi, 2004). The summer of 2019 in Western Europe was marked by two major periods of exceptionally high temperatures. The first period with extremely high temperatures occurred during the last week of June. For some European cities, those temperatures were the highest ever registered. In France, a heatwave of exceptional intensity affected almost the entire country. In south France (Occitanie region), where the heatwave was the most severe, many meteorological stations measured exceptionally high temperatures (43.5 °C in Montpellier and 44.4 °C in Nîmes). In particular, on 28 June, near the town of Nîmes in Vérargues, maximum temperatures reached 46 °C (Météo France, 2019; Vautard *et al.*, 2020). Exceptional damage was observed on vineyard plots in the Montpellier and Nîmes sectors. A significant number of plots showed severe symptoms of burned foliage and desiccated berries depending on the variety, the age and the growing conditions of the vines (ITK Labs, 2019; Chambre d'agriculture Hérault, 2019).

Over the last decades, remote sensing satellites, which provide a continuous spatial view of all land surfaces at different spatial resolutions depending on the considered instrument, have been used in the agricultural sector. Many methods using satellite data have been developed on a wide range of applications, including crop phenological development (Atzberger, 2013; Nasrallah *et al.*, 2019), stress monitoring (El Hajj *et al.*, 2019) and drought impacts (Kogan, 1995). However, the implementation of remote sensing and imagery techniques for detecting the effects of extreme heat events is still underdeveloped. Remote-sensing-based vegetation indices such as normalized difference vegetation index (NDVI), canopy-level chlorophyll indices (Transformed Chlorophyll Absorption Reflectance Index/Optimized Soil Adjusted Index), Green Normalized Difference Vegetation Index (GNDVI), TCARI (Transformed Chlorophyll Absorption Ratio) and CARI (Chlorophyll Absorption Ratio) derived from medium spatial resolution (10 meters) images have shown to be valuable tools to assess and map the spatial variability of drought

within vineyards (Cogato *et al.*, 2019; Espinoza *et al.*, 2017; Meggio *et al.*, 2010). Similar conclusions have been reached with the use of the Visible Atmospherically Resistant Index (VARI) and the Normalized Difference Greenness Vegetation Index (NDGI) derived from a handheld spectroradiometer (Pôças *et al.*, 2015).

The arrival of the Sentinel-2 (S2) satellites which provide free and open access to multispectral images with spatial resolution from 10 m to 60 m (depending on the spectral band) and short revisit time (5 days over Europe), opens the way toward building operational approaches capable of detecting possible damage on vineyard plots. Specifically, a climatic event with short term impacts on vineyards, like heatwaves, can be explored using the short revisit time of these satellites. This study aims to evaluate the feasibility of using Sentinel-2 data to detect damage in vineyards after the heatwave event of 28 June 2019 in the southeastern region of France. Multi-temporal S2 images and field data have been collected within the area to evaluate the potential of S2 imagery to observe the impact of this heatwave event on the vines. After describing the studied area and the dataset used in Section 2, Section 3 presents the methodology employed to spatially characterise the heatwave consequences on vineyard plots. The analysis of the heatwave impact on vine growing areas from Sentinel-2 data is described in Section 4, followed by a discussion in Section 5. Finally, the main conclusions are presented in Section 6.

## MATERIALS AND METHODS

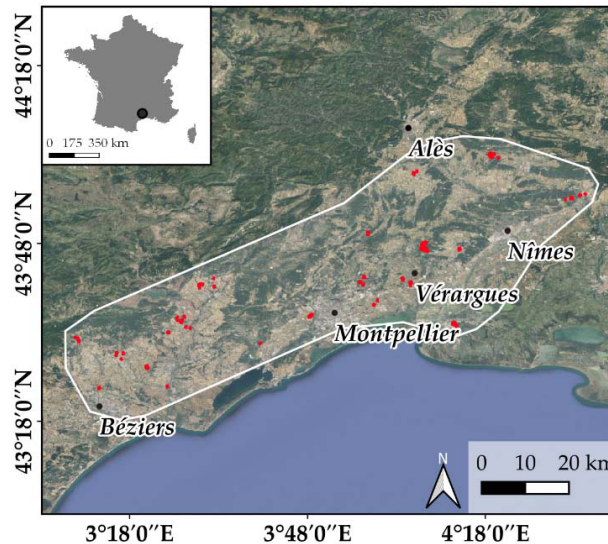
### 1. Study site

The study area is located in Southern France, particularly in the Hérault and Gard departments (Occitanie region) (Figure 1). The total area is about 4800 km<sup>2</sup> with 100.85 ha of vineyard plots considered in this study (141 plots). Bathed in more than 2500 hours of sunshine per year, the study area benefits from a Mediterranean climate, characterised by hot and dry summers (25 °C, summer mean air temperature) and cool and mild winters (7 °C, winter mean air temperature). However, summer maximum temperatures can occasionally reach over 40 °C and lead to severe heatwave events (Figure 2). The autumn season often brings storms and heavy rains.

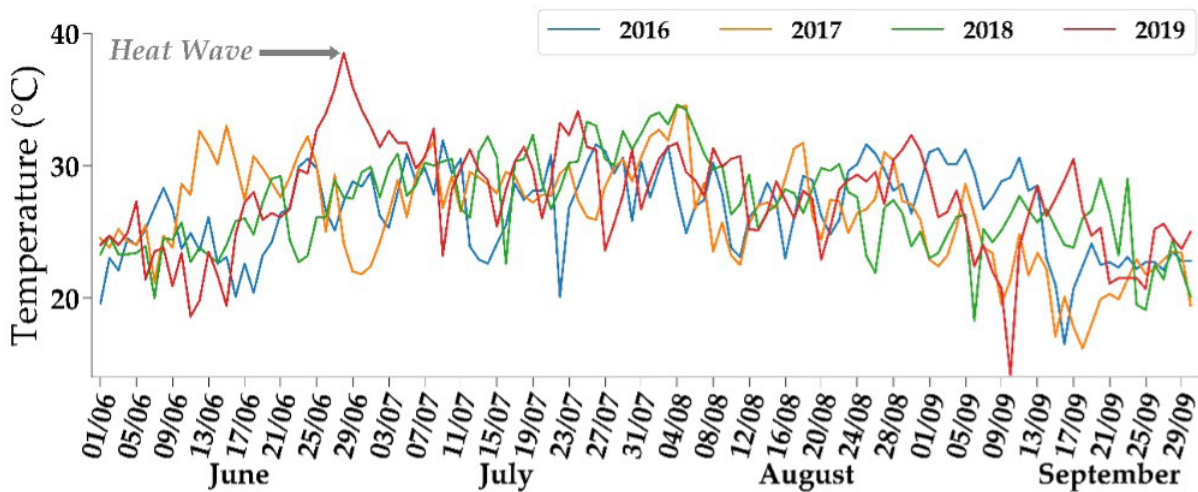
### 2. Materials

#### 2.1. Sentinel-2 images

One hundred and two Sentinel-2A (S2A) and Sentinel-2B (S2B) optical images acquired over our study site from March to October 2016 to 2019 were used. Currently, S2A and S2B sensors provide images with a revisit time of 5 days and a spatial resolution of 10 m for the blue, green, red and near infra-red bands. The S2 images have been downloaded from the Theia website, a French open-source data and service centre (<https://www.theia-land.fr/>). Theia provides S2 images of Level-2A corrected for atmospheric effects and ortho-rectified.



