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A new integrated methodology for characterizing and assessing suitable areas for viticulture: A case study in Northwest Spain

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ABSTRACT

In 2018, Spain was the third largest producer and the leading exporter of wine in the world. Viticulture is an important economic activity in the Castilla y León region, and is an element capable of halting the flight from the countryside and favouring demographic settlement in rural areas. A new integrated methodology for characterizing and delimitating areas suitable for vineyard cultivation is proposed here. The approach combines traditional climate indices with others used in bioclimatology and with soil variables, and applies various statistical analyses to select the predictors that best characterize the vineyards. These predictors are then integrated in species distribution models and a geographic information system. The methodology was tested in the Denomination of Origin León (hereafter DO León) in northwest Spain. Ten single models using the maximum entropy modelling algorithm were run for each of the six wine-grape varieties. Single-model projections built as a consensus of the ten models into an ensemble-forecasting approach were later used to generate maps of suitable areas for each variety.

The results confirm the delimitation of the DO León as a Denomination of Origin. The bioclimatic variables Compensated Thermicity Index and Continentality Index and the soil variables pH, Clay Content, Soil Retention Capacity and Soil Saturation Humidity are defining for all the varieties studied. Garnacha and Mencía were the most different varieties in relation to their bioclimatic and soil requirements. Suitability maps revealed that the DO could be extended into neighbouring areas up to 30 km around it.

The proposed methodology is a useful tool for agronomic and oenological management; it allows a more effective selection of sites for new vineyards, improves vineyard management, and can even be used to protect territories with a historical and cultural heritage of grape cultivation, thus favouring demographic settlement in rural areas and avoiding depopulation.

1. Introduction

Vineyards are present in 34 countries, and the area under vines is over 32 kha, with a global area under vines of 7.4 mha in 2018 (OIV, 2019). Europe accounts for 53 % of this area, concentrated in Spain, France, Italy and Portugal (36 %).

The wine market has outstanding economic, environmental and social importance for Europe, where it accounts for approximately 67 % of global production and exports (OIV, 2019).

In 2018, Spain had the largest area of wine-exporting vineyards and the third largest in terms of wine production (OIV, 2019). The wine sector therefore plays a key role in both the global wine industry and in the domestic Spanish economy (Fraga et al., 2014a). Most viticultural regions in Spain are organised according to Denominations of Origin

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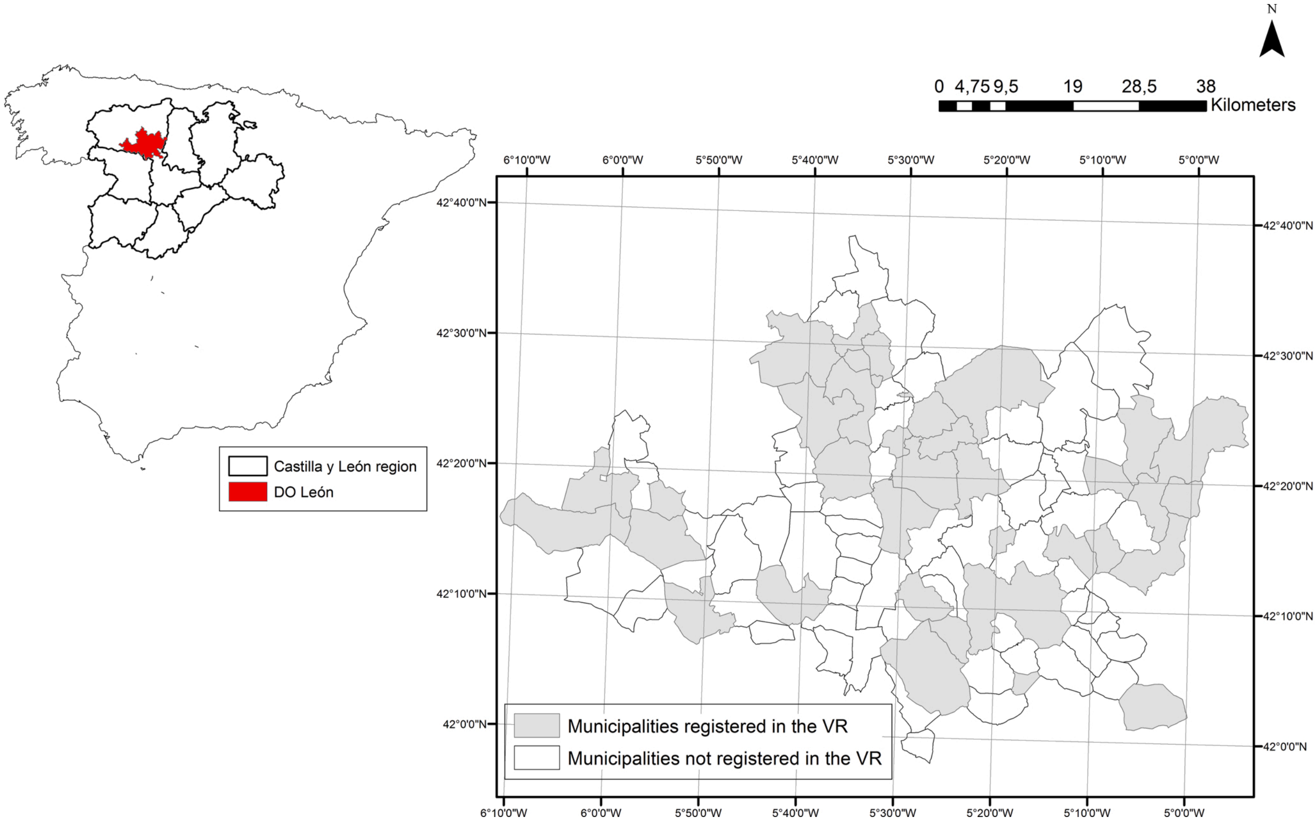

Fig. 1. Location of the study area. VR: Viticola Registry.

(DO) which are imposed by government institutions and controlled by strict regulations. The DO is a concept that identifies a product originating from a particular place, whose quality and characteristics are due fundamentally or exclusively to a specific geographic environment, with its inherent natural and human factors, and whose production phases take place entirely in the geographic area defined (Spanish Conference of Wine Regulatory Councils, CECRV). This is the system used in Spain to recognise a differentiated quality. The DO is thus synonymous with quality and singularity, and describes a product with unique and special characteristics. A specific DO establishes the conditions for the production and preparation of its wines, and combines natural (soil and climate) and human factors (know-how) to ensure they are of the highest quality, linked to their origin. In Spain there are about 70 Denominations of Origin.

The current legislation for wine products is Regulation (EU) 1308/2013 of the European Parliament and of the Council, which establishes a common organization of markets in agricultural products (OJEU L 347 of 20.12.2013), including the regulation of wine products covered by a quality mark (Articles 92–111).

Along with soil elements, climate is one of the most important factors for selecting suitable areas for growing grapevines and zoning wine varieties, and is also decisive in the quantity and quality of the wine (Gladstones, 1992; Ruml et al., 2012; Moral et al., 2014; Ramos et al., 2015; Irimia et al., 2018; Honorio et al., 2018; Sánchez et al., 2019).

The analysis of climate in a wine-growing region is essential for understanding its suitability and sustainability for wine production (Carbonneau, 2003). Wine grapes are very sensitive to long- and short-term climate fluctuations, which could have consequences for the economy of wine-growing areas in the future.

