Ecological Indicators 107 (2019) 105646

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Index for the calculation of future wine areas according to climate change application to the protected designation of origin "Sierra de Salamanca" (Spain)

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ARTICLE INFO

Keywords:
Viticultural zoning
Bioclimatic index
Climate change
Projections
Viticulture

ABSTRACT

Climate variables such as temperature, insolation, and precipitation directly affect production as well as the quality of wine. This article simulates the climatic conditions of the Protected Designation of Origin (PDO) Sierra de Salamanca in 2050, in order to delimit the potential areas for the cultivation of Vitis vinifera, and thus, adapt the current vineyards in addition to developing new vineyards in potential areas with suitable varieties. The 2050 climatic conditions were calculated from the study of different bioclimatic indexes including the Growing season suitability (GSS), Growing season precipitation (GSP), Degree-days of Winkler and Amerie (Winkler Index), and Huglin Index (HI), etc. from 1950 to 2018. Based on the trends observed from each index, continuous maps were developed by the interpolation of the inverse of the distance to classify the area bioclimatically. These indices were later extrapolated and analysed in order to biographically map the PDO in the year 2050, dividing the study area into three zones for the cultivation of the vineyard: very favourable, favourable, and appropriate. This study proved that in the next 30 years, temperature will increase and rainfall will decrease in the PDO Sierra de Salamanca, causing a 75% reduction in the very favourable area for the cultivation of the vineyard. The favourable area will be reduced by half while the appropriate area will increase by four times its current size.

1. Introduction

Grapevines are one of the most important crops in the world because they are cultivated in > 40 countries. Although distribution is very extensive, this crop is very sensitive to climate. Climate variables such as temperature, insolation, and precipitation directly and decisively affect plant production and the quality of the wine. These aspects have been previously studied by various authors (Fregoni, 1973), who have highlighted variety as the most important factor for the vintage, followed by climate (Fernandez Seoane, 2006). Several studies have demonstrated significant correlations between monthly mean temperatures and precipitation totals in the growing season with the quantity and quality of wine obtained (Makra et al., 2009). For the vine to begin its growing cycle, the basal temperature must exceed 10 °C with relatively high solar radiation intensities with many hours of exposure. Just as the vine exhibits little/no resistance to low temperatures, prolonged exposure to high temperatures (over 40 °C) can damage the vintage, producing low yields and loss of colour and sweetness of the grapes. Likewise, rainfall is also an important factor. If there is severe dryness during the growing season, this can cause water stress and reduce the productivity of the vineyard; however, if humidity is high, this condition favours the prevalence of pests and diseases, such as downy mildew, which can result in the loss of the entire vintage.

Several studies in different areas have identified the optimal climatic conditions of the Vitis vinifera in different areas. These studies are based on different wine producing regions and were conducted at different scales: worldwide (Tonietto and Carbonneau, 2004), continental (Fraga et al., 2012; Jarvis et al., 2018), country (Esteban-Rodríguez and Climent-López, 2018; Fraga et al., 2014), and regional (Ramos et al., 2015; Silva et al., 2017), at both climatic macroscales and mesoscales. Knowledge of the spatial distribution of a wine-growing region and performing subsequent analyses are essential to understanding the sustainability of wine production (Nicholas et al., 2011).

Several studies have analysed the suitability of wine areas through different indices that vary from air temperature during the growing season (GSS), precipitation during the growing season (GSP), and the sum of the temperatures that exceed the growth base temperature (10 °C) of the wine grapes (Ita y Itwa), etc. Several indexes have been

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https://doi.org/10.1016/j.ecolind.2019.105646
Received 27 January 2019; Received in revised form 1 June 2019; Accepted 12 August 2019
Available online 17 August 2019
1470-160X/

combined in order to study all of the climatic conditions and adjust the needs of the vines (Jones and Alves, 2012). The methodologies applied for the extrapolation of these indexes in the different viticulture zones have also been considered, such as extrapolation by simple regression (Ninyerola et al., 2007), splines (Plouffe et al., 2015), kriging (Honorio et al., 2018), and inverse of distance (Velásquez et al., 2017).

With humans accelerating the rate of climate processes and climate change (Intergovernmental Panel on climate change, 2014), temperatures are increasing, precipitation is diminishing, and interannual variability is disappearing, which produces extreme episodes more frequently. This phenomenon causes changes in the vine phenology (Malheiro et al., 2013), the distribution patterns of pests and diseases (Iltis et al., 2018), and even the appearance of new pests, thereby reducing the productivity and quality of the wine (Fraga et al., 2017).