**FIGURE 1.** Study site location (white polygon). Red polygons delineate reference vineyard plots.



**FIGURE 2.** Temporal evolution of the daily maximum air temperatures at Garons station (Nîmes), between June and September 2016 to 2019.

## 2.2. Observations on reference vineyards

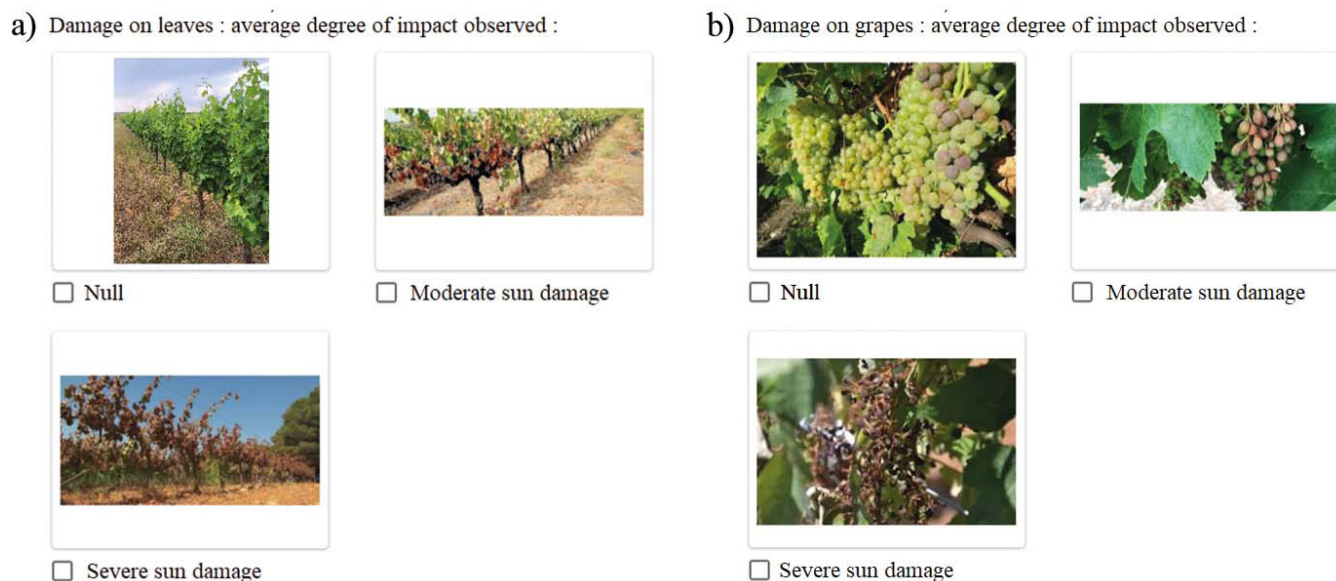
The reference dataset is composed of 141 vineyard plots with observed damage caused by the heatwave that took place between 24 and 28 June 2019 (Figure 2). In these 141 plots, red wine varieties are the most common, comprising mainly *Syrah*, *Mourvèdre* and *Grenache*. The vineyard management differs largely among winegrowers. For example, the spacing between rows in the studied vineyard is 2 meters for 22 % of the reference dataset plots and 2.5 meters for 74.5 %. Only 3.5 % of the 141 vineyard plots have a row spacing between 2.5 and 3 meters. Moreover, 66 % of the reference plots were found to apply the cover cropping technique. Cover cropping consists of covering the bare soil between or under the vine rows by different types of plants. Referring to the 141 reference surveyed plots, 62 % of the plots have a surface area greater than 0.5 ha. The width of the plots varies between 11.33 m

and 221.75 m, and the length ranges between 22.39 m and 413.11 m.

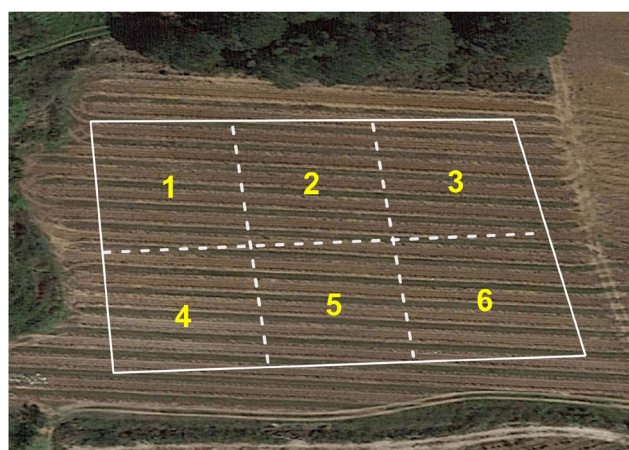
The reference dataset, estimated at the whole farm level, derives from winegrowers' declarations of yield loss registered by French institutions in the summer of 2019, just after the heatwave. Then, winegrowers were selected in 2020, covering the whole area affected by the 2019 heatwave, to conduct personal interviews and field surveys. This resulted in 141 reference plots that were geo-referenced and delineated where the winegrowers confirmed the damage declared in 2019. Reference plots described as damaged could include only desiccated berries or both burned leaves and desiccated berries on all or part of the plot.

These different damage types caused by the 2019 heatwave and their location within plots were detailed for 18 of the 141 reference plots during a second field survey carried out in June 2021 with six winegrowers. Each of the 18 surveyed





**FIGURE 3.** Illustrative figures used for the detailed field campaign in 2021 to determine the degree of damage caused by the 2019 heatwave on leaves (a) or berries (b).



**FIGURE 4.** Example of a reference plot gridded into cells for the detailed survey carried out in 2021.

plots was gridded into cells of 100 to 400 m<sup>2</sup>. In each cell, leaf and berry damage were classified by the winegrowers in three classes for the leaf damage and three classes for the berry damage based on representative photographs (Figure 3a,b):

- Severely damaged when all the leaves/berries suffered strong browning (desiccation);
- Moderately damaged when most of the leaves/berries were burned;
- Null when no damage was detected on the leaves/berries.

For example, Figure 4 shows a vineyard plot gridded into 6 different cells surveyed during the 2021 campaign. For this plot, the winegrower reported severe damage on leaves and berries in cells 1, 2 and 3 and moderate damage on leaves but severe damage on berries in cells 4, 5 and 6.

Among the 141 reference plots surveyed at plot level in 2020, 134 were globally registered as severely damaged by the 2019 heatwave and 7 were registered as undamaged. For the 18 reference plots, which were further characterised in 2021, Table 1 summarises both the global declaration collected in 2020 at plot level and the percent area of the plot declared in 2021 as damaged on leaves or berries by the 2019 heatwave. Sixteen out of the eighteen detailed surveyed plots in 2021 present damage symptoms at the leaf and berry levels, simultaneously.