Several authors have studied the climate characteristics of numerous wine-producing regions in different ways and at different scales, for instance: worldwide (Tonietto and Carbonneau, 2004; Jones et al., 2009); Europe (Malheiro et al., 2010; Santos et al., 2012); Australia (Hall and Jones, 2010; Jarvis et al., 2017); Chile (Montes et al., 2012); England (Nesbitt et al., 2018); Italy (Herrera et al., 2011); New Zealand (Anderson et al., 2012), Portugal (Santos et al., 2011; Fraga et al., 2013, 2014b; Costa et al., 2019); Scotland (Dunn et al., 2017); Serbia (Ruml et al., 2012); Romania (Irimia et al., 2018); USA (Jones et al., 2010).

For Spain as a whole or for smaller areas it is worth mentioning, among others: Blanco-Ward et al. (2007), Ramos et al. (2008), Camps and Ramos (2012), Lorenzo et al. (2013), Fraga et al. (2014a), Moral et al. (2014), Resco et al. (2016), González-Fernández et al. (2017, 2019), Esteban and Climent (2018), Honorio et al. (2018), Sánchez et al. (2019).

Climatic and bioclimatic indices are useful metrics for assessing the influence of climate on vineyards, and several have been described in the literature for application in viticulture. The most frequently used (mainly associated with temperature and rainfall parameters) are: Branas Index (Branas et al., 1946); Huglin Index (Huglin, 1978); Wrinkler Index (Winkler et al., 1974); growing season temperature (Jones, 2006); growing season precipitation (Mullins et al., 1992); and cool night index (Tonietto, 1999). Nevertheless, as highlighted by Honorio et al. (2018), it is also important to combine different indices for a better assessment of climate differences in the case of wine production, and to determine the suitability of the area under study for wine growing.

In agreement with Honorio et al. (2018), and based on the results of this study, the authors also propose integrating certain parameters and bioclimatic indices from "The Worldwide Bioclimatic Classification System" (WBC) (Rivas-Martínez et al., 2011) in studies on viticulture, due to their high predictive value. Bioclimatology is an ecological science that studies the relationship between the climate and the distribution of living beings and their communities on the earth. It has a very high predictive value and has applications in other natural sciences and in programmes for the study and conservation of biodiversity and habitats, and can be used to predict agricultural and forestry resources, in climate change studies, and others (Rivas-Martínez et al., 2011).

Table 1
Climatic/bioclimatic initial variables taken into consideration in the study. * Final selected variables.

Climatic/ bioclimatic variables	Definition /formula	Source
Annual Ombrothermic Index (IO) *	IO = (Pp/Tp) 10 Pp = Positive Precipitation, Tp = Positive Temperature	Rivas-Martínez et al. (2011)
Growing Season Maximum Temperature (GSTmx)	GSTmx = ∑ Tmx from April to September Tmx = Maximum temperature	Ramos et al. (2008)
Growing Season Minimum Temperature (GSTmn)	GSTmn = ∑ Tmn from April to September Tmn = Minimum temperature	Ramos et al. (2008)
Growing Season Mean Temperature (GST)	GST = ∑ T from April to September T = Mean temperature	Malheiro et al. (2010)
Coldest month of the year (TCmin)	TCmin = Average temperature of the coldest month of the year	Rivas-Martínez et al. (2011)
Continentality Index (IC) *	IC = Tmax- Tmin Tmax = Average temperature of the warmest month, Tmin = Average temperature of the coldest month	Rivas-Martínez et al. (2011)
Cool Night (CN)	CN = Minimum temperature of September	Tonietto and Carbonneau (2004)
Fourmonthly Estival Ombrothermic Index (Ios_4)	Ombrothermic index of the four warmest months	Rivas-Martínez et al. (2011)
Growing Season Precipitation (GSP) *	GSP = ∑ P from April to September P = Precipitation	Blanco-Ward et al. (2007)
Huglin Index (HI)	HI = ∑ k [((Tmx-10) + (Tmn-10))/2] from April to September k = length of day coefficient (dependent on the latitude of the location); Tmx = Maximum temperature, Tmn = Minimum temperature	Huglin (1978)
Hydrothemic Index of Branas (BI) *	BI= ∑ T x P from April to September T = Mean temperature, P = Precipitation	Branas et al. (1946)
Positive Precipitation (Pp)	Pp = Yearly precipitation in mm of months with an average temperature above 0 °C	Rivas-Martínez et al. (2011)
Positive Temperature (Tp)	Tp = Sum of the average monthly temperatures above 0 °C (in tenths of degree)	Rivas-Martínez et al. (2011)
Temperature Range During Ripening (DTR)	$DTR = Tmx_9 – Tmn_8$ Tmx_9 = Maximum temperature of September, Tmn_8 = Minimum temperature of August	Mullins et al. (1992)
Thermicity Compensated Index (ITC) *	ITC = (Ty + M+m)*10 Ty = Yearly average temperature, M = Average maximum temperature of the coldest month of the year, m = Average minimum temperature coldest month of the year	Rivas-Martínez et al. (2011)
Wrinkler Index (WI)	WI= ∑ ((Tmx + Tmn)/2)-10 from April to October Tmx = Maximum Temperature, Tmn = Minimum Temperature	Winkler et al. (1974)

In addition to identifying the climate and soil characteristics of wine-growing regions, the spatial delimitation of suitable areas for vineyard plantation is very important for viticulture as it allows comparisons between wine regions and offers growers a measure for assessing appropriate cultivars and sites (Jones et al., 2010).

Some authors have used different methodologies (multivariate analysis, fuzzy techniques, weighted overlays, multicriteria analysis, etc.) combined with geographic information systems (GIS) to delimitate suitable locations for vineyard plantation: Sertel et al. (2011), Irimia et al. (2013), Tagarakis et al. (2014), Moral et al. (2014, 2016), Bollati et al. (2015), González-Fernández et al. (2017, 2019), Zorer et al. (2017), Nesbitt et al. (2018), Alganci et al. (2019), Alsafadi et al. (2020), Beauchet et al. (2020), Cogato et al. (2020), Wanyama et al. (2020).

Species distribution models (SDMs) are numerical tools that combine observations of species occurrence or abundance and environmental estimates (Elith and Leathwick, 2009). MaxEnt (maximum entropy approach) is one of the most commonly used distribution modelling tools for predicting species distributions and environmental tolerances using occurrence data (Warren and Seifert, 2010; Tóth and Végvári, 2016). SDM is also recognized as a powerful method to forecast the most likely impact of climate change on the geographic distribution of a target species by means of environmental data and future global climate model (GCM) outputs (Pecchi et al., 2019). Very few researches have studied the impact of climate change on viticulture using this methodology (Callen et al., 2016; Roehrdanz and Hannah, 2016), and even fewer studies (Tóth and Végvári, 2016; Callen et al., 2016), García-Martínez (2019) have applied this technique to analyse the current potential distribution for wine-grape cultivation.

This study proposes a new integrated methodology for the characterization and delimitation of suitable areas for the cultivation of vineyards. The approach combines traditional bioclimatic indices with others used in bioclimatology, and with soil variables. Several statistical analyses were also considered in order to select only the significant predictors that best characterize the vineyards.

The variables selected are then integrated in SDMs and GIS to delimit suitable areas for vineyard plantation. The main aim of the study is to provide a useful, objective and universal tool for the bioclimatic and soil characterization of vineyards, and to accurately delimit suitable areas for their plantation.

2. Material and methods

2.1. Study area

The northwest part of the Iberian Peninsula is a very productive wine-growing area, with certain zones awarded their own Denomination of Origin (DO) (Lorenzo et al., 2012). The proposed methodology has been tested in the Denomination of Origin León (DO León) (Fig. 1).

