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Article

Characterization of Two Vineyards in Mexico Based on Sentinel-2 and Meteorological Data

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Abstract: In Mexico viticulture represents the second source of employment in the agricultural area after the fruit and vegetable sector. In developed countries, remote sensing is widely used for vineyard monitoring, however, this tool is barely used in developing countries of Iberoamerica. In this research, our overall objective is to characterize two vineyards in the state of Queretaro (Mexico) using Sentinel-2 and meteorological data, specifically spectral and thermal indices. Results showed that spectral indices obtained from Sentinel-2 bands have characterized adequately the phenological evolution of the different varieties of the vineyards. The Modified Soil-Adjusted Vegetation Index (MSAVI) was adequately used to discriminate the first stages of vineyards, while the Normalized Difference Vegetation Index (NDVI) was useful to monitor vineyards during the rest stages of vineyards. Thermal indices have shown that the best grape varieties were those that can adapt to both cooler and warmer temperatures, have a reasonable ripening period, and can produce wines with balanced acidity and flavors. In conclusion, the combination of meteorological (including thermal indices) and remote sensing data (NDVI and MSAVI) provide information for choosing the suitable grape variety for this region.

Keywords: NDVI; MSAVI; thermal indices; vineyard's phenology; grape varieties

1. Introduction

Vineyards occupied 7.3 million of hectares worldwide in 2021 according to the International Organization of Vine and Wine [1]. Although viticulture is concentrated around Mediterranean countries [1,2], there are other regions in the world in which viticulture shows importance, such as Mexico, where vineyards occupy 36000 ha and represent the second source of employment in the agricultural sector after the fruit and vegetable sector [3]. Specifically, in the state of Queretaro, viticulture is clearly in expansion and numerous wineries are being consolidated in the last decade [4]. Grapevine health and productivity are influenced by various factors, such as topography, climate, soil characteristics, and pests and diseases. These factors create spatial and temporal variations within vineyards, leading to differences in grape quality and yield. This can result, in some circumstances, in lower-quality wine and reduced volume. The wine industry needs to consider these variabilities in quality and yield to produce a higher-value product.

Remote sensing allows for continuous monitoring at different spatial and temporal scales of crops over large areas [5,6], providing valuable information on their health, growth, and overall condition, also can be used to estimate crop yields by analysing vegetation indices and other indicators of plant health. Remote sensing information is usually summarized as spectral indices which are related with physiological processes such as photosynthesis [7,8]. The Normalized Difference Vegetation Index (NDVI) [9] is the most used vegetation index that quantifies the density and health of vegetation by analysing the difference between the near-infrared (NIR) and red (Red) bands. Other ratio spectral indices are the Enhanced Vegetation Index (EVI) [10] and the Modified

Soil-Adjusted Vegetation Index (MSAVI) [11] which it is a modification of the Soil-Adjusted Vegetation Index (SAVI) [12] that aims to reduce the sensitivity of the index to soil background effects. The MSAVI considers the vegetation and soil reflectance properties and provides a more accurate measure of vegetation density and health than other indices during the first vegetative stages. The study of vineyards through spectral indices have been widely used in the last decades [13–15]. Low spatial resolution sensors, such as MODIS (Moderate Resolution Imaging Spectroradiometer), have been used to assess vineyards management by estimating growing season length [16] or monitoring grapevine requirements [17]. The results of MODIS data analyses have contributed to our understanding of the Earth system and informed policy and management decisions [10,18]. Higher-resolution sensors present a new opportunity for monitoring crops, such as vineyards. In this sense, Sentinel-2 has combined higher resolution images (10 m) with a higher temporal resolution (5 days). There are recent and multiple applications with spectral Sentinel-2 indices in vineyards, such as quantifying the impact of heatwaves [19], the damage of frosts [20], estimating actual evapotranspiration [21] and characterizing vineyards in different regions. In this sense, Devaux et al. [22] showed the ability to monitor vine growth with Sentinel-2 images in a southern region of France. Besides, Stolarski et al. [23] used Sentinel-2 images and unmanned aerial vehicles for assessing vigour management and to detect vineyard variability in two vineyards of Portugal.

Remote sensing for vineyard monitoring has been widely used in developed countries, however, this tool is barely used in developing countries of Iberoamerica [24]. It is essential that these regions can access these new tools for satisfying the sustainable development goals (SDG) of the United Nations (web SDG). Goal number 2 (Zero hunger) implies the use of technology for crop management for achieving this goal. In addition, goal number 9 highlights “that technological progress is a key factor to finding lasting solutions to both economic and environmental challenges” [25].

On the other hand, thermal indices, based on different temperature data, are widely used in vineyards to assess the suitability of climate conditions for grapevine growth and development [26–28]. Several thermal indices have been developed specifically for viticulture, including the Winkler index [29,30], the Huglin index [31], the Growing Season Temperature [26,32], and the Cold Index [33]. The Winkler index estimates the grapevine's heat summation during the growing season, which is the sum of the mean daily temperature above 10°C, while the Huglin index estimates the potential grape yield based on growing degree days (GDD) above 10°C during the growing season. The Growing Season Temperature (GST) index is another important index that considers both temperature and the timing of key growth stages to provide a measure of the climate suitability for specific grapevine varieties. Finally, the Cold Index (CI) considers the number of frost-free days and the sum of GDD to estimate the suitability of a region for grapevine growth. Thermal indices provide complementary information and allow us to compare our results in Mexico with those from different parts of the world. Altogether, classifying vineyards with thermal indices can provide valuable insights for vineyard management and grape production [34,35].

In this paper, our overall objective is to characterize two vineyards in the state of Queretaro (Mexico) using Sentinel-2 and meteorological data with the following specific objectives:

- To assess the meteorological dynamics of the two vineyards.
- To assess the phenology of the two vineyards through spectral vegetation indices (NDVI and MSAVI).
- To obtain thermal indices of the two vineyards and compare them with other wine producing regions.
- To relate meteorological information with spectral indices.

2. Materials and Methods

2.1. Study Area

Queretaro is a state in Mexico located between the parallels 21.7° N and 20.0° N, and specifically, the vineyards are located between 20.4° N and 20.8° N. The vineyards are completely outside of the "wine belt", which is between latitudes 30° and 50° (Figure 1), in both hemispheres. The climate of

the studied vineyards is arid, steppe, cold, Bsk according the Köppen-Geiger climate classification [36]. However, the large altitude, close to 2000 m above sea level (asl), produces mild winters that allow the vine to rest. Two separate representative vineyards were selected in Queretaro State, one in the municipality of El Marques (22.7 ha), Puerta del Lobo, henceforth PL, and other in the municipality of Colon (23.8 ha), Vinaltura, henceforth VA (Figure 2). The predominant soil (more than 60%) in both vineyards is vertisol, with areas of leptosols and phaeozems in PL, and the texture is clay-loam. Vertisols are very heavy clay soils with a high proportion of swelling clays.

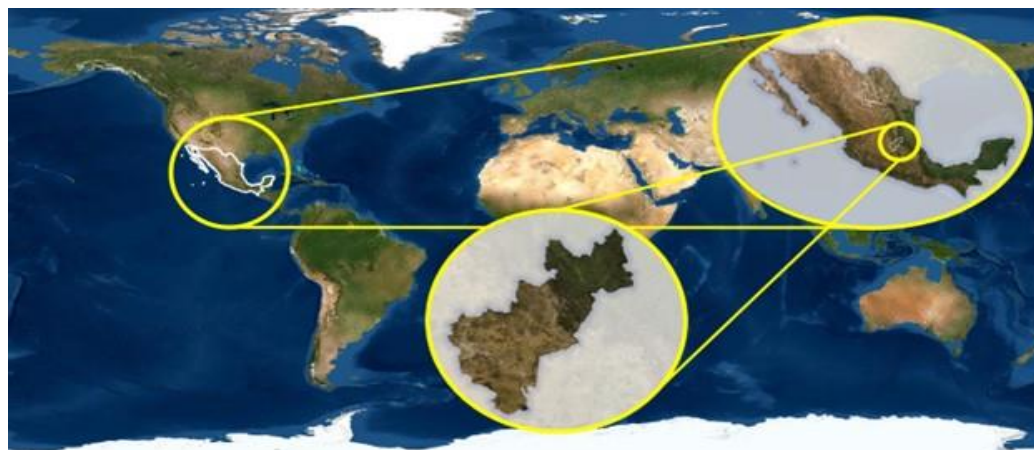


Figure 1. Queretaro in the world. Images taken from ESRI satellite for QGIS.

The physical characteristics of vineyards play a crucial role in determining the quality and yield of grapes. Table 1 summarizes the key physical characteristics of both vineyards, revealing striking similarities in their extension, precipitation, slope, temperature, and other factors. These similarities are not surprising given that vineyards require specific climatic conditions to flourish, and both are located relatively close (~24 km).