As the reference dataset is not extensive for each vine variety and plot management type, the relationship between these vineyard parameters and the consequent impacts of the heatwave could not be evaluated in this study. Therefore, all reference plots were analysed without distinguishing vine variety or plot management type.

**TABLE 1.** Damage caused by the 2019 heatwave on 18 reference plots surveyed at plot level in 2020 (overall damage on the vines estimated by the winegrower) and at the subplot level in 2021 (damage estimated separately for leaves and berries by the winegrower, with the calculation of the percent plot area corresponding to each type of damage).

Plot ID	2020 campaign	2021 campaign	
		Leaves	Berries
P1	Very damaged	15 % Moderate	15 % Moderate
		85 % Null	85 % Null
P2	Very damaged	50 % Null	50 % Null
		50 % Moderate	50 % Severe
P3	Not damaged	100 % Null	100 % Moderate
P4	Very damaged	100 % Moderate	100 % Moderate
P5	Very damaged	100 % Moderate	50 % Severe
			50 % Moderate
P6	Not damaged	100 % Moderate	100 % Moderate
P7	Very damaged	100 % Severe	100 % Moderate
P8	Very damaged	100 % Severe	100 % Severe
P9	Very damaged	100 % Null	100 % Moderate
P10	Not damaged	100 % Null	100 % Null
P11	Very damaged	50 % Severe	100 % Severe
		50 % Moderate	
P12	Very damaged	100 % Severe	100 % Severe
P13	Very damaged	50 % Severe	50 % Severe
		50 % Moderate	50 % Moderate
P14	Very damaged	50 % Severe	50 % Severe
		50 % Moderate	50 % Moderate
P15	Very damaged	50 % Severe	100 % Severe
		50 % Moderate	
P16	Very damaged	22 % Moderate	22 % Severe
		78 % Null	78 % Null
P17	Very damaged	10 % Moderate	100 % Null
		90 % Null	
P18	Very damaged	11 % Severe	11 % Severe
		56 % Moderate	89 % Moderate
		33 % Null	

### 3. Methods

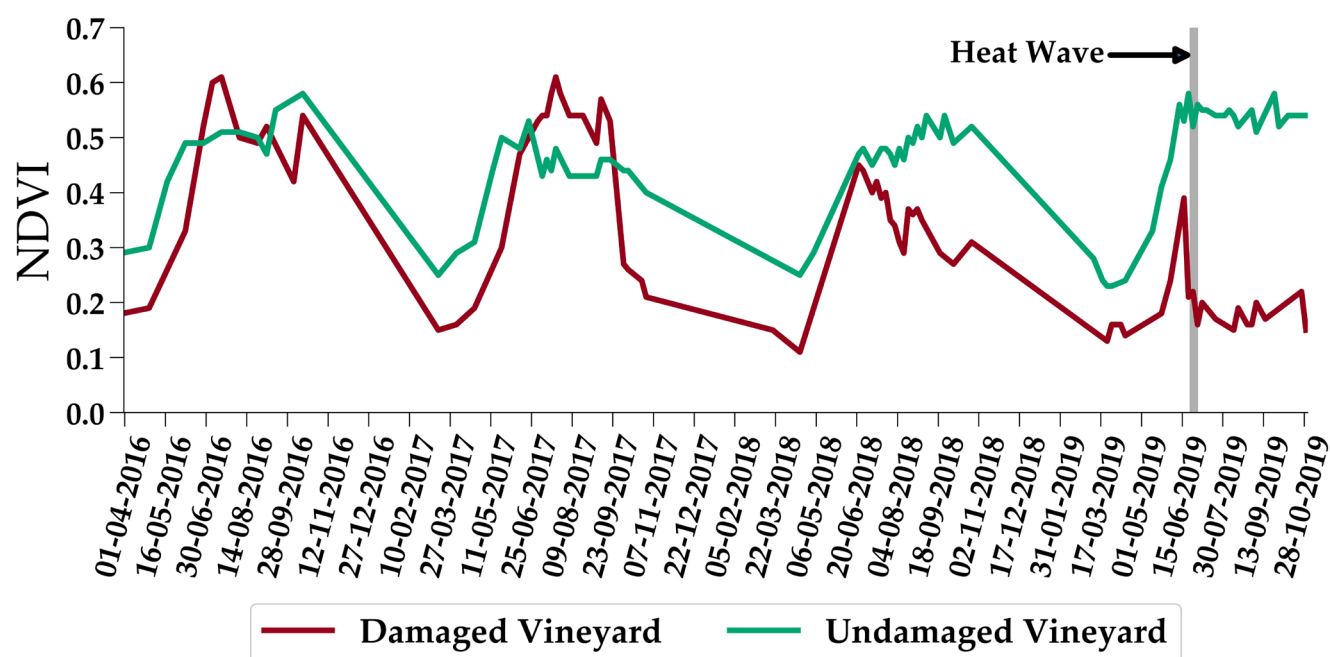
The method to assess the impact of the heatwave event on vineyard plots is based on the analysis of NDVI time-series derived from S2A and S2B images. NDVI has been computed using bands 4 (Red) and 8 (Near-Infrared) of S2 images (Tucker, 1979) at 10 m spatial resolution. Ranging from 0 to 1 for agricultural areas, high NDVI values indicate dense and very high vigour crop, whereas areas of bare soil or low vigour vegetation usually reveal very low positive NDVI values.

Figure 5 shows the NDVI time-series over four years (2016 to 2019) generated from S2 images for two vineyard plots, one undamaged and one damaged by the heatwave. The temporal behaviour of NDVI reveals the vegetative growth cycle of the vineyard. During winter (between November and March), NDVI in the vineyard is approximately 0.3 due to the absence of grapevine canopy but is related to local soil conditions and the presence of evergreen plants. The beginning of vine growth occurs in spring with budburst followed by shoots development in April. Then NDVI substantially increases to about 0.5 to 0.6 in June, corresponding to the flowering and fruit set stages. Veraison marks the beginning of berry ripening which takes place in July and August and NDVI tends to remain stable between 0.4 and 0.6. From late August onwards, the harvest begins and lasts until the temperature falls and chlorophyll in the leaves begins to break down. The vegetation cycle finishes when the leaves fall as the vine enters its winter dormancy period marked by the decrease in NDVI (back to NDVI around 0.3). This description of the vegetation cycle corresponds to a growth cycle in normal weather conditions (Figure 5). However, vegetation dynamics is significantly influenced by

the climate. An analysis of the temporal evolution of NDVI for a plot identified as damaged by the June 2019 heatwave shows that NDVI reached a maximum of approximately 0.4 (17 June) followed by an abrupt and dramatic decrease to 0.2 (27 June) due to the heatwave (Figure 5).