If these climatic changes are analysed together with the sensitivity of the Vitis vinifera to climatic variations, the zoning of crops varies and they will move to areas where temperatures adapt to their requirements (Silva et al., 2017). In areas that currently have large expanses of Vitis vinifera, production will decrease, giving rise to significant socio-economic losses in the wine sector in many regions. Therefore, the forecast of areas that are no longer optimal and those that will be suitable for cultivation in a few years is very important for this sector to commence planting Vitis vinifera varieties that support the impending climatic conditions (Hidalgo, 1993).

The present study investigates the potential changes in the climatic suitability of the Protected Designation of Origin (PDO) Sierra de Salamanca for the cultivation of the Vitis vinífera vine in the future, taking the variation of climatic conditions caused by climate change into account. In order to determine the suitability of the area, the climate characteristics of the area were studied from the year 1950 to the present, year 2017, and seven bioclimatic indexes were combined, and their tendencies throughout the past years observed. Continuous cartographies of the study area were created for each bioclimatic index from the inverse interpolation of the distance. By studying the climate data trends, the bioclimatic indexes were extrapolated and predicted to a later date of 30 years, year 2050. On the basis of the bioclimatic indexes of the year 2050, the climatic conditions of the study area in the future were simulated, and potential areas were mapped for the cultivation of the vine. Thus, the adaptation measures of the vineyards were adapted in the present and expected to provide the location and optimal varieties for the cultivation of Vitis vinifera in the future in the PDO Sierra de Salamanca.

1.1. Study area and physical environment context

The study area was the Protected Designation of Origin (PDO) Sierra de Salamanca, which is located south of the Province of Salamanca (Fig. 1) and has an area of 482.10 km^2. The soils have limited development due to the steep slopes (Martínez-Graña et al., 2017), and are dominated by Eutric Regosols, Eutric Leptosols, Dystric Regosols, and Dystric Leptosols (Martinez-Graña et al., 2015).

In general, the vineyards have a large area (410 ha) and are mostly located to the north of the study area. Two of the most characteristic varieties include the Rufete and the Tempranillo, which correspond to 46% and 38% of the surface, respectively. This is followed by the Garnacha red (5.5%) and to a lesser extent, white grape varieties consisting of Albillo (3.5%), Palomino-Pedro Ximenez (2.9%), and Verdejo (2%). A total of 18 varieties were identified, but the remaining strains were not present in significant numbers.

2. Material and methods

2.1. Database

Daily meteorological observations were obtained from 11 climatic stations, some belonging to the study area and others close to the limits, in order to create a continuous climate cartography of the PDO Sierra de Salamanca. All the stations belong to the Spanish Meteorological Agency (Aemet) of the Spanish Government. A period of 67 years (1950–2017) was used, twice exceeding what is recommended by the World Meteorological Organization as the optimal duration for a data series with the goal of making predictions predictable. The database provided by Aemet contained the geographical coordinates, elevation, daily precipitations, and the maximum, minimum, and average daily temperatures of each station.

2.2. Bioclimatic indices

Bioclimatic indicators were used to establish the wine potential of the area. The following bioclimatic indexes were used to classify the zones and verify their potential for the vineyard, and thus, enable the characterisation of the bioclimatic winemaking zoning for the PDO Sierra de Salamanca: Growing season suitability (GSS) (Jackson, 2001), Growing season precipitation (GSP) (Blanco-Ward et al., 2007), Thermal Integral of the growth period (Ita), Degree-days of Winkler and Amerie (Winkler Index) (Itwa) (Winkler, 1962), Branas Heliothermic Index (BHI), Branas Hydrothermal Index (HyB) (Branas et al., 1946), and the Huglin Index (HI) (Huglin, 1978). The mathematical equations of these indices and their definitions are listed in the Table 1. These indices are mainly associated with parameters of daily temperatures and rainfall, as well as hours of light, and therefore, they represent the relationships between climate characteristics to a greater extent.

2.3. Calculation of future climate indices

The predictions of future indices were studied using data from the last 67 years, and the trend line of each index was evaluated. Based on these trends, the current year (2017) was calculated and validated with data obtained from the State Meteorological Agency. Once the accuracy of the trend line was verified, the theoretical climatic indices for 2050 were calculated. All of these calculations and analyses were conducted in the SPSS Statistics 25 program.

Where D: days with temperature exceeds 10 °C; P: precipitation; Ta: Average temperature above 10 °C; Tm: average daily temperature; and H: hours of light per day.

