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Spatial climate variability and viticulture in the Miño River Valley of Spain

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Summary

Understanding spatial variations in climates that are crucial for crop suitability form the basis of zonation studies in viticulture. This research applies principal components analysis and cluster analysis to 39 climate stations in the Galician region of northwest Spain to examine the applicability for zonation in the region and produce a better understanding of the spatial climate structure in Galicia. Roughly 90 % of the spatial variation in climate types is explained by three main components, which are defined by precipitation, temperature, and frost risk variations across the region. The climate variables or indices most important for the Galician region include the three main indices (Huglin index, Dryness index, and Cool night index) used within the Multicriteria Climatic Classification System (Geoviticulture MCC System). The results provide evidence that the Geoviticulture MCC System, which was developed at the global scale, has tremendous applicability at the mesoscale. The identification of six climate types of the Geoviticulture MCC System, which are used quite extensively for wine growing in the region, depicts the great spatial diversity of viticultural potential found within the relatively small area of Galicia.

K e y w o r d s : Climate variability, viticulture, wine, climate indices.

Introduction

Grape growing and wine production are largely weather and climate driven. Extreme weather events such as hard frosts, heavy rains, and hail can result in major losses in a given vintage, while variability in growing season temperatures can result in major differences in ripening potential and the quality of wine (Gladstones 1992, Jones 1997). The major wine producing regions in the world each experience climate variability, however, depending on location (*i.e.* coastal vs. continental) they are subjected to different types, frequencies, and magnitudes of climate and weather events. One region of particular interest is Galicia, Spain which is in the extreme NW portion of the Iberian Peninsula just north of Portugal. Regionally, Galicia and Portugal share a cool maritime climate, the production of similar wine varieties (e.g. 'Alvarinho', 'Loureira'), viticultural areas (e.g. the Tamega and Miño river valleys), as well as various aspects of traditional viticultural practices (e.g. terracing, pergolas, etc).

The Miño River is the most important drainage in NW Spain with a basin that extends over 17,757 km^2 with abundant viticultural areas distributed along its path to the Atlantic Ocean. Wine producing regions in Spain are given denominations of origin (D.O.) status, which provides the legal nomenclature used to recognize those areas favorable for production and to specify a high quality level for the wines produced. In this region there are more than 10,000 ha of vines that include six denominations of origin (D.O.). Four of these growing regions (Bierzo, Valdeorras, Ribeira Sacra and Ribeiro) are each located in the Miño Valley and a fifth (Rias Baixas) is located near the end and mouth of the river as it flows into the Atlantic (Figure). Vineyards in these regions produce an average of more than 40 million kilograms of grapes a year, with nearly 85 % being white varieties (Albarinho, Palomino, Treixadura, and Godello) and the remainder predominantly the red varieties Garnacha and Mencia.

The landscape of Galicia is dominated by the valleys and relief created by the Miño River and its principal tributary the Sil River. Along the roughly 380 km course of the Miño, the river runs through both deep gorges and valleys, some of which are true narrow canyons whose flanks are almost vertical and other valleys with gentle hills including even some almost flat hollows. At the macroscale, the climate of the Iberian Peninsula is influenced by the Atlantic Ocean and the seasonality and position of the Icelandic low and Azores high pressure regions, but also has Mediterranean climate structure inland due to the relief of the landscape (Köppen 1931).

The spatial distribution of mesoclimates in a region is very important for understanding viticultural suitability (Carbonneau 2003) and this is never more evident than in the heterogeneous landscape of Galicia. Viticulture zonification studies include the identification and characterization of the mesoclimates in an area, apart from the macroscale variations that may affect the frequency and intensity of certain climatic factors (temperature, rainfall, sunlight, frost, drought, etc.) and how their variations impact the vine's development. These factors are not normally examined separately, but are more commonly integrated as mathematical expressions that permit the calculation of a series of bioclimatic indices (Fregoni 2003), which are typically summed over a period of time important to the vine's growth and production (usually the 6 or 7 months of the vine's growth and development cycle). Among these indices some of the most utilized in viticultural zonification studies are the Winkler index (1962), the Heliothermic index (Huglin 1978), Branas index (1974) and the