Table 1. Characteristics of both vineyards: Puerta del Lobo (PL) and Vinaltura (VA).

Vineyard	Area (Ha)	Average Temperature (°C)	Annual Precipitation (mm)	Primary Soil	Secondary Soil	Altitude (masl)	Mean Slope
PL	22.7	18.4	216	Vertisol/Leptosol	Phaeozems	1950	3.8°
VA	23.8	17.4	211	Vertisol	Vertisol	1967	2.4°

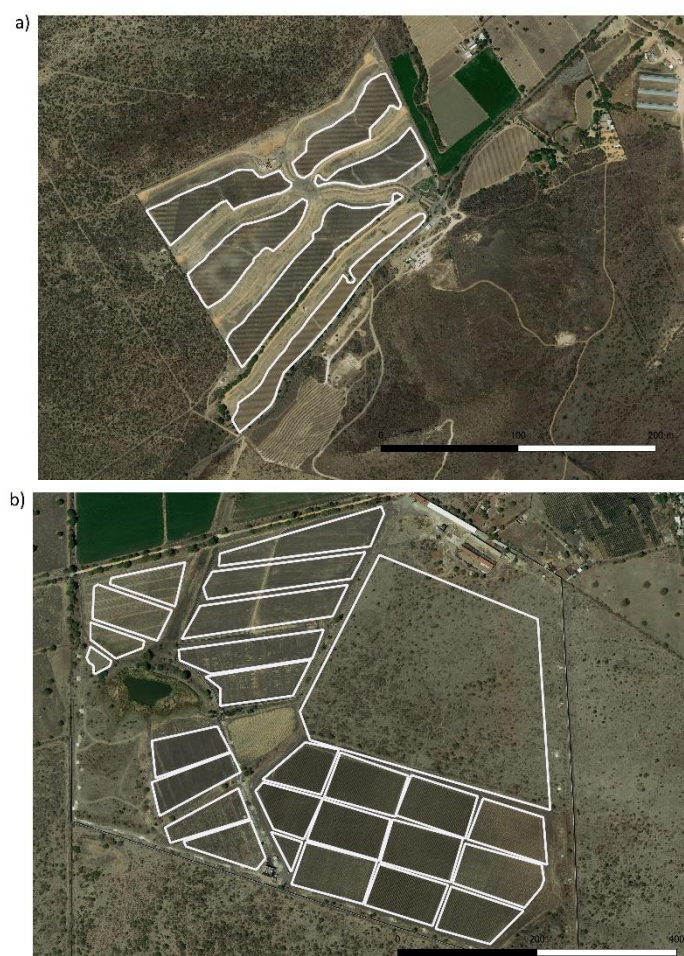


Figure 2. Images from Google Satellite of the studied vineyards: (a) Puerta del Lobo (PL) and (b) Vinaltura (VA).

2.2. Remote Sensing and Reanalysis Data

The images to calculate spectral or vegetation indices (NDVI and MSAVI) are from Sentinel-2, downloaded through Google Earth Engine. The Sentinel-2 mission is part of the Copernicus program, which has been developed and it is operated by the European Space Agency (ESA, [37]). The mission relies on a constellation of two identical satellites that provides images with a high spatial (10 m, 20 m and 60 m) and temporal resolution (5 days).

In this research, Level-2A Bottom-Of-Atmosphere (BOA) images of 10 m were used, that means, these images are already atmospheric and topographically corrected from the Top-Of-Atmosphere (TOA) Level-1C orthoimage products.

Apart from Sentinel-2, images from the Shuttle Radar Topography Mission (SRTM, [38]) were used to calculate the altitude and slope/inclination of the vineyards. Temperatures to calculate the Thermal indices were obtained from ERA-5 Land a reanalysis dataset (spatial resolution \approx 11 km) produced by Copernicus Climate Data Store [39] and DAYMET-V4 (spatial resolution \approx 1 km) [40]. The Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) was used for calculating precipitation (spatial resolution \approx 5.5 km) when there was no data observed with the meteorological stations [41].

2.3. Meteorological Data from AWS (Automatic weather stations)

Meteorological information obtained by the Davis Vantage Pro 2 station is of great importance to vineyards. The station is able of monitoring the meteorological conditions of vineyards, including temperature, relative humidity, precipitation, wind, and solar radiation. These meteorological variables affect the growth and development of grapes, and therefore, play a crucial role in the quality

and yield of the final wine product. For instance, temperature and humidity influence the ripening process of grapes, while wind and precipitation can damage grapevines and affect the yield.

2.4. Methods

Biweekly Sentinel-2 MSI Level-2A composite images, from January 2022 to December 2022, were used, with a maximum cloud cover of 5% in each tile, which in all cases resulted in cloud-free images for the studied area, except on second half of August and first half of September, when cloudiness was much higher in these areas, and we used 50% maximum coverage to better cancel cloud or clouds shadows by calculating the median image).

2.4.1. Spectral Indices

2.4.1.1. Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) [9] ranges from -1 to 1 (Equation 1), with higher values indicating more dense and healthy vegetation. Table 2 shows the interpretation of the values [42].

NDVI is a useful tool for vineyards to monitor vegetation health and vigour. NDVI values can be used to estimate the amount of photosynthetically active biomass in the vineyard, which is a critical factor in grapevine growth and productivity. By monitoring NDVI values over time, vineyard managers can track changes in vineyard health and identify areas that may require additional irrigation or nutrient management. The NDVI can also be used to map the vineyard and identify areas of stress or variation in growth, which can be used to make informed decisions about planting, pruning, and harvesting. In short, the NDVI is a valuable tool for vineyard management, allowing for efficient and effective monitoring of vineyard health and productivity.

For Sentinel-2, this index is defined as Equation 1:

$$NDVI = \frac{NIR + Red}{NIR - Red} = \frac{B8 - B4}{B8 + B4} \quad Eq. (1)$$

Where B8 is the NIR band and B4 is the Red band.

Table 2. Range values for NDVI and interpretation.

Value	Interpretation
< 0.1	Bare soil, water or clouds
0.1 – 0.2	Almost absent canopy cover
0.2 – 0.3	Very low canopy cover
0.3 – 0.4	Low canopy cover with low vigour or very low canopy cover with high vigour
0.4 – 0.5	Mid-low canopy cover with low vigour or low canopy cover with high vigour
0.5 – 0.6	Average canopy cover with low vigour or mid-low canopy cover with high vigour
0.6 – 0.7	Mid-high canopy cover with low vigour or average canopy cover with high vigour
0.7 – 0.8	High canopy cover with high vigour
0.8 – 0.9	Very high canopy cover with very high vigour
0.9 – 1.0	Total canopy cover with very high vigour

2.4.1.2. Modified soil adjusted vegetation index (MSAVI)

The Modified Soil-Adjusted Vegetation Index (MSAVI) [11] (Equation 2). considers the vegetation and soil reflectance properties and provides a more accurate measure of vegetation density and health than other indices (Table 3, [42]). It is commonly used in remote sensing applications to monitor vegetation growth, drought stress, and other environmental changes during seed germination and leaf development stages. The MSAVI has been shown to be effective in a variety of vegetation types, including forests, croplands, and grasslands. In general, the MSAVI is a valuable tool for assessing vegetation health and monitoring changes in vegetation density over time.

For Sentinel-2, this index is defined as:

$$MSAVI = \frac{2NIR + 1 - \sqrt{(2NIR + 1)^2 - 8(NIR - Red)}}{2}$$

$$= \frac{2B8 + 1 - \sqrt{(2B8 + 1)^2 - 8(B8 - B4)}}{2} \quad Eq. (2)$$

Table 3. Range values for MSAVI and interpretation.

Value	Interpretation
-1.0 – 0.2	Bare soil
0.2 – 0.4	Seed germination stage
0.4 – 0.6	Leaf development stage
>0.6	Vegetation is dense enough to cover the soil, use NDVI

2.4.2. Thermal Indices

Thermal indices were calculated with data taken every 30 minutes from the weather stations for the year 2022-These results were compared when it was possible from catalogue images of ERA5-Land (Copernicus Climate Data Store, [39]) and from NASA DAYMET catalogue [40]. In addition, due to the climate variability of the area, the different average climate indices for the period 2000-2022 [43] were compared with our results.

2.4.2.1. Winkler Index (WI)

The Winkler Index (WI), also referred to as the Winkler Scale or Winkler Regions, first proposed by Amerine and Winkler [29] and later modified by Winkler [30], is a method of categorizing wine-growing regions based on the accumulation of heat or growing degree-days (Equation 3). The technique divides geographical areas into five climate regions, labelled as Regions I to V, based on the temperature that is converted to growing degree-days.

$$WI = \sum_{\text{April 1}}^{\text{October 31}} (T_{\text{mean}} - 10^{\circ}\text{C}) \quad Eq. (3)$$

This index determines the suitability of crop growth in different climates. Region I (cold) produces table wines, light-moderate and good balance, only early ripening varieties achieve high quality; Region II (temperate) early and mid-season table wine varieties will produce good quality wines; Region III (temperate-warm) dry and sweet table wines, light dessert wines, favourable for high production of standard to good quality table wines; Region IV (warm) is favourable for high production, but acceptable table wine quality at best and Region V (very warm) is typically only suitable for extremely high production, fair quality table wine or table grape varieties destined for early season consumption.