2.4. Generation of bioclimatic maps

Once each index was calculated for the different climatic stations, the cartography was determined using inverse distance interpolation. This technique reflects the influence of the observations under the premise that the distances of the known values are located when the values of the unobserved points are estimated (Jo et al., 2018). The basic formula for Inverse Distance Weighting (IDW) is (Eq. (1)):

$$Z_j = \sum_{i=1}^{n} K_{ij} Z_i \tag{1}$$

where Z_j is the estimated value for point j; n is the number of points used in the interpolation; Z_i is the value at the i^{th} point, and K_{ij} is the weight associated with the data i in the calculation of the node j. The weights for K vary between 0 and 1 for each data and their total sum is the unit.

However, since the weight is inversely proportional to the distance, its value decreases as the distance increases. This is expressed by the following equation (Eq. (2)):

$$K_{ij} = \frac{\left(\frac{1}{d_i}\right)^P}{\sum_{i=1}^{N} \left(\frac{1}{d_i}\right)^P} \tag{2}$$

where d_i is the distance between Z_i and Z_j. Weigh the degree of change in height according to distance.

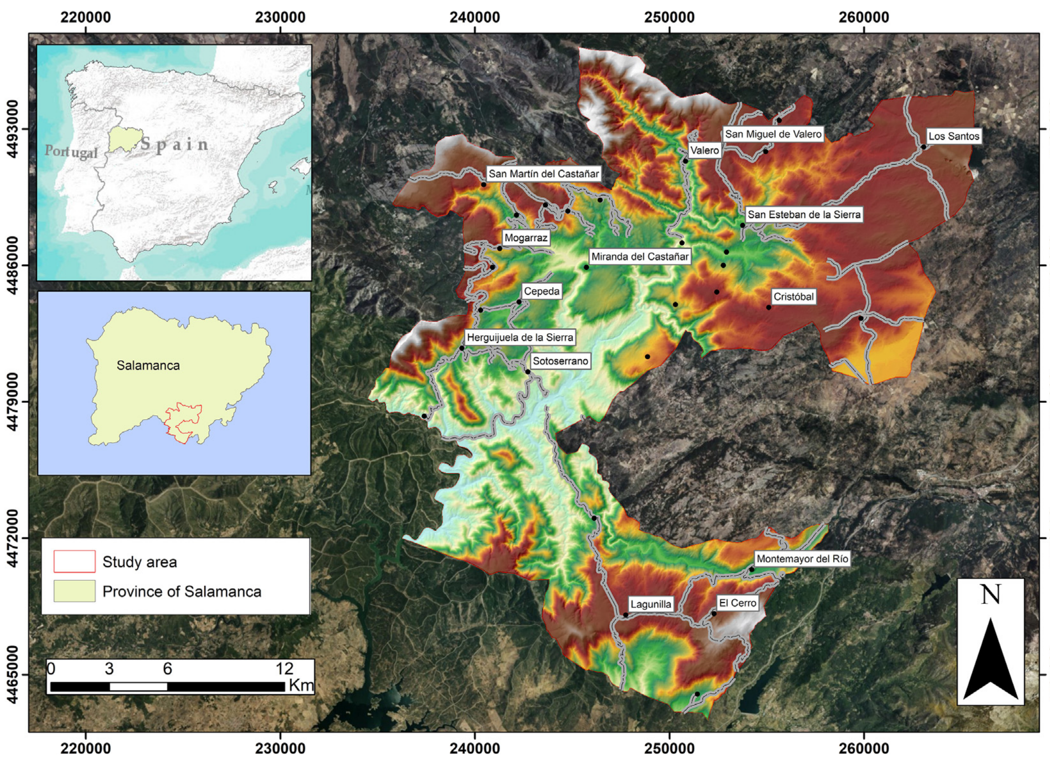

Fig. 1. Location map of the Protected Designation of Origin Sierra de Salamanca (Study area). DEM of Study área is show.

In order to calculate the degree of change between the height and distance of the climatic seasons, the heights were extracted from the Digital Terrain Model (DTM) provided by the National Geographic Institute of Spain with a resolution of 5 × 5 m mesh. The ability to calculate the points information was unavailable, allowed us to create a continuous cartography of the study area. All of these operations were carried out using the ArcGIS 10.5 IDW tool.