The DO León is located in the northwest quadrant of Spain (Castilla y León region), specifically in the south of the León province. It includes part of the Valladolid province and borders the provinces of Zamora and Palencia (DO León Regulatory Council). The production area is about 3317 km^2, with a registered area of 1369 ha. The soils are very suitable for vine cultivation as they are established on alluvial terraces. The altitudes do not exceed 900 m. The average temperature in the summer months is above 20 °C, the autumns are mild, and there is persistent fog and frost in the winter, although without exceeding absolute minimum temperatures of -15 °C. The average annual rainfall is about 500 mm, distributed during the summer and autumn periods (so vineyards only exceptionally require watering). There is high luminosity (with an average of 2,700 h of sunshine per year) and strong continentality.

The particularity of this area, which differentiates it from other wine-producing areas in the world, is its native grape variety – Prieto Picudo – used for the production of rosé and red wines, and Albarín used for white wines. The authorized varieties in this DO are: Prieto Picudo and Mencía (red grapes), Tempranillo and Garnacha (complementary red grapes), Albarín, Verdejo and Godello (white grapes), and Malvasía and Palomino (complementary white grapes).

Most of the territories (municipalities) in the DO León suffer from a widespread problem of depopulation, shared with the rest of the rural areas of Castilla y León. A marked demographic decline has been observed since 2008 (the date the DO was established) with an average density of 16.83 inhabitants per square kilometre in 2008, falling to 15.57 inhabitants in 2019; a mean value that is far lower than for the province of León as a whole (31.74 and 29.55) and a considerable

Table 2
Soil initial variables taken into consideration in the study. * Final selected variables.

Soil variables	Definition /formula	Source
Clay Content (CC) *	Percentage by weight of fine soil in the sample. Particles with a diameter less than 0.002 mm	ITACYL-AEMET (2013) USDA
Field Capacity (FC)	Moisture content present in the soil matrix after free draining for 2 or 3 days after rain or heavy watering. It depends solely on the soil texture and is not affected by salinity or gravel content. It is expressed as volumetric humidity in percentage, that is, the volume of the liquid fraction with respect to the volume of the soil sample	Atlas ITACYL-AEMET (2013)
Organic Matter Content (OM)	Organic matter content expressed as a percentage by weight	ITACYL-AEMET (2013)
Permeability (PE) *	Permeability defines the speed with which a saturated soil transmits water through it under the influence of gravity. A soil is saturated when all of its pores are filled with water, and therefore the permeability value is at its maximum. It is expressed as mm per day	ITACYL-AEMET (2013)
pH *	Soil acidity expressed as pH	ITACYL-AEMET (2013)
Sand content (SC) *	Percentage by weight of fine soil in the sample. Particles with a diameter between 0.05 and 2 mm	ITACYL-AEMET (2013) USDA
Silt content (SLC) *	Percentage by weight of fine soil in the sample. Particles with a diameter between 0.002 and 0.05 mm	ITACYL-AEMET (2013) USDA
Soil retention capacity (SRC) *	Maximum amount of water available to plants that can store a given soil. It is the difference between the water content at Field Capacity and Wilting Point. It is expressed as volumetric humidity in percentage, that is, the volume of the liquid fraction with respect to the volume of the soil sample	ITACYL-AEMET (2013)
Soil saturation humidity (SSH) *	Moisture content in the soil matrix when all of its pores are filled with water. It depends solely on the soil texture and is not affected by salinity or gravel content. It is expressed as volumetric humidity in percentage, that is, the volume of the liquid fraction with respect to the volume of the soil sample	ITACYL-AEMET (2013)
Wilting point (WP)	Soil water content retained so firmly that plants cannot extract it causing irreversible wilt. It depends solely on the soil texture and is not affected by salinity or gravel content. It is expressed as volumetric humidity in percentage, that is, the volume of the liquid fraction with respect to the volume of the soil sample	Atlas ITACYL-AEMET (2013)

distance from the rest of Spain (91.38 and 93.7).

A more precise knowledge of the bioclimatic and soil factors that characterize the vineyards in the DO can help promote and reactivate this economic activity in the area and thus halt the demographic decline observed in the last decade.

2.2. *Data on the presence of grapevines*

Data from vineyards planted in the study area and contained in the Wine-growers' Registry of Castilla y León (Registro Vitícola, hereafter VR) were provided by the DO León. All cultivated vineyard plots must be registered in the VR. These data were combined with information from the Geographic Information System of Agricultural Plots (SIGPAC) using ArcGis 10.6 (ESRI, 2018). SIGPAC is a GIS application from the Spanish Government (Ministry of Agriculture, Food and Environment) that geographically identifies the plots declared by farmers and ranchers. The areas for each grapevine variety were converted to point features using conversion tools for application in species distribution models (SDMs).

Table 3
Variables that characterize better each variety (**X**). ALB: Albarín, GAR: Garnacha, MEN: Mencía, PIC: Prieto Picudo, TEM: Tempranillo, VER: Verdejo.

	ALB	**GAR**	**MEN**	**PIC**	**TEM**	**VER**
Bioclimatic variables						
Annual Ombrothermic Index (IO)	X			X		
Continentality Index (IC)	X	X	X	X	X	X
Temperature Range During Ripening (DTR)		X				
Growing Season Precipitation (GSP)			X		X	X
Hydrothermic Index of Branas (BI)		X				
Thermicity Compensated Index (ITC)	X	X	X	X	X	X
Edaphic variables						
Clay content (CC)	X	X	X	X	X	X
Permeability (PE)	X		X	X	X	X
pH	X	X	X	X	X	X
Sand content (SC)	X	X		X		
Silt content (SLC)		X	X			
Soil retention capacity (SRC)	X	X	X	X	X	X
Soil saturation humidity (SSH)	X	X	X	X	X	X

Data on six varieties (Albarín, Garnacha, Mencía, Prieto Picudo, Tempranillo and Verdejo) were considered in this study. Godello, Malvasía and Palomino were not included in the study due to their scarce representation in the DO. A total of 2440 points of occurrence were used in this study.

2.3. *Selection of predictor variables and characterization of each variety*

Climate (mean monthly maximum and minimum temperatures and rainfall data) and soil data for the period 1981–2010 were compiled from layers obtained from the Castilla y León Agroclimatic Atlas (ITACYL-AEMET, 2013). The continuous surfaces of these variables were later used to generate several parameters and bioclimatic layers at the spatial resolution of 500 m using Map Algebra.

We initially took into consideration the agroclimatic and bioclimatic indices previously used and accepted for an understanding of the climate characteristics that are favourable for viticulture (Jones et al., 2010), as well as others that have not traditionally been used with vineyards, namely the bioclimatic parameters and indices proposed in the Worldwide Bioclimatic Classification System (Rivas-Martínez et al., 2011).

In the first stage of this study, 26 variables were used based on previous research on viticulture and on expert criteria. They were grouped into two categories: bioclimatic variables (16) (Table 1) and soil-related variables (10) (Table 2).

Several statistical techniques were applied to determine the bioclimatic and soil variables that best characterize and differentiate each wine-grape variety in the DO León, and thus identify potential suitable areas for their plantation. The combination of statistical techniques and expert knowledge can improve the quality of the suitability models (Tourne et al., 2019).

The models must be easy to interpret if they are to be useful for decision-making. The problem of multicollinearity with a large number of indices is aggravated when models are built with a substantial number of common variables, as in our case. The coefficients become very sensitive to small changes in the data and can address the "wrong sign", thus invalidating both the model and the results.