Examples of Region I are Champagne and Burgundy (France), Rhine Valley (Germany) and Ribera del Duero (Spain). For Region II are Piedmont (Italy), Anjou (France) or Rioja (Spain). Region III is well represented by Rueda and Priorat (Spain), Sonoma Valley (California), Bordeaux (France) or Chianti and Toscana (Italy). In Region IV we have Napa Valley (California), Tuscany (Italy) or Reus (Spain). Finally, examples of Region V are Madeira (Portugal), Patras (Greece) and Jerez (Spain).

2.4.2.2. Huglin Index (HI)

The Huglin Heat Sum Index (HI) is a bioclimatic heat index developed by Huglin [31] for vineyards. It calculates the temperature sum over a threshold of 10°C, by summing the average daily and maximum temperatures for all days from the beginning of April to the end of September (Equation 4). The calculated total is slightly modified based on the latitude of the area (factor K). The HI is used to determine the suitability of an area for cultivating different grape varieties over the long term, as each variety requires a specific amount of heat for successful cultivation.

$$HI = K \cdot \left[\sum_{\text{April } 1}^{\text{Sept } 30} \frac{T_{\text{mean}} + T_{\text{max}}}{2} - 10^{\circ}\text{C} \right] \quad \text{Eq. (4)}$$

2.4.2.3. Cold Nights Index (CI)

The Cold Night Index (CI) is a viticultural climate index developed by Tonietto [33] and Tonietto & Carbonneau [34] to estimate the microthermal condition during the grape maturation period. The index utilizes minimum temperatures (Equation 5) as an indicator of the region's potential characteristics related to secondary metabolites such as polyphenols, aromas, and colour in grapes and wines [44].

The Cold Night Index is a variable that considers the average minimum night temperatures during the ripening month, extending beyond the ripening period.

$$CI = \sum_{\text{Sept } 1}^{\text{Sept } 30} \frac{T_{\text{min}}}{30} \quad \text{Eq. (5)}$$

2.4.2.4. Growing Season Temperature

The growing season temperature (GST) index is a metric used in viticulture to assess the suitability of a specific region for wine production [26,32]. It considers the temperature conditions during the growing season (April 1st to 31st October), which is crucial for grape development and ripening (Equation 6).

The index typically involves calculating the sum of average daily temperatures during the growing season, which allows for an estimation of the accumulated heat units or degree-days experienced by the grapevines. This information is important for determining grape phenology, such as bud break, flowering, veraison (colour change of grapes), and harvest time.

The GST index indicates the daily mean temperature between 1 April and 31 October in the northern Hemisphere. This index broadly correlates with the maturity potential of winegrape cultivars.

$$GST = \sum_{\text{April } 1}^{\text{October } 31} \frac{T_{\text{mean}}}{n} \quad \text{Eq. (6)}$$

3. Results

3.1. Meteorological dynamics of the vineyards

Figure 3 shows the evolution of Temperature(°C), Precipitation (mm), Relative Humidity (%) and Dew Point (°C), during the year 2022 in the two vineyards, according to the meteorological stations. As it can be observed, in PL there was no data from January to March.

For both stations, monthly temperature was minimum during January (14°C) then it increased until May reaching a maximum around 21°C. After May, monthly temperature decreased approximately steadily until December when minimum values were reached again.

In this type of climate, the rainy season lasts around 4 months between June and September. Precipitation showed their monthly maximum values in August and their minimum values between December and March.

The evolution of relative humidity and dew point depends strongly on the precipitation and temperature dynamics as well as on the phenology of the vineyards. Both variables showed their minimum in January and then, they increased during the following months with the increase on temperature and especially with the availability of water. Relative humidity reached its maximum in summer due to the high precipitation and the evapotranspiration which was maximum due to the full development of the vineyards, in addition to the water content accumulated in the soil due to precipitation of the preceding months, although temperature was high also in summer which could entail a reduction in relative humidity.

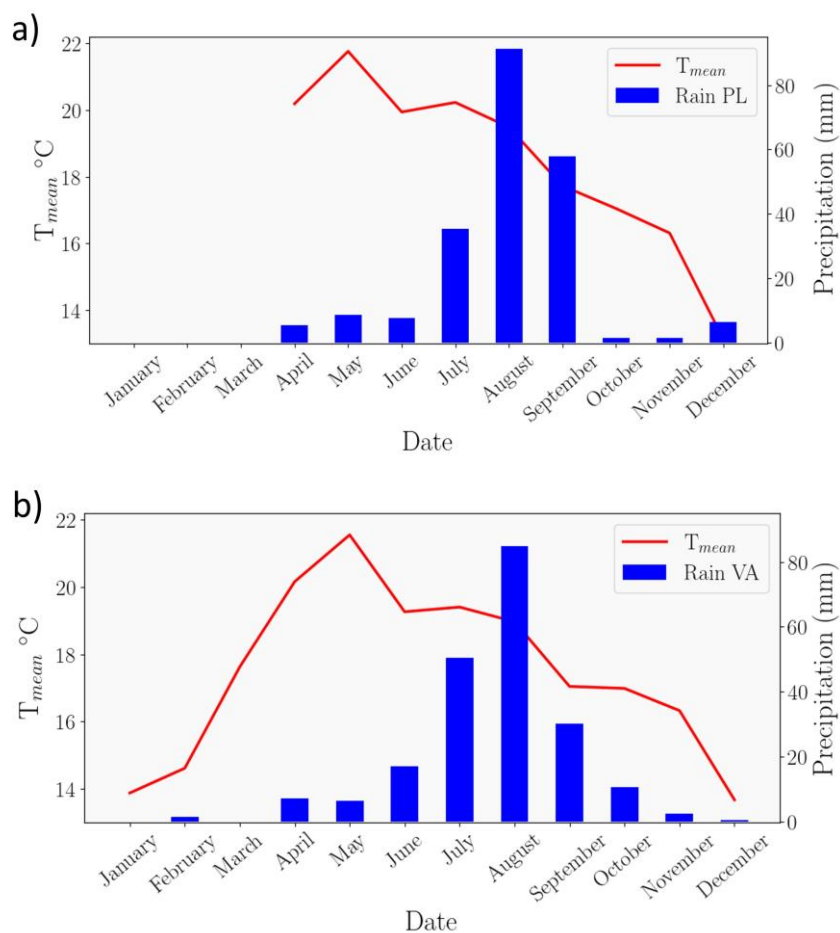
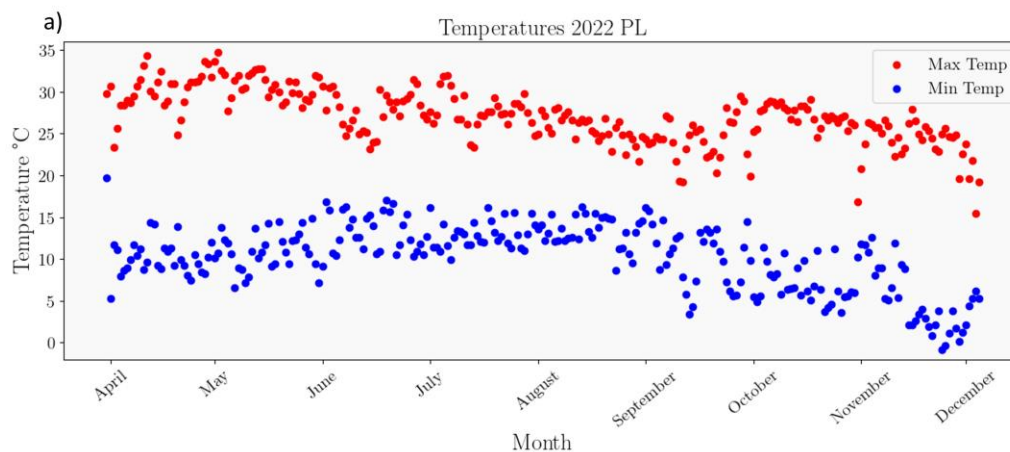


Figure 3. Evolution of the studied meteorological variables in the two vineyards during year 2022: (a) Evolution of Temperature(°C) and Precipitation (mm) in Puerta del Lobo (PL), (b) Evolution of Temperature(°C) and Precipitation (mm) in VA, (c) Evolution of Relative Humidity (%) and Dew Point (°C) in PL and (d) Evolution of Relative Humidity (%) and Dew Point (°C) in Vinaltura (VA).

