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INVESTIGATION BETWEEN VEGETATION INDICES, METEOROLOGICAL DATA AND PHENOLOGY OF WINE GRAPE VARIETIES

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Abstract

The successful cultivation of vines must be aware of the phenological phases during the growing season. However, conventional phenological measurements on the ground are limited due to their spatial coverage. The use of Sentinel-2 imagery has led to an increased interest in its application to viticulture, with the data providing access to global spatial coverage and the potential for high temporal resolution. The present study was conducted during the period 2021-2022 in the experimental vineyard of the Agricultural University of Plovdiv, with the aim of studying the phenological phases of the wine grape varieties Merlot, Mavrud and Chardonnay. The results will enhance the interpretation of the spatiotemporal dynamics between meteorological data, vegetation indices (Normalized Difference Vegetation Index Normalized Difference Vegetation Index - NDVI), and phenological stages in vine cultivation. This study highlights the effectiveness of remote sensing for monitoring vineyard phenology, both retrospectively and in real time, as a valuable tool for maintaining high-quality standards in precision viticulture.

***Key words**: Grape varieties, meteorological data, NDVI, phenological stages.*

INTRODUCTION

Climate is a key factor in enabling plants to complete their vegetative and productive cycles, directly influencing the timing and duration of the main phenological stages (Dalla Marta et al., 2010). The influence of air temperature on grapevine development and the timing of growth phases has been well-documented in numerous studies (Chuine et al., 2013; De Cortázar-Atauri et al., 2009; Parker et al., 2011; 2013; 2020). Network analyses of meteorological stations have been used to characterize temperature variability on regional scales (Bois, 2007; Cuccia, 2013; Madelin & Beltrando, 2005). In the context of global climate change, growers must adapt to the spatial variability of temperature and its temporal evolution. There is broad scientific consensus that the climate is changing (IPCC, 2013). The recent rise in temperatures has already impacted grapevine development, particularly by accelerating the timing of phenological phases (Bock et al., 2011; Duchêne et al., 2012; Tomasi et al., 2011; van Leeuwen et al., 2019). According to Cunha et al. (2010), conducting phenological observations in vineyards is essential for improving the ecological adaptability of grape varieties, as well as for effective crop management and modeling. Traditionally, these observations are made on the ground, offering localized insights but limited spatial coverage and temporal frequency. In contrast, time-series satellite imagery provides a fast and objective view of grapevine dynamics, enhancing vineyard management. Integrating ground-based phenology observations with the temporal profiles of the Normalized Difference Vegetation Index (NDVI), as captured by the SPOT VEGETATION sensor, is particularly useful for regional, inter-annual vineyard monitoring. Earth observation data and NDVI are vital tools for assessing vineyard vegetation health (Pastonchi et al., 2020), while also enabling efficient and accurate data collection in remote areas (Krishna, 2017). The use of vegetation indices (VIs) is a practical approach for applying remote sensing in viticulture, relying on spectral information to assess vine development and yield (Hall et al., 2002; Arnaudova & Stalev, 2024). Remote sensing technologies - such as UAVs, airborne sensors, and satellite imagery - are among the most employed methods for vineyard monitoring (Hall et al., 2002; Matese & Di Gennaro, 2015). UAVs equipped with multispectral sensors, along with radar measurements, provide high-resolution imagery that enables the extraction of various types of information about vineyards (Pichon et al., 2019). However, the high cost of this equipment can limit the spatial coverage needed for generating reliable results (Candiago et al., 2015).

Satellites are more time-efficient and cost-effective for monitoring large areas, but they are less adaptable to growers' needs due to limitations in revisit frequency and spatial resolution (Sozzi et al., 2019). In recent years, the availability of free satellite data - such as that provided by the Copernicus program through the European Space Agency (ESA)'s Sentinel-2 mission - has sparked increased interest in its application to viticulture. Studies have demonstrated that Sentinel-2 imagery can support regional vineyard management by extracting agricultural information and quantifying drought impacts (Devaux et al., 2019; Cogato et al., 2019). The use of geographic information systems (GIS) enhances image acquisition and processing for vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Green Normalized Difference Vegetation Index (GNDVI). A geoprocessing approach further integrates environmental parameters - such as rainfall, temperature and soil moisture - as key variables (Jesus et al., 2020).