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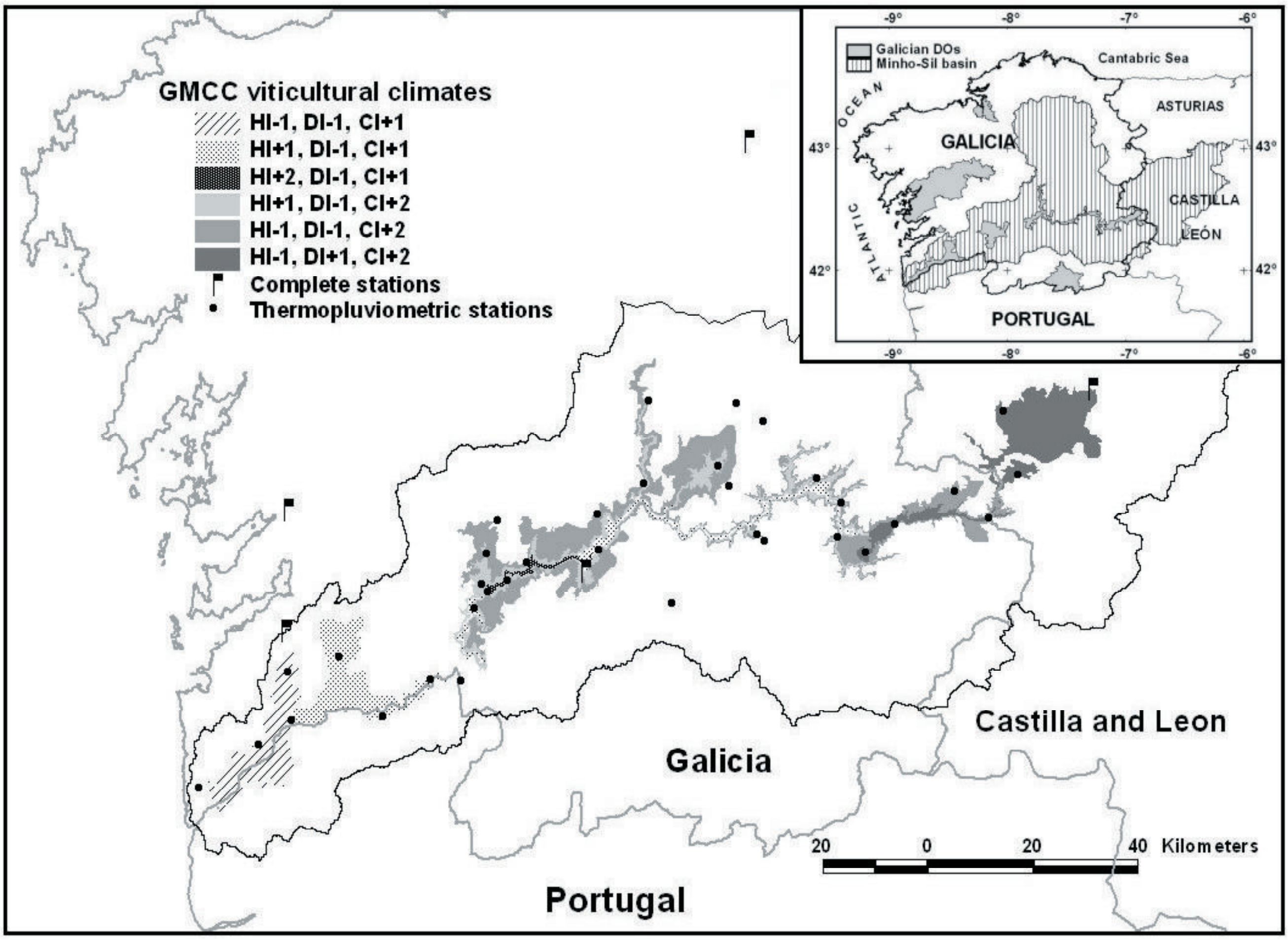

Figure: Miño basin areas where vines are grown more extensively and their respective viticultural climates classified according to the Geoviticulture MCC System. Solid dots denote the locations of the temperature and precipitation only meteorological stations used in this study and flags show the locations of the complete meteorological stations. The map in the upper right hand corner depicts the location of the Miño-Sil river drainage and the Galician Denominations of Origin (D.O.).

quality index of Fregoni (1985). However, each of these indices have been criticized in one way or another (*i.e.* too simplistic or appropriate for one region only) (Gladstones 1992, Jones *et al.* 2005).