In order to reduce multicollinearity and dimensionality, a factorial

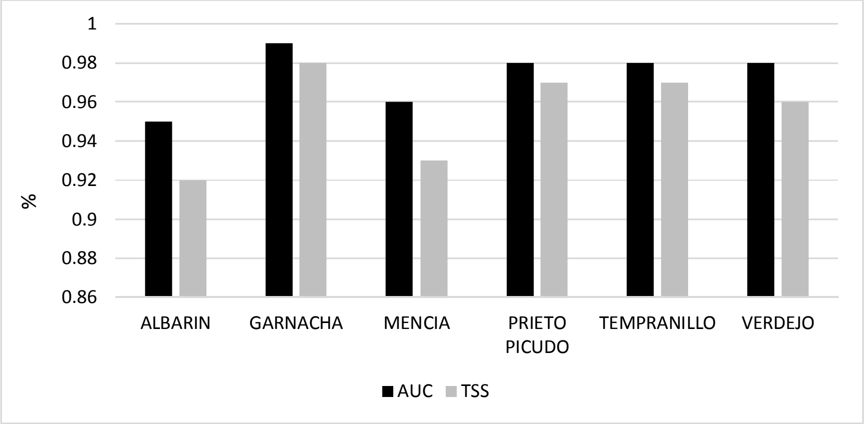

Fig. 2. Average of the AUC and TSS values for 10 runs. AUC: Area under the curve, TSS: True skill statistic.

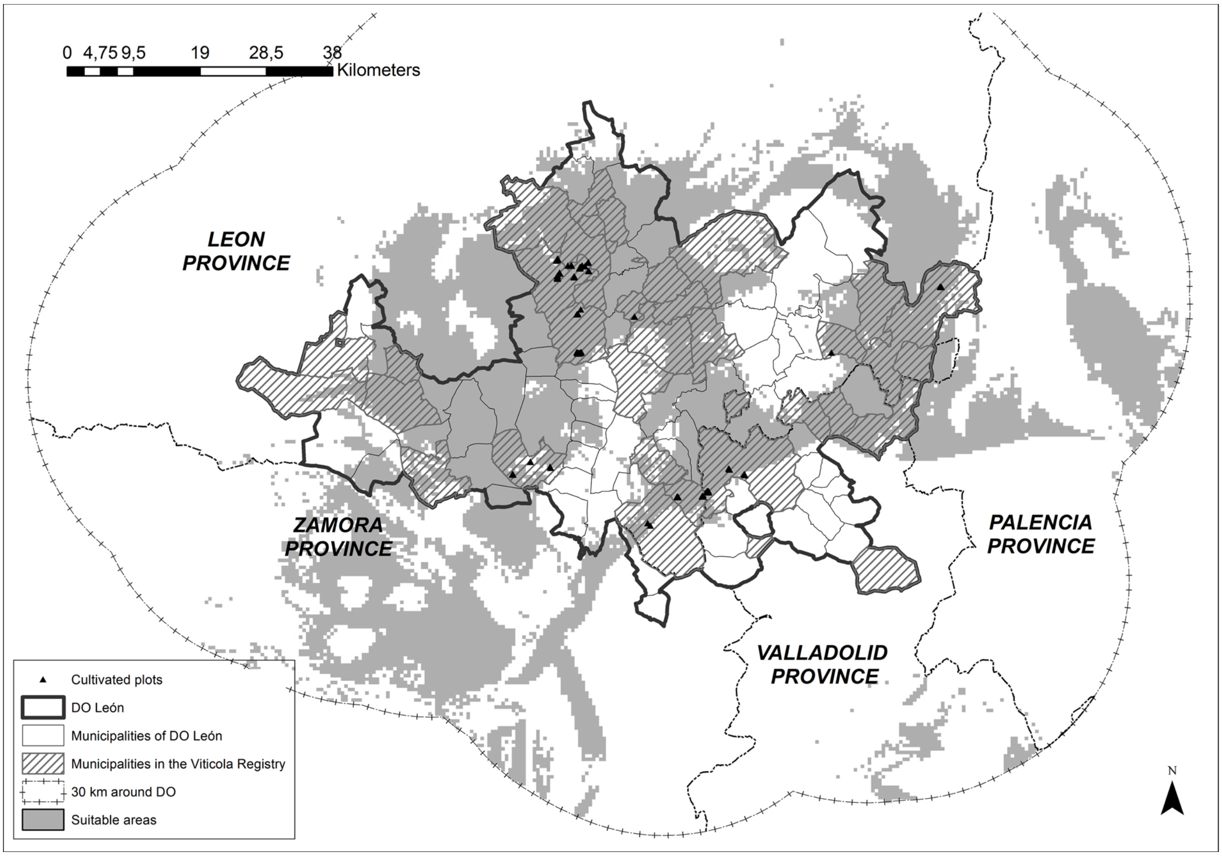

Fig. 3. Suitable areas for Albarín.

Table 4
Squared kilometres forecasted by the ensemble models for each variety. VR: Viticola Registry. Total includes overlapping areas.

	Municipalities VR (MaxEnt) (km^2)	DO (MaxEnt) (km^2)	DO + buffer 30 km (MaxEnt) (km^2)
ALBARIN	1032,25	2029.25	4131.75
GARNACHA	281.75	479.25	1117.00
MENCIA	830.00	1765.00	3466.25
PRIETO PICUDO	1211.50	2388.50	4302.50
TEMPRANILLO	1128.00	2277.25	4301.00
VERDEJO	866.00	1798.00	2625.00
TOTAL	1288.75	2628.00	6417.75

analysis with principal components extraction method was applied in this research for each grape variety (Tabachnick and Fidell, 2007; Vieira et al., 2012; Cruz-Cárdenas et al., 2014; Tourne et al., 2019). The factors explaining at least 90 % of the total variance were retained.

The correlations between variables and factors were analysed to obtain the predictors that contribute the most to explaining the variance in each factor and to interpreting how the set of variables can be related to each type of grape. In this orthogonal factor model, the factors can be used as uncorrelated latent variables, thus avoiding the multicollinearity problem. These statistical analyses were carried out using the software package IBM SPSS Statistics v.25.0 (IBM Corp. Released, 2017).

The selected variables must be rejected if the multicollinearity persists. The next step was therefore to apply a correlation analysis to the