The objective of this study was to explore the relationship between vegetation indices derived from Earth observation and climatic data, and the phenology of wine grape varieties measured in situ.

MATERIALS AND METHODS

Study area

The experiment was conducted on the experimental training field of the Agricultural University, located in the town of Kuklen, Plovdiv District, in Central-Southern Bulgaria (Figure 1).

In situ measurements

The study was conducted in the experimental vineyard of the Agricultural University of Plovdiv, situated near the town of Kuklen, on the border with the village of Brestnik, in Rodopi Municipality. The vineyard is in full fruit-bearing condition. Vines are planted with a spacing of 3.0 meters between rows and 1.0 meter between vines within a row, resulting in a planting density of approximately 333 vines per hectare.

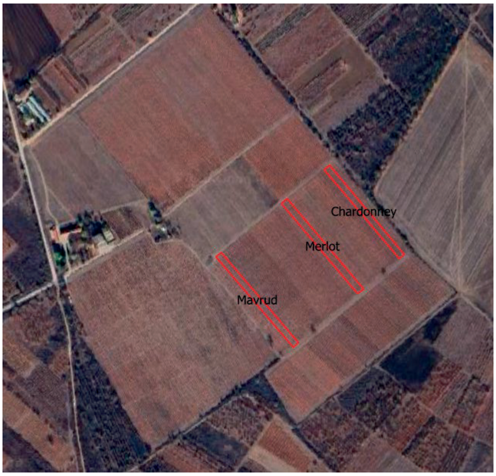

Figure 1. Location of study area
(Google Earth 17.11.2024)
L 42° 3'29.71"N B 24°47'0.18"E

The vineyard rows are oriented northwest–southeast (NW-SE) and are situated on a gentle eastward slope of 3.2% (1.8°), at an average elevation of 194 meters above sea level. Vines are cultivated using a tall-stem training system with a double-sided cordon formation supported by an appropriate trellis structure. The vineyard is managed under non-irrigated (dry-farmed) conditions.

The experimental scheme includes the following variants:

- V_1 - Mavrud variety;
- V_2 - Merlot variety;
- V_3 - Chardonnay variety.

Each variant consists of 60 vines, arranged in four replications of 15 vines each.

A series of in situ observations were made to The phenological development of the main growth stages of vine development during the vegetation period was monitored, including: bud burst, first leaf appearance, mass flowering, "pea"-size berries, veraison, and technological maturity. Observations were conducted on normally developed, fully fruiting vines. For the *Mavrud*, *Merlot*, and

Chardonnay varieties, the phenological stages were recorded as the calendar days when most of the vines (50%) had reached each respective stage. The identification and classification of the phenological phases followed the methodology described by Braykov et al. (2005).

Climatic data for the study period (April to October) in 2021 and 2022 including mean daily air temperature (°C) and daily precipitation (mm) were obtained from the meteorological station located within the university vineyard. According to Del Rio et al. (2024), the following heat indices were calculated from the temperature data:

The Winkler Index (WI) is a viticultural metric used to assess cumulative heat exposure during the grapevine growing season. It is calculated by summing the average daily temperatures that exceed 10°C. Also known as the Winkler Scale or Winkler Regions, this index was developed by Winkler et al. (1974) to classify wine-growing regions based on growing degree-days (GDD). It divides geographical areas into five climatic regions (Regions I to V), with each category corresponding to a range of accumulated heat units (Table 1), thereby guiding the selection of grape varieties suitable for each region.

$$\mathrm{WI} = \sum_{April\ 1}^{Oct31}(T_{mean} - 10^0C)$$

where:
- T_{mean} is the average daily temperature in °C from 1st April to 31 October;
- 10°C is the baseline temperature below which grapevine does not grow.