2.5. Optimal data of vineyard areas

The optimal climatic conditions of the vineyards in the study area were obtained from the continuous cartography of the quality indexes for the cultivation of vineyards. Bioclimatic index values were extracted for the 1159 vineyards with areas ranging from 0.008 ha to 17.30 ha located at different slopes, altitudes, soil types, and geomorphology, etc. Once the index values for each vineyard were computed with SPSS software Statistics 25, we proceeded to calculate the statistics of each index which enabled the determination of the optimal ranges for vineyard cultivation in the PDO Sierra de Salamanca. For optimal zones (Fig. 2), the range between the mean value minus once the standard deviation was assigned to the mean value plus once the standard deviation, which is the range that 68% of the vineyards had in the most productive years (Value 3). According to the bioclimatic indexes, the

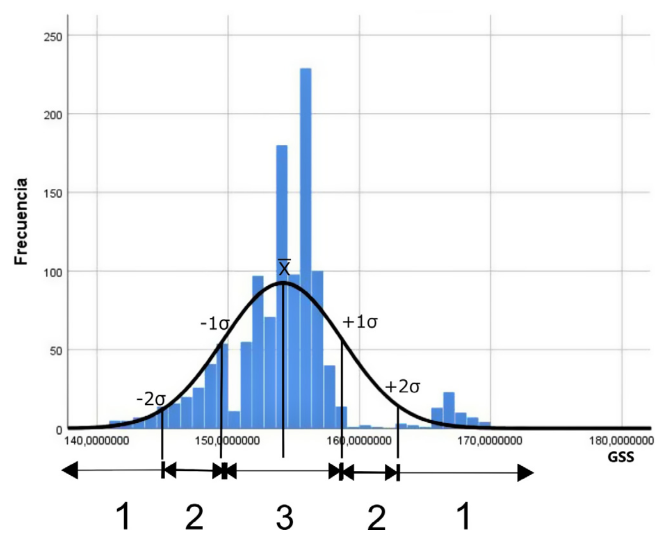

Fig. 2. Normal distribution of the GSS index, and explanation of the subsequent reclassification of the values. Graphic of SPSS software Statistics 25.

Table 1
Bioclimatic index.

bioclimatic indeces	Equation	Unids	Definition
Growing season suitable (GSS)	$\sum D$	days	Number of days per year exceeding 10°
Growing season precipitation (GSP)	$\sum_{April}^{Sept} (P)$	mm	Precipitation recorded during the months of growth.
Thermal Integral of the growth period (Ita)	$\sum Ta$	°C	Physiological maturity indicator of wine
Degrees-days of Winkler and Amerie (Itwa)	$\sum (Ta - 10)$	°C	It is the sum of the effective daily average temperatures
Heliothermic of Branas (HlB)	$\sum [(Tm - 10)x(H)]x10^{-6}$	°C·days	The optimal grape variety according to the weather
Hydrothermal of Branas (HyB)	$\sum Tm_{mensual} * P_{mensual}$	°C·mm	Possibility of attack by downy mildew
Huglin Index (HI)	$\sum_{april}^{sept} [Ta - 10) + (tm - 10)_{*} k/2$	°C	It allows to evaluate the heliothermic possibilities

normal zones would include the intervals that are between the optimum range of the indices and the mean value minus two standard deviations and the mean value plus two standard deviations. This provided a range where 95% of the vineyards are found (Value 2), and the unsuitable areas would be the areas with climatic indices outside of the previous ranges (Value 1).

2.6. Optimal areas for vineyards today and in 2050

Once the optimum conditions of the Sierra de Salamanca DOP vineyards were determined, they were reclassified into three zones (appropriate, favourable, and very favourable). A score of 3 was attributed to the very favourable value, 2 was attributed to the favourable value, and 1 corresponded to the remaining values. This process was repeated for each of the cartographies of the indexes (Fig. 2) for the present time period and prediction for the year 2050.

Once the reclassifications were established, the numerical cartography was added from the ArcGIS 10.5 Raster Calculator tool, and only the production indexes were added:

$$ZV = Rita + RItwa + RBHI + RHyB + RHI \quad (3)$$

where ZV is the vineyard cultivation area; Rita is the reclassification of the Thermal Integral cartography of the growth period; Ritwa is the reclassification of the Grades-days index of Winkler (Itwa); RBHI the reclassification of the cartography of the Branas Heliothermic Index; RHyB is the reclassification of the hydrothermal mapping of Branas, and RHI is the reclassification of the Huglin Index cartography.

Thus, the cartography was obtained by differentiating the three zones: very favourable zone, favourable zone, and appropriate zone. Once the cartographies of the zonal delimitation of both the present and the forecast for the year 2050 were obtained, the cartographies were compared and studied. Observations were made with respect to the loss of very favourable areas for the cultivation of the vine as well as the displacement of these areas.