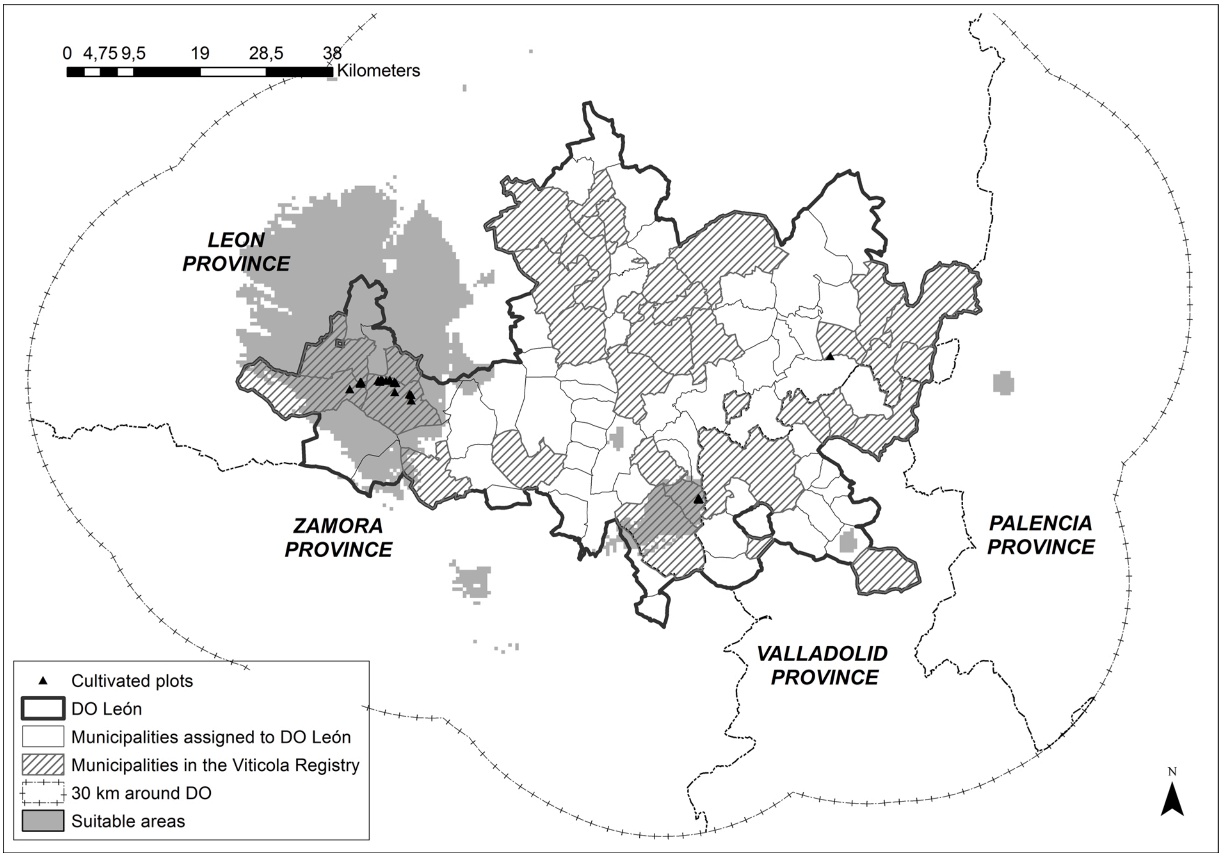

Fig. 4. Suitable areas for Garnacha.

variables retained previously using the VIF (variance inflation factor) function included in the usdm R package (Naimi et al., 2014). Correlated variables were finally rejected. Correlation analyses were run for each group of variables and for each variety.

The variables finally selected were used to generate maps of potential suitable areas for planting each wine-grape variety in the DO León using species distribution models (SDMs).

All the analyses previously described allowed us to establish the bioclimatic and soil requirements that characterize and discriminate the grapevine varieties in the study area.

2.4. Delimitation of suitable areas for each variety

The maximum entropy modelling algorithm (MaxEnt) included in Biomod version 2 (Thuiller, 2003) in RStudio version 4.03 (R Core Team, 2019) was used to model suitable areas for planting each variety. MaxEnt uses a machine-learning algorithm that applies the principle of maximum entropy to predict the potential distribution of species from presence-only data and environmental variables (Phillips et al., 2004).

This methodology allows the combination of several variables. Honorio et al. (2018) pointed out the need to combine bioclimatic indices to better assess the climate differences in wine production and the wine-growing suitability of the Spanish territory.

Single models were run for each variety. The occurrence data were randomly partitioned into 80 % for training and 20 % for testing (Fielding and Bell, 1997) to evaluate the quality of the predictions. The recommended default parameters for MaxEnt (Phillips and Dudík, 2008) and for Biomod (Thuiller et al., 2009) were used. The procedure was replicated ten times to obtain more robust estimations (Elith et al., 2011), meaning that a total of 60 single models were computed. Two different statistical measures available in Biomod were considered to estimate the model performance: area under the curve (AUC) of a receiver operating characteristic plot (ROC) and the true skill statistic (TSS). We also use TSS to obtain information on the specificity and sensitivity of the models: specificity reflects a model's ability to correctly predict an absence at a location, and sensitivity reflects its ability to correctly predict a presence at a location (Freeman and Moisen, 2008).

Ensemble-forecasting models were then generated for each variety of grapevine by computing a consensus of single-model projections (Araújo and New, 2007; Thuiller et al., 2009). The ensemble models were built by giving higher importance to models with a better performance according to the criteria of AUC and TSS (only models with AUC $\geq$ 0.95 and TSS $\geq$ 0.85 were selected to create the ensemble models). The median probability of occurrence across the selected models for each grid cell was used in their construction.

The results of the distribution modelling from probabilities were transformed to binary maps (of 0 and 1) using a probability threshold that maximizes sensitivity and specificity to differentiate suitable and non-suitable areas for each grape variety. This threshold has been proven to be a good approach in threshold determination (Allouche et al., 2006; Jiménez-Valverde and Lobo, 2007). Maps of habitat suitability were imported into ArcGis 10.6. Geographic information systems (GIS) are a powerful tool to analyse terroir potential in new wine regions. Terroir relates the sensory attributes of wine to the environmental conditions in which the grapes are grown (Van Leeuwen and Seguin, 2006).

Suitable areas were analysed for each variety and for three possible contexts:

1) within the municipalities registered in the Viticola Registry
2) for the whole of the production area
3) adding a buffer of up to 30 km around the DO to identify suitable areas outside the production zone which are not currently occupied by vineyards but have adequate conditions for their plantation.