Table 1. Winkler Index classification (Winkler et al., 1974)

Region	GDD Range (°C)	Climate Type
Region I	< 1,390	Cool
Region II	1,391-1,670	Intermediate
Region III	1,671-1,940	Warm
Region IV	1,941-2,220	Hot
Region V	> 2,220	Very Hot

The Huglin Index (HI) is a bioclimatic heat index developed by Huglin for vineyards. It is a metric used to predict the potential maximum temperature of a given location over a given period (Huglin, 1978). The index is calculated by taking the meaning of the maximum and average daily temperatures recorded from early April to late September (Table 2). The calculated total is slightly adjusted based on the latitude of the area, using the K factor.

$$HI = K\left(\sum_{April\ 1}^{Sept30}\frac{T_{mean+}T_{max}}{2} - 10^0C\right)$$

where:
- T_{mean} is daily mean temperature (°C);
- T_{max} is daily maximum temperature (°C);
- 10°C is the baseline temperature below which grapevines do not grow;
- K is a latitude correction factor (ranges from 1.02 to 1.06).

Table 2. Huglin Index Classification (Huglin, 1978)

HI Range	Climate Classification
≤ 1500	Very Cool
1,500-1,800	Cool
1,800-2,100	Temperate
2,100-2,400	Warm
2,400-2,700	Hot

Growing Season Temperature (GST) - The growing season temperature index is an indicator employed in viticulture to assess the suitability of a particular region for wine production. The GST index is calculated as the mean daily temperature between 1 April and 31 October in the Northern Hemisphere. A positive correlation has been observed between the GST index and the maturity potential of grape varieties (Table 3). Different varieties of wine grapes grow within different GST thresholds (Jones, 2007).

$$\mathrm{GST} = \sum_{April\ 1}^{Oct\ 31}\frac{T_{mean}}{n}$$

where:
- T_{mean} is daily mean temperature (°C);
- n is days from April 1 to October 31.

Table 3. GST Index classification (Jones, 2007)

GST (°C)	Climate Type
< 13°C	Very Cool
13-15°C	Cool
15-17°C	Intermediate
17-19°C	Warm
19-21°C	Hot
> 21°C	Very Hot

Satellite imagery

The Sentinel-2 multispectral images for the NDVI were obtained from the official open-access site of the Copernicus Land Monitoring Service (Copernicus Europe's Eyes on Earth, n.d.). Within this online database, cloud-free images were selected according to their proximity to the dates of the phenological stages.

NDVI was obtained from the Copernicus Land Monitoring Service as a daily update of the NDVI, provided at pan-European level and in near real time. The data were available at 10 m x 10 m spatial resolution from Sentinel-2 HR multispectral satellite imagery (according to Data Viewer - Copernicus Land Monitoring Service).

NDVI defines values from - 1.0 to 1.0, where negative values are mainly formed from clouds, water and snow, and values close to zero are primarily formed from rocks and bare soil.

Very small values (0.1 or less) of the NDVI function correspond to empty areas of rocks, sand or snow.

Moderate values (from 0.2 to 0.3) represent shrubs and meadows, while large values (from 0.6 to 0.8) indicate temperate and tropical forests (Eos Date Analytics, n.d.)

The formula for the NDVI is as follows:

$$\text{NDVI} = \frac{NIR - RED}{NIR + RED}$$

where:

- NIR is near-infrared light;
- RED is red light.

For Sentinel-2:

$$\text{NDVI} = \frac{B_8 - B_4}{B_8 + B_4}$$

where:

- B8 = 842 nm;
- B4 = 665 nm.

The images and sample raster values from NDVI imagery were processed by QGIS 3.34.14.

Time series imageries were downloaded for the main stages of the vine plant in the experimental field and in situ data collection for 2021-2022. The growth stages are calculated in the Days Of the Year (DOY). The correlations between the studied variables were obtained by regression analysis in Excel Microsoft 365 and were valid within the time range studied.

RESULTS AND DISCUSSIONS

The grape varieties included in the study demonstrated varying ripening periods within the Plovdiv region.

Mavrud, a red wine variety, is distinguished by its protracted ripening period, which can extend from late summer to the onset of winter. In 2021, bud burst commenced on 16 April/DOY 116, and technological maturity was achieved on 6 October/DOY 279. The duration of the period from the initial phase to technological maturity is 174 days. In the second experimental year of the study (2022), the onset of budbreak occurred earlier than in the first year, on 9 April/DOY 111. The attainment of technological maturity was observed on 1 October/DOY 274. As presented in Table 4, the duration of the period from the budding growth phase to technological maturity is 176 days.