More recent research (Carbonneau and Tonietto 1998, Tonietto 1999, Carbonneau 2003, Tonietto and Carbonneau 2004) has combined a reduced number of climatic indices that account for solar, frost, and drought variability and provide a classification of viticulture climates that are arguably more universally valid. The Multicriteria Climatic Classification System (Geoviticulture MCC System) results in 36 different climatic types from a summation of three indices; the Huglin index (HI), a cool night index (CI), and a dryness index (DI). The classification has been successfully tested to differentiate the climate of 97 viticulture zones worldwide (Tonietto and Carbonneau 2004). However, there are many regions such as Galicia where the Geoviticulture MCC System has not been applied. Therefore, the main purpose of this research is to use the Geoviticulture MCC System to investigate the potential to provide a more comprehensive viticultural zonation of the region. In addition, the Geoviticulture MCC System will be compared to other commonly used climatic indices in viticultural zonation studies to investigate which methods/variables provide the most suitable description of the mesoclimates present in wine-producing areas of the Miño Valley. The overall aim is to provide a comprehensive and climatically appropriate zonation of viticultural potential in the region.

Data and Methods

To carry out this study, data were obtained from a network of weather stations maintained by six organizations i.e. The National Meteorological Institute of the Ministry of Environment (IMN), the Geographical Information System of the Ministry of Agriculture, Fishing and Food (SIGA), the Environmental Information System of the Council of Environment for the Galician government (SIAM), the Station of Areeiro of Pontevedra, the hydrologic services of the western electrical company FENOSA, and the Institute of the Higher Agronomic Studies of the Technical University of Lisbon (ISAUL). In addition, to account for a lack of data in the Sil Canyon, three stations were collected from a 1945-1974 database published by Carballeira *et al.* (1983).

Variables available for the analysis include: monthly mean maximum temperature, monthly mean minimum temperature, monthly average temperature, absolute minimum temperature per month, and monthly total precipitation. Five of the stations also collected data on solar radiation, surface wind speed, and relative humidity (complete stations), and were used to compute the potential monthly evapotranspiration by the Penman-Monteith method (Allen *et al.* 1988). Evapotranspiration for the stations with only temperature and precipitation variables were computed by the hybrid method of Blaney and Criddle (1950).

The data were combined into a geographic information system (GIS), along with layers depicting land use from the Territorial Information System of Galicia (Sitga 2004), a digital terrain model (90 m resolution) from the SRTM mission (Void-filled seamless Srtm V1 2004), and other vector features (e.g. political boundaries, water, etc.). Using the GIS, 43 stations located in the vine growing areas of the Miño Valley and neighboring countryside were selected for further analysis.

The temperature and precipitation data from the selected weather stations have both varying time periods, ranging from 5 to 40 years, and quality in respect to station changes, missing data, and anomalous data. Quality control measures were carried out to minimize potential data inhomogeneities; detection and elimination of anomalous data was carried out with frequency histograms (Aguilar *et al.* 2002), correction of station changes by the means of the standard homogeneity test (Alexanderson and Moberg 1997), the filling of data gaps by linear adjustment (González-higalgo et *al*. 2002), and the estimation of average maximum and minimum temperatures for five stations in the FENOSA network and two in the SIGA network due to horizontal and vertical gradients (Carballeira *et al.* 1983, Ninyerola *et al.* 2000). Station artificial tendencies were detected in five stations for temperature with no issues found for precipitation. Finally, each station's data series were then normalized to a common time period of 1971-2000 by differencing for the temperature data and coefficient corrections for the precipitation data using Anclim (Aguilar *et al.* 2002, González-hidalgo *et al.* 2002, Wijngaard *et al.* 2003).