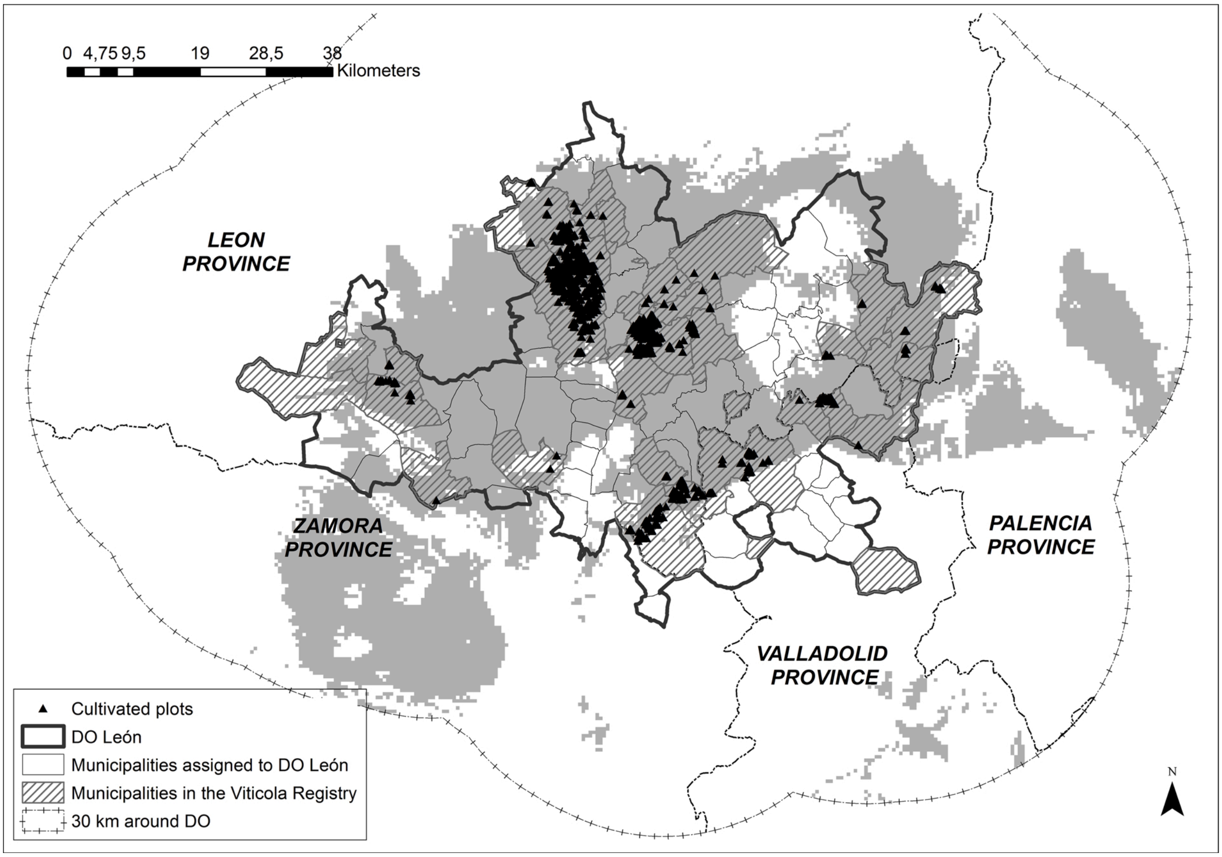

Fig. 5. Suitable areas for Prieto Picudo.

3. Results and discussion

3.1. Selection of predictor variables and characterization of each variety

Factorial Analysis and the study of the correlation and multicollinearity of the variables allowed us to establish the final set of predictors for characterizing and delimitating the vineyards in the León DO. The analyses revealed that 13 variables (out of the 26 analysed, Tables 1 and 2) were key for characterizing the varieties in the study area. The set of 13 predictors comprises six bioclimatic variables: Annual Ombrothermic Index (IO), Continentality Index (IC), Growing Season Precipitation (GSP), Hydrothermic Index of Branas (BI), Compensated Thermicity Index (ITC) and Temperature Range During Ripening (DTR); and seven soil predictors: Clay Content (CC), Sand Content (SC), Silt Content (SLC), Permeability (PE), pH, Soil Retention Capacity (SRC) and Soil Saturation Humidity (SSH). These results confirm that some of the bioclimatic indices proposed by Rivas-Martínez et al. (2011) can be useful for the characterization of vineyards, and that soil also plays a key role in viticulture.

The summary of the main descriptive statistics for the 13 variables selected and for each variety is shown in Table S.1. The results for the Compensated Thermicity Index (ITC: 172–220) (Table S.1.A) reveal that the DO León belongs to the lower supramediterranean thermotype (according to Rivas-Martínez et al., 2011), and more specifically to the weak lower supramediterranean. The highest values for this index are observed in the southernmost areas of the DO. These results agree with the areas observed by us for grapevine cultivation in Spain, which are typically mesomediterranean and lower supramediterranean. This bioclimatic index, also known as the “cold index” takes into consideration the annual mean temperature and the maximum and minimum temperatures of the coldest month of the year. The physiological processes of many grapevines begin when temperatures reach around 10 °C (Bernardo et al., 2018), so this index can be very useful for delimitating suitable areas for viticulture.

Values for the Annual Ombrothermic Index (IO) range from 2.8 to 3.73 (Table S.1.B), meaning that the DO belongs to the lower subhumid ombrotype (Rivas-Martínez et al., 2011). These results are in agreement with data observed by us for Spanish grapevine cultivation (although these findings are not yet published). The lowest values for this bioclimatic index (and therefore the driest conditions) were observed in the southern territories of the study area.

The values for the Continentality Index (IC) (Table S.1.C) indicate that the types of continentality for DO León vineyards ranged from the weak euoceanic type (IC: 15.0–17.0), mainly located in the northern and westernmost areas of the DO, to weak semicontinental (IC: 17.0–19.0) (Rivas-Martínez et al., 2011). The highest continentality values occur in the southeast of the study area, and the most oceanic territories are located in the western zones.

The Branas Index (BI) takes into account the influence of both temperature and precipitation, and is a good indicator for grape yield and wine quality, as it assesses the potential risk of exposure by grapevines to diseases such as mildew. The risk of contamination with mildew is generally considered low for Branas values below 2500 (Malheiro et al., 2010; Lorenzo et al., 2016). All the Branas (BI) values in the DO León were < 2500, and ranged from 1787 (for Prieto Picudo) to 2202 (for Mencía) (Table S.1.D).

The highest mean data for Temperature Range During Ripening (DTR) correspond to the westernmost parts of the study area, and are associated with plots planted with Garnacha (18.5 °C) (Table S.1.E). Gatto et al. (2009) also reported values of 17−19 °C for this variety in California.

Growing Season Precipitation (GSP) is one of the most discriminating climate variables for vineyards in northwest Spain in current conditions (Blanco-Ward et al., 2007). It is an essential variable, as rainfall during

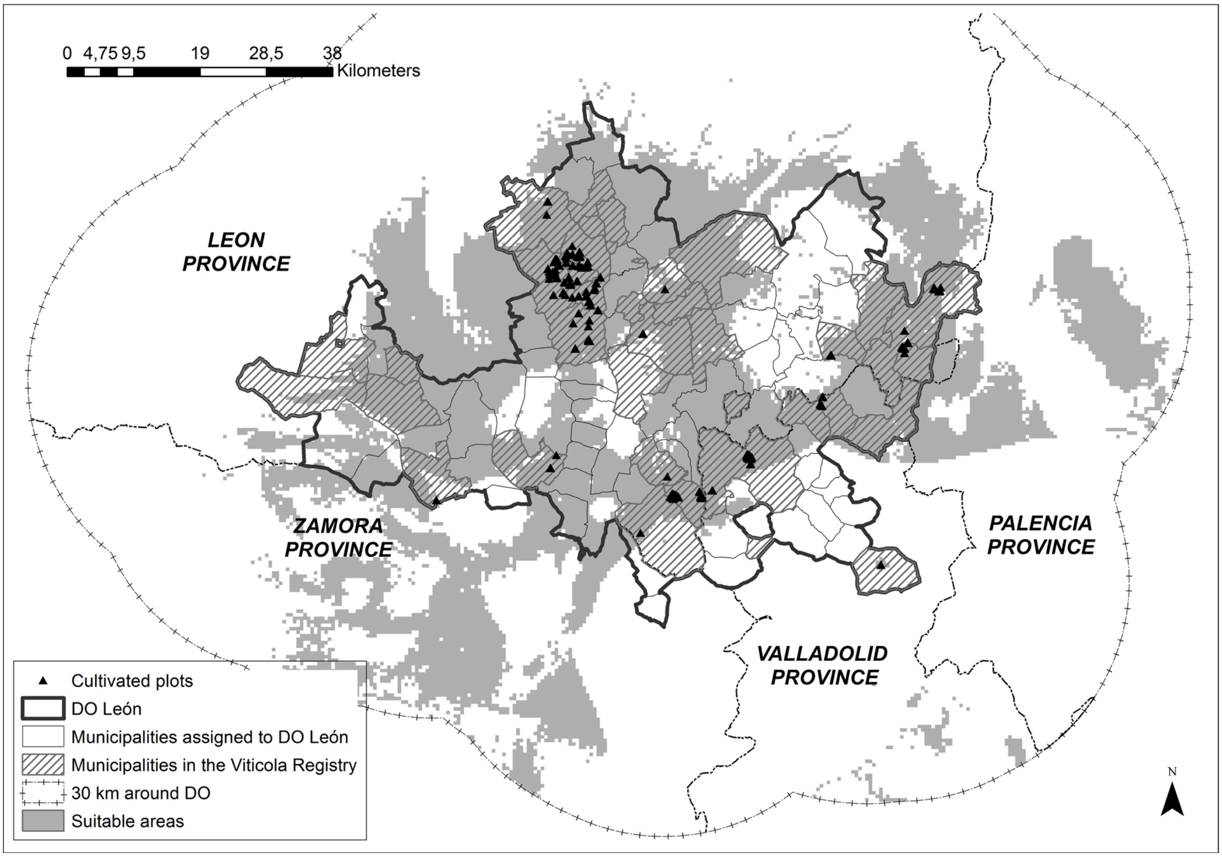

Fig. 6. Suitable areas for Tempranillo.