Merlot is a late-ripening French red wine variety. In 2021, bud burst is initiated on 12 April/ DOY 102, and technological maturity is observed on 13 September/ DOY 256. The duration of the period from the initial growth stage to technological maturity is 155 days. In consequence of the increased temperatures recorded in April 2022, the phenological stage of bud burst occurred earlier than in the first year, on 6 April/ DOY 96, and harvesting took place on 10 September/DOY 256. The duration of the period from bud burst to technological maturity is 158 days.

Chardonnay is a medium ripening French white wine variety. The onset of bud burst is observed on 10 April 2021 (DOY 100), while technological maturity is recorded on 30 August 2021 (DOY 242). The duration of the period from bud burst to technological maturity is 145 days. In 2022, bud burst occurred on 5 April/DOY 95, and technological maturity was attained on 28 August/DOY 240. The vegetation period was therefore 146 days.

The ripening process of the grapes was influenced by the average daily air temperature and the amount of precipitation. During the two experimental years, resulting in changes in the phenological stages during the growing season. At a temperature of 25ºC, the flowering of the vines was observed to occur at a shorter time. The temperature in July plays a major role in the ripening of the grapes and should be between 28-32ºC for high quality table wines. The highest recorded precipitation (103.8 mm) was in June 2022 (Figure 2 and Figure 3).

Table 4. Phenological stages of Mavrud, Merlot and Chardonnay grape varieties for 2021 and 2022

Phenological Stage	Year	Mavrud	Merlot	Chardonnay
		Date/DOY	Date/DOY	Date/DOY
Bud Burst	2021	16.04.21/116	12.04.21/102	10.04.21/100
	2022	09.04.22/111	06.04.22/96	05.04.22/95
First Leaf Appearance	2021	30.04.21/120	22.04.21/112	19.04.21/109
	2022	24.04.22/114	16.04.22/106	10.04.22/100
Mass Flowering	2021	09.06.21/160	31.05.21/151	27.05.21/147
	2022	03.06.22/153	29.05.22/149	25.06.22/145
"Pea" Size	2021	10.07.21/191	05.07.21/186	30.06.21/181
	2022	06.07.22/187	01.07.22/182	27.06.22/178
Veraison	2021	20.08.21/232	04.08.21/216	29.07.21/210
	2022	16.08.22/228	02.08.22/214	25.07.22/206
Technological Maturity	2021	06.10.21/279	13.09.21/256	30.08.21/242
	2022	01.10.22/274	10.09.22/253	28.08.22/240
Bud Burst - Technological Maturity (Days)	2021	174	155	145
	2022	176	158	146

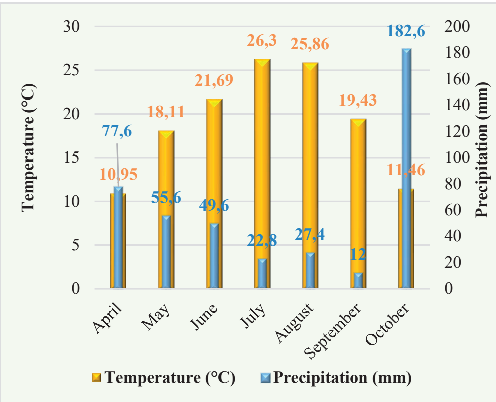

Figure 2. Monthly climate characteristics - mean temperatures and sum of precipitation for 2021

The meteorological data obtained from the station in the vineyard is of great importance for the vines. It enables the monitoring of temperature and precipitation, which influences the growth and development of the vines and plays a decisive role in the quality and yield of the grapes.

An assessment of the microthermal conditions during the grape harvesting period was conducted by determining the Winkler Index, the Huglin Index, and the Growing Season Temperature (GST) Index for the years 2021 and 2022 (Table 5).

The thermal indices allow for the comparison of vineyards with wine-growing areas all over the territory. These indices suggest that the optimal grape varieties are those capable of adapting to both lower and higher temperatures, exhibiting a suitable ripening period, and yielding wines with balanced acidities and flavours.