Figure 4 shows the evolution of daily maximum and minimum temperature of both sites. In PL, maximum temperature ranges between 17 °C in December and 35 °C in May, while minimum temperature ranges between 0 °C in December and 16 °C in June. In VA temperatures are slightly lower ranging maximum temperature between 11°C in December and 34 °C in May and minimum temperature ranging between -1 °C in January and 15 °C in July.



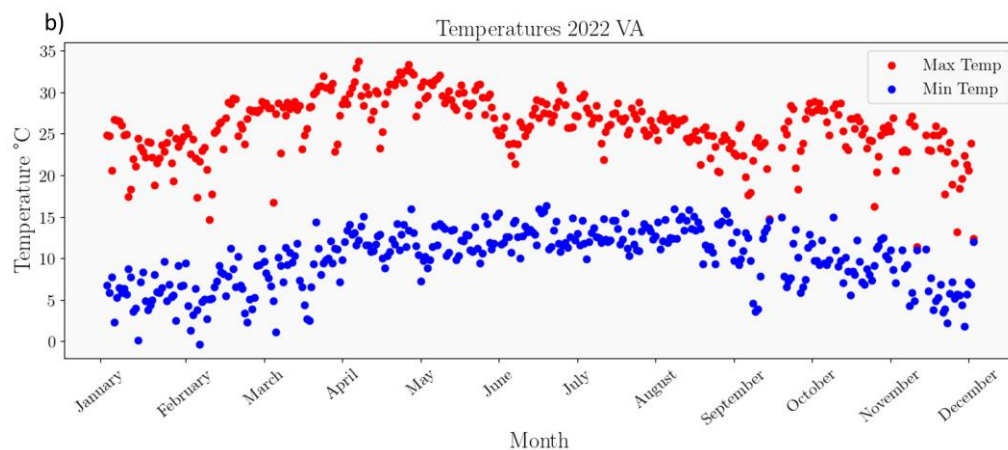
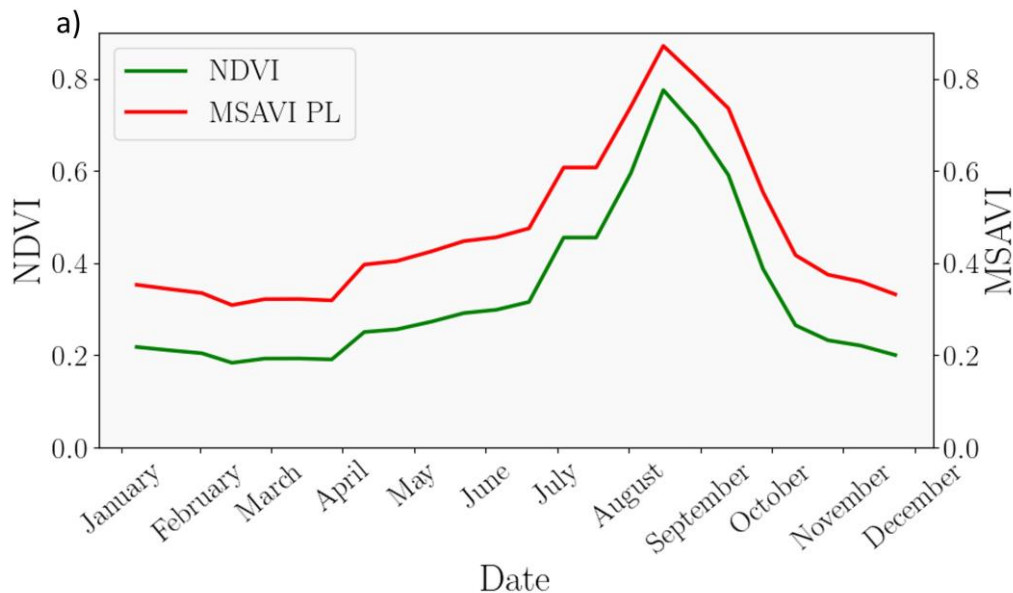


Figure 4. Maxima and Minima daily temperatures in Puerta del Lobo (PL) (a) and in Vinaltura (VA) (b).

3.2. Phenological evolution for the two vineyards through NDVI and MSAVI

Figure 5 shows the dynamics of NDVI and MSAVI of the mean of the plots for the two vineyards during year 2022. As it is observed, the two spectral indices showed a very similar dynamics in the two vineyards. NDVI and MSAVI began to increase on the 15th of April when the bud-break occurred. Then, during May and June the two indices increase during leaf expansion. In VA during May and June values were higher than in PL due to the early development of some vine varieties (see Discussion). After that, spectral indices increase during leaf growth and flowering (except a small decrease in VA at the end of June) until their maximum at mid-September when most grape vine varieties were harvested.



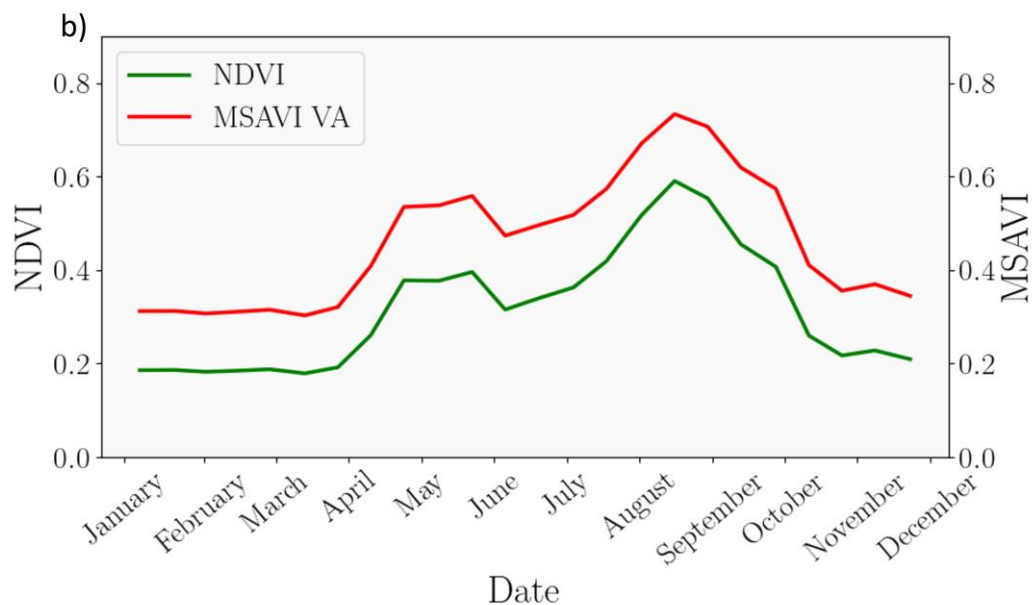


Figure 5. Evolution of the spectral vegetation indices, NDVI and MSAVI, of the mean of the plots for the two vineyards (a) Puerta del Lobo (PL) and (b) Vinaltura (VA).

Figures 6–9 show the biweekly images of the NDVI and MSAVI for the two vineyards during year 2022. From January to June August, MSAVI was observed due to its ability to discriminate better the first phenological stages than NDVI. Then, NDVI was shown from July to December.

These images are consistent with the evolution of the mean plots showed in Figure 5 for both vineyards. In VA, the growing season started in mid-April in the southwest plots and in the northwest plots. During May, all plots showed high MSAVI values and during June, July and August MSAVI continued increasing. In September, NDVI values were the highest in most of the plots. From 2nd mid-October to November, NDVI decreased due to the fall of leaves. In PL, the dynamic was similar than in VA. It must be highlighted that the growing season started a bit later than in VA and finished before in the southern plots than in the northern plots.

