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MULTISPECTRAL DATA FROM SENTINEL-2 AS A TOOL FOR MONITORING LATE FROST EVENTS IN VINEYARDS

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Abstract

Aim: Climate change is altering some aspects of winegrape production with an advancement of phenological stages which may endanger viticultural areas in the event of a late frost. This study aims to evaluate the potential of satellite-based remote sensing to assess the damage and the recovery time after late frost events.

Methods and Results: Multispectral images derived from the Copernicus Sentinel-2 mission were used to monitor an area in north-eastern Italy affected by late frost in 2017. The study focused on *Vitis vinifera* cv. Garganega, a white variety mainly cultivated in the provinces of Vicenza and Verona. The reflectance values obtained from satellite imagery of the frost affected area (F) and control area (NF) were used to compute several vegetation indices (VIs). The reflectance of the spectral bands and VIs were compared using an unpaired two-sample t-test. Frost damage was detected by Chlorophyll Absorption Ratio Index (CARI), Enhanced Vegetation Index (EVI) and Modified Triangular Vegetation Index 1 (MTVI1) ($P \leq 0.0001$, 0.0001, 0.05, respectively). The spectral bands more sensitive to assess the frost damage were Near-Infrared (NIR) and Red Edge ($P \leq 0.0001$). The previous VIs/spectral bands, the Normalised Difference Vegetation Index (NDVI) and the Modified Simple Ratio (MSR) provided information on the full recovery time ($P \leq 0.0001$) approximately 40 days after the frost event.

Conclusions: The results suggest that multispectral data from Sentinel-2 have the potential to assess the damage and the recovery time of late frost in vineyards. Moreover, the analysis highlighted the spectral regions and the VIs more related to frost damage and recovery time detection. These findings suggest that Sentinel-2 data may represent a tool for prompt assessment and quantification of the damage, supporting reactive and effective decision-making.

Significance and Impact of the Study: The findings suggest that Sentinel-2 data may represent a cost-effective tool for prompt assessment and quantification of the damage, supporting reactive and effective decision-making. The insurance industry, which usually manage farmers' risk, may benefit from a timely and near real-time overview of crop conditions.
Moreover, achieving valuable information from open-access imagery would represent the tool to extend the frost management from local to global scale.

Keywords: Spring frost, multispectral remote sensing, vegetation indices, grapevine, frost damage, *Vitis vinifera*

Introduction

In spring 2017 an advective frost from the Arctic reached central and Western Europe. The wave of frost followed an unusually warm period, which had caused advanced budbreak in grapevine, thus causing severe injuries to the young shoots.

In the current context of a warming climate, a forward shift of phenological development was observed (Menzel *et al.,* 2006). Thus, late frost events may affect viticulture more frequently (Meier *et al.,* 2018). Late frost can cause severe damage to tissues and organs, resulting in reduced yield (Mills *et al.,* 2006; Poling, 2008).

Prompt assessment of frost damage allows effective decision-making. However, the conventional methods for damage assessment, based on visual and thermal field examination of vines, are tedious and unemployable on a large scale.

Alternative approaches, such as remote sensing techniques, proved to have potential to assess abiotic stress detection (Cogato *et al.,* 2019; Rao *et al.,* 2019), and some studies have been carried out on frost damage detection. For example, She *et al.* (2017) found a good correlation between Normalised Difference Vegetation Index (NDVI) derived from moderate- and medium-resolution imaging spectroradiometer (MODIS and MERIS) and frost damage indices in oilseed rape in China. Su *et al.* (2016) identified vines affected by frost injuries using an RGB camera installed on an Unmanned Aerial Vehicle (UAV).

To date, the spectral reflectance derived from medium-spatial resolution data has not been used to assess late frost damage in vineyards. Therefore, the objective of this study was to verify the effectiveness of using the reflectance values and the vegetation indices (VIs) collected from Sentinel-2 imagery to identify frost damage in vineyards and assess the recovery time.

Materials and Methods

An area cultivated with *Vitis vinifera* cv. Garganega located in the north-east of Italy (45°23’29.30”N and 11°24’15.36”E) was studied. The area was affected by late frost on 19 April 2017. The training system was the traditional “Pergola”. Due to the earliness of the variety and the anomalously warm temperatures preceding the frost event, frost injuries were severe. In an area of 20 km^2, we identified three plots affected by frost damage (F), and three plots unaffected (NF). The total area of the sample plots was 4.96 ha and 11.43 ha for F and NF, respectively.

To monitor the temporal pattern of frost, we acquired five Sentinel-2 images from the Copernicus Open-Access Hub from 14 April to 23 June 2017 (Table 1). The reflectance values were used to assess eight spectral bands and seven VIs (Table 2). Concurrently, we acquired images from the same dates in 2018 and 2019. These latter images were used to normalise the value of every single pixel of the 2017 images. The normalisation was done by dividing each value by the average reflectance of 2018 and 2019. The normalisation aimed to reduce the influence of different interannual conditions (Kamp *et al.,* 2013). Once the normalised values were obtained, we divided every pixel of S2, S3, S4 and S5 by the value of S1, equating to 1. Therefore, values < 1 indicate lower performance compared to before frost, whereas values > 1 indicate higher performance. F and NF were compared with a Student unpaired, *t*-test.

Table 1: List of the Sentinel-2 images used in this study.

Date	Image ID
14/04/2017	S1
14/05/2017	S2
24/05/2017	S3
03/06/2017	S4
23/06/2017	S5

Table 2: Spectral bands and vegetation indices used in this study.

