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Agro-ecological terroir units in the North West Iberian Peninsula wine regions

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ABSTRACT

Viticultural zoning studies that support the definition of terroir units general follow two main approaches of geographic differentiation related either to: a) land capability or vineyard suitability, or b) grape, grapevine or wine characteristics. Both approaches are commonly considered in the definition of terroir at regional and local approaches.

The purpose of this preliminary study was to develop and apply a methodology for viticultural zoning in order to establish the basis of studies on wine typicality. This will allow to question and compare the existent Protected Designations of Origin (D.O.) in the North West Iberian Peninsula wine regions (North of Portugal and Galicia-Spain).

The assessment of Agro-ecological Terroir Units for viticulture includes climate and soil environmental factors selected for their relevance at regional scale, with the use of state-of-the-art variables and indices appropriate for the specified regions. The methodology considers the International Organisation of Vine and Wine guidelines (OIV, 2012), it is based upon the development of a Geographic Information System (GIS) and uses multivariate zoning with principal component analysis and clustering procedures.

The results suggest that the sub-regions of Monção e Melgaço and Rías Baixas are integrated in a different terroir unit from the other Minho Sub-regions, which could give way to further inquiry with the purpose of reclassification based on studies on quality and typicality for the Alvarinho Wine.

This regional and national cross-border classification provides a useful framework for territorial and viticultural policies with further validation at local and farm scales. This validation includes experimental surveys in selected vineyards for geographic differentiation of wine profiles and for supporting precision viticulture at plot and landscape scale.

1. Introduction – land evaluation and agro-ecological zoning for viticulture

In rural planning studies and processes, land evaluation is a tool to assess the natural conditions of a territory, potential or optimal land use, and limitations for general land uses, according to human activities and interests. Rural land use planning considers two main types of land evaluation – capability and suitability classifications (FAO, 1974, 1976). The first refers to "the inherent capacity of land to perform at a given level for a general use, and suitability as a statement of the adaptability of a given area for a specific kind of land use (…)" (FAO, 1976). Land suitability analysis developed to agro-ecological zoning which refers to the territorial delimitation of zones or homogeneous land units in what regards to climate, landform, soils and/or land cover (FAO, 1996). These have a definable land suitability, potential production and environmental impact (FAO, 1996).

According to the International Organisation of Vine and Wine (OIV) "terroir" has a spatial dimension, which implies a need for delimitation and zoning, particularly physical environment aspects (soil and climate) (OIV, 2012). As such, terroir spatial approaches (Vaudour, 2002) imply a land classification in homogeneous zones, having a similar agro-ecological features such as climate, topography, geology and soils

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(Bonfante, Basile, Langella, Manna, & Terribile, 2011). For the grapevine (*Vitis vinifera* L.) this can entail as well the study of the "relationships that involve these factors and the types of wine to be obtained" (Bucelli & Costantini, 2009).

Geographic research in viticulture had for long a place in regional and agricultural geography studies (Dion, 1990; Pijassou, 1980; Stanislawski, 1970; Vince, 1946), and has developed concepts, methods, spatial tools and geospatial technologies to: 1) vineyard site location and suitability analysis (Laville, 1992; Morlat & Asselin, 1992; Watkins, 1997); 2) vineyard land cover identification; and 3) precision viticulture (Bramley, Ouzman, & Boss, 2011; Mathews, 2013; Vaudour, Costantini, Jones, & Mocali, 2015).

Viticultural zoning pertains to the characterisation of land units or Agro-ecological Terroir Units (ATU), which can be defined on a map from natural resource surveys akin to land suitability evaluations, here undertaken for the production of high quality wine (Bucelli & Costantini, 2009). It considers the "analysis and implementation of terroirs", a concept which refers to: "an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied vitivinicultural practises develops, providing distinctive characteristics for the products originating from this area" (OIV, 2010).

Terroir is a concept that relates the sensory attributes of a wine to the environmental conditions in which the grapevine is grown (Van Leeuwen & Seguin, 2006), affecting the quality and typicality of the wine produced in a particular area or location. It is a place-based interactive ecosystem, that includes the climate, soil and the vine (Seguin, 1988) as well as the agronomic techniques and the vegetative, productive and qualitative results of the vine crop. Therefore, human factors should also be considered such as history, socioeconomics, viticultural and oenological techniques and practices (Seguin, 1986; Van Leeuwen & Seguin, 2006), associated to local/regional collective knowledge and cultural material heritage.

In fact, the expression of terroir as the basis of high-quality wines with typicality is considered dependent on technical knowledge and experience (Van Leeuwen, 2010). Wine typicality can be defined as the characteristics that allow the identification of a wine with the terroir where it has been produced and includes environmental, technical, historical and sensory dimensions (Letablier & Nicolas, 1994).

According to Vaudour and Shaw (2005), Deloire, Vaudour, Carey, Bonnardot, and Van Leeuwen (2005) and Bonfante et al. (2011) the analysis and implementation of terroirs implies either one or both of the following steps of geographic differentiation, as the basis for zoning: a) delimitation of Environmental Terroir Units (TU); b) consideration of the geographical differentiation of wines, grapes, or grapevine characteristics. The first step of delimitation of TU implies establishing a set of similar ecological environments based on the classification of features such as climate, soils, topography and geology, with land capability or vineyard suitability methodologies. The second step entails the analysis of the plant material (rootstock and grape variety), its cultivation techniques, and a validation using quantitative and qualitative analysis of grapes and wine (Bonfante et al., 2011; Deloire et al., 2005; Vaudour & Shaw, 2005).

According to Carbonneau (2001), Vaudour and Shaw (2005) and Bucelli and Costantini (2009) both steps a) and b) should be considered in the definition of terroir, respectively at regional and local approaches, leading to the concept of Viticultural Terroir Unit (VTU), that includes viticultural and oenological technology (Carbonneau, 2001; Deloire et al., 2005). In viticultural zoning it is generally agreed that there are several approaches of analysis for each spatial level, undertaken with different aims, methodologies and sets of variables. These spatial levels range from the "macro" or regional scale (< 1:50.000), the "meso" or local scale, to the "micro" or farm/plot scales (> 1:25.000) (Gómez-Miguel, 2003; Vaudour, 2002).

Viticultural zoning allows then to affirm the vocation for certain productions, table grape or wine grape e.g., choose which varieties are more suitable, to know the environmental limitations for the grapevine, to apply terroir sustainability practices (e.g. soil conservation), to establish the basis of studies on typicality and to enhance agroviticultural and enological management (Tonietto, 2008; Vaudour & Shaw, 2005). Studies on typicality allow to establish areas with geographical indication or Protected Designation of Origin (D.O.) and, within them, differentiate the suitability potential for quality wines with the representation of its spatial distribution (Gómez-Miguel & Sotés, 2003; Vale et al., 2016a).

Other study cases of viticultural zoning in Portugal and Galicia considered the North West Iberian Peninsula region, but analysed mostly climatic environmental factors (Blanco-Ward, Queijeiro, & Jones, 2007; Fraga, Malheiro, Moutinho-Pereira, & Santos, 2014; Queijeiro, Blanco, & Álvarez, 2006). Generally, when the integration of other factors is considered, as well as the inter-connections between them, the results are not spatially explicit (Fraga, Malheiro, Moutinho-Pereira, Cardoso, et al., 2014; Fraga, Costa, & Santos, 2017). An exception to this are the studies for integrated terroir zoning in the Iberian Peninsula developed by Gómez-Miguel & Sotés, and similar studies produced for Spanish Protected Designations of Origin (D.O.) (Goméz-Miguel, 2011; Gómez-Miguel & Sotés, 2003; Lázaro-López, Cámara, Martínez, Sotés, & Gómez-Miguel, 2016).