3. Results and discussion

3.1. Current wine zoning

The bioclimatic indexes were determined using the climatic data and formulas described above (Table 1, Supplementary material). Based on the active Thermal Integral (Ita), it can be inferred indicated that the entire area of the PDO is suitable for the cultivation of the vine. This index exceeded 3100 °C in the study area, and according to Ribereau-gayón and Pyneaud (Hidalgo, 1993), this is an optimum value for obtaining good levels of production. With the Index Integral Thermal Winkler and Amerie (Itwa), three zones were established based on the effective temperatures. In the northeast, the effective temperatures corresponded to Region I, the central zone and of greater extension to Region II, and the southern zone to Region III. For this reason, the varieties of characteristics of dry quality table wines have a high sugar content and little acid, are very well balanced, and are optimal for this area. According to the climate of the PDO, the Tempranillo varieties in red wines and the Pedro Ximenez and Garnacha in white varieties (Fregoni, 1973) would be the most suitable. In addition, the Branas Heliothermic Index indicates that under these conditions the grapes will have a cultivation cycle close to 185 days north of the study area. The number of days will increase to the south, exceeding 185 days per crop cycle in the central and southern areas (Branas et al., 1946).

The PDO Sierra de Salamanca has an average of > 163 days GSS, in which the temperature exceeds 10 °C, allowing the vine to develop during this time. In Fig. 3, it can be observed that the southern area had a longer development period while the northern area had a lower GSS Index. The Huglin Index (HI) correlated significantly with the GSS pattern since it divided the PDO into two very different zones, the northern area that had an HI between 1800 °C and 2100 °C with a temperate climate, while the southern zone had an HI from 2100 °C to 2211 °C with a warm temperate climate.

With respect to rainfall, the GSP Index had a direct relationship to altitude, with the highest points exhibiting more annual rainfall. By relating temperatures to rainfall through the Hydrothermal Index, we can eliminate all possibilities of mildew attacks. For the possibility of a fungal attack to occur, the minimum limit of an area is 1500, and therefore, with a maximum of 986, the study area would be considered null towards the attack of downy mildew.

The climate zoning of the PDO Sierra de Salamanca using Geographic Information Systems (GIS) and inverse interpolation methods of distance have provided accurate results for climate data in high-altitude environments (Velásquez et al., 2017) and created highly precise cartography (Jo et al., 2018). The cartography obtained is comparable with studies carried out for regions with similar characteristics (Fraga et al., 2013) or that are close to the areas, cartographies could be continued in a higher project (Moral et al., 2014). These cartographies would allow us to accurately and determine the conditions for each plot, and thus, compare this information in future studies on the production of the vines and verify how the climate affected production.

3.2. Vineyard zoning in 2050

Climate change in Spain is evident with each passing year, and the impacts are dominated by an increase in temperature and decrease in rainfall which results in long periods of drought and catastrophic events due to flooding (Jones et al., 2005). According to the predictions for 2050, if conditions continue on the current trend in the PDO Sierra de Salamanca, temperatures will increase on average by 1 °C and rainfall will decrease by approximately 100 mm per year. The wine indexes were also affected by these projected impacts and the number of days exceeding 10 °C increased leaving areas that once had 178 days a year with a longer 201 days (Fig. 4), and the sum of rainfall at the monitoring points decreased from 774 to 687. According to the Ita, as temperatures rise, the area would become suitable for the cultivation of the vine. In certain areas, such as the south of the PDO, the area could be overcome since previous studies for optimal crop conditions determined a value of 5000 °C (Hidalgo, 1993). However, the Itwa Thermal Region I would disappear and the different regions would move further north making Thermal Region IV appear to the north of the PDO. Hence, the varieties of grapes to be planted will change since the wines will have a higher acidity which can cause possible risks of losses. All of the harvests would have a culture cycle superior to 185 days which will complicate the grape varieties of 3° time, giving with greater ease the varieties of 4ª time with harvest of means to delays.

This finding was also expressed by the Huglin Index (HI) which showed that the area with a temperate climate would decrease in size, leaving the remainder in the north zone. Most of the cultivation area would have a warm temperate climate, of greater extension, and in areas south of the PDO Sierra de Salamanca, the observed climate would be warm compared to cities such as Jerez and Malaga (South of Spain). The appearance of fungi in the vineyards would be even more unlikely since less rainfall means that the fungi cannot develop; however, the plants could experience water stress due to the lack of water. Similar occurrences take place today in regions of Portugal, and in order to produce wines of similar quality and alcohol concentration, it is necessary to apply irrigation (Fraga et al., 2018), even at the risk of water resource shortages (Martínez-Graña et al., 2014). These anticipated water resource shortages and the prediction that optimum zones will increase in altitude, can be considered for all countries in order to determine ideal vine cultivation sites in the future.