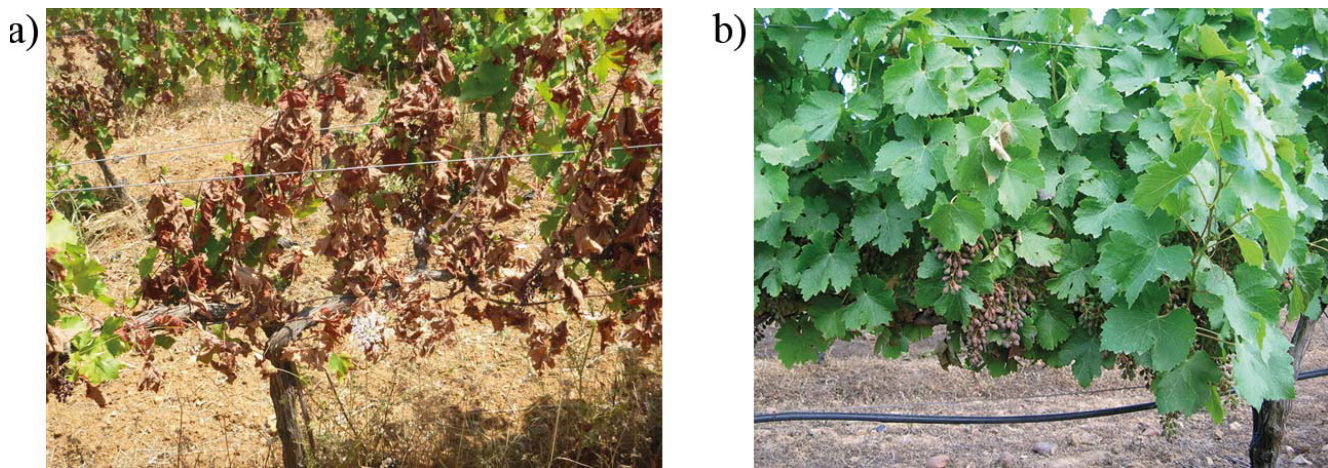
Two findings arose from the analysis of the NDVI time series:

- Typical NDVI observed in vineyards from early June to late September are far greater than 0.2, corresponding to the typical development of the grapevine canopy under normal Mediterranean weather conditions (Figure 5). As a consequence, only pixels with NDVI mean values higher than 0.2 over the time period ranging from 27 June to 5 September 2016, 2017 or 2018 have been considered in the analysis;
- Using NDVI to detect vineyard damage caused by the heatwave is challenging as multiple causes can result in changes in NDVI. On the one hand, the heatwave is expected to induce a rapid drop down in NDVI due to either leaf fall, leaf desiccation or simply chlorophyll breakdown. On the other hand, decreases in NDVI may also result from the management of inter-row cover, shoot thinning or regular senescence of the grapevine canopy. However, impacts of the heatwave on NDVI can be distinguished assuming that they are more severe and less repeatable across years for a given plot than impacts of many other recurrent events. Accordingly, we used two criteria aimed at characterising heatwave impact on the grapevine, taking two timescales into account:
  - An inter-annual criterion, using NDVI from 2019 and a few preceding years, compares the vegetation growth



**FIGURE 5.** Normalized Difference Vegetation Index (NDVI) time-series over an undamaged vineyard (green) and a damaged vineyard (red). The grey line points out the heatwave occurring on 28 June 2019.





**FIGURE 6.** Leaves and berries of grapevines damaged in the 2019 summer heatwave. (a) Burned leaves; (b) only desiccated grapes.

cycle of 2019 (year stroke by a severe heatwave) with the mean growth cycle of the plot over the years;

- An intra-annual criterion, using only the NDVI values from 2019, to compare the vine health status before and after the heat event.

The summer of 2019 was marked by two heatwaves that affected the whole of France. This study focused on the impact of the first heatwave because it mainly affected the southeast of France and took place during the last week of June, a crucial time for the development of the vine. Additionally, according to our field campaigns, winegrowers in the Hérault and Gard departments described June's heatwave as being the most damaging. For this reason, this study concentrated on mapping vineyard heatwave damage during the first heatwave.

### 3.1. Inter-annual criterion

The inter-annual criterion compared the NDVI for the year 2019 (year of the heatwave) and the NDVI of the previous years (years without heatwave). As the temperature peak occurred between 24 and 28 June 2019, only the S2 images acquired right after this period were used to compare the NDVI of 2019 to that of 2016, 2017 and 2018. In addition, given that the damage persisted after the heatwave, this comparison was based on the use of time-averaged NDVI: for each S2 pixel, the averaged NDVI over a given period in 2019 is compared to the averaged NDVI over the same period in 2016, 2017 and 2018.

Accordingly, the averaged NDVI was calculated over the period ranging from the 27 June to the 5 September, which corresponds to a nearly two-month duration following the heatwave. 27 June was chosen as it corresponds to the date of the first S2 image acquired in 2019 during the heat event. Averaging the NDVI over two months enabled minimising the slight variations in NDVI due to the uncertainties in the reflectance calculation and smoothing small variations of NDVI due, for example, to mild water stress.

In addition, the use of averaged NDVI over a two-month period allowed overcoming the problem of missing data on a given date due to cloud cover. For a year with no heatwave (2016, 2017 or 2018) and over the chosen period (27 June to 5 September), NDVI in vineyards is at (or close to) its maximum with slight temporal variations. We hypothesise that the NDVI average over this period with a significantly lower value in 2019 than in the preceding years is likely due to an alteration of plant health owing to the heatwave. Hence, the difference in averaged NDVI for a given Sentinel-2 pixel between 2019 and the over the mean for 2016, 2017 and 2018 should highlight the possible consequences of the heatwave in 2019. This difference was calculated as follows (1):

$$C_1 = \overline{NDVI}_{2019} - \text{Mean}(\overline{NDVI}_{2016}; \overline{NDVI}_{2017}; \overline{NDVI}_{2018})$$

where  $\overline{NDVI}_x$  is NDVI for year  $x$  averaged over all the available Sentinel-2 images within the period from 27 June to 5 September.

As mentioned before, only pixels with averaged NDVI higher than 0.2 were considered as characterising vineyard plots to be included in the calculation of  $C_1$ . To detect changes in the health status of vineyards plots potentially induced by the heatwave, it was essential to determine thresholds on  $C_1$  (Equation 1). To determine this threshold, we used the 18 plots selected for the detailed field survey in 2021. First, two classes were defined based on winegrowers' declarations for plots or subplot cells as damaged and undamaged. Plots or subplots registered as having moderate and severe damage were grouped in the same class (damaged) because very similar NDVI values were observed. Then the distribution of the  $C_1$  values for all the pixels within each class (damaged and undamaged) was analysed to determine the  $C_1$  threshold that best discriminates between the two classes.

### 3.2. Intra-annual criterion

The intra-annual criterion compared the NDVI calculated from the last S2 image acquired before the heatwave (22 June 2019) and the maximum NDVI value calculated using S2 images taken during the heatwave and soon afterwards, from 27 June to 31 July 2019. In fact, for the years with more usual Mediterranean weather conditions (2016, 2017 and 2018), well-developed canopies resulted in high NDVI values throughout June and July. Thereby, a drastic drop in the NDVI values during the period following the heatwave (after 28 June) could be related to the possible effect of the heat event on the vineyard health status. The second criterion can be written as follows (2):

$$C_2 = \text{Max}(NDVI_{[27/06 \text{ to } 31/07]}) - NDVI_{22/06}$$

where represents the NDVI value of the day before the heatwave and represents the maximum NDVI value of the period after the heatwave at each pixel.