After normalizing the station data, 14 climate variables or indices commonly used in viticultural zoning were summarized or calculated (Amerine and Winkler 1944, Branas *et al.* 1946, Hidalgo 2002, Huglin 1978, Gladstones 1992, Gómez-miguel and Sotés 2003, Tonietto and Carbonneau 2004, Yglesias 1983). The first processing included calculating normalized values of six main climate variables:

- Annual temperature and precipitation (Ta and Pa)
- Growing season temperature and precipitation (April-September; Tgs and Pgs)
- Summer precipitation (Ps, June-August)
- Length of the frost-free period (Tmin > 0ºC; FF).

From these variables, eight climatic indices commonly used in viticulture bioclimatology were derived (Tab. 1), resulting in a total of 14 climate parameters that were used in the study.

To identify the main factors of spatial climate variability in the wine regions studied, the climate variables and indices for the 43 stations were then analyzed with a two-stage multivariate procedure. The first step used principal components analysis (PCA) with a correlation matrix of the station data and applying a Varimax rotation. The second step used average linkage hierarchical cluster analysis (CA) to group the stations into sub-groups based on their similarity. A dendogram identified four stations as being outliers in the clustering due to station distances and were removed from further analysis leaving 39 stations. The PCA/CA analysis results were then used to parse the redundancy in the parameters down to the most significant ones that explain the spatial climate structure in the region.

Results

Summarizing the 39 stations used in the final analysis shows that they range from 29 to 800 m above sea level (294 m average) and 11 to 286 km from the coast (Tab. 2). Annual temperatures across the stations average 13.4 °C

Table 1

Climate indices, their equations, and sources which are evaluated for the 39 stations used in the analysis. Variable abbreviations are given in the footnotes

Index and Abbreviation	Equation	Source
Winkler index (WI)	Σ ((Tmax+Tmin)/2)-10°C)	Amerine and Winkler 1944
Huglin index (HI)	Σ ((Tavg-10°C)+(Tmax-10°C)/2)*d	Huglin 1978
Branas Heliothermic index (BHI)	Σ (Tavg-10ºC)* Σ I_e*10^{-6})	Branas 1974
Hydrothermic index of Branas, Bernon and Levadoux (HyI)	Σ (Tavg* Pgs)	Branas *et al.* 1946
Hidalgo bioclimatic index (HBI)	Σ (Tavg-10ºC)* Σ I_e*10^{-6}) / Pa	Hidalgo 2002
Dryness index (DI)	Σ W_o+P–T_v-E_s	Riou *et al.* 1994
Cool night index (CI)	NH=Tmin(Sept); SH=Tmin(March)	Tonietto 1999
Continentality index (CT)	NH=Tavg(July)-Tavg(Jan); SH=Tavg(Jan)-Tavg(July)	Gladstones 1992

Variables in the equations above include; Tmax, Tmin, Tavg are maximum, minimum, and average temperatures respectively; a coefficient of correction (d) which takes into account the average daylight period for the latitude studied (40-50°); I_e is the effective insolation; Pgs is growing season precipitation; Pa is annual precipitation; W_o is the initial useful soil water reserve; P is monthly precipitation; T_v is potential monthly transpiration; E_s monthly direct evaporation from the soil and NH and SH are the Northern and Southern Hemisphere, respectively.

Table 2

Summary statistics of the climate variables or indices for the 39 stations used in the analysis. Parameter abbreviations are as given in the Data and Methods section. Distance to the Ocean is measured along the river valley reach