This survey is developed in the scope of the research project Terr@alva – Definition and influence of the terroir in the quality of the wine Alvarinho. Terr@alva has several aims: 1) to build and test a terroir zoning methodology for the definition and characterisation of the terroir associated with the Vinho Verde's Alvarinho variety in the chosen territory; 2) to study the typicality for the Alvarinho Wine through the differentiation of wines produced in different regions in the North West of Portugal. In what concerns the latter aim, the wine profiles in the regions of production will be differentiated using sensory descriptive analyses by a panel of professional wine tasters. As such, this project intends to provide the information for the selection of experimental vineyards in order to further analyse the terroir effect on the wines geographic differentiation for the North of Portugal wine regions.

The purpose of this preliminary study entails the first aim referred, namely to develop and apply a methodology for Viticultural zoning in order to establish the basis of studies on typicality that will allow to question and compare the existent Protected Designations of Origin (D.O.) in the North West Iberian Peninsula wine regions (North of Portugal and Galicia-Spain).

The results to obtain can also be used for the definition of strategies and the adoption of specific policies for the vitivinicultural sector and contribute to the promotion and marketing of wine regions, highlighting regional differences and similarities in the cross-border territory of the North West Iberian Peninsula.

2. Material and methods

2.1. Study area – North West Iberian Peninsula wine regions

North West Iberian Peninsula wine regions present, according to the global bioclimatic classification (Rivas-Martínez, 2011, 2004), a transition between the macrobioclimates: a) Temperate – with two bioclimates (depending on the continentality and ombrothermic index) – Hyperoceanic to Oceanic, and b) Mediterranean – Mediterranean pluviseasonal-oceanic. Temperate macrobioclimate territory has never two or more consecutive months with aridity during the warmest period of the year, which is understood to characterise the major part of Galicia territory and extends throughout the whole of the Galician coast to the vicinity of Porto and the south-western extreme of the Douro river basin (Rivas-Martínez, Penas, del Río, Díaz González, & Rivas-Sáenz, 2017). The Mediterranean macrobioclimate, that characterises mainly the south-eastern part of the case study area, presents seasonal and irregular precipitation, with at least two consecutive months with aridity during the warmest period of the year, and elevated temperatures in summer (Rivas-Martínez et al., 2017).

Considering the geological outline, the region is defined by the Hercynian Basement or Hesperian Shield geological units, which corresponds to an extensive area constituted by Pre-Cambrian and Paleozoic rocks consolidated essentially during a Hercynian orogeny. In what concerns the types of substrate, in NW Iberian Peninsula, are dominant the siliceous areas, where the Hesperian Shield integrates plutonic rocks, such as granites, together with a wide variation of metamorphic rocks (slate, gneiss, quartzite, schists).

These major geological regions determine the geomorphological characteristics and the hydrographic network is also related with the nature of the rocks, tectonic accidents and types of climate of the crossed areas. Watercourses, located along fracture zones, are a very striking feature of granite modelling, especially in northern Portugal. Hydrography in the region is rich, contributing to the existence of numerous small coast watercourses and inland watercourses that are tributaries of the two main rivers, Minho and Douro.

Generally, in the North West Iberian Peninsula wine regions, the heterogeneity of the current agro-ecological conditions results from the conjugation of several fundamental factors associated with: a) the altitude and relief characteristics, with a hypsometric amplitude between the mean sea level and 1955 m; b) the watershed positioning and orientation, as well as the distance from the main watercourses and valley bottoms; and c) proximity to the Atlantic Ocean.

The study area includes several Vitivinicultural regions form North Portugal and Galicia (Spain) (Fig. 1), where Douro and Minho, can be highlighted by having a prominent position in the international market. The Douro is one of the most important winemaking regions in Portugal that was, in 1756, the first demarcated and regulated wine region in the world. The Minho Wine Region, demarcated since 1908, produces a unique wine type “Vinho Verde”, a fresh, fruity wine with low alcohol content and high acidity. This wine has been popular in the foreign market, with the main exporting countries being Germany, the United States and France (EUROSTAT, 2018; Vale et al., 2016b).

2.2. Methodology – principal component analysis and multivariate geographic clustering

2.2.1. Data selection, acquisition and processing

Geographic Information Systems (GIS) and spatially explicit models expanded land evaluation methodologies and comprise presently three major groups of approaches to land-use suitability analysis (Hopkins, 2007; Malczewski, 2004): a) assisted overlay mapping (McHarg, 1969; Steinitz, Parker, & Jordan, 1976); b) multicriteria evaluation methods, and c) artificial intelligence methods.

The present study used a multicriteria evaluation method that included state-of-the-art environmental parameters such as climate, topography, and soil selected for their relevance at “macro” or regional