Sentinel-2 band	Vegetation Index
Band 2 - Blue	Chlorophyll Absorption Ratio Index (CARI)
Band 3 - Green	Enhanced VI (EVI)
Band 4 - Red	Green Normalized Difference VI (GNDVI)
Band 5 – Red Edge	Modified Simple Ratio (MSR)
Band 6 – Red Edge	Modified Triangular VI 1 (MTVI1)
Band 7 – Red Edge	Normalized Difference VI (NDVI)
Band 8 – Near Infrared (NIR)	Soil Adjusted VI (SAVI)
Band 11 – Short Wave Infrared (SWIR)	

Results and Discussion

VIs, nCARI, nMTVI1 and nEVI proved to be effective in detecting damages with a sharp decrease in F after the frost event (-5.26%, -5.77% and-16.29%, respectively). Moreover, these VIs could recognise vines recovery after the 24th of May (+17.70%, +48.03% and +33.43%, respectively). nNDVI and nMSR were not able to capture the frost injuries but identified the recovery time accordingly to the previous VIs. nGNDVI and nSAVI did not provide valuable results, as they exhibited a better performance in F during all the observed period. Figure 1 reports the temporal pattern of nCARI and nNDVI.

Compared to the other VIs used in this study, CARI, MTVI1 and EVI include in their equation three spectral bands. Three-band VIs were specifically perfected to address the saturation issue (Gitelson *et al.,* 2005). For this reason, they proved to be more effective in detecting structural and chlorophyll changes, which are commonly associated with frost damage (Duddu *et al.,* 2018). On the other hand, in the early season, two-band VIs may have been influenced by interrow cover crops reflectance (Kazmierski *et al.,* 2011), thus proving to be effective only for recovery assessment.

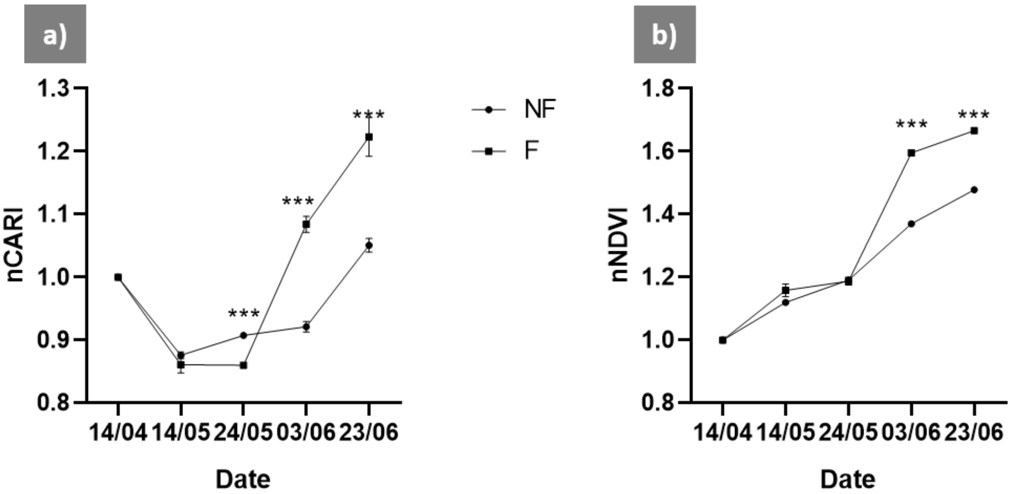

Figure 1: Change of normalised CARI and NDVI from May to June 2017. The values reported in y-axis represent the reflectance values normalised on the first date, equating to 1. Statistical significance was determined by Student's *t*-test. Triple asterisk indicates a statistical difference, p < 0.001 (unpaired *t*-test). Error bars represent standard error of the mean.

The spectral bands more sensitive to capture frost damage were nNIR and nRed Edge (Sentinel-2 band 7). Both these bands showed a significant difference in F and NF after the frost event. After the 24th of May, the reflectance values of NIR and Red Edge increased both in F and NF, but the 3rd and the 23rd of June reflectance was significantly higher in F, allowing to assess the full recovery. The differences in the relative reflectance of nNIR and nRed Edge 7 are reported in Table 3.

Table 3: Differences in the relative reflectance of nNIR and nRed Edge 7 in F compared to NF. Triple asterisk indicates a statistical difference, p < 0.001 (unpaired *t*-test); ns = non-significant.

Spectral band	**Difference (%)**			
	14/05/2017	**24/05/2017**	**03/06/2017**	**23/06/2017**
nNIR	−14.33 (***)	−16.65 (***)	+5.89 (***)	+17.04 (***)
nRed Edge 7	−16.67 (ns)	−6.53 (***)	+5.91 (***)	+17.90 (***)

Previous studies proved the effectiveness of NIR and Red Edge to assess frost injuries in perennial crops (Duddu *et al.,* 2018; Wei *et al.,* 2017). The Red Edge is sensitive to leaf area index and chlorophyll concentration, which are likely affected by late frost events. Lower reflectance of NIR region after frost may derive from the modifications in cellular water content and pigment concentration after frost.

Overall, VIs and spectral bands provided evidence of higher vigour of F vines after recovery, proving the replacement of the damaged by the development of secondary buds.

Conclusions

The results showed that the spectral reflectance from medium-resolution imagery is responsive to frost damage in vineyards. The study identified the spectral regions and the VIs which are more sensitive to assess frost injuries. Moreover, the approach allowed to assess the recovery time of frost-affected plots.

These findings are encouraging for taking frost management from local to global scale. The traditional damage assessment methods are tedious and only employable in small areas. Further investigation will be needed, testing different varieties and training system. Nevertheless, the results provide evidence that the methods implemented can provide useful information to assess the impact of late frost on grapevines.

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