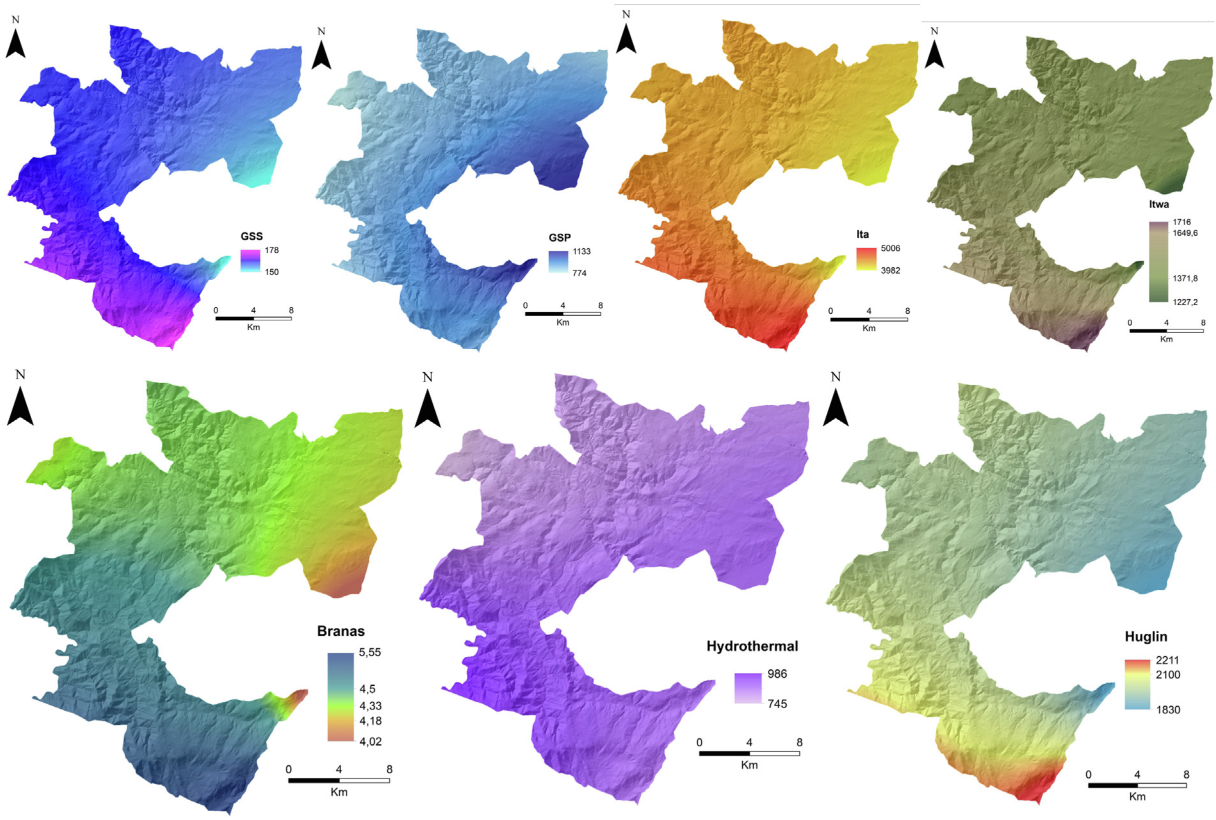

Fig. 3. Cartography of bioclimatic indices of the PDO Sierra de Salamanca at present.