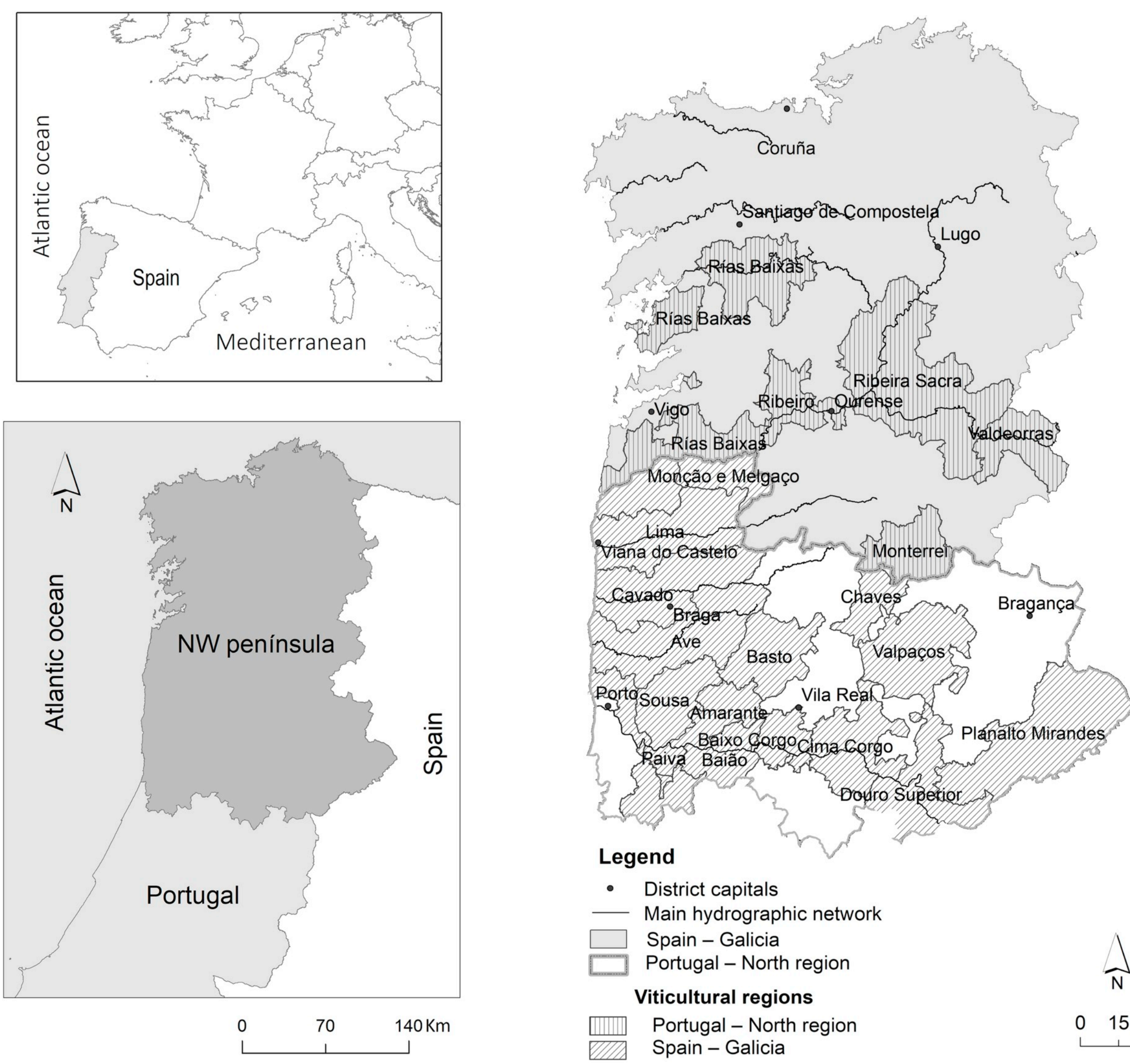

Fig. 1. Location map of North West Iberian Peninsula region. Viticultural regions and sub-regions in Galicia and North Portugal.

Table 1
List of the Bioclimatic indices used for this study, their corresponding mathematical definitions, and sources. Tmax is maximum air temperature (°C), Tmin is minimum air temperature (°C), Tavg is mean air temperature (°C), NH is Northern Hemisphere, SH is Southern Hemisphere, k is the length of day coefficient and P is precipitation (mm).

Index and Abbreviation	Equation	Source
Winkler index (WI)	Σ ((Tmax + Tmin)/2)-10 °C)	Amerine and Winkler (1944)
Selianinov index (SI)	ΣP/(ΣTavg-10)	Seljaninov (1966)
Cool night index (CI)	NH = Tmin(Sept); SH = Tmin(March)	Tonietto (1999)
Huglin index (HI)	Σ (((Tavg-10 °C) + (Tmax-10 °C))/2)*k	Huglin (1978)
Branas index (BI)	Σ (Tavg* P)	Branas et al. (1946)

scale and for the specified regions (Table 1). In what regards bioclimatic zoning, was considered the Multicriteria Climatic Classification system (MCC) (Tonietto & Carbonneau, 2004), the OIV guidelines for studying climate variability on vitiviniculture (OIV, 2015), and regional studies of climatic viticultural zoning (Blanco-Ward et al., 2007; Fraga, Malheiro, Moutinho-Pereira, & Jones et al., 2014; Fraga et al., 2017). According to the OIV (2012), when the objective of the study is to define the suitability of a particular region for viticulture (or for growing particular varieties), the role of the climatic variables in zoning should be higher than that of soil.

Specifically, from the MCC System (Tonietto & Carbonneau, 2004) were selected the indices that describe the thermal conditions and solar radiation (heliothermal potential and night temperature), frequently used to account for the influence of climate on vine development and grape ripening. These indices are considered by the OIV (2012) when the zoning purpose is to determine the potential of a territory in producing wines of a certain type (Fig. 2).

At the macroclimate level (regional climatic variations), besides temperatures and solar radiation, rainfall is also an important factor to consider. Water availability is crucial for general grapevine development, although research has proven that water deficit stress, in a part of the growing season, influences terroir expression (Van Leeuwen, 2010) and wine quality (Jackson & Lombard, 1993). As such, the chosen hydrothermic indexes are suited not only to define large wine-growing zones, in accordance with natural water availability (Seljaninov, 1966), but to derive disease pressure (downy mildew e.g.), that increases in relation to hydric conditions and to temperature (Branas, Bernon, & Levadoux, 1946).

To assess climate were used high-resolution raster datasets produced by the ClimateEU project (Hamann et al., 2013), at ca. 1 km spatial resolution. Monthly climatic variables (average, minimum and maximum air temperature and precipitation), for the 1961 to 1990 period, were used for the calculus of the bioclimatic indices according to the Multicriteria Climatic Classification (MCC) system (Tonietto & Carbonneau, 2004) and other in common use in studies of climatic zoning in viticulture (OIV, 2012, 2015). The chosen indices included: Huglin heliothermal index (HI) (Huglin, 1978), Cool night index (CI) (Tonietto & Carbonneau, 2004), Branas hydrothermic index (Branas et al., 1946), Winkler index (WI) (Amerine & Winkler, 1944), Selianinov hydrothermic index (SI) (Seljaninov, 1966).

Topography was integrated by means of elevation data obtained from NASA's Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) in raster format at 30 m spatial resolution (Fig. 2). It was considered that for this scale of terroir zoning other variables derived from terrain morphology, such as aspect and slope, were not appropriate for they describe local/meso characteristics.

2.2.2. Data analysis

The delineation of homogeneous agro-ecological terroir units (ATU) was carried out using a principal component analysis (PCA) and a subsequent Multivariate geographic clustering with the ISODATA clustering methodology, using ArcGIS (version 10.5) (Fig. 3). A similar method was proposed for the definition of agroecozones (Williams, Hargrove, Liebman, & James, 2008) and also in the scope of terroir regional zoning (Herrera Nuñez, Ramazzotti, Stagnari, & Pisante, 2011; Lázaro-López et al., 2016; Moral, Rebollo, Paniagua, & García-Martín, 2016). First, variable values of each raster cell were standardized (from 0 to 1). Second, the methodology included the multivariate statistical analyses: a) Principal components analysis (PCA), a data reduction technique, that allows the compression of correlated variables into a restricted number of orthogonal components translating the maximum of total variance; b) Cluster analysis, was performed using the selected PCA components in the ISODATA (iterative self-organizing data analysis technique) algorithm to produce three a priori grouping schemes of 3-6-8-12 non-contiguous zones or ATU, representing areas of similar agro-ecological or vine-relevant environmental conditions.

2.2.3. Results validation, discussion and proposal

The next methodological step was to compare, for validation, the resulting ATU with the viticultural regions boundaries, in Portugal and Spain (IVV, 2017; MAPAMA, 2009) and vineyard land cover area for the North Portugal (DGT, 2018). Finally, the overlay of the obtained terroir units with the major soil groupings and soil units was performed for the Minho region (DRAEDM, 1995), in order to exemplify how to obtain ATU that integrate the climate-soil-topography elements.

3. Results and discussion

The first three resultant PC contain a cumulative variance of ca. 52–99%, which means they explain up to 99% of the spatial variation in climate types and elevation and were therefore used in the clustering algorithm (Table 2). All six layers were used as they have for the three resultant Principal Components (PC) similar Eigenvector values or PC loadings, except for the Cool night index with a moderately high loading for the first two PC (Table 2). As such the PCA was not used as a data reduction technique but as a tool to include all the variability in the definition of terroir units. The classification by means of cluster analysis produced several maps with 3–12 homogeneous zones or agro-ecological terroir units within the NW Iberian Peninsula (Fig. 4).

The summary statistics of the indices and variables used in the analysis for the 12 agro-ecological terroir units of the North West (NW) Iberian Peninsula are shown in Table 3.

The climate indices most important for the NW Iberian Peninsula, by descending order, include the Huglin index, Winkler index, Selianinov hydrothermic index and Branas, Bernon and Levadoux hydrothermic index.