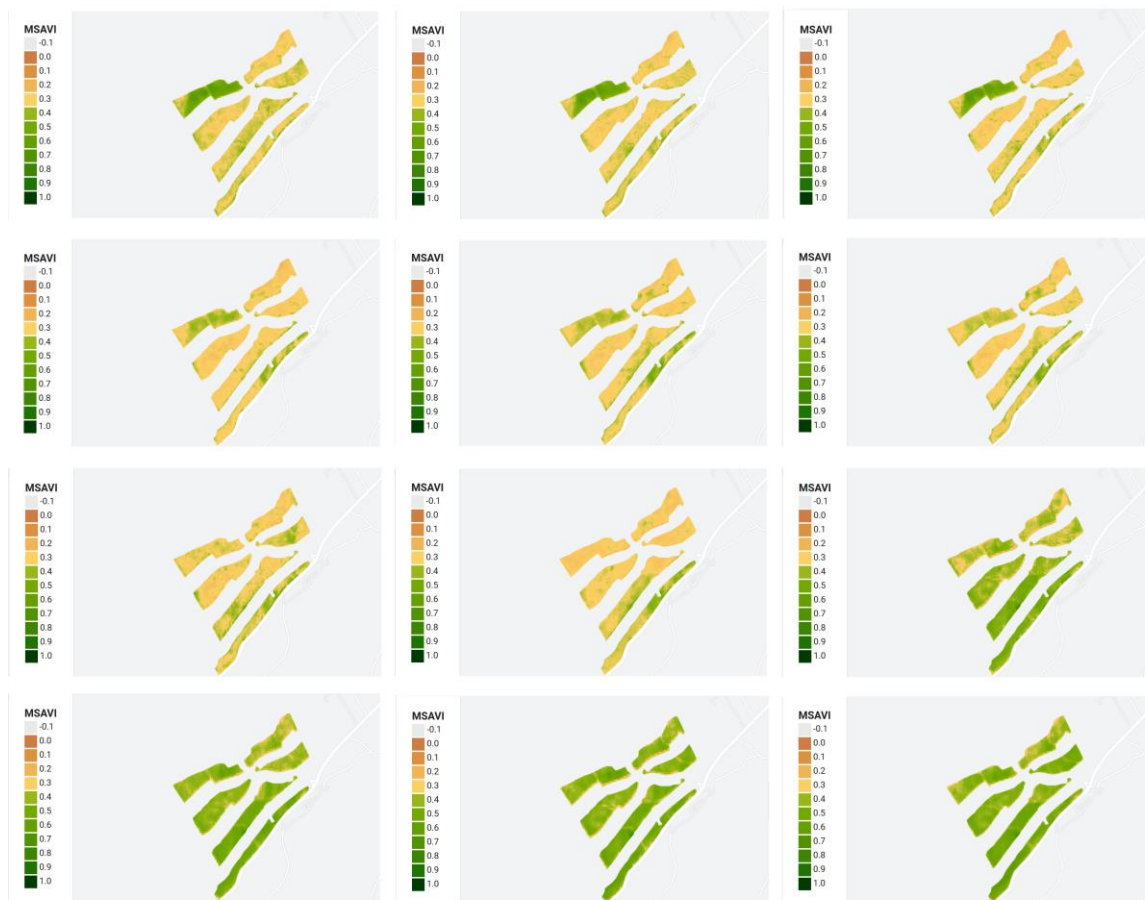


Figure 6. MSAVI maps, every 15 days, from January to June 2022, for Puerta del Lobo (PL).

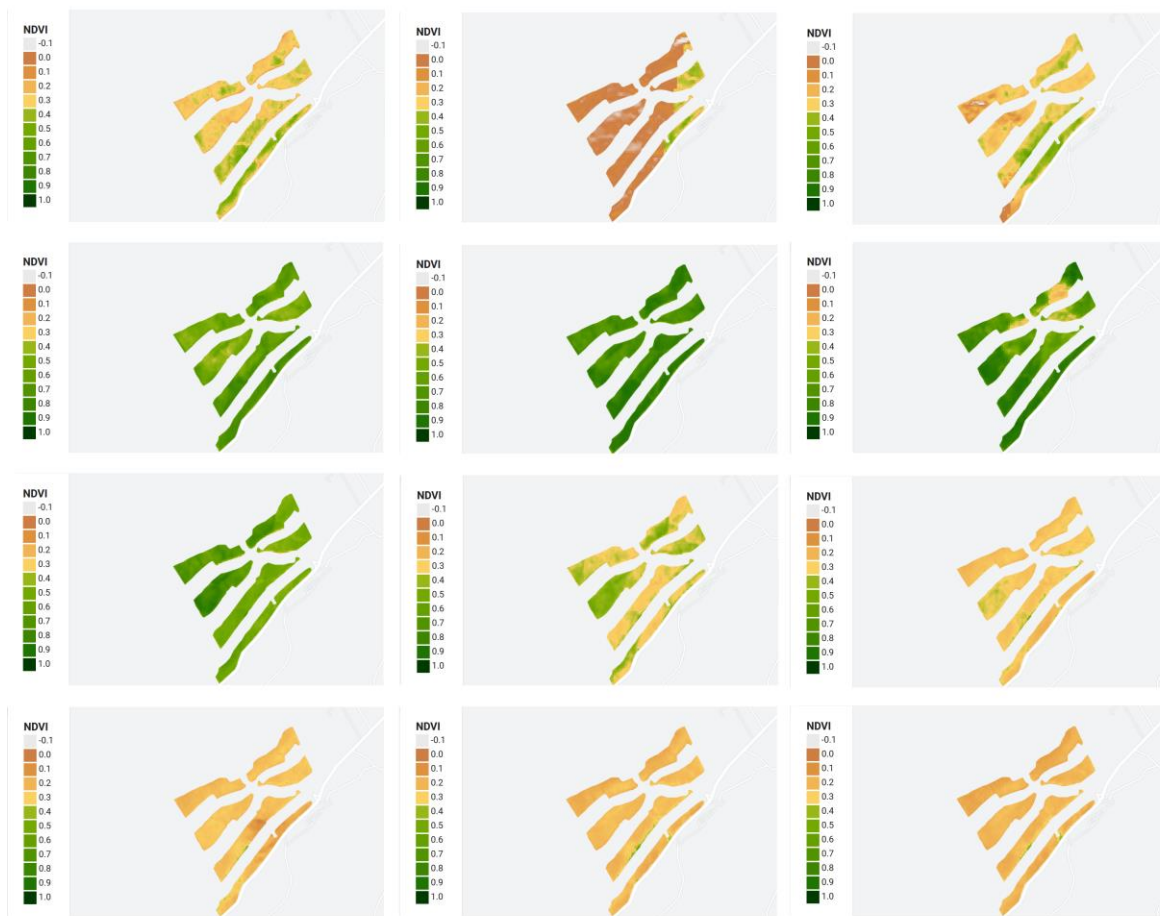


Figure 7. NDVI maps, every 15 days, from July to December 2022, for Puerta del Lobo (PL).