Unfortunately, some pixels of the S2 image from 22 June were cloudy. To recover these cloudy pixels, an extrapolation with the least-squares method has been applied using images in May and the first three weeks of June, assuming a linear NDVI increase with time between May and June (Faivre and Fischer, 1997).

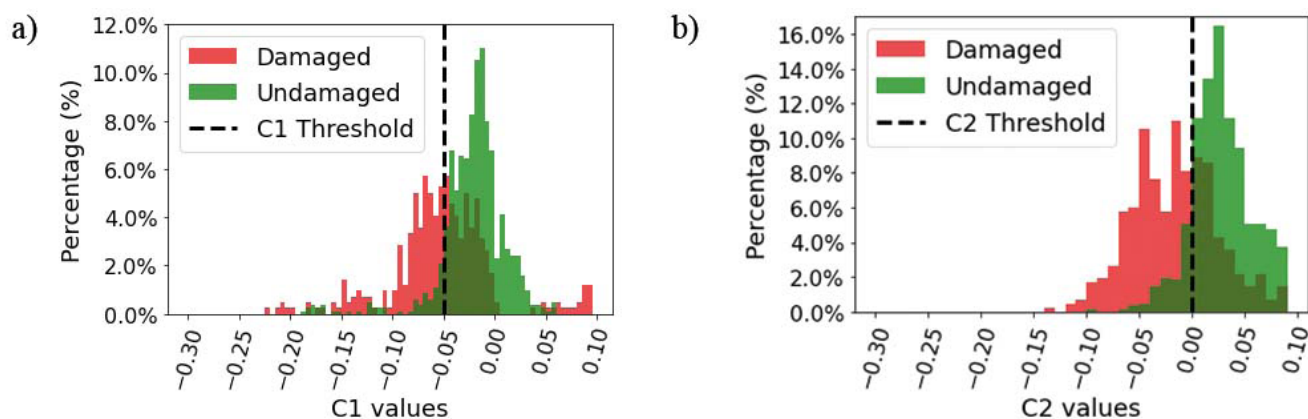
If the NDVI drops sharply between 22 June and the period during and soon after the heatwave (27 June to 31 July), then we can assume a strong degradation of vineyards, at least of the leaves. Consequently, negative values of  $C_2$  reveal vines damaged during the heatwave event, with a considerable greenness decrease between the 22 of June and the days after the heatwave. By contrast, positive values indicate that the vineyards pursued the vegetative cycle and were not impacted by the heatwave. The determination of the threshold for this second criterion was based on the same analysis as for the inter-annual criterion (Section 3.2). Using the distribution of  $C_2$  values for damaged and undamaged plots, the threshold value of  $C_2$  that best discriminates between the two classes was determined.

### 3.3. Determination of $C_1$ and $C_2$ threshold values

This section describes how the threshold values for criteria  $C_1$  and  $C_2$  have been determined using the detailed survey performed in 2021 for the 18 plots to differentiate between pixels registered as damaged or undamaged.

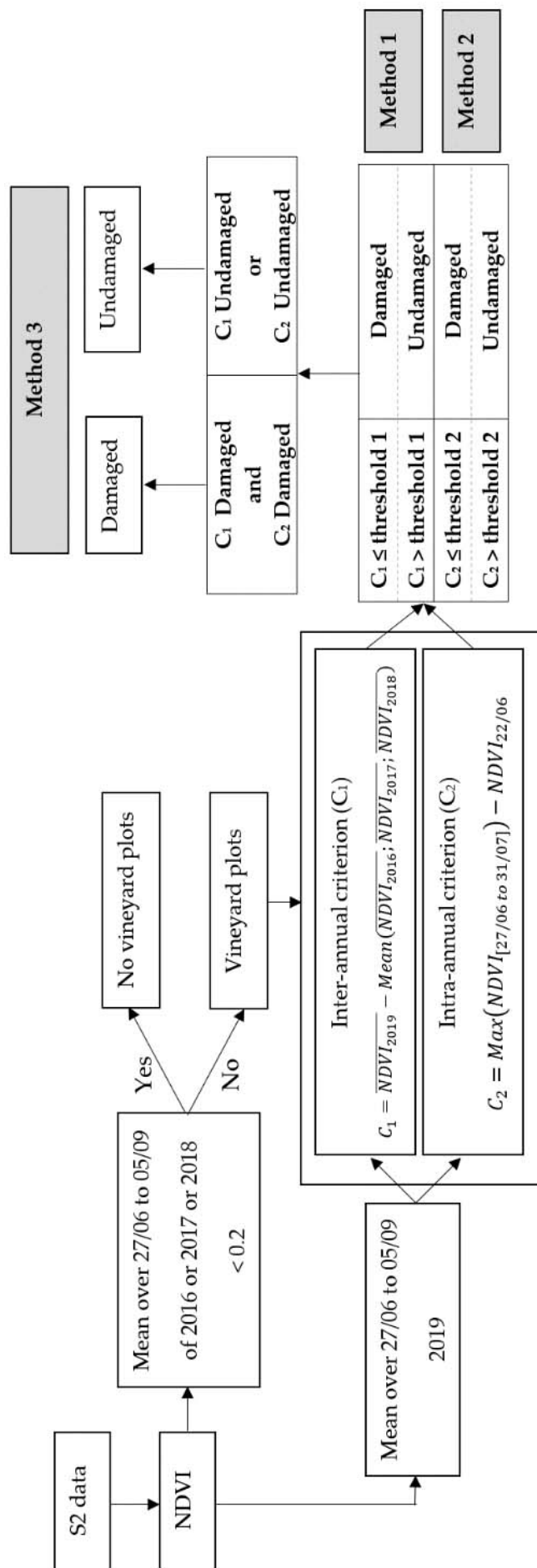
Figure 7a shows the distribution of  $C_1$  for all the pixels within the 18 plots identified as damaged (red) or undamaged (green) during the detailed survey in 2021. For these pixels,  $C_1$  ranged between  $-0.1$  and  $0.05$ , with an average of  $-0.02$  for pixels registered as undamaged and between  $-0.2$  and  $0$  with an average of  $-0.04$  for pixels registered as damaged. Based on the distribution of  $C_1$  for each category, a threshold value of  $-0.05$  (Figure 7a, dashed black line) was fixed to discriminate between pixels estimated as damaged and undamaged when applying the method to any plot. Pixels with  $C_1$  values less than or equal to  $-0.05$  were estimated as damaged, whereas pixels with  $C_1$  values greater than  $-0.05$  were estimated as undamaged.  $C_1$  values lower than  $-0.05$  corresponded to a substantially lower NDVI in 2019, showing the damage estimated following the heatwave period compared to the previous years. By contrast,  $C_1$  values greater than  $-0.05$  were considered a negligible difference in averaged NDVI between 2019 and 2016, 2017 and 2018. This corresponded to pixels where the vines likely pursued a normal vegetative cycle.