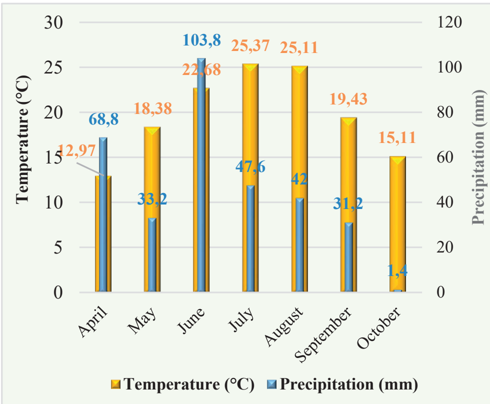

Figure 3 Monthly climate characteristics - mean temperatures and sum of precipitation for 2022

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Table 5. Assessment microthermal conditions

	Index	2021Year/ Category	2022 Year/ Category
Meteo station Brestnik village	Winkler (WI)	1990°C Region IV	2132°C Region IV
	Huglin (HI)	2619°C Warm	2689°C Warm
	Growing Season Temperature (GST)	19.4°C Hot	19.8°C Hot

Satellite observations

The dynamics of the NDVI values were traced by the average index values in the plots, obtained from the zonal statistics in QGIS in 2021 and 2022. The index values are for the stages from the first leaf appearance to the technological maturity for the three varieties. Each of the varieties under observation cover an area of 2,500 square meters (Figure 4, Figure 5). The obtained results for the varieties are corresponding to the occurrence of the respective stages in each of the varieties. On the Figure 4 and Figure 5 are presented NDVI images for the growth stages of Mavrud variety in 2021 and 2022.

It is observed that the NDVI values start to increase with the beginning of flowering in May, and reach their maximum at the "pea" size in June. From August, due to the onset of drought and maturity, the leaves turn yellow and the index values decrease. The two years under consideration, 2021 and 2022, differ significantly in terms of climate, particularly with regard to rainfall, which has a direct impact on plant development.

In 2021, July and August rainfall were significantly lower, with values of 22.8 mm and 27.4 mm respectively. This results in a deficiency of moisture in the leaves, consequently leading to reduced NDVI values.

In 2022, the rainfall was almost double that of the previous year, at 47.6 and 42 mm, which is indicative of favourable conditions for the development of the vine crop. Consequently, NDVI values are elevated.

This provides a rationale for the observed delay in the onset of the phenophases, which in 2021 occurred 4-5 days later than in 2022.The phenological development of the varieties was established on the basis of climatic data and in situ observations (Figures 6 and 8).

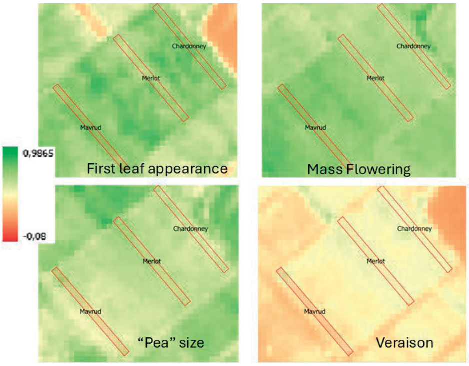

Figure 4. NDVI images for the phenological stages of Mavrud in 2021

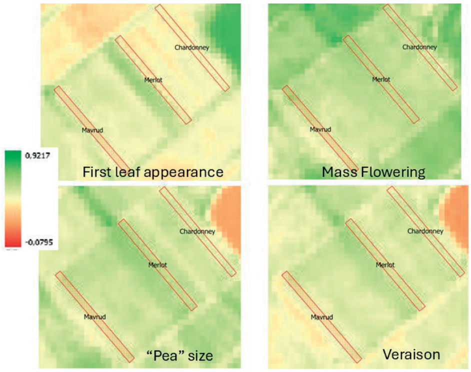

Figure 5. NDVI images for the phenological stages of Mavrud in 2022

There were no significant differences in the index values, but due to the different timing of the phenological phases and the development of the varieties, differences were observed. The analysis indicates a high degree of correlation.