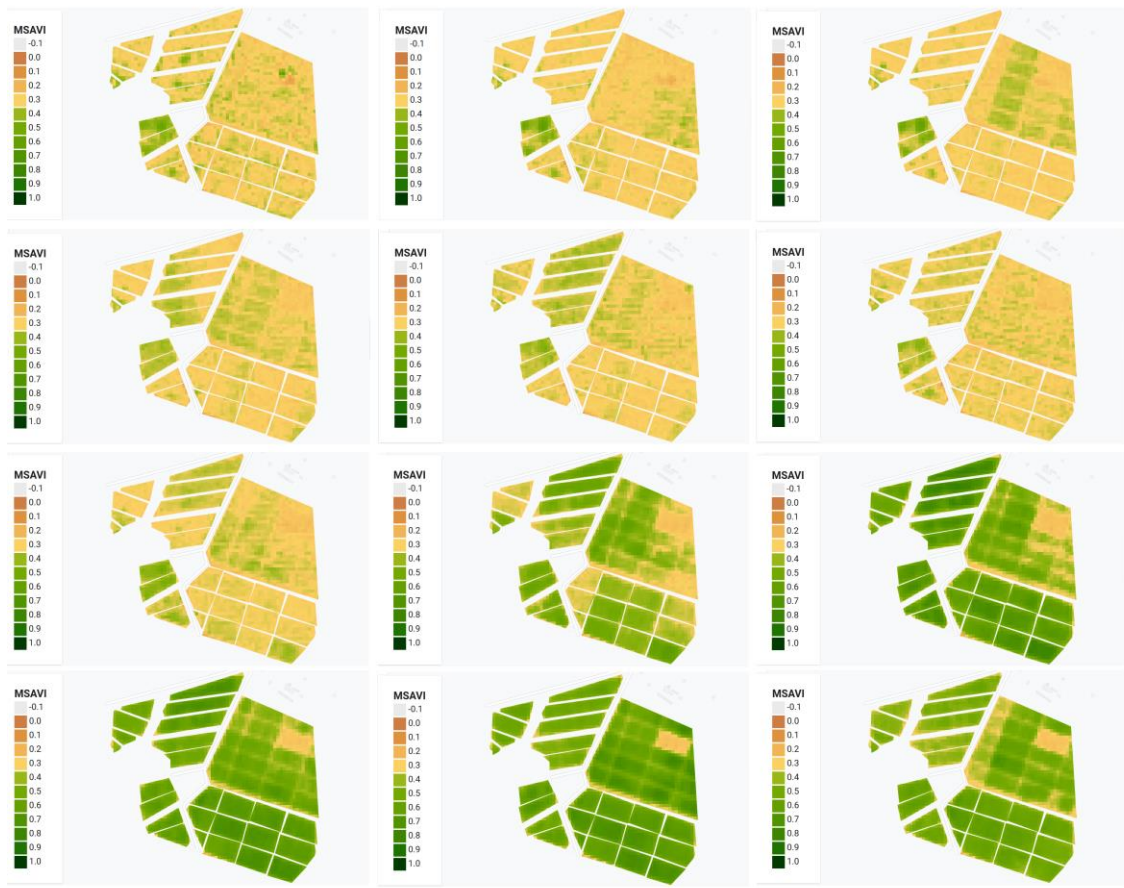


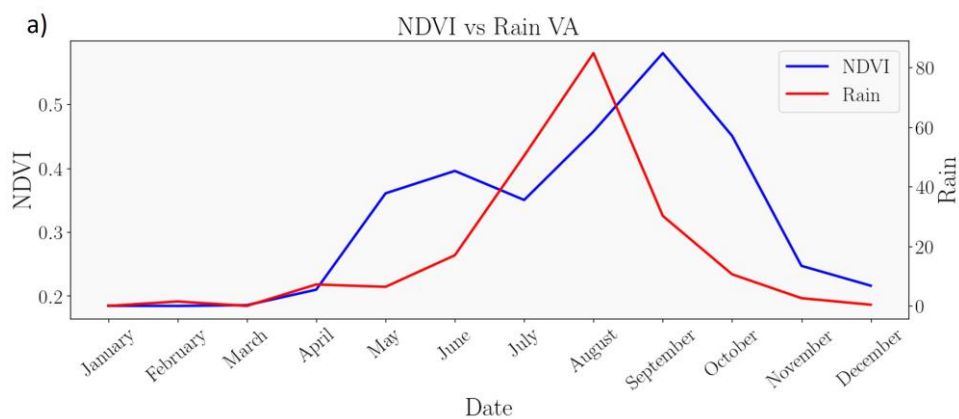
Figure 8. MSAVI maps, every 15 days, from January to June 2022, for Vinaltura (VA).



Figure 9. NDVI maps, every 15 days, from July to December 2022, for Vinaltura (VA).

4.3. Relationship between NDVI and Precipitation

Figure 10 shows the evolution of NDVI and Precipitation obtained from CHIRPS in both sites. A high correlation was found between precipitation and spectral indices (NDVI and MSAVI), although this last not shown, with a 15-day lag for PL ($R^2 = 0.81$), and with a one-month lag for VA ($R^2 = 0.77$).



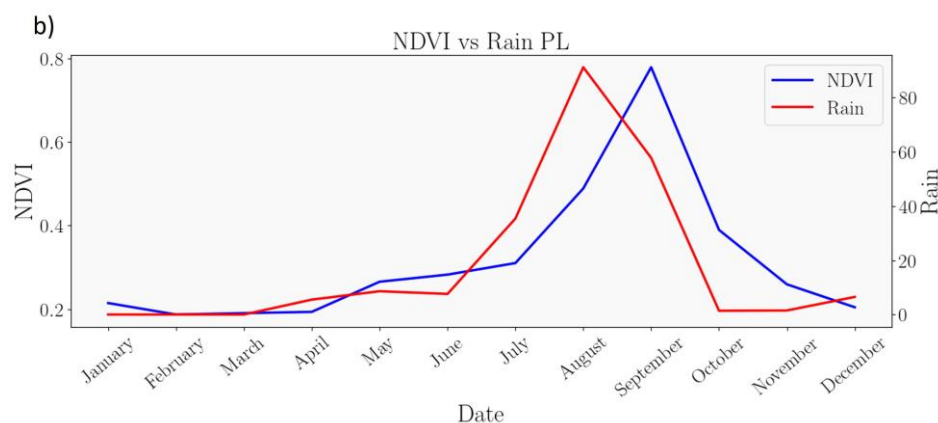


Figure 10. Evolution of NDVI and Precipitation obtained from CHIRPS in Puerta del Lobo (PL) (a) and Vinaltura (VA) (b).

4.4. Classification according to thermal or bioclimatic indices

Table 4 shows the classification of the vineyards according to thermal indices obtained from the observations of the meteorological stations and from the remote sensing data and reanalysis. As it can be observed, the results obtained from both ways were perfectly compatible. In addition, Table 4 shows the classification of the vineyards through thermal indices for the period 2000-2022.

Although, PL was classified as Winkler region IV during 2022, the average for the period 2000-2022 showed that both vineyards were located in Winkler zone III, similar to Rioja (Spain) or Sonoma Valley (California).

According to Huglin's classification, the vineyards were located in a warm zone (2400-2700°C), similar to Toro (Spain) or Napa Valley (California). This region is conducive to growing varieties well-suited to warmer climates, such as Cabernet Sauvignon, Grenache, Tempranillo or Syrah.

Our vineyards are in the CI+1 viticultural climate class according to Tonietto & Carbonneau [34], similar to Bordeaux (France), or Sonoma and Napa Valleys (California), where a maximum threshold of night temperature favourable to ripening will not be exceeded for any variety as seen in Figure 4.

According to the GST index, the results obtained for 2022 from the data from the meteorological stations (19.4°C for PL and 19.1°C for VA) placed both vineyards at the lower limit of the warm zone. However, they were located in the temperate zone taking into account the period 2000-2022. Therefore, they meet the phenological requirements for high- to premium-quality wine production with grapes cultivated in both vineyards.

Table 4. Classification of the vineyards according to thermal indices obtained from the observations of the meteorological stations and from the remote sensing data and the classification of the vineyards through thermal indices for the period 2000-2022.

	Index	PL	VA
Local Meteorological Stations	WI	2020°C Region IV	1911°C Region III
	HI	2541°C Warm	2442°C Warm
	GST	19.4°C Warm	19.1°C Warm
	CI	12.4°C Cold	12.3°C Cold
	WI	2019°C Region IV	1934°C Region III
	HI	2652°C Warm	2654°C Warm

Satellites	GST	19.4°C Warm	19.0°C Warm
	CI	13.1°C Cold	13.2°C Cold
Average 2000-2022	WI	Region III	Region III
	HI	Warm	Warm
	GST	Temperate	Temperate
	CI	Cold	Cold

4. Discussion

4.1. Spectral indices and phenology

The phenological evolution found based on spectral indices (NDVI and MSAVI) is consistent with the field information obtained about the different varieties. In this sense, Bramley et al. [45] used remote sensing data to identify zones of contrasting vineyard performance in a Cabernet Sauvignon vineyard in the Murray Valley region obtaining satisfactory results. More recently, Vélez et al. [46] showed that NDVI provided by Sentinel-2 images could be used for an agronomic classification of three vineyards in Spain and for an evaluation of their wines, and Pádua et al. [47] obtained a vineyard classification using multispectral data in three vineyards located in Portugal and in Italy.

In the present work, using the MSAVI index, we have observed that the first varieties to bud in VA are Chenin Blanc, Sauvignon Blanc, Syrah, and Chardonnay, towards the end of March, with the index response in the first half of April (see reference image). They are followed by Malbec, Marselan, Merlot, and Tempranillo, with the index response observed in the second half of April. The latest varieties, which bud in May, are Cabernet Franc, Riesling, and Gewürztraminer.

With the NDVI index, we observe significant differences within the same varieties. This is because some are studying the effect of early defoliation on yield components, berry maturity, wine composition, and sensory properties of Malbec and Tempranillo vineyards (N-NE plots). The maximum NDVI value is found in September when the harvest of all varieties ends, and from then on, the vines start to turn yellow, entering their period of seasonal rest.

Bud break in PL is slightly later, becoming noticeable in the second half of April, with the varieties Tempranillo, Macabeo, Xarel·Lo, Sauvignon Blanc, and Verdejo. Meanwhile, Syrah and Merlot vigorously bud in the first half of May. Due to high cloudiness between mid-July to mid-August, the NDVI index is not suitable. However, from the second half of August, we observe that the vineyard is at its peak (maximum greenness). From the first half of October, the vine leaves start to turn yellow, with Tempranillo being the last variety to lose its leaves.

4.2. Thermal indices

On a worldwide scale, the typical range of temperatures that is considered suitable for viticulture, or grape cultivation, during the growing season falls between 12–22°C in each hemisphere. This temperature range of 12–22°C generally indicates that grape production is well-suited to mid-latitude regions. However, it's worth noting that there are also many areas in higher elevations within sub-tropical to tropical zones that also fall within this climate range and are viable for winegrape cultivation [48].

In the present day, our understanding of the climate suitability for many well-known grape varieties worldwide reveals that the production of high-quality wine is most realistically achievable within the range of 13°C to 21°C for average Growing Season Temperatures. Towards the upper end of this climatic spectrum, some grape production can still be successful, particularly in regions with

average growing season temperatures exceeding 21°C. However, such areas are primarily associated with the production of fortified wines, table grapes, and raisins (up to 24°C) [49].