critical growth stages may have fatal effects on wine production and quality. The values for this variable for vineyards in the DO León ranged from 176.74 mm (for Prieto Picudo) to 226.09 mm (for Mencía) (Table S.1.F). The lowest figures were noted in the south of the study area, coinciding with the lowest values of the Annual Ombrothermic Index (IO).

Soil texture refers to the relative content of sand (SC), clay (CC) and silt (SLC) particles and is also crucial in viticulture. Sandy soils are coarse and usually excessively drained, with low water retention capacity (Fraga et al., 2014a). Clay soils have fine particles and retain large amounts of water, although they are poorly drained and generally difficult to manage (Fraga et al., 2014a). Loamy soils have a relatively even balance of particle proportions and are typically well drained with sufficient nutrient retention for viticulture (Lanyon et al., 2004), making them favourable for agricultural use (Fraga et al., 2014a). For DO León vineyards, the percentage of Sand Content (SC) (Table S.1.G) ranges from 34.3–57.6; from 15.9–29.4 for clay (CC) (Table S.1.H) and from 22.1–48.3 for silt (SLC) (Table S.1.I).

Based on these data, and according to the USDA soil texture classification (USDA, 2006), the soils of the DO León are classified as having a loamy texture (Category 9). Winkel et al. (1995) and Carey et al. (2008) suggest that loamy soils may be conducive to high quality wines. Our results agree with those of Fraga et al. (2014a). Garnacha (39.8) and Mencía (47.8), the dominant varieties in the western areas of the DO, have the lowest SC requirements (Table S.1.G). Conversely, these varieties have the highest needs for SLC (41.1 and 33.4, Table S.1.I).

90 % of vineyards are distributed in soils with pH values ranging between 7.14 and 8.03 (Table S.1.J). The Garnacha variety has the lowest requirements for this predictor. The soils with the highest pH values are located in the southeast of the DO.

Permeability values (PE) for the vineyards in the study fluctuate between 128 and 546 (Table S.1.K). It is worth noting that Garnacha and Mencía (and to a lesser extent Tempranillo) show values below the average. The areas with the lowest levels for this variable are situated in the east of the study area.

The descriptive statistics for the two variables associated with hydraulic properties, Soil Retention Capacity (SRC) and Soil Saturation Humidity (SSH), are shown in Table S.1. L and Table S.1.M. Both parameters are expressed as volumetric moisture in percentage, that is, the volume of the liquid fraction with respect to the volume of the soil sample. Values varied from 9.97 to 15.56 for SRC and from 40.96 to 44.51 for SSH. The highest values for both variables were observed in soils with low percentages of sand and high percentages of silt. They are located in the westernmost zones of the DO León and are planted with Garnacha.

The statistical analysis applied to the set of these 13 variables also allowed us to select those that best characterized and differentiated each variety in the DO León (Table 3).

These bioclimatic and soil variables were later used to generate maps of the areas suitable for planting each wine-grape variety.

The bioclimatic variables Compensated Thermicity Index (ITC) and Continentality Index (IC), and the soil variables Clay Content (CC), pH, Soil Retention Capacity (SRC) and Soil Saturation Humidity (SSH) are defining for all the six varieties studied. Albarín and Prieto Picudo can be characterized by the same variables as Tempranillo and Verdejo. Garnacha and Mencía were the most different varieties in relation to their bioclimatic and soil requirements.

3.2. *Delimitation of suitable areas for each variety*

Fig. 2 shows the average AUC and TSS values for the ten runs carried out for each variety. It can be seen that AUC had higher values than TSS for all the wine-grape varieties in the study. The average of the AUC scores ranged from 0.95 (Albarín) to 0.99 (Garnacha), indicating that

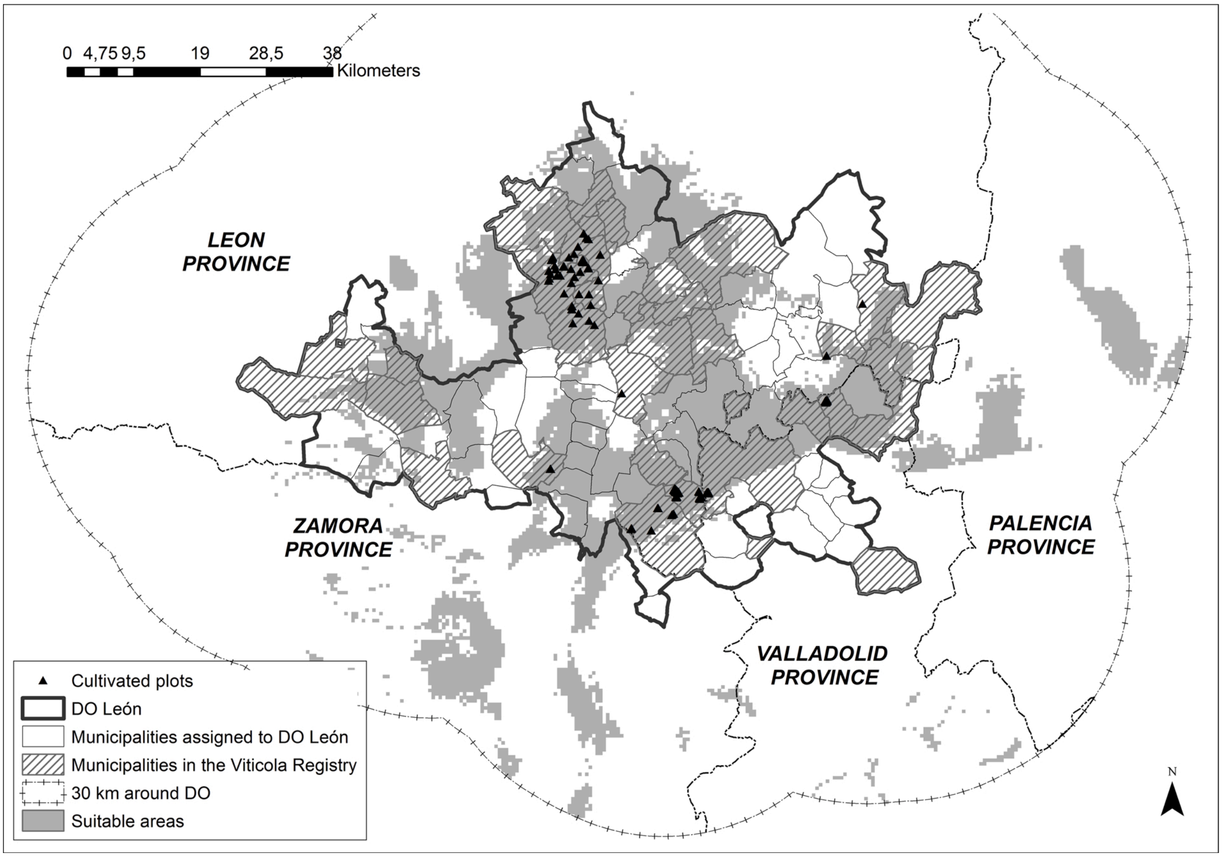

Fig. 7. Suitable areas for Verdejo.

our models have excellent predictive ability, and therefore that the selected predictors correctly describe the distribution of the varieties in the DO León. The average of the TSS values for the ten single models ranged from 0.92 (Albarín) to 0.98 (Garnacha). Average sensitivity percentages were between 92 % (obtained from ROC for Albarín) and 99.4 % (for Prieto Picudo), and between 90 % (obtained from TSS for Albarín) and 99.3 % (obtained from TSS for Prieto Picudo). Average specificity percentages were $>$ 98 % for both ROC and TSS for all the varieties analysed.