The highest degree of multiple correlation is observed for the red varieties Merlot and Mavrud with R^2=0.99 for 2021 and R^2=0.97 for 2022 and R^2 = 0.90 and R^2=0.94, respectively.

In the case of Chardonnay, the coefficient of possible correlation is lower degree than the others, but also with a very good result. R^2=0.8 for 2021 and R^2=0.73 for 2021.

Figures 7 and 9 illustrate the NDVI from Sentinel-2 images for the verasion growth stage for the three varieties. The phases between the Chardonnay and Mavrud varieties exhibit a 20-day discrepancy, with the Chardonnay variety entering its phase at a more accelerated rate. A clear distinction in the years and index values is evident between the earlier veraison phase in

Chardonnay and the later veraison growth stage in Mavrud.

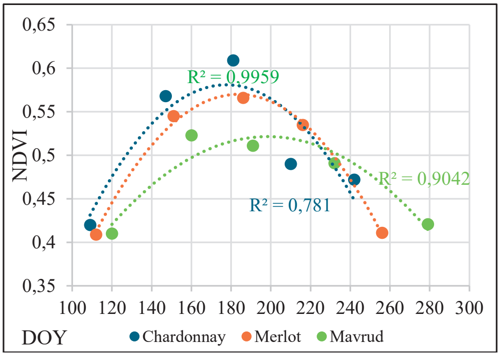

Figure 6. Dynamics of NDVI values for main growth stages for 2021

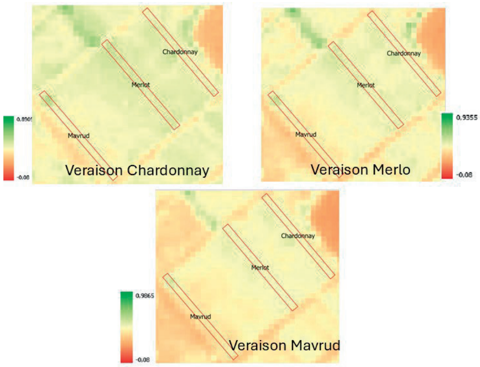

Figure 7. NDVI images for the growth stage Veraison in 2021

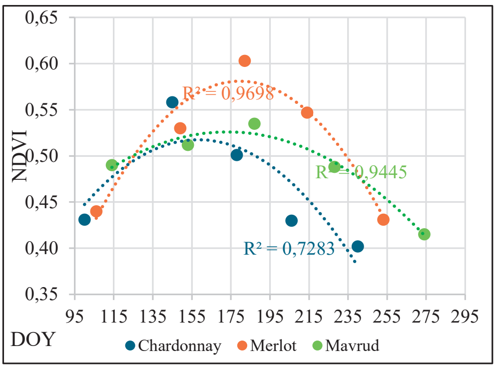

Figure 8. Dynamics of NDVI values for main growth stages for 2022

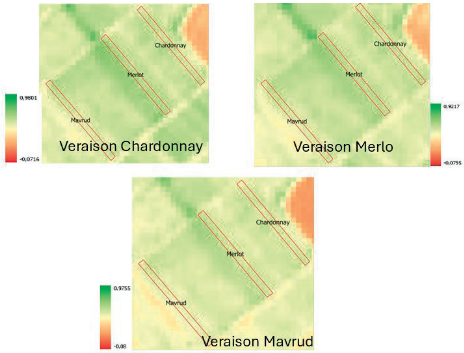

Figure 9. NDVI images for the growth stage Veraison in 2022

CONCLUSIONS

The present study employed regression equations and multiple correlation to evaluate the relationship between NDVI and the phenological phases of cultivars with varying maturation dates and growing season durations. The coefficients' values for R^2 in both years exhibited analogous results. The analysis revealed the highest result for the Merlot and Mavrud varieties. The multiple correlation coefficient for the Merlo variety was found to be $R^2 = 0.99$ and 0.97 for the year 2021 and 2022, respectively.
The NDVI time series has been utilised to monitor vineyard phenological phases, exhibiting a high degree of data validity. The survey is subject to several significant limitations. Firstly, there is a high probability of cloud cover and precipitation during the months of May and June. This may result in a lack of NDVI values during the growth stages of "flowering" and "pea size".
The evaluation of the investigated varieties was conducted by means of thermal indices in the experimental field in which they were cultivated.
The integration of meteorological data, vegetation indices and heat indices has demonstrated its potential in determining the phenological dynamics of diverse grape varieties. The integration process under discussion has been demonstrated to facilitate the identification of the most suitable grape variety for specific regional contexts. This, in turn, has been shown to contribute to the optimisation of viticultural practices.