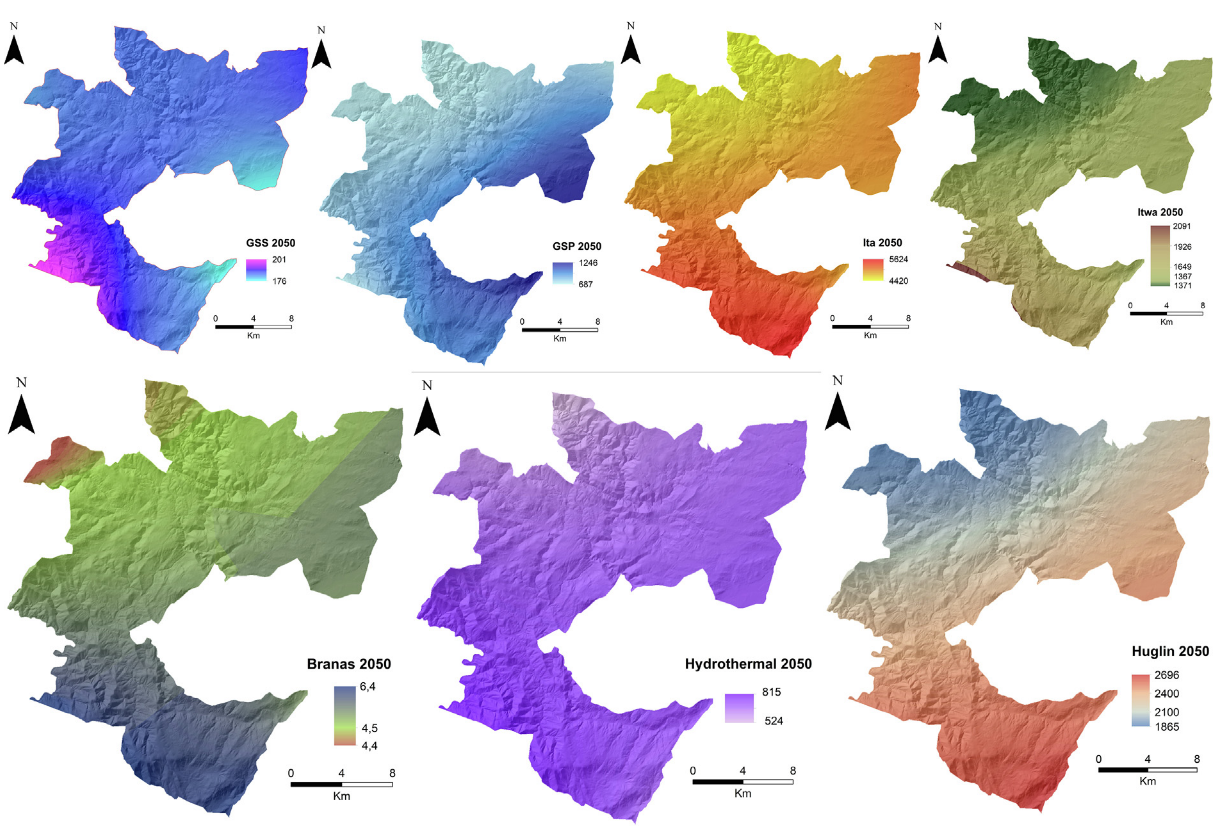

Fig. 4. Cartography of bioclimatic indices of the PDO Sierra de Salamanca at future.

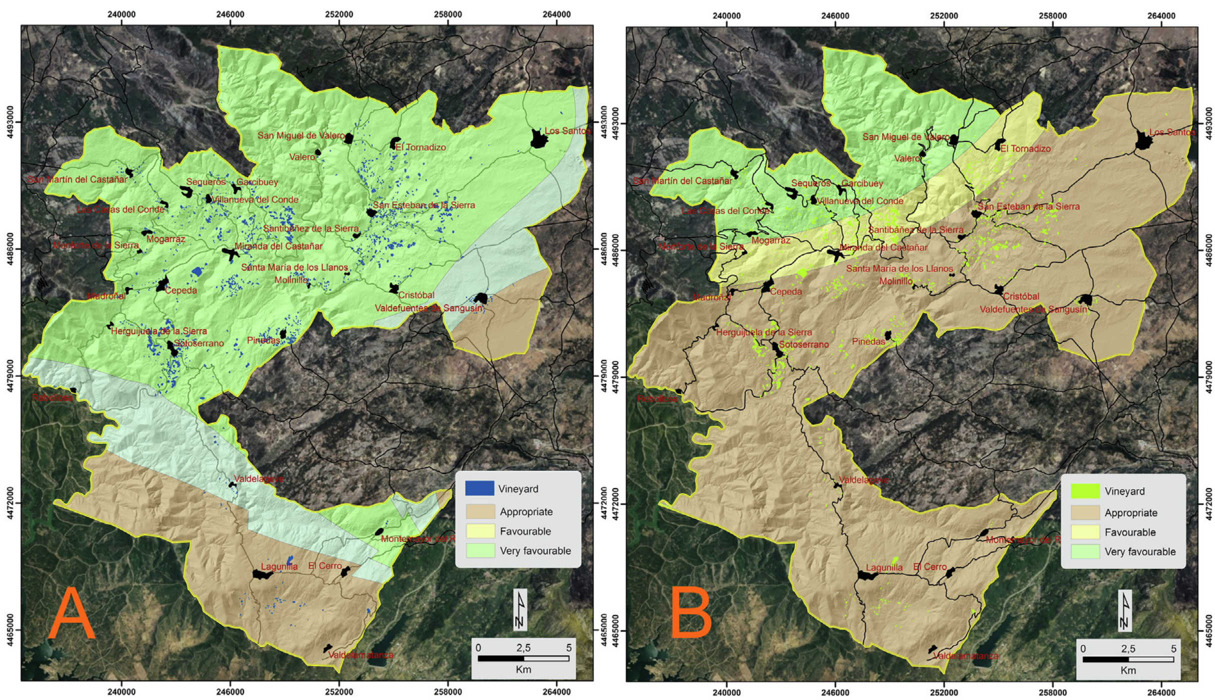

Fig. 5. A) Map of the viticultural zones in the present; B) Theoretical map of the viticultural zones in 2050.