Variable	Mean	Std. Dev.	P10 %	P90 %	Maximum	Minimum
Elevation (m)	294	206	50	600	800	29
Distance to Ocean (km)	149	74	41	258	286	11
Ta (°C)	13.4	1.0	12.2	14.9	15.3	11.0
Tgs (°C)	17.3	1.0	16.1	18.7	19.1	14.7
WI	1382	221	1152	1674	1858	872
HI	2049	238	1727	2300	2512	1454
BHI	3.5	0.5	2.9	4.1	4.3	2.2
Pa (mm)	1097	331	670	1635	1715	628
Pgs (mm)	349	94	230	484	557	217
Ps (mm)	105	24	75	139	177	70
HyI	4439	1263	2835	6220	7138	2607
HBI	3.5	1.1	2.1	5.1	5.9	1.7
DI	83	26.5	46	121	136	37
FF (days)	247	40	205	290	365	186
CI	11.4	1.2	9.7	13.0	13.6	9.4
CT	14.4	1.7	12.3	17.4	17.8	11.5

while growing season mean temperature averages 17.3 °C with approximately a 4 °C range across the stations for both periods. The frost-free period averages 247 days across the region with a minimum of 186 days and two locations that, on average, never experience a frost during the year. The Cool night index (CI) shows similar spatial variability to frost potential (r = 0.72) while the Continentality index (CT) reveals an inverse relationship (r = -0.31) (Tab. 3). Heat and solar accumulation during the growing season as given by the Winkler index (WI), the Huglin index (HI), and the Branas Heliothermic index (BHI) are strongly inter-correlated (Tab. 3) and show a wide range of potential from cooler climate structures at lower elevations near the coast to warmer regions inland (Tab. 2).

Precipitation values across the stations average 1,097 mm on an annual basis, 349 mm during the growing season, and 105 mm during the hottest months of the year (June, July, and August). Large spatial variations in precipitation are evident with ranges in each annual or seasonal period that are roughly equal to the mean values (Tab. 2) and are due mostly to the distances from the coast (Tab. 3). Further evidence for wide spatial variations in rainfall is seen in the correlations between the Hydrothermic index of Branas, Bernon and Levadoux (HyI), Dryness index (DI), and Hidalgo bioclimatic index (HBI).

The principal components analysis of the station climate variables and indices resulted in 89.8 % of the total variance being explained by three components (Tab. 4). The first PC explains 40.1% of the total variance and loads highly on precipitation-related parameters or continentality. The two highest loading climate parameters are annual (Pa) and growing season (Pgs) precipitation. The second PC explains 37.6 % of the remaining variance with the highest loading climate parameters being temperature-related; growing season temperatures (Tgs), the Winkler Index (WI), the Huglin Index (HI), and the Branas Heliothermic Index (BHI) (Tab. 4). The third PC explains 12.1 % of the remaining variance and is also related to temperature, but is driven more by parameters related to cold risk; the frost-free period (FF) and the cool night index (CI).

Comparing the component loadings from Tab. 4 with the correlation matrix in Tab. 3, reveals that some of the climate parameters are strongly inter-correlated and therefore are providing redundant information. Therefore a subset of the climate parameters for each factor was chosen for further analysis based on the magnitude of their loading and either low or non-existent scores on the other axes. This selection process ensures minimal inter-correlation between the parameters and that the best variable mix important for describing viticultural climates are chosen.

From the component loading matrix a total of 10 parameters loaded significantly on the three PCs (Tab. 4). For the climate variables, the most discriminating were clearly the average growing season temperature (Tgs), total precipitation during the growing season (Pgs), and the frost-free period (FF). For the climate indices, the most important include the Branas hydrothermic index (Hyl), the Hidalgo bioclimatic index (HBI), the dryness index (DI), the Winkler Index (WI), the Branas Heliothermic Index (BHI), the Huglin Index (HI), and the cool night index (CI). However, the Branas hydrothermic index (Hyl) is already well represented by growing season precipitation (Pgs; r = 0.95) and is therefore not used further. In addition, the Hidalgo Bioclimatic index (HBI) was dropped in favor of the dryness index (DI) as the DI takes into account multiple climate variables (maximum, mean and minimum temperatures, and precipitation, relative humidity, effective sunlight hours, and surface wind speed during the growing season) and has a significant loading on PC 1 while presenting the lowest correlation with Pgs (r = 0.80) of all the climatic in-

Table 3

Correlation matrix for the climate station, variables, and indices for the 39 stations used in the analysis. Only those correlations significant at the 0.05 level are shown. Parameter abbreviations are as given in the Data and Methods section