Some characteristics of NW Iberian Peninsula Viticultural regions and sub-regions and the ATU obtained in the analysis are discussed, taking into account the summary statistics presented in Table 3 and the boxplots presented as Supplementary material (Fig. S1 e Fig. S2). The summary statistics of the climatic indices and variables used in the analysis for the viticultural sub-regions of the NW peninsula are also presented as Supplementary material (Table S1).

Winkler index (WI) provides information on the accumulation of heat during the growing season (Amerine & Winkler, 1944). Considering the NW Iberian Peninsula agro-ecological terroir units the 1–6,

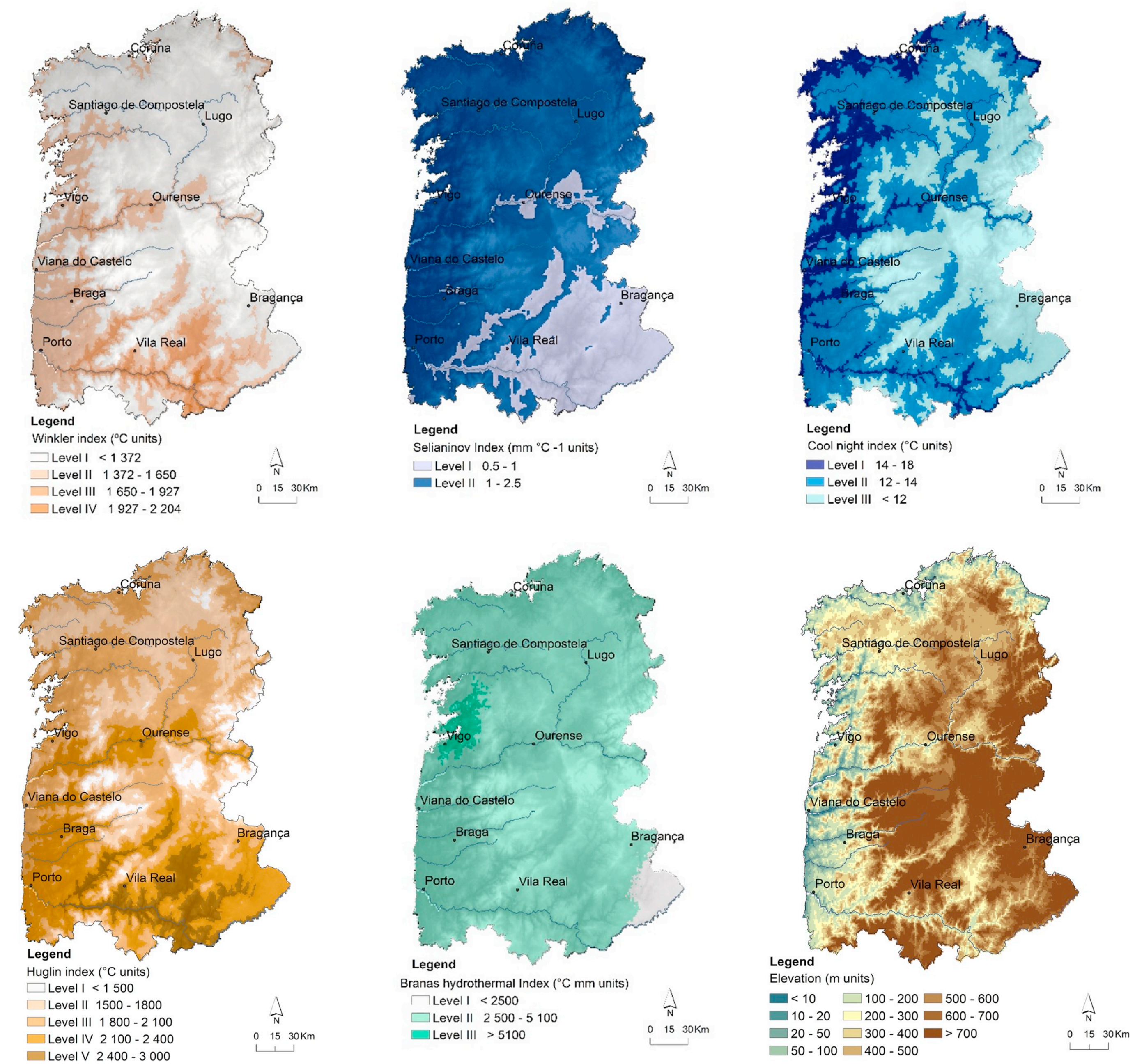

Fig. 2. Maps of climate indices and elevation used for the multivariate clustering.

8 and 10 are included in the first Winkler's Region I (WI – I, < 1372), which are integrated in the Viticultural sub-regions of Valdeorras, Ribeira Sacra, Monterrei, Monção e Melgaço, Lima e Baião. Agro-ecological terroir units 7, 11 and 12 are second level (WI – II, ≥1372 < 1650) and include almost all the remaining Viticultural sub-regions. Finally, only 9 is a third level region with median values above 1650 (WI – III ≥1650 < 1927), areas that integrate mainly the Viticultural sub-regions of Douro – Douro Superior and Baixo Corgo. When we consider extreme values Baixo Corgo, Cima Corgo, Douro Superior and Planalto Mirandês are the only viticultural sub-regions that attain WI values above 1927 °C, and are included in Winkler Region IV (WI – IV > 1927 < 2204).

The Selianinov's hydrothermic index (SI) is here used to assess the existence and intensity of drought in its agro-climatic sense during the vineyard growing season. A dry period is defined when SI is lower than 1.0 and an extreme dry period (drought) when is lower than 0.5. In what concerns the Selianinov hydrothermic index, the ATU 3, 7 and 9 present an Insufficient hydric regime (SI – I, < 1), whereas all the other have a Normal hydric regime (SI – II, > 1 ≤ 3). The Viticultural Regions of Trás-os-Montes and Douro are the ones characterised by the Insufficient hydric regime (SI – I, < 1).

The cool night index (CI) (Tonietto, 1999) accounts for minimum temperatures during maturation and provides, as such, complementary information about the thermal regime involved in the grape-ripening period. This stage is fundamental for the grape composition parameters (titratable acids, pH, phenols/anthocyanins) and flavour/aroma potential, and therefore CI is a reliable index for indications of potential quality associated to viticultural climates (Jackson & Lombard, 1993). In the NW Iberian Peninsula, and considering the ATU obtained from 1 to 9 have CI minimum values that correspond to Very cool nights (CI – III, ≤12), even though when considering the medium values only zones 1 to 4 and 6 are under this class. This class includes the Viticultural sub-regions of Valdeorras, Monterrei, Ribeira Sacra and Planalto Mirandês. ATU 5 and 7 to 11 have Cool nights (CI – II, > 12 ≤ 14) and only 12