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REFERENCES

Arnaudova, Z., & Stalev, B. (2024). Relationships between spectral vegetation indices (SVIS) and growth stages in a table grape vineyard. *Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering, 13*, 750–755.

Bock, A., Sparks, T., Estrella, N., & Menzel, A. (2011). Changes in the phenology and composition of wine from Franconia, Germany. *Climate Research, 50*, 69–81. https://doi.org/10.3354/cr01048

Bois, B. (2007). *Cartographie agroclimatique à méso-échelle: Méthodologie et application à la variabilité spatiale du climat en Gironde viticole. Conséquences pour le développement de la vigne et la maturation du raisin* (Doctoral dissertation). Université de Bordeaux.

Braykov, D., Pandeliev, S., Masheva, L., Mievska, T., Ivanov, A., Roychev, V., & Botyanski, P. (2005). *Viticulture [Students' guide to viticulture]*. Academic Publishing House of the Agricultural University, Plovdiv.

Candiago, S., Remondino, F., De Giglio, M., Dubbini, M., & Gattelli, M. (2015). Evaluating multispectral images and vegetation indices for precision farming applications from UAV images. *Remote Sensing, 7*(4), 4026–4047.

Chuine, I., de Cortázar-Atauri, I. G., Kramer, K., & Hänninen, H. (2013). Plant development models. In M. D. Schwartz (Ed.), *Phenology: An integrative environmental science* (pp. 275–293). Springer.

Cogato, A., Pagay, V., Marinello, F., Meggio, F., Grace, P., & De Antoni Migliorati, M. (2019). Assessing the feasibility of using Sentinel-2 imagery to quantify the impact of heatwaves on irrigated vineyards. *Remote Sensing, 11*(23), 2869.

Copernicus Europe's Eyes on Earth. (n.d.). *Land monitoring service*. https://land.copernicus.eu/en

Cuccia, C. (2013). *Impacts du changement climatique sur la phénologie du Pinot noir en Bourgogne* (Doctoral dissertation). Université de Bourgogne.

Cunha, M., Marçal, A. R., & Rodrigues, A. (2010). A comparative study of satellite and ground-based vineyard phenology. In *Imagine [e, g] Europe* (pp. 68–77). IOS Press.

Dalla Marta, A., Grifoni, D., Mancini, M., Storchi, P., Zipoli, G., & Orlandini, S. (2010). Analysis of the relationships between climate variability and grapevine phenology in the Nobile di Montepulciano wine production area. *The Journal of Agricultural Science, 148*(6), 657–666.

De Cortázar-Atauri, I. G., Brisson, N., & Gaudillère, J. P. (2009). Performance of several models for predicting budburst date of grapevine (*Vitis vinifera* L.). *International Journal of Biometeorology, 53*, 317–326. https://doi.org/10.1007/s00484-009-0217-4

Del Rio, M. S., Cicuéndez, V., & Yagüe, C. (2024). Characterisation of two vineyards in Mexico based on Sentinel-2 and meteorological data. *Remote Sensing, 16*(14), 2538.

Devaux, N., Crestey, T., Leroux, C., & Tisseyre, B. (2019). Potential of Sentinel-2 satellite images to monitor vine fields grown at a territorial scale. *OENO One, 53*(1).

Duchêne, E., Butterlin, G., Dumas, V., & Merdinoglu, D. (2012). Towards the adaptation of grapevine varieties to climate change: QTLs and candidate genes for developmental stages. *Theoretical and Applied Genetics, 124*, 623–635. https://doi.org/10.1007/s00122-011-1734-1

Eos Data Analytics. (n.d.). *Satellite data analytics for daily Earth insights & decision-making*. https://eos.com

Hall, A., Lamb, D. W., Holzapfel, B., & Louis, J. (2002). Optical remote sensing applications in viticulture: A review. *Australian Journal of Grape and Wine Research, 8*(1), 36–47.