A similar analysis was run for the intra-annual criterion  $C_2$  (Figure 7b).  $C_2$  ranged from  $-0.05$  to  $0.09$ , with a mean of  $0.05$  for pixels identified as undamaged during the detailed survey in 2021. The criterion value ranged between  $-0.12$  and  $0.05$ , with an average of  $0$  for pixels identified as damaged. The threshold selected for  $C_2$  was fixed at  $0$  to separate pixels estimated as damaged or undamaged. A vineyard pixel was thus estimated as damaged when  $C_2$  was less than  $0$ , corresponding to a decrease in NDVI right after the heatwave. By contrast, a pixel with positive  $C_2$  was estimated as undamaged, which corresponded to an increase in NDVI, suggesting that the vegetative cycle of the vineyard pursued the normal cycle.



**FIGURE 7.** Distribution of the  $C_1$  (a) and  $C_2$  (b) values for the pixels identified as damaged or undamaged during the detailed survey performed in 2021.





**FIGURE 8.** Scheme of the methodology applied using C1 and C2 criteria.

### 3.4. Pixel classification as damaged or undamaged

Three ways to combine criteria C1 and C2 are proposed for the cartography of heatwave damage estimated from S2 images. The first cartography approach consisted of using only the inter-annual criterion C1, which compares the vegetation vine growth cycle between 2019 (year stroke by a severe heatwave) and the three previous years (normal Mediterranean climatic setting) (Section 3.1). The use of C1 ensures that the cause of the change in pixel characteristics is specific to 2019 and is not due, for example, to recurrent practices like shoot thinning. The second cartography approach uses the intra-annual criterion C2, which is built on the comparison between the vine health status before and after the heat event. The use of criterion C2 denotes an abrupt and dramatic impact in canopy characteristics which is unlikely to happen except in the presence of burns caused by heatwaves. Finally, the third approach is based on the intersection of the two criteria, C1 and C2 (Figure 8). The intersection of the two criteria aims to exclude most of the NDVI variations which are not associated with the occurrence of a severe heatwave. In this third approach, the pixel is classified as damaged if detected as damaged with C1 and C2 and undamaged in other cases (Figure 8).

A confusion matrix for damaged and undamaged classes was then constructed for both C1 and C2 classifications. The classification accuracy was assessed using the overall accuracy (OA), the weighted F<sub>score</sub>, the precision and the recall values. These metrics have been widely used in several studies to evaluate the accuracy of the classification. While OA is interpreted as the percentage of correctly classified pixels to the total number of pixels, the weighted F<sub>score</sub> is the harmonic mean between the recall and the precision.

## RESULTS

In this section, first, we built a confusion matrix to assess the performance of C1 and C2 classifications, either separately or in combination, using the data collected for the 18 detailed surveyed plots (intra-plot scale). Then, the classification methods were applied to 141 reference plots where damage caused by the 2019 heatwave were surveyed in 2020 at the whole plot scale. A sensitivity analysis was also reported to test the influence of changing the threshold values of the criteria C1 and C2 on the results.

### 1. Assessment of the classification performed with the 18 detailed surveyed plots in 2021

The performance of the proposed thresholds for C1 and C2 were assessed by comparing observed and estimated damage within the plots that were surveyed in detail in 2021. Within the 18 gridded plots, 825 pixels were registered as undamaged and 418 as damaged. Table 2 summarises the metrics derived from the confusion matrix built from the binary classifications with either C1 or C2. The overall accuracy obtained for the classification with C1 reached 76 % and the F<sub>score</sub> (which combines precision and recall scores) reached 75 %. In more detail, 91 % of the pixels registered as undamaged during the field survey were correctly classified as undamaged using C1 (true negatives). On the other hand, 46 % of pixels registered as damaged in the 18 plots were correctly classified as damaged (true positives). A similar result was obtained using C2 (Table 2), where the overall accuracy reached 80 % and the F<sub>score</sub> was 79 %. Over the 18 plots, 62 % of the pixels registered as damaged were correctly classified as damaged (true positives). In addition, 88 % of the pixels registered as undamaged pixels were correctly classified (true negatives).

Table 3 shows the confusion matrix obtained from the classification using the intersection of C1 and C2. The combination of the two criteria correctly classified 99 % of the pixels that were registered as undamaged (true negatives). By contrast, only 40 % of the pixels declared

**TABLE 2.** Confusion matrix of pixel classification into damaged or undamaged by the 2019 heatwave using C1 alone and C2 alone for the 18 reference plots surveyed in 2021.

		Criterion 1 (C1)		Criterion 2 (C2)	
		Undamaged	Damaged	Undamaged	Damaged
Field campaign	Undamaged	91 %	9 %	88 %	12 %
	Damaged	54 %	46 %	38 %	62 %
	Accuracy	76 %		80 %	
	F <sub>score</sub>	75 %		79 %	
	Precision	75 %		78 %	
	Recall	69 %		75 %	

**TABLE 3.** Confusion matrix of pixel classification into damaged or undamaged by the 2019 heatwave using the combination of C1 and C2 for the 18 reference plots surveyed in 2021.

		Classification using both C1 and C2	
		Undamaged	Damaged
Field campaign	Undamaged	99 %	1 %
	Damaged	60%	40%
Accuracy		79 %	
F_score		76 %	
Precision		86 %	
Recall		69 %	

as damaged were classified as damaged by the intersection of C1 and C2 (true positives). The overall accuracy of the intersection of C1 and C2 reached 79 %, with an F\_score value of 76 %.

## 2. Results on the 141 reference plots

The proposed threshold values were then applied to the 141 plots of the first terrain campaign performed at the whole plot scale in 2020. The objective here was to assess the performance of the proposed classifications to map damaged vineyard pixels. For these 141 plots, only global information about the existence or absence of damage was available (severe damage or no damage) without information about the location and type of damage within the plots. The objective here is to assess the performance of the proposed classifications to map damaged vineyard pixels. Therefore, to compare with the field survey, a plot was classified by the method as damaged (respectively undamaged) when more than 50 % of the pixels within the plot were classified as damaged (respectively undamaged).

Using C1, 5 of the 7 plots recorded as undamaged during the field survey were correctly classified as undamaged, while 62 of the 134 plots registered as damaged were correctly classified as damaged. Regarding the classification with C2, 6 of the 7 plots registered as undamaged were correctly classified as undamaged, while only 41 of the 134 plots recorded as damaged were correctly classified as damaged. The combination of C1 and C2 resulted in the correct classification of all the 7 plots registered as undamaged during the field campaign. However, only 28 of the 134 plots registered as damaged were correctly classified as damaged by the intersection of C1 and C2.