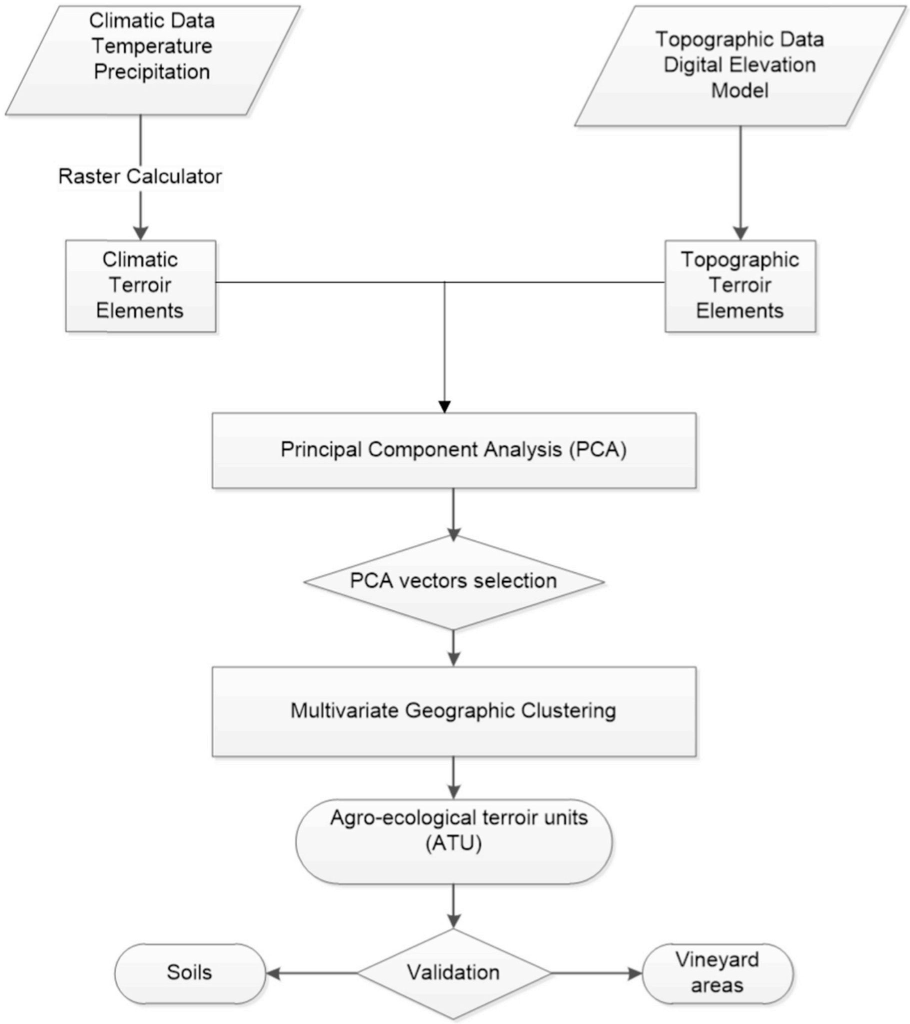

Fig. 3. Schematic explanation of the methodology to delineate Agro-ecological terroir units.

Table 2
Results of the principal component analysis for the six layers. PC loadings and eigenvectors for each variable. Bold values indicate the most dominant loadings of each parameter in the first three PCs.

	Principal component					
	PC1	PC2	PC3	PC4	PC5	PC6
Cumulative variance (%)	**51.86**	**95.11**	**98.62**	99.58	99.95	100.00
Explained variance	0.52	0.43	0.04	0.01	0.00	0.00
Layer	**Eigenvectors**					
Winkler index	**−0.49**	0.34	0.08	−0.06	0.78	0.16
Selianinov index	**0.47**	−0.09	**0.47**	−0.38	0.12	0.63
Cool night index	0.35	0.36	−0.09	0.79	0.07	0.32
Huglin index	**0.52**	0.08	0.32	0.01	0.40	−0.68
Branas index	−0.13	**0.77**	0.38	−0.17	−0.45	−0.09
Elevation	−0.37	−0.38	**0.72**	0.44	−0.09	−0.03

has Temperate nights (CI – I1, > 14 ≤ 18); the latter including the Viticultural sub-regions Rías Baixas, and Baixo Corgo and Cima Corgo (Douro Region).

When considering the Huglin index (HI) the range of values for the NW Iberian Peninsula goes from HI – I (Very cool, ≤1500) to HI – IV (Temperate warm, > 2100 ≤ 2400). Taking into account the summary statistics for the HI, zones 1, 2 and 6 present minimum values of HI – I (≤1500) that correspond to the Very cool viticultural climate class. According to Tonietto and Carbonneau (2004) this class includes all the regions which are at the inferior thermal limit for viticultural production. These heliothermal conditions are suitable only for the very early/early varieties that can reach maturity, especially the white varieties. In this case, most of these areas are not included in the viticultural regions, in Portugal and Spain, and correspond to areas where the elevation is superior to 355 m (up to 1955 m) and where for the Cool night index (CI) the values are under the CI – III (Very cool nights, ≤12). Therefore, the heliothermal potential may not ensure on these ATU or zones (1, 2, and 6) a good level of grape ripening for a given variety (Tonietto & Carbonneau, 2004) and the climatic suitability is very low to null. In fact, some of these areas when included in the Viticultural sub-regions, e.g. in Lima and Monção e Melgaço, are not occupied by vineyards according to Land use and land cover datasets (Fig. 5) (DGT, 2018). In what regards the medium values of HI, only ATU 1 is Very cool (HI – I, ≤1500) and ATU 2 and 6 are cool (HI – II, > 1500 ≤ 1800). The following classes are represented by ATU 5,4, 8, 10 and 12 which are Temperate (HI – III, > 1800 ≤ 2100), and ATU 3, 7 and 11 that are Temperate warm (HI – IV, > 2100 ≤2400). Finally, only ATU 9 is warm (HI – V, > 2400 ≤ 3000).

The Viticultural sub-regions from NW Iberian Peninsula are allocated by the described heliothermal classes in the following way: Temperate – Valdeorras, Monção e Melgaço, Ribeira Sacra, Lima, Rías Baixas, Monterrei, Cávado, and Baião; Temperate warm – Ave, Ribeiro, Basto, Sousa, Paiva, Planalto Mirandês, Chaves, Amarante and Valpaços; and finally Warm – Baixo Corgo, Cima Corgo and Douro Superior, all from Douro region.