Huglin, M. P. (1978). Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. *Comptes Rendus des Séances de l'Académie d'Agriculture de France, 64*.

Intergovernmental Panel on Climate Change (IPCC). (2013). *Climate change 2013: The physical science basis*. Cambridge University Press.

Jesus, J., Santos, F., Gomes, A., & Teodoro, A. C. (2020, September). Temporal analysis of the vineyard phenology from remote sensing data using Google Earth Engine. In *Remote Sensing for Agriculture, Ecosystems, and Hydrology, XXII* (Vol. 11528, pp. 39–50). SPIE.

Jones, G. V. (2007, July). Climate change and the global wine industry. In *Proceedings of the 13th Australian Wine Industry Technical Conference* (Vol. 28). Adelaide, Australia.

Krishna, K. R. (2017). *Push button agriculture: Robotics, drones, satellite-guided soil and crop management*. CRC Press.

Madelin, M., & Beltrando, G. (2005). Spatial interpolation-based mapping of the spring frost hazard in the Champagne vineyards. *Meteorological Applications, 12*, 51–56. https://doi.org/10.1017/S1350482705001568

Matese, A., & Di Gennaro, S. F. (2015). Technology in precision viticulture: A state-of-the-art review. *International Journal of Wine Research*, 69–81.

Parker, A. K., De Cortázar-Atauri, I. G., van Leeuwen, C., & Chuine, I. (2011). General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera* L. *Australian Journal of Grape and Wine Research, 17*, 206–216. https://doi.org/10.1111/j.1755-0238.2011.00140.x

Parker, A. K., García de Cortázar-Atauri, I., Gény, L., Spring, J.-L., Destrac, A., et al. (2020). Temperature-based grapevine sugar ripeness modelling for a wide range of *Vitis vinifera* L. cultivars. *Agricultural and Forest Meteorology, 285–286*, 107902. https://doi.org/10.1016/j.agrformet.2020.107902

Parker, A., de Cortázar-Atauri, I. G., Chuine, I., Barbeau, G., Bois, B., Boursiquot, J.-M., et al. (2013). Classification of varieties for their timing of flowering and veraison using a modelling approach. *Agricultural and Forest Meteorology, 180*, 249–264. https://doi.org/10.1016/j.agrformet.2013.06.005

Pastonchi, L., Di Gennaro, S. F., Toscano, P., & Matese, A. (2020). Comparison between satellite and ground data with UAV-based information to analyse vineyard spatio-temporal variability. *OENO One, 54*(4), 919–934. https://doi.org/10.20870/oeno-one.2020.54.4.4028

Pichon, L., Leroux, C., Macombe, C., Taylor, J., & Tisseyre, B. (2019). What relevant information can be identified by experts on unmanned aerial vehicles' visible images for precision viticulture? *Precision Agriculture, 20*, 278–294.

Sozzi, M., Kayad, A., Giora, D., Sartori, L., & Marinello, F. (2019). Cost-effectiveness and performance of optical satellites constellation for precision agriculture. In *Precision Agriculture, 19*, 501–507. Wageningen Academic.

Tomasi, D., Jones, G. V., Giust, M., Lovat, L., & Gaiotti, F. (2011). Grapevine phenology and climate change: Relationships and trends in the Veneto region of Italy for 1964–2009. *American Journal of Enology and Viticulture, 62*, 329–339. https://doi.org/10.5344/ajev.2011.10108

van Leeuwen, C., Destrac-Irvine, A., Dubernet, M., Duchêne, E., Gowdy, M., Marguerit, E., et al. (2019). An update on the impact of climate change in viticulture and potential adaptations. *Agronomy, 9*, 514. https://doi.org/10.3390/agronomy9090514

Winkler, A. J., Cook, J. A., Kliewer, W. M., & Lider, L. A. (1974). *General viticulture*. University of California Press.