	Elev	Lat	Lon	Dist	Ta	Tgs	WI	HI	BHI	Pa	Pgs	Ps	DI	HyI	HBI	FF	CI	CT
Elev	1																	
Lat		1																
Lon	0.75		1															
Dist	0.75		0.97	1														
Ta	-0.86		-0.60	-0.66	1													
Tgs	-0.73		-0.30	-0.39	0.92	1												
WI	-0.68		-0.33	-0.42	0.91	0.96	1											
HI	-0.64				0.80	0.94	0.90	1										
BHI	-0.72			-0.38	0.92	1	0.96	0.94	1									
Pa	-0.54		-0.83	-0.80						1								
Pgs	-0.44		-0.79	-0.76						0.94	1							
Ps			-0.55	-0.54				-0.37		0.77	0.87	1						
DI	-0.28		-0.60	-0.50		0.30		-0.37	-0.31	0.76	0.80	0.71	1					
HyI	-0.58		-0.83	-0.83	0.38					0.91	0.95	0.85	0.67	1				
HBI			0.64	0.57		0.40	0.39	0.43	0.41	-0.82	-0.82	-0.69	-0.78	-0.70	1			
FF	-0.54		-0.53	-0.56	0.60	0.44	0.44		0.43	0.36				0.38		1		
CI	-0.57		-0.48	-0.52	0.78	0.69	0.74	0.49	0.68							0.72	1	
CT			0.67	0.60				0.38		-0.67	-0.71	-0.60	-0.56	-0.68	0.69	-0.31		1

dices. A further reduction in the number of parameters was done by dropping the Branas Heliothermic index (BHI) and average temperature of the growing season (Tgs) because they are variables directly correlated to each other and also with the Huglin index (HI) and the Winkler index (WI) which has a longstanding use in viticultural studies (Jones and Davis 2000). The frost free period (FF), which loaded highly on PC 3, was also removed in favor of the more widely used cool night index (CI). The process resulted in a subset of five parameters that characterize the main spatial variability of climate types present in the Miño Valley: precipitation during the growing season (Pgs) and four climatic indices, the Winkler index (WI), the Huglin index (HI), the dryness index (DI), and the cool night index (CI). However, because the dryness index captures precipitation variations and the Huglin index captures heat accumulation variations as with the Winkler index, the main structure of climate in the region can be largely explained by the three

Table 4

Principal component communalities and loadings for the first three components from the analysis of the climate variables and indices for the 39 stations. Bold values indicate the most dominant loadings of each parameter in the PCs. Parameter abbreviations are as given in the Data and Methods section

Variable	Communality	Component		
		1	2	3
Ta	.97	.17	**.90**	.36
Tgs	.99	-.12	**.97**	.18
WI	.96	-.10	**.95**	.22
HI	.97	-.21	**.96**	
BHI	.99	-.13	**.97**	.17
Pa	.94	**.95**	.14	.12
Pgs	.97	**.98**		
Ps	.80	**.89**	-.16	
DI	.76	**.84**	-.21	
HyI	.94	**.94**	.19	.14
HBI	.83	**-.86**	.31	
FF	.85	.22	.31	**.84**
CI	.88		.60	**.72**
CT	.74	**-.70**	.24	-.44
% Explained variance		40.1	37.6	12.1
% Cummulative variance		40.1	77.7	89.8

indices used in the Multicriteria Climatic Classification System (Geoviticulture MCC System), showing its validity for viticultural zonation in the region.

The Geoviticulture MCC System (Tonietto and Carbonneau, 2004) combines the three indices into structural classes based on each index (Tab. 5). The HI is summed over the April to September growth period and produces bounds on cool (1,500-1,800) to hot (2,400-3,000) growing climates that are suitable for varieties such as 'Pinot Noir' and 'Cabernet Sauvignon', respectively. The DI enables the characterization of the soil-water component of climate in a growing region and indicates the potential water availability in the soil as related to the level of potential dryness. DI values are grouped into classes that differentiate between very dry, moderately dry, sub-humid, and humid conditions. The CI was derived to account for ripening characteristics during maturation and results in classes that distinguish between areas with very cold nights, cool nights, temperate nights, and warm nights (Tab. 5). Below is a more in depth overview of the spatial characteristics of each of the three climate indices in the region and the application of the Geoviticulture MCC System to viticultural zonation in the region.