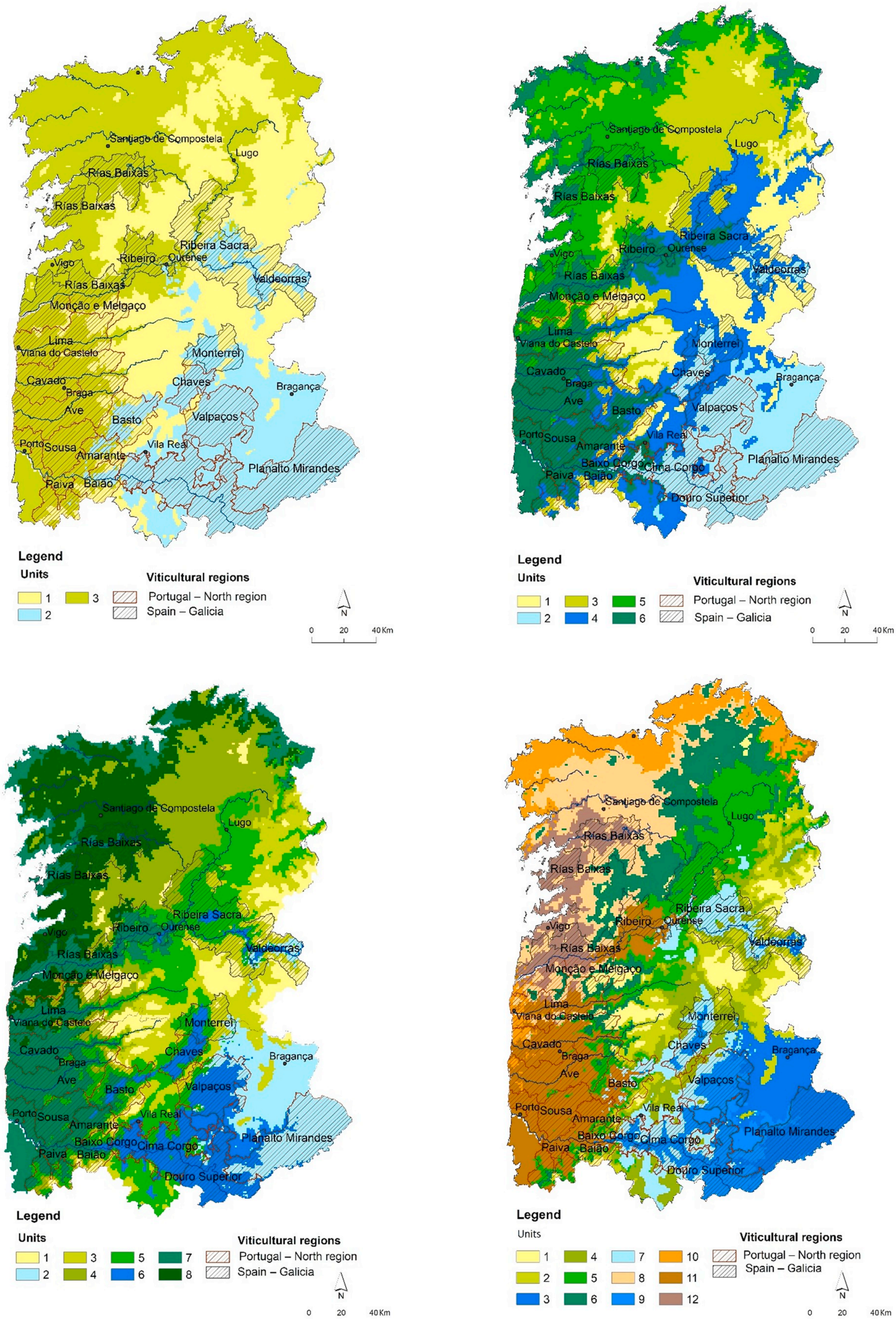

Fig. 4. Maps of grouping schemes of 3-6-8-12 non-contiguous zones or terroir land units resulting from PCA and multivariate zoning.

Table 3
Summary statistics of the variables used in the analysis (bioclimatic indices and elevation). The mean values and standard deviations (SD) of the twelve agro-ecological terroir units (ATU) are listed.

Land units	**1**		**2**		**3**		**4**		**5**		**6**	
Variables	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Winkler index	668.95	104.57	908.91	71.75	1308.31	125.31	1133.91	85.57	1197.77	87.06	1000.11	76.60
Selianinov index	1.61	0.17	1.30	0.13	0.74	0.10	1.13	0.09	1.20	0.08	1.47	0.10
Cool night index	8.99	1.08	10.23	0.56	11.16	0.62	11.28	0.44	12.11	0.36	11.62	0.48
Huglin index	1369.76	140.69	1680.26	85.13	2195.24	123.89	1931.64	101.25	1925.84	106.48	1685.36	89.12
Branas index	3589.45	407.96	3565.65	328.07	2621.94	220.81	3588.52	248.93	4058.23	171.57	4369.20	227.56
Elevation	1175.85	183.43	929.07	121.30	689.93	105.82	762.93	110.20	522.08	96.90	622.20	125.84
Land units	**7**		**8**		**9**		**10**		**11**		**12**	
Winkler index	1435.24	105.37	1206.94	84.85	1709.27	128.52	1309.48	87.83	1539.52	92.96	1483.11	88.80
Selianinov index	0.94	0.07	1.39	0.07	0.70	0.08	1.19	0.07	1.06	0.07	1.23	0.09
Cool night index	12.44	0.45	13.10	0.48	13.28	0.59	13.95	0.52	13.55	0.47	14.61	0.54
Huglin index	2242.04	114.83	1824.88	100.36	2538.11	116.69	1869.41	89.64	2225.30	112.24	2050.60	100.00
Branas index	3574.45	250.18	4710.60	233.90	3066.79	320.28	4236.73	143.82	4265.20	138.12	4894.90	222.75
Elevation	550.67	130.07	378.46	83.26	392.73	119.81	151.78	86.81	226.45	133.76	139.60	86.73

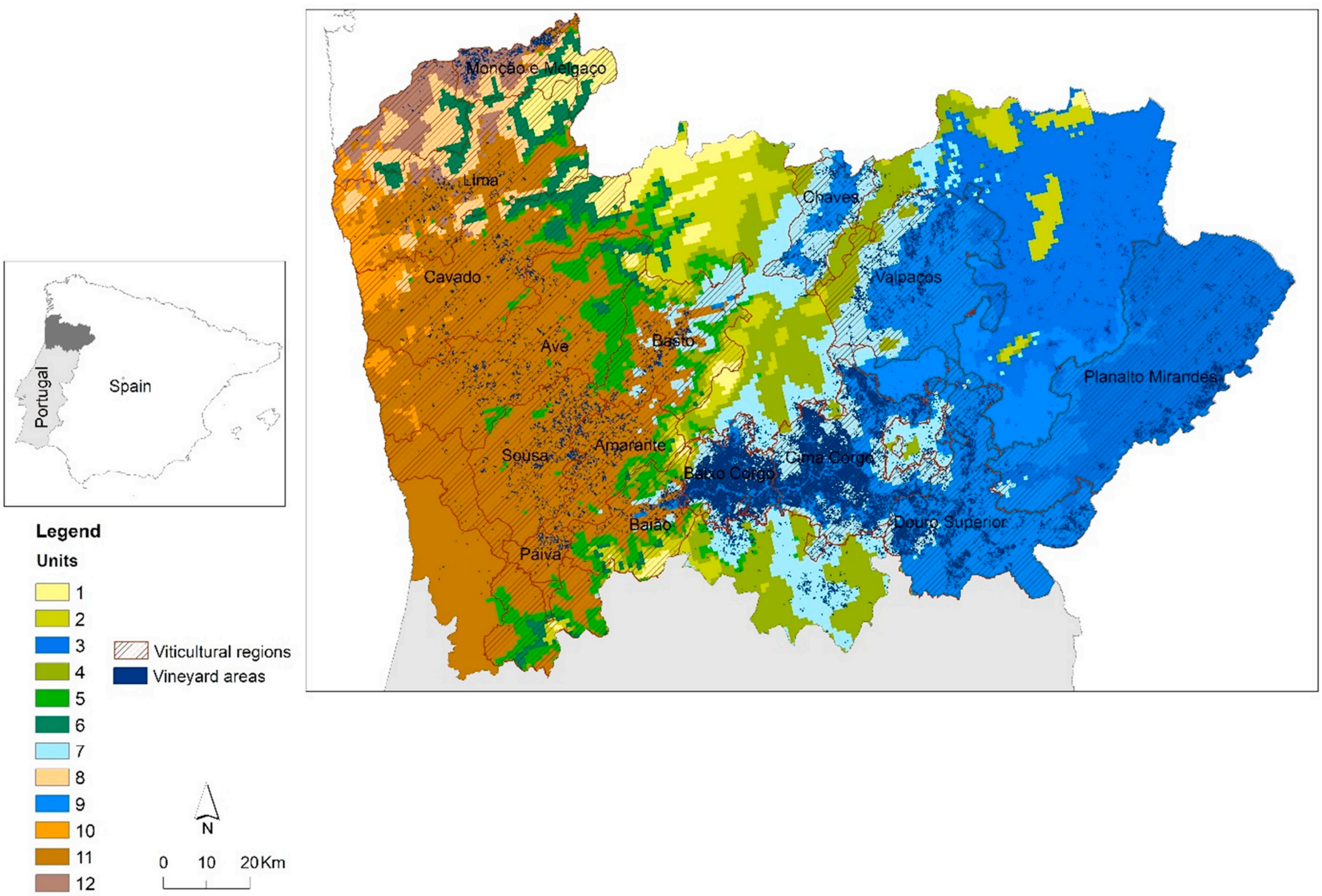

Fig. 5. Overlay of vineyard areas (DGT, 2018) with the 12 non-contiguous zones or terroir land units resulting from PCA and multivariate zoning.