To better analyse the 134 plots registered as damaged during the field survey, we further calculated the percentage of pixels within these plots that were classified as damaged. When using C1, 45 % of the pixels within plots registered as damaged were classified as damaged by C1. This suggests

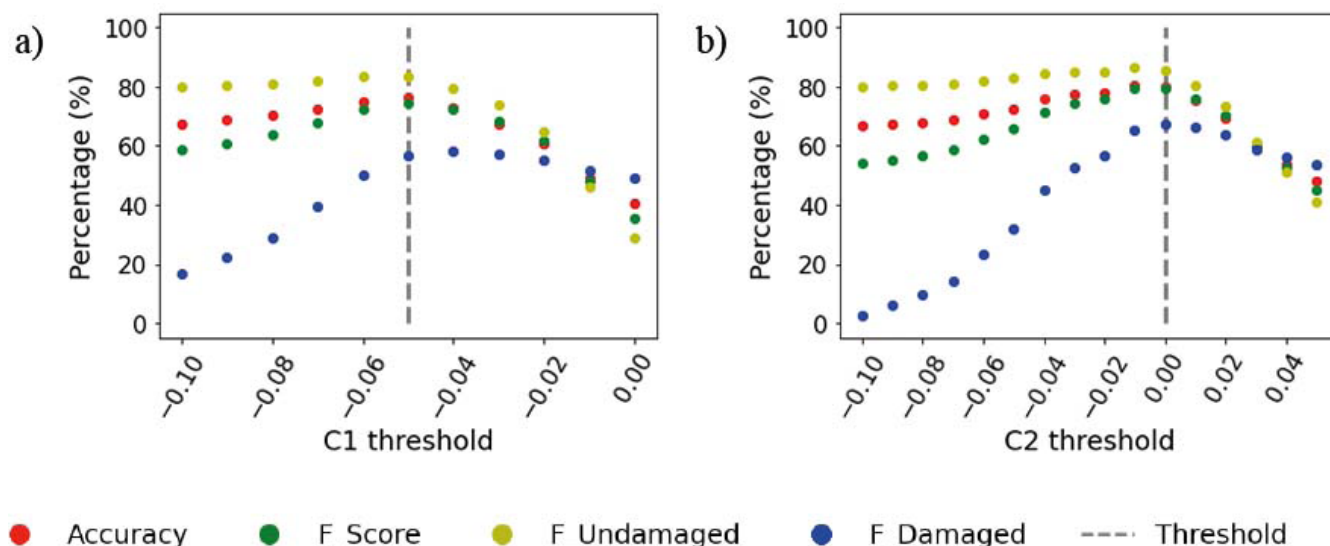
that plots registered as damaged could have been better classified by considering them as damaged when they contained a little less than 50 % of their pixels themselves classified as damaged. However, this percentage decreased to 33 % of the pixels when classified with C2 and only 21 % when classified by the intersection of C1 and C2.

## 3. Sensitivity analysis for C1 and C2 thresholds

To assess the robustness of the method, we performed a sensitivity analysis using different values of C1 and C2 thresholds for these parameters. Figure 9 shows the evolution of the four accuracy metrics used in this study (Overall accuracy, F\_Score, F\_Score for damaged class and F\_Score for undamaged class). A threshold value of -0.1 for C1 (threshold1 in Figure 8) did not allow the accurate detection of the damaged pixels as indicated by the F\_Score of the damaged class, which did not exceed 20 %. When varying the C1 threshold value from -0.1 and -0.05 (the actual threshold used in previous analyses), the accuracy for the detection of the damaged pixels (F\_Score of damaged class) increased from 20 % to 57 %, and the overall accuracy of the classification reached a maximum of 77 % for C1 threshold of -0.05. For the undamaged class, the F\_Score value remained stable (around 81 %) when varying the C1 threshold between -0.01 and -0.05. With the C1 threshold increasing beyond -0.05, the four accuracy metrics decreased, showing a decline in the classification accuracy. This was expected since a C1 value above -0.05 does not represent any degradation in the NDVI, which could be due to the heatwave event.

The same behaviour is shown for the C2 threshold value in Figure 9b. When varying the C2 threshold from -0.1 until 0 (the threshold used in previous analyses), the F\_score of the damaged class increased from 0 % to 67 %, the overall accuracy increased by 13 % and the F\_Score value of the undamaged class increased by 5 %. With the C2 threshold increasing beyond 0, the four metrics decreased, showing a





**FIGURE 9.** Evolution of the four accuracy metrics used in this study (Overall accuracy, F\_Score, F\_Score for damaged class and F\_Score for undamaged class) as a function of C1 and C2 threshold values.

decrease in the classification performance: the F\_Score of the undamaged class sharply decreased by 40 %. This decrease in the accuracy was expected as high C2 above 0 corresponds to an increase in NDVI after the heatwave period, which is an absence of heatwave damage. Setting the C2 threshold in this range means that undamaged pixels would be predicted as damaged.

**4. Assessment of the method using the years excluding the heatwave**

The robustness of the method was further tested using S2 images of the years without a heatwave event (2016, 2017 and 2018). Table 4 shows the percentage of vineyard pixels predicted as damaged and undamaged using only the C1 classification approach in 2016, 2017 and 2018. The C1 criterion used the average NDVI calculated on the period after the 2019 heatwave and on the same period in other years without heatwave. This period corresponds to the most developed stage of the vine. The criterion C2 compared two NDVI images, one before and one after the heatwave. Without any heatwave event in 2016, 2017 and 2018, we could not select a heatwave period for comparison with 2019. For this reason, the results of the method using criterion C2 were not analysed. The same C1 threshold calculated in 2019 was applied for 2016, 2017 and 2018. In addition, the criterion C1 for a given year (i.e., 2018) was calculated

as the difference between the averaged NDVI of this year and the averaged NDVI over the other years excluding 2019 as it was a heatwave year. The results revealed that most S2 pixels from the 18 detailed surveyed plots are detected as undamaged using the C1 threshold value for the three studied years (89 % in 2016, 72 % in 2017, 96 % in 2018). In fact, the results obtained suggested that the study area benefited from a normal Mediterranean climate in 2016 and 2018, in agreement with meteorological (Figure 2) and yield records. In 2017, the results showed that 28 % of the pixels are classified as damaged. In fact, the summer of 2017 (Figure 2) began with a very hot month of June marked by very high temperatures. High temperatures in early June could have caused a drop in the NDVI values. This is also ensured by the recorded grape yield in 2017. In fact, the total volume of grapes harvested in France decreased by 15 % for the year 2017 compared to 2016 and 2018 (Agreste, 2020).

**5. Performances of the classification methods**

The accuracies obtained with the different approaches are limited but showed an encouraging potential for using S2 images to detect vineyard damage. When comparing the obtained results of the three methods (C1, C2 and the intersection of C1 and C2), we found first that both C1 and C2 can lead to a good detection of damaged vineyard pixels with an accuracy reaching 76 % and 80 %, respectively, for C1

**TABLE 4.** Percent of detected vineyard pixels as damaged or undamaged in years without severe heatwave events during 2016, 2017 and 2018.

Years	2016		2017		2018	
Damage type	Damaged	Undamaged	Damaged	Undamaged	Damaged	Undamaged
Criterion 1 (C1)	11 %	89 %	28 %	72 %	4 %	96 %

and C2. However, the intersection of C1 and C2 proved to be the strictest but most reliable method to avoid classifying undamaged pixels as damaged. Using the intersection of C1 and C2, only 1 % of the undamaged pixels were misclassified as damaged, but only 40 % of the damaged pixels were detected as damaged.