3.3. Optimal areas for growing grapes

Once the different climatic zones of the study area were investigated, the values of the different climatic indices were extracted in years of good production for each vineyard. This indicates the optimal conditions for the cultivation of the vine in the PDO Sierra de Salamanca (Table 1).

The delimitation of the zones, both for the present time and for the year 2050, were classified into the following categories for growing grapes: very favourable, favourable, and appropriate (Fig. 5). The loss of area of the very favourable category was clearly observed. Currently, the area suitable for vineyard cultivation is 32,202 ha; however, in 2050, it is expected to be reduced to 8695 ha, which is an approximate loss of three-quarters of the surface. 70% of the vineyards will be outside this area, and the same applies to the favourable area to a lesser extent. At present, there are 8882 ha in the favourable area category, and in 2050, it is expected that this area will be reduced by half to 4458 ha; however, the appropriate area will increase from 9710 ha to 37,300 ha. The very favourable areas will move towards the northwestern parts of the PDO Sierra de Salamanca. This is because these are higher altitude areas and precipitation is currently in line with the necessary minimum. Within a period of 30 years, they will transform so that temperature and precipitation conditions will be optimal production of quality wines. This is comparable with studies conducted in a mountainous area of the French Mediterranean, which has similar conditions to the PDO Sierra de Salamanca (Chabin et al., 2007). It was found that a 20-year interval of different maturation dates and optimal for the temperatures were equal to that of a at a higher altitude of 200 m. However, approximately 75% of the vineyards will go out of these very favourable zones so that production will be decimated along with the quality of the wines.

4. Conclusion

In a period of 30 years the temperatures in the PDO Sierra de Salamanca will increase and precipitation will decrease, thereby altering the optimal conditions for the vineyards. This study has verified that all of the bioclimatic indices have a tendency to increase (Table 2 Supplementary material), with the exception of the Branas Hydrothermal Index, which indicates a low possibility of the appearance of downy mildew in the vineyards.

Specifically, the Sierra de Salamanca area of the PDO was separated into three subzones depending on the bioclimatic conditions for the cultivation of the vine. These subzones were delimited based on the following indices: Growing season suitability (GSS), Growing season Precipitation (GSP), Thermal Integral of the growth period (Ita), Degree-days of Winkler (Itwa), Branas Heliothermic Index (BHI), Branas Hydrothermal Index (HyB), and the Huglin index (HI), and with ranges according to the maximum production in recent years of the vineyards in this area. Results indicate a reduction of almost 75% of the very favourable areas of the vineyards, 50% of the favourable areas for cultivation, and an increase in almost four times the appropriate zones. The Vitis vinifera will be displaced to the north-west of the PDO Sierra de Salamanca, which are areas of higher altitude and where although

Table 2
Limits of the values of each index for the delimitation of the viticultural zone.

	GSS	GSP	Ita	Itwa	HlB	HyB	HI
Appropriate	> 164	> 1021	> 4571	> 1484	> 4,81	> 902	> 2061
Favourable	164	1021	4571	1484	4,81	902	2061
Very favourable	160	972	4467	1429	4,63	872	2018
	151	873	4258	1318	4,27	813	1931
Favourable	147	823	4154	1263	4,09	783	1888
Appropriate	< 147	< 823	< 4154	< 1263	< 4,09	< 783	< 1888

temperatures rise and rainfall decreases, are still maintained within an acceptable range for the crop (See Table 2).

This implies that approximately 75% of the vineyards that are presently at maximum production will observe a reduction by the year 2050, with consequences such as the irrigation of the vineyards or the cultivation of varieties that better withstand high temperatures and water stress, as well as the production of wines with higher acidity and lower quality. This study confirms the great influence that the climate has on the distribution of vineyards and the impact of increasing temperatures and decreasing rainfall on grape production and the quality of the wines. This study also demonstrates the importance of geographic information systems (GIS) for the future modelling of wine-growing zones in the PDO Sierra de Salamanca, in order to obtain the most precise locations with the highest productivity and the varieties that will best adapt to the changes that are being produced in the climate.

Future research will be carried out to verify the impact of climatic variations in the growth cycle of the vines in the PDO Sierra de Salamanca. Further, comparisons will be made for years with low productivity and high productivity to demonstrate the fluctuations of the harvest in relation to the climate and the bioclimatic indexes, as well as the very favourable zones of crops within the appropriate zones.

Acknowledgments

This research was funded by projects: Junta Castilla y León SA044G18 and USAL (2017) 46AC0; and projects from the Ministry of Economy and Competitiveness CGL2015-67169-P and CGL2015-69919-R.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.105646.

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