For Branas, Bernon and Levadoux hydrothermic index (BI) (Branas et al., 1946), that evaluates the potential risk of grapevine exposure to diseases such as downy mildew, there is only an area of Planalto Mirandês, in the southeast part of the case study region, that presents a Low risk of contamination (BI – I, ≤ 2500). This Viticultural sub-region is located in Trás-os-Montes and ATU 3 (to a lesser extent in 9), where the climate is defined by very hot summers, with high temperatures and low rainfall. Therefore, is also where for the Selianinov hydrothermic index, that includes precipitation in its definition, is verified an Insufficient hydric regime: (SI – I, < 1). Still for the NW Iberian Peninsula and considering BI index the overall area falls under a Medium risk of contamination (BI – II, > 2500 ≤ 5100), except for an area between the D.O. Rías Baixas sub-regions located near the coast, between the Rias of Vigo and Pontevedra.

When considering the current vineyard areas for validation of results in the Minho Viticultural region these occupy mainly ATU 11 and 12, and only ATU 7 and 9 in the sub-regions Basto and Baião (Fig. 5). In fact, as it was discussed before, the heliothermal potential may not

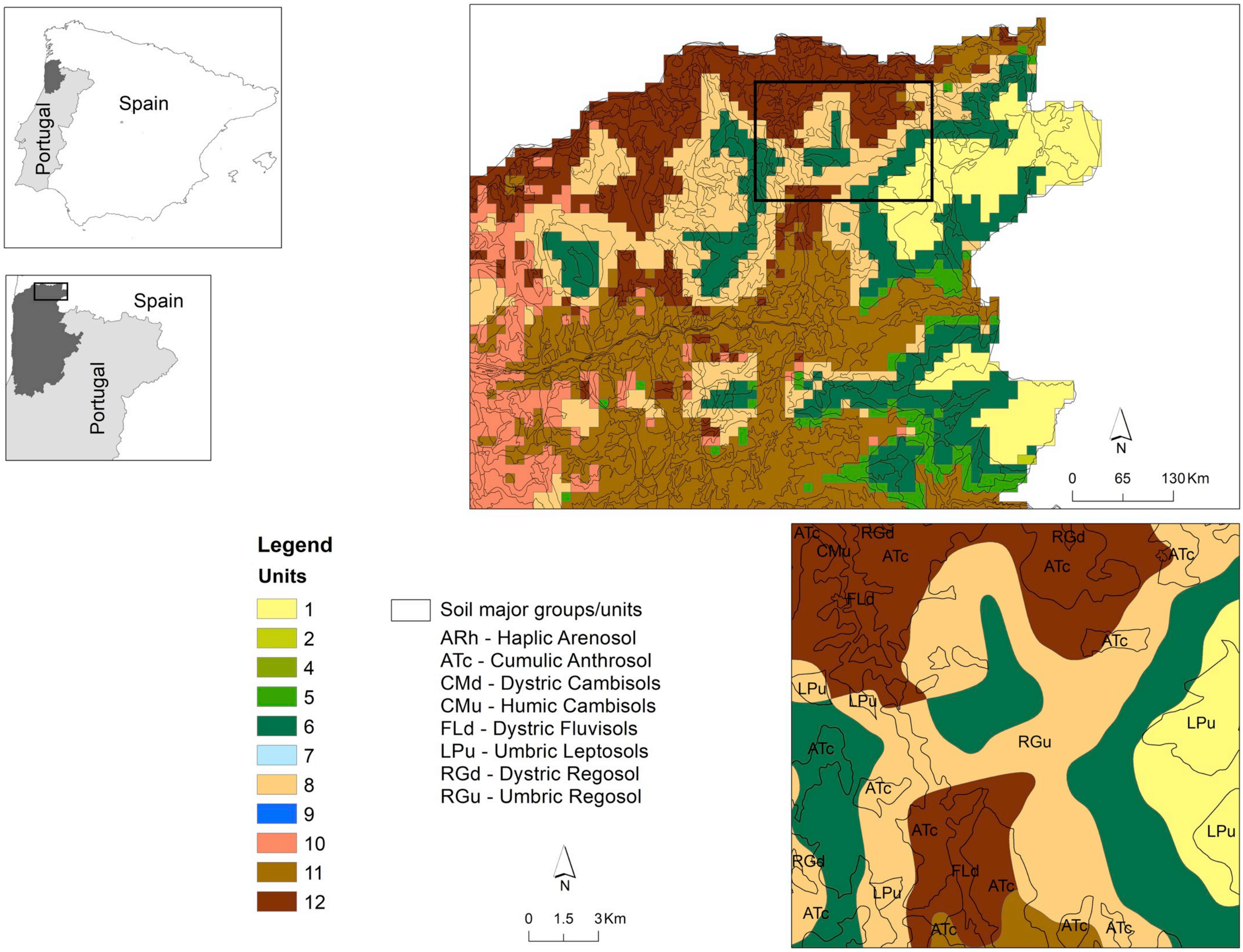

Fig. 6. Integration of soil major groups and units with the 12 non-contiguous zones or terroir land units resulting from PCA and multivariate zoning.

ensure on ATU 1 a good level of grape ripening, as it is an Oro-atlantic ATU where medium elevation is above 1100 m, and as such this ATU is mainly occupied by forestry areas and natural spaces, in particular shrubland (DGT, 2018). Mean Elevation is also above 600 m for ATU 1–4 and 6, which may also explain why these zones are not considered for viticulture in Entre Douro e Minho region, and only ATU 5, and 7–12 have this land cover. Garrido (1984) considers that, in Monção Melgaço sub-region, the main white wine variety Alvarinho, Protected Designation of Origin (D.O.), does not produce quality wine above 300 m of altitude (Garrido, 1984).

In regards to the other Viticultural regions – Douro and Trás-os-montes are mainly located in ATU 3, 7 and 9 where elevation is not a limitation to vineyard suitability, since the macrobioclimate is Mediterranean (Rivas-Martínez, 2011) and the thermal conditions (heliothermal potential) are favourable, since at least all ATU are Temperate warm for the Huglin index (HI – IV, $> 2100 \leq 2400$).

From the integration of soil major groups and units with the twelve non-contiguous zones or agro-ecological terroir units resulting from PCA and multivariate zoning, in Minho, we obtain a more discrete subdivision of the different ATU (Fig. 6). In Table 4 are shown the percentages of soil major groups and units within each terroir land unit for the Minho Region. The region integrates the “Vinho verde” Viticultural Region where vineyards are mostly located within ATU 11 and 12. Here predominate both Cumulic Anthrosols and Umbric Regosols, secondly within ATU 11 – Umbric Leptosols, and in ATU 12 – Humic Cambisols.

In consideration of further improvements to this study we consider to focus on the selection of the highest quality ATU. This could include the hierarchisation of soil major groups and units according to quality for viticulture, as a tool for further characterisation of terroir (Badr et al., 2018; Lázaro-López et al., 2016).