Winkler Region III and Huglin 'Warm' are both wine region classification systems that consider the climate and growing conditions of a particular area. In general, grapes that do well in warmer climates with longer growing seasons are better suited for Huglin 'Warm', while grapes that have a shorter ripening period and can tolerate cooler temperatures are more likely to thrive in Winkler Region III. There are some grape varieties that may be suitable for both Winkler Region III and Huglin 'Warm', as Tempranillo, Chardonnay, Pinot Noir, Cabernet Franc, Sauvignon Blanc, Merlot or Syrah.

GST 'temperate' indicates a region that has a moderate temperature during the growing season. In such a region, grapes that require a longer ripening period would be suitable. CI 'cold' indicates a region that experiences cold temperatures at night during the growing season. In such a region, grapes that are more resistant to cold and have a shorter ripening period would be suitable. Here are some grape varieties that may be suitable for GST 'temperate' and CI 'cold' regions: Pinot Noir, Chardonnay, Cabernet Franc, Gewürztraminer, Riesling or Albariño. However, according to GST, a general warming trend was observed (results not shown), and vineyards were shifting from the temperate zone to the warm zone. Further research is needed to consider the effect of climate change and warming trends for future classifications of vineyards.

4.3. Meteorology, dynamics and relations

The climate in the area allows for the cultivation of various grape varieties. Temperature is not limiting for vine growth, although average minimum temperatures rounded 6 °C in December and January. However, these minimum temperatures did not occur in the growing period and frosts were not commonly in our study area. On the other hand, precipitation and soil moisture content are limiting factors for vine growth during the growing period corroborated by the high correlation found between precipitation and spectral indices with a one-month lag. Bonifacio et al. [50] also showed a similar period of response of vines to precipitation. The development of the vines in this region is linked to rainfall rather than irrigation or water stored in the subsurface, as observed in other regions [51]. Thus, droughts could be a special factor to consider for the development of vineyards in our study area as other researchers have found in other regions [19,51].

5. Summary and conclusions

Results showed that spectral indices (MSAVI and NDVI) obtained from Sentinel-2 bands have characterized adequately the phenological evolution of two vineyards in Queretaro (Mexico). While MSAVI was mainly useful to characterize the first phenological stages of vineyards, NDVI was a good index to detect the last phenological stages of vineyards. Differences between varieties were detected using both indices.

In this region, precipitation and soil moisture content are limiting factors for vine growth during the growing period. In fact, due to the lack of precipitation during the first months of the year that could coincide with the bud-break of leaves, irrigation could be the only solution to avoid damages in the vineyards.

On the other hand, thermal indices have shown that the best grape varieties were those that can adapt to both cooler and warmer temperatures, have a reasonable ripening period, and can produce wines with balanced acidity and flavors. Many of the varieties best adapted to the weather conditions are the ones cultivated in these vineyards. However, there are also successfully cultivated varieties that, at first glance, should not be as comfortable with these soil/rain/temperature combinations, such as Tempranillo, Malbec or Sauvignon Blanc. This is due to the wide spectrum found, as some indices classify these vineyards as cool-temperate zones, while others classify them as temperate-warm zones. This successfully expands the range of possibilities when choosing a grape variety.

The combination of meteorological, remote sensing data and thermal indices have managed to characterize the phenological evolution of the different varieties of the vineyards and to provide information for choosing the suitable grape variety for this region.

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References

1. OIV International Organisation of Vine and Wine Available online: <https://www.oiv.int/> (accessed on 16 October 2023).
2. Yu, Y.; Rodrigo-Comino, J. Analyzing Regional Geographic Challenges: The Resilience of Chinese Vineyards to Land Degradation Using a Societal and Biophysical Approach. *Land (Basel)* **2021**, *10*, 227, doi:10.3390/land10020227.
3. Uvayvino.Org Available online: <https://uvayvino.org.mx/> (accessed on 16 October 2023).
4. Cruz-de Aquino, M.A. de la; Martínez-Peniche, R.A.; Becerril-Román, A.E.; Chávaro-Ortiz, Ma. del S. Physical and Chemical Characterization of Red Wines Produced in Querétaro. *Revista fitotecnia mexicana* **2012**, *35*, 61–67.
5. Weiss, M.; Jacob, F.; Duveiller, G. Remote Sensing for Agricultural Applications: A Meta-Review. *Remote Sens Environ* **2020**, *236*, 111402, doi:10.1016/j.rse.2019.111402.
6. Palacios-Orueta, A.; Huesca, M.; Whiting, M.L.; Litago, J.; Khanna, S.; Garcia, M.; Ustin, S.L. Derivation of Phenological Metrics by Function Fitting to Time-Series of Spectral Shape Indexes AS1 and AS2: Mapping Cotton Phenological Stages Using MODIS Time Series. *Remote Sens Environ* **2012**, *126*, 148–159.
7. Cicuéndez, V.; Rodríguez-Rastrero, M.; Huesca, M.; Uribe, C.; Schmid, T.; Inclán, R.; Litago, J.; Sánchez-Girón, V.; Merino-de-Miguel, S.; Palacios-Orueta, A. Assessment of Soil Respiration Patterns in an Irrigated Corn Field Based on Spectral Information Acquired by Field Spectroscopy. *Agric Ecosyst Environ* **2015**, *212*, 158–167.
8. Viña, A.; Gitelson, A.A.; Nguy-Robertson, A.L.; Peng, Y. Comparison of Different Vegetation Indices for the Remote Assessment of Green Leaf Area Index of Crops. *Remote Sens Environ* **2011**, *115*, 3468–3478.
9. Tucker, C.J. Red and Photographic Infrared Linear Combinations for Monitoring Vegetation. *Remote Sens Environ* **1979**, *8*, 127–150.
10. Huete, A.; Didan, K.; Miura, T.; Rodriguez, E.P.; Gao, X.; Ferreira, L.G. Overview of the Radiometric and Biophysical Performance of the MODIS Vegetation Indices. *Remote Sens Environ* **2002**, *83*, 195–213, doi:10.1016/S0034-4257(02)00096-2.
11. Qi, J.; Chehbouni, A.; Huete, A.R.; Kerr, Y.H.; Sorooshian, S. A Modified Soil Adjusted Vegetation Index. *Remote Sens Environ* **1994**, *48*, 119–126, doi:10.1016/0034-4257(94)90134-1.
12. Huete, A.R. A Soil-Adjusted Vegetation Index (SAVI). *Remote Sens Environ* **1988**, *25*, 295–309, doi:10.1016/0034-4257(88)90106-X.
13. Hall, A.; Lamb, D.W.; Holzzapfel, B.; Louis, J. Optical Remote Sensing Applications in Viticulture - a Review. *Aust J Grape Wine Res* **2002**, *8*, 36–47, doi:10.1111/j.1755-0238.2002.tb00209.x.
14. Kazmierski, M.; Glémas, P.; Rousseau, J.; Tisseyre, B. Temporal Stability of Within-Field Patterns of NDVI in Non Irrigated Mediterranean Vineyards. *OENO One* **2011**, *45*, 61, doi:10.20870/oeno-one.2011.45.2.1488.
15. Puig-Sirera, À.; Antichi, D.; Warren Raffa, D.; Rallo, G. Application of Remote Sensing Techniques to Discriminate the Effect of Different Soil Management Treatments over Rainfed Vineyards in Chianti Terroir. *Remote Sens (Basel)* **2021**, *13*, 716, doi:10.3390/rs13040716.
16. Badr, G.; Hoogenboom, G.; Davenport, J.; Smithyman, J. Estimating Growing Season Length Using Vegetation Indices Based on Remote Sensing: A Case Study for Vineyards in Washington State. *Trans ASABE* **2015**, *58*, 551–564, doi:10.13031/trans.58.10845.