The average HI of the stations researched in this study is 2,049, ranging from a minimum 1,454 to a maximum 2,512. This signifies that locations in the Miño Valley could be classified under 5 of the 6 HI groupings described by Tonietto and Carbonneau (2004) in the Geoviticulture MCC System (Tab. 5). The highest proportion corresponds to temperate and temperate-warm classes (41 % each) with the temperate locations found closer to the ocean and at higher elevations inland, while temperate-warm to hot climate stations are further inland. The DI averages 83 over the region, placing the majority of the region in the sub-humid class in the Geoviticulture MCC System (Tab. 5). The highest DI values (signifying more moist conditions) are found in the coastal areas, while the lowest values (moderately-dry zones on the DI) are found inland and in the rain shadow zones of the valleys. The CI values for the stations along the Miño Valley fall mostly into the very cool night class (69 %) or cool night class (31 %) in the Geoviticulture MCC System (Tab. 5). Spatially, the coolest nighttime temperatures are found further inland and at higher elevations while the slightly more moderate nights are found in the coastal zones or close to reservoirs.

Combining the HI, DI, and CI results for the weather stations in the Miño Valley in the Geoviticulture MCC System, classifies the region into 8 different climatic types, of which two correspond to areas where no vineyards exist or their presence is marginal. The resulting eight climatic types identified in the Miño Valley represents approxi-

Table 5

Class groupings for the Huglin index (HI), cool night index (CI), and dryness index (DI) defined in the Geoviticulture MCC System (Tonietto and Carbonneau 2004)

Index	Class Name	Abbreviation	Class Interval
Huglin Index (HI)	Very Warm	HI+3	HI > 3000
	Warm	HI+2	2400 < HI ≤ 3000
	Temperate Warm	HI+1	2100 < HI ≤ 2400
	Temperate	HI-1	1800 < HI ≤ 2100
	Cool	HI-2	1500 < HI ≤ 1800
	Very Cool	HI+3	HI ≤ 1500
Cool Night Index (CI)	Very Cool Nights	CI+2	CI ≤ 12
	Cool Nights	CI+1	12 < CI ≤ 14
	Temperate Nights	CI-1	14 < CI ≤ 18
	Warm Nights	CI-2	CI > 18
Dryness Index (DI)	Very Dry	DI+2	DI ≤ -100
	Moderately Dry	DI+1	-100 < DI ≤ 50
	Sub-Humid	DI-1	50 < DI ≤ 150
	Humid	DI-2	DI > 150

mately, one quarter of all of the climatic groups identified with the Geoviticulture MCC System worldwide (Tonietto and Carbonneau, 2004). This result depicts the diversity of the viticultural potential of the Miño Valley where, in an area nearly 18,000 km^2, a wide range of climates can be found. In addition, the results indicate that the Geoviticulture MCC System is not only adequate for distinguishing worldwide viticulture climates, but also allows the differentiation of mesoclimates.

In terms of the frequency and distribution of the range of different climatic types encountered in the Miño Valley, the majority of the current areas planted to viticulture are established in areas were the climate is temperate warm (H1 + 1) although some of the more westward (coastal) and Sil basin vineyard areas are in mild climates (H1 -1) (Figure). The sub-humid (D1 - 1) dryness index class is predominant, with the moderately dry class (DI +1) found only in the most eastern part of the Sil basin, close to the boundary with Castilla. Nights are mostly very cool (CI + 2) in the interior with the exception of the valley bottoms and hillsides near the inland reservoirs in the center section of the Miño basin, while the western areas are in the cool night class (CI + 1).