The results also evince that further subdivision of ATU could be achieved with the integration of other environmental parameters such as a continentality index (Rivas-Martínez et al., 2017) or distance to coastline, and the distance to major rivers. This could enhance the subdivision of the “Vinho Verde” Region with a further differentiation of its sub-regions, predominantly integrated in terroir land unit 11, and also achieve a better differentiation between Trás-os-Montes and Douro regions, both included in ATU 3, 7 and 9.

The pertinence of the approach proposed is justified by the potential uses of the spatially explicit results obtained. Therefore, at first these serve for drawing similarities/differences between different viticultural regions, sub-regions and D.O., in Galicia and the North of Portugal that a single region study, more common in terroir zoning literature, does not allow to ascertain. This is the case of the sub-regions Monção e Melgaço and Rías Baixas that correspond both to terroir land unit 12, and between D.O Ribeiro and Cávado or all the “Vinho Verde” Sub-regions, integrated in the terroir land unit 11.

This definition and characterisation of ATU and indirectly of the existent Viticultural regions and sub-regions can serve the purpose to

Table 4
Percentage of soil major groups and units within each terroir land unit for the Entre Douro e Minho region.

Land units	1	2	4	5	6	7	8	9	10	11	12
Soil groups	%										
ARh - Haplic Arenosol									4.79	0.35	0.36
ATc - Cumulic Anthrosol	0.66	8.10	12.33	22.53	6.37	16.58	22.17	44.07	26.04	39.44	35.79
CMd - Dystric Cambisols							0.04		13.94	4.34	
CMu - Humic Cambisols									7.32	1.88	11.63
FLd - Dystric Fluvisols						0.33	0.11		2.67	2.64	5.61
LPu - Umbric Leptosols	58.40	15.24	8.81	4.17	23.80	5.12	7.85		5.23	12.88	7.42
RGd - Dystric Regosol		0.38			0.22		0.41		0.08	0.72	1.10
RGu - Umbric Regosol	40.90	76.28	78.85	73.19	68.95	77.83	69.24	51.32	36.36	30.88	35.66

inform Protected Designation of Origin (D.O.) delimitation procedures, wine marketing management and guide policies for the Viticultural sector, as well as introduce potential activities of sharing of practices between non-continuous homogeneous terroir units with no previous institutional connection.

The results highlight that areas that are currently devoted to other land uses have suitability to the expansion of vineyard according to the ATU obtained, and specifically for certain types of wine and varieties known in those specific zones (e.g. Alvarinho in Monção and Melgaço). As such the results can be of use for different types of territorial and vine/wine-sector agents as a decision support tool.

Therefore, besides product protection terroir zoning is an instrument, not only of use for the development of vitiviniculture, but also for landscape planning, management and conservation of agricultural areas with suitability for viticulture. According to Costantini and Bucelli (2014) the public acknowledgement of the "vocation" of a territory is important not only as an effective tool for the protection of quality and typicity of products, as well as for soil protection.

This is especially relevant at local scale in countries such as Portugal where in general, even if Municipal Director Plans limit urban development in National Agricultural Reserve (NAR) areas[1] or under agricultural land use classification, land use regulation is discretionary and does not establish legal duties to use rural land in particular ways. Consequently, these planning instruments, are alone insufficient to determine the active use of agricultural areas and, if inoperative in terms of planning proposals for rural land uses, put at risk land with potential for viticulture that may be destined for urban development. Suitable areas for quality product may be not protected in Portugal under NAR. This is the case as the best terroir have soils often characterised by moderate chemical fertility (Costantini & Bucelli, 2014), as the vineyard is much less exigent than other agricultural crops in terms of soil fertility and capacity for biomass production.

4. Conclusions

This paper develops an agro-ecological zoning for viticulture at cross-border and regional scale that provides the information needs to further analyse the terroir effect on the wines geographic differentiation for the North West Iberian Peninsula (North of Portugal and Galicia-Spain) wine regions.

The assessment of homogeneous agro-ecological terroir units includes climate and soil environmental factors selected for their relevance at regional scale, with the use of state-of-the-art variables and indices appropriate for the specified regions. The methodology considers the International Organisation of Vine and Wine (OIV) guidelines and it is based upon the development of a Geographic Information System (GIS) that uses multivariate zoning with principal component analysis and clustering procedures.

Within the study area, twelve agro-ecological terroir units were obtained and the results show that climate indices most important for the NW Iberian Peninsula, by descending order, include the Huglin index, Winkler index, Selianinov hydrothermic index and Branas, Bernon and Levadoux hydrothermic index.

Considering the NW Iberian Peninsula agro-ecological terroir units (ATU), and the information provided by the zoning study it is worth highlighting the following:

1. ATU 1–6, 8 and 10 are included in the first Winkler's Region I (WI – I, < 1372); 7, 11 and 12 are second level (WI – II, ≥1372 < 1650) and only 9 is a third level region with median values above 1650 (WI – III, ≥1650 < 1927;
2. ATU 3, 7 and 9 present an Insufficient hydric regime (SI – I, < 1) whereas all the other have a Normal hydric regime (SI – II, > 1 ≤ 3);
3. ATU 1 to 4 and 6 are under the class Very cool nights (CI – III, ≤12), ATU 5 and 7 to 11 have Cool nights (CI – II, > 12 ≤ 14) and only 12 has Temperate nights (CI – I, > 14 ≤ 18);
4. ATU 1 is Very cool (HI – I, ≤1500, 2 and 6 are cool (HI – II, > 1500 ≤ 1800); 5,4, 8, 10 and 12 are Temperate (HI – III, > 1800 ≤ 2100); 3, 7 and 11 are Temperate warm (HI – IV, > 2100, ≤2400); and 9 is warm (HI – V, > 2400 ≤ 3000);
5. There is only an area of Planalto Mirandês, in the southeast part of the case study region, that presents a Low risk of contamination (BI – I, ≤ 2500) by mildew, in Trás-os-Montes and ATU 3 (to a lesser extent in 9);
6. Elevation is above 600 m for ATU 2–4 and 6 and above 1100 m for ATU 1, which influences directly the macroclimate and justifies that these ATU in Minho region are not occupied by viticulture;
7. Vineyard areas in Entre Douro e Minho occupy mainly Cumulic Anthrosols (ATc) and Umbric Regosols (RGu).

When considering the current vineyard areas for validation of results in the Minho Viticultural region these occupy mainly ATU 11 and 12, and only ATU 7 and 9 in the transition sub-regions Basto and Baião. In what regards the other Viticultural regions – Douro and Trás-os-montes are mainly located in ATU 3, 7 and 9. This is mainly justified by the terroir unit's agro-ecological characteristics, evinced by the Viticultural zoning described.

The methodology deployed is suited to delineate homogeneous ATU at "macro" or regional scale (< 1:50.000) and "meso" or local scale, even though for the "micro" or farm/plot scales (> 1:25.000) other zoning procedures should be devised, based on different environmental factors and methodologies. Therefore, this study can integrate a phase of survey before selecting experimental vineyards in order to research subsequently terroir zoning at the "micro" or farm/plot scales. These scales will allow to study the typicality for the Alvarinho Wine through the geographic differentiation of wine, grape, or grapevine characteristics.

[1] Regime of protection of soils with high biomass production capacity that is considered in the National Planning System since 1989, and includes by definition the areas which, due to land characteristics in terms of agro-climatic, geomorphological and pedological conditions, are more suitable for agricultural activity (Decree-Law no. 73/2009).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2019.03.011.

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