## DISCUSSION

The spatial resolution of S2 images for the red and near-infrared band (10 m × 10 m) may not be suitable to detect all damage types. The main challenge of using medium resolution satellite images for vineyard analysis is the spatial organisation of the vine plots (inter-rows). When studying vegetation by remote sensing, the reflectance measured by the satellite sensor depends on the spatial plant organisation, among other parameters. As the vines are organised in rows, the signal measured by the sensor integrates both the soil reflectance and that of the vegetation (mixed pixels). This can affect the precise assessment of the crop status. Several authors have reported this topic and proved the difficulty of using S2 images to analyse crops with a discontinuous arrangement, such as vineyards (Borgogno-Mondino *et al.*, 2018; Khaliq *et al.*, 2019). The work of Khaliq *et al.* (2019) focused on analysing vine vigour through the calculation of NDVI, measured from S2 images and high-resolution aerial images (UAV). Their study proved that, for the analysis of the vineyard vigour, the NDVI calculated from high-resolution UAV images was more appropriate than that calculated from S2 images. The vineyard vigour estimation was even more accurate after delineating the canopies (from UAV images) and considering only pixels representing the vegetation cover. In contrast, Sozzi *et al.* (2020) performed the same comparison between the high (UAV) and medium (S2) spatial resolution images to characterise canopy vigour patterns in vineyard blocks. They showed a good correlation between the NDVI calculated from the two types of images. However, the correlation was even more significant after deleting border pixels, filtering plots smaller than 0.5 ha and having grassed inter-rows. In addition, Devaux *et al.* (2019) proved the potential interest of S2 time-series images to characterise vineyard block vigour at the regional scale. Indeed, this monitoring was limited in the case of small or narrow plots due to S2 spatial resolution.

Cogato *et al.* (2019) conducted a study to assess the effectiveness of using S2 data to quantify the impact of heatwaves on irrigated vineyard plots. The main challenge posed was using S2 data to describe row crop plots such as vineyards. In fact, the spacing of the rows between trees could affect the calculation of the vegetation index. To resolve this challenge, they compared between the S2 derived NDVI values at 10 m spatial resolution and World View 2 (WV2) derived NDVI values at very high spatial resolutions of 34 cm. They showed a good correlation between the S2 NDVI and the WV2 NDVI values. They concluded that the S2 images at 10 m spatial resolution are

suitable to characterise the vineyards. However, they showed in their study that the vegetation index that best described the consequences on vineyards under heatwave conditions were TCARI (Transformed Chlorophyll Absorption Ratio) and CARI (Chlorophyll Absorption Ratio), which use the green and red-edge spectral bands. In addition, they demonstrated that the heat stress was better correlated to the green and red-edge spectral bands of the S2 data.

The studies cited above highlighted that S2 images and the NDVI derived are a good tool for characterising vineyards and for quantifying the impact of extreme climatic events such as heatwaves. However, these studies have shown several limitations in using 10-metre resolution images, including and not limited to the inter-row grass cover, plot size and plot borders.

Our study had no precise information about the inter-row cover type and their management practices. However, the data collected from the field surveys allowed testing of the hypothesis that at the end of June (heatwave event), the leaves of the vine are fully developed and cover the inter-row areas. In addition, it is often common in Southern France that the inter-row crop cover are weeded from April to mid-May (Cogato *et al.*, 2020; Devaux *et al.*, 2019). Later in the summer, as most vineyards are not irrigated, the strong water deficit causes the inter-row grass to dry out (Sozzi *et al.*, 2020). Thus, the inter-row crop was considered to have a very small influence on the NDVI calculation at the end of June (the studied heatwave period) (Kazmierski *et al.*, 2011). Nevertheless, to confirm the results of this study, further research will be needed on different geographical areas with diverse vine varieties and management practices.

The possibility to detect vineyard damage by satellite remote sensing is also strongly dependent on the damage type (canopy or grape damage), the spatial extent of the damage compared to the spatial resolution of satellite data, and the severity of damage (moderate or severe damage). In fact, in our classification results, 81 % and 91 % of the pixels for C1 and C2, respectively, misclassified as undamaged, knowing that these pixels are damaged according to field surveys, were found to be moderately damaged. Therefore, the in situ moderate damage pixels on the vineyards had S2 reflectances closer to the undamaged pixels more than the severely damaged pixels due to the 10 m × 10 m spatial resolution of S2. Only significant damage distributed on a wide area can be detected in a 10-meter resolution.

Using satellite observations at medium resolutions, such as that of the S2, to detect berry damage, is challenging. In fact, the vertical vision of the satellite at medium spatial resolution does not integrate sufficient information about the fruit characteristics as the berries are dominantly covered by the leaves. In addition, for the detailed surveyed plots (18 plots) used in this study, most plots had both leaf and berry damage simultaneously. For this reason, it was hard to distinguish between the separate effect of berry damage and leaf damage on the S2 reflectances, especially at a 10-meter

spatial resolution. However, it would be relevant to use side-view cameras on ground robots, for example, which move between the vineyard rows to map damaged berries.

Using optical satellite images, cloud cover can represent a limitation, especially when the climatic conditions are unstable. In this study, the cloud cover problem affecting some pixels of some S2 images was resolved by performing a linear interpolation between two dates. Cogato *et al.* (2020) also used linear interpolation to overcome cloud cover when analyzing the effectiveness of S2 images to detect vineyard damage from a late frost. However, the high temporal resolution of the S2 satellite over Europe (5 days) helps obtain a detailed NDVI time-series avoiding the cloud cover problem.

The high cost, the limited spatial acquisition and the post-processing of the high-resolution UAV images are the drawbacks driving researchers to investigate the use of free and open access medium-resolution images, such as S2 and Landsat 8, for vineyard analysis. Despite the inability of S2 to finely monitor the vine characteristics, the combination of the S2 spatial, spectral and temporal resolutions makes it a very interesting tool to monitor vineyards at a territorial scale.

## CONCLUSION

This study aimed to address the feasibility of using Sentinel-2 optical remote sensing data to map heatwave consequences on vineyards. The vegetative vine cycle is highly dependent on the climate, so much of its variability affects vineyard development. Accordingly, different levels of vine damage were reported by winegrowers following the June 2019 heatwave in southeast France. Part of the vineyard damage could be detected using NDVI derived from Sentinel-2 images at 10 meters resolution. Three methods were tested based on two criteria to predict the impacts of a heatwave on NDVI. Within 18 plots where the heatwave damage was recorded in detail, only 46 % of their total area was predicted as damaged by the inter-annual NDVI-based method (C1) and 62 % by the intra-annual method (C2). Combining the two criteria revealed 40 % of damaged pixels, which were correctly predicted. Despite fewer pixels being predicted as damaged among those actually recorded as damaged, the combination of both criteria appeared to be the most suited approach in detecting vineyard heatwave damage. The results also showed that only severe damage could be precisely detected using S2 derived NDVI. A high spatial resolution could improve the accuracy of the mapping of the impacts of a heatwave event and better discriminate between the damage levels (moderate or severe).

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