17. Zorer, R.; Rocchini, D.; Metz, M.; Delucchi, L.; Zottele, F.; Meggio, F.; Neteler, M. Daily MODIS Land Surface Temperature Data for the Analysis of the Heat Requirements of Grapevine Varieties. *IEEE Transactions on Geoscience and Remote Sensing* **2013**, *51*, 2128–2135, doi:10.1109/TGRS.2012.2226465.
18. Shammi, S.A.; Meng, Q. Use Time Series NDVI and EVI to Develop Dynamic Crop Growth Metrics for Yield Modeling. *Ecol Indic* **2021**, *121*, 107124, doi:10.1016/j.ecolind.2020.107124.
19. Cogato, A.; Pagay, V.; Marinello, F.; Meggio, F.; Grace, P.; Migliorati, M.D.A. Assessing the Feasibility of Using Sentinel-2 Imagery to Quantify the Impact of Heatwaves on Irrigated Vineyards. *Remote Sens (Basel)* **2019**, *11*, doi:10.3390/rs11232869.
20. Cogato, A.; Meggio, F.; Collins, C.; Marinello, F. Medium-Resolution Multispectral Data from Sentinel-2 to Assess the Damage and the Recovery Time of Late Frost on Vineyards. *Remote Sens (Basel)* **2020**, *12*, doi:10.3390/rs12111896.
21. García-gutiérrez, V.; Stöckle, C.; Gil, P.M.; Meza, F.J. Evaluation of Penman–Monteith Model Based on Sentinel-2 Data for the Estimation of Actual Evapotranspiration in Vineyards. *Remote Sens (Basel)* **2021**, *13*, 1–26, doi:10.3390/rs13030478.
22. Devaux, N.; Crestey, T.; Leroux, C.; Tisseyre, B. Potential of Sentinel-2 Satellite Images to Monitor Vine Fields Grown at a Territorial Scale. *OENO One* **2019**, *53*, doi:10.20870/oeno-one.2019.53.1.2293.
23. Stolarski, O.; Fraga, H.; Sousa, J.J.; Pádua, L. Synergistic Use of Sentinel-2 and UAV Multispectral Data to Improve and Optimize Viticulture Management. *Drones* **2022**, *6*, doi:10.3390/drones6110366.
24. Giovos, R.; Tassopoulos, D.; Kalivas, D.; Lougkos, N.; Priovolou, A. Remote Sensing Vegetation Indices in Viticulture: A Critical Review. *Agriculture* **2021**, *11*, 457, doi:10.3390/agriculture11050457.
25. Sustainable Development Goals Available online: <https://sdgs.un.org/goals> (accessed on 16 October 2023).
26. Jones, G.V. Climate Change in the Western United States Grape Growing Regions. *Acta Horti* **2005**, 41–60, doi:10.17660/ActaHorti.2005.689.2.
27. Karoglan, M.; Telišman Prtenjak, M.; Šimon, S.; Osrečak, M.; Anić, M.; Karoglan Kontić, J.; Andabaka, Ž.; Tomaz, I.; Grisogono, B.; Belušić, A.; et al. Classification of Croatian Winegrowing Regions Based on Bioclimatic Indices. In Proceedings of the XII International Terroir Congress; Zaragoza, Spain, June 22 2018; p. 01032.
28. Badr, G.; Hoogenboom, G.; Abouali, M.; Moyer, M.; Keller, M. Analysis of Several Bioclimatic Indices for Viticultural Zoning in the Pacific Northwest. *Clim Res* **2018**, *76*, 203–223, doi:10.3354/cr01532.
29. Amerine, M.; Winkler, A. Composition and Quality of Musts and Wines of California Grapes. *Hilgardia* **1944**, *15*, 493–675.
30. Winkler, A.J. *General Viticulture*; University of California Press: Berkeley, CA, USA, 1974;
31. Huglin, P. *Nouveau Mode d'évaluation Des Possibilités Héliothermiques d'un Milieu Viticole*. *Comptes Rendus de l'Académie d'Agriculture*; Académie d'agriculture de France: Paris, France, 1978;
32. Jones, G.V. Climate and Terroir: Impacts of Climate Variability and Change on Wine. In *Fine wine and terroir – the geoscience perspective*; Macqueen R.W., Meinert L.D., Eds.; Geological Association of Canada: St John's, NL, Canada, 2006; pp. 203–216.
33. Tonietto, J. Les Macroclimats Viticoles Mondiaux et l'influence Du Mésoclimat Sur La Typicité de La Syrah et Du Muscat de Hambourg 447 Dans Le Sud de La France: Méthodologie de Caractérisation., Ecole Nationale Supérieure Agronomique: Montpellier, 1999.
34. Tonietto, J.; Carbonneau, A. A Multicriteria Climatic Classification System for Grape-Growing Regions Worldwide. *Agric For Meteorol* **2004**, *124*, 81–97, doi:10.1016/j.agrformet.2003.06.001.
35. Honorio, F.; García-Martín, A.; Moral, F.J.; Paniagua, L.L.; Rebollo, F.J. Spanish Vineyard Classification According to Bioclimatic Indexes. *Aust J Grape Wine Res* **2018**, *24*, 335–344, doi:10.1111/ajgw.12342.
36. Beck, H.E.; Zimmermann, N.E.; McVicar, T.R.; Vergopolan, N.; Berg, A.; Wood, E.F. Present and Future Köppen-Geiger Climate Classification Maps at 1-Km Resolution. *Sci Data* **2018**, *5*, 180214, doi:10.1038/sdata.2018.214.
37. European Space Agency Available online: www.esa.int (accessed on 16 October 2023).
38. Farr, T.G.; Rosen, P.A.; Caro, E.; Crippen, R.; Duren, R.; Hensley, S.; Kobrick, M.; Paller, M.; Rodriguez, E.; Roth, L.; et al. The Shuttle Radar Topography Mission. *Reviews of Geophysics* **2007**, *45*, RG2004, doi:10.1029/2005RG000183.
39. Muñoz-Sabater, J.; Dutra, E.; Agustí-Panareda, A.; Albergel, C.; Arduini, G.; Balsamo, G.; Boussetta, S.; Choulga, M.; Harrigan, S.; Hersbach, H.; et al. ERA5-Land: A State-of-the-Art Global Reanalysis Dataset for Land Applications. *Earth Syst Sci Data* **2021**, *13*, 4349–4383, doi:10.5194/essd-13-4349-2021.
40. Thornton, M.M.; Shrestha, R.; Wei, Y.; Thornton, P.E.; Kao, S.; Wilson, B.E. Daymet: Daily Surface Weather Data on a 1-Km Grid for North America, Version 4. ORNL DAAC, Oak Ridge, Tennessee, USA. **2020**.

41. Funk, C.; Peterson, P.; Landsfeld, M.; Pedreros, D.; Verdin, J.; Shukla, S.; Husak, G.; Rowland, J.; Harrison, L.; Hoell, A.; et al. The Climate Hazards Infrared Precipitation with Stations—a New Environmental Record for Monitoring Extremes. *Sci Data* **2015**, *2*, 150066, doi:10.1038/sdata.2015.66.
42. Eos Data Analytics <https://eos.com/>.
43. del Río, M.S.; Raventós, L.; Garza, V. Zoning of the Querétaro Wine Region. In Proceedings of the 44th World Congress of Vine and Wine. **2023**, In press.
44. Blanco-Ward, D.; Ribeiro, A.; Barreales, D.; Castro, J.; Verdial, J.; Feliciano, M.; Viceto, C.; Rocha, A.; Carlos, C.; Silveira, C.; et al. Climate Change Potential Effects on Grapevine Bioclimatic Indices: A Case Study for the Portuguese Demarcated Douro Region (Portugal). *BIO Web Conf* **2019**, *12*, doi:10.1051/bioconf/20191201013.
45. Bramley, R.G.V.; Ouzman, J.; Boss, P.K. Variation in Vine Vigour, Grape Yield and Vineyard Soils and Topography as Indicators of Variation in the Chemical Composition of Grapes, Wine and Wine Sensory Attributes. *Aust J Grape Wine Res* **2011**, *17*, 217–229, doi:10.1111/j.1755-0238.2011.00136.x.
46. Vélez, S.; Rubio, J.A.; Andrés, M.I.; Barajas, E. Agronomic Classification between Vineyards ('Verdejo') Using NDVI and Sentinel-2 and Evaluation of Their Wines. *Vitis - Journal of Grapevine Research* **2019**, *58*, 33–38, doi:10.5073/vitis.2019.58.special-issue.33-38.
47. Pádua, L.; Matese, A.; Di Gennaro, S.F.; Morais, R.; Peres, E.; Sousa, J.J. Vineyard Classification Using OBIA on UAV-Based RGB and Multispectral Data: A Case Study in Different Wine Regions. *Comput Electron Agric* **2022**, *196*, 106905, doi:10.1016/j.compag.2022.106905.
48. Jones, G. V.; Reid, R.; Vilks, A. Climate, Grapes, and Wine: Structure and Suitability in a Variable and Changing Climate. In *The Geography of Wine*; Dougherty, P., Ed.; Springer Netherlands: Dordrecht, 2012; pp. 109–133.
49. Jones, G. V.; Alves, F. Impact of Climate Change on Wine Production: A Global Overview and Regional Assessment in the Douro Valley of Portugal. *International Journal of Global Warming* **2012**, *4*, 383, doi:10.1504/IJGW.2012.049448.
50. Bonifacio, R.; Dugdale, G.; Milford, J.R. Sahelian Rangeland Production in Relation to Rainfall Estimates from Meteosat. *Int J Remote Sens* **1993**, *14*, 2695–2711, doi:10.1080/01431169308904302.
51. De la Casa, A.; Ovando, G. Relación Entre La Precipitación e Índices de Vegetación Durante El Comienzo Del Ciclo Anual de Lluvias En La Provincia de Córdoba, Argentina. . *RIA. Revista de Investigaciones Agropecuarias* **2006**, *35*, 67–85.

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