The temperate warm, sub-humid, with very cool nights class (HI + 1, DI - 1, CI + 2) is one of the most frequently found climate types with 23 % of the stations. The areas associated with this climate type are mostly located on the lower hill slopes east of the first mountain range from the ocean (the Dorsal Gallega) where grapevines are already extensively cultivated (Figure). The temperate, sub-humid, with very cool night class (HI - 1, DI - 1, CI + 2) makes up 21 % of the stations and are found at mid-elevations or within smaller tributary basins and represent areas where vines are cultivated less extensively. Nearly 13 % of the stations are classed as temperate, moderately dry, with very cool nights (HI - 1, DI + 1, CI + 2) and are located within the Sil tributary basin close to or within Castilla and show a marked influence of continentality eastward. Less representative are the cool, sub-humid, with very cool nights type (HI - 2, DI - 1, CI + 2) along with the very cool, sub-humid, with very cool night class (HI - 3, DI - 2, CI + 2): These two types are present at latitudes or elevations where vines are not grown within the Miño basin and add up to 13 % of the stations. Finally, the cool night classes (CI + 1) are spatially associated with sub-humid conditions (DI - 1) and are either temperate coastal areas (HI-1, 8%), temperate warm (HI + 1, 18 %) areas on both sides of the coastal mountains along the Miño and Sil rivers, or even reaching warm conditions (HI + 2, 5 %) further inland near the reservoirs in the proximity of the town of Ourense.

Discussion and Conclusions

Climate has a strong influence on all forms of agriculture, providing the overriding environmental means by which crop suitability and economic viability can be maximized. This connection is never more evident than with the cultivation of grapevines for wine production where narrow geographical and therefore climatic zones provide the conditions necessary to produce a given wine style and quality. The Miño River basin of northwest Spain is a region that has a long history of grapevine cultivation and wine production and, while a relatively small area of just under 18,000 km^2, has numerous climate types due to its geographical location and complex topography.

This research details the spatial variability in climate over the basin in order to produce a zonation of viticultural potential in the region. The research uses 14 climate variables or indices important for grapevine growth over a 39 weather station network in the region along with principal components analysis and clustering algorithms to produce the zonation of climate types. The results reveal that three components explain roughly 90 % of the spatial variability in climate with precipitation-related parameters or indices being most important. This details the spatial nature of rainfall in the region with higher amounts in the coastal areas and along the higher, more exposed, elevations and lower amounts further inland and in rain shadow zones. Temperature-related climate parameters or indices are found to be the second most important spatial mode of variability with a similar pattern to that of precipitation. The third component of spatial variation in climate is related to frost potential with the more inland areas and upper elevations having shorter frost-free periods and colder nights during ripening.

Reducing the number of climate variables and indices to those most important resulted in five parameters that describe most of the spatial variability in climate types; precipitation during the growing season (Pgs) and four climatic indices, the Winkler index (WI), the Huglin index (HI), the dryness index (DI), and the cool night index (CI). The results show that the application of the Multicriteria Climatic Classification System (Geoviticulture MCC System), which uses three of the indices (HI, DI, and CI), is a good method for viticultural zonation in the region. The eight climatic types identified with the Geoviticulture MCC System in the Miño Valley represent approximately one quarter of all of the viticulture zones identified with the system worldwide and shows the outstanding spatial diversity of viticultural potential in the Miño Valley. The majority of the region is defined in the Geoviticulture MCC System as one that is temperate warm, sub-humid, with very cool nights or temperate, sub-humid, with very cool nights. Next there are the regions with cool nights in the areas closer to the coast (roughly 30 km along the main valleys of the Miño and Sil rivers), which range from temperate to temperate warm conditions before reaching the Dorsal Gallega coastal mountains. Further inland, the area near the reservoirs in the proximity of the town of Ourense can even reach warm conditions. Further east, in the Galician DO (Valdeorras) and Bierzo DO in Castilla, areas can be found that are classed as temperate, moderately dry, with very cool nights. The final categories of cool, sub-humid, with very cool nights; or very cool, sub-humid, with very cool nights can be found at higher elevations where vines are not typically cultivated.

While this research provides the first comprehensive zonation of viticulture in the Galicia region, the results also indicate that the Geoviticulture MCC System is not only adequate for distinguishing worldwide viticulture climates, but also allows for the differentiation of mesoclimates that are so important for viticultural zonation within wine-growing regions.

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