The two bioclimatic variables with the highest contribution to the single models were Compensated Thermicity Index (ITC) and Growing Season Precipitation (GSP) for Mencía, Tempranillo and Verdejo; ITC and Annual Ombrothermic Index (IO) for Albarín and Prieto Picudo; and ITC and Branas Index (BI) for Garnacha. Based on these results, it should be noted that ITC is a good bioclimatic indicator for the delimitation and characterization of cultivars in the DO León, while soil saturation humidity and pH were among the three soil variables with the greatest contribution to single models in all varieties.

The ensemble models were built to give more importance to models with a better performance according to the criteria of AUC and TSS (only models with AUC $\geq$ 0.95 and TSS $\geq$ 0.85 were selected to build the ensemble models in this study). The AUC results for the ensemble models were above 0.97 in all varieties analysed and above 0.93 for TSS. Sensitivity values were always $\geq$ 93 % and specificity values were $\geq$ 99 %.

Maps of suitable areas were generated for each variety and for three contexts: 1) within the municipalities registered in the Vitícola Registry, 2) for the whole of the production area, and 3) adding a buffer of up to 30 km around the DO (Figs. 3 to 8). The aim was to determine the existence of any zones in the study area that are potentially suitable for planting grapevines but are not currently occupied by vineyards, and to identify whether any areas presently included in the DO do not have the optimum conditions for growing a particular variety.

It was also confirmed that new suitable areas for cultivation have values for the Wrinkler Index (WI) $>$ 1000 and data for the Huglin Index (HI) of between 1500 and 3000, which are the reference values for viticulture (Amerine and Winkler, 1944; Tonietto and Carbonneau, 2004). Table 4 shows the square kilometres predicted by the ensemble models for each variety and for the three scenarios mentioned.

The cultivated plots analysed in the current study comprise 1432 ha, and are distributed in the 32 municipalities registered in the Winegrowers' Registry. Our results confirm that these municipalities are suitable for the plantation of vineyards throughout their extension, comprising a new suitable area of 1288.75 km^2 in total. Taking into account the whole of the production area, 60 new municipalities that are not currently cultivated meet the requirements for the plantation of vineyards, conforming an area of 1339.25 km^2. In total, 2628 km^2 (out of the 3317 km^2 in the production zone) could be planted with vineyards under the current climate and soil conditions (Table 4).

Based on the results reported in this study, the south-eastern areas of the DO León do not fulfil the optimum conditions for the cultivation of this crop. This could be because the soils have high pH values and a higher percentage of clay content than in the other areas of the DO. Lanyon et al. (2004) pointed out that the availability of metal ions is reduced in soils with pH $>$ 8.0, and that these high soil pH values are also associated with boron toxicity and elevated concentrations of very fine carbonates that can cause severe lime-induced chlorosis (iron deficiency).

There are also smaller areas currently included in the production zone which do not meet the optimum conditions for the plantation of vineyards. These are generally areas located at over 900 m above sea level (on the borders of the DO) and therefore with the lowest ITC values. The values for Temperature Range During Ripening in these areas are higher than in the rest of the DO.

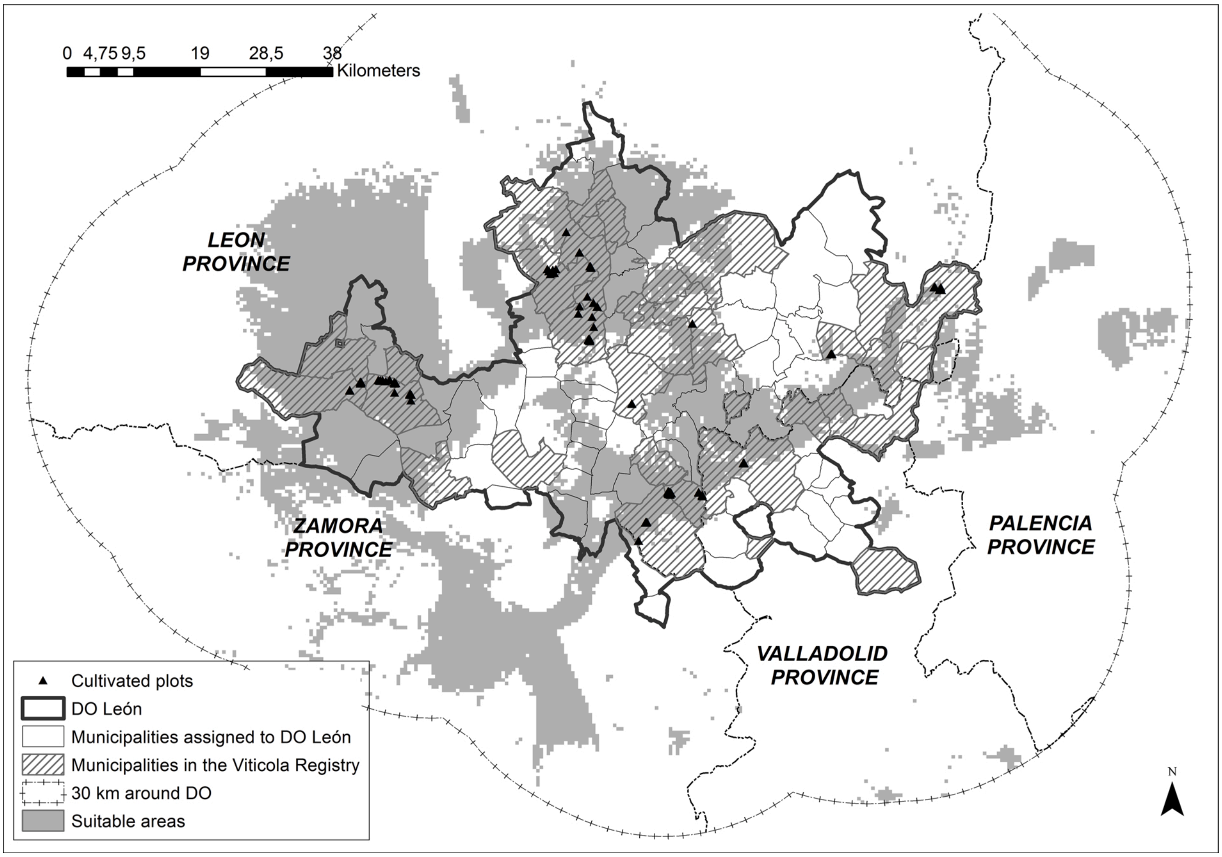

Fig. 8. Suitable areas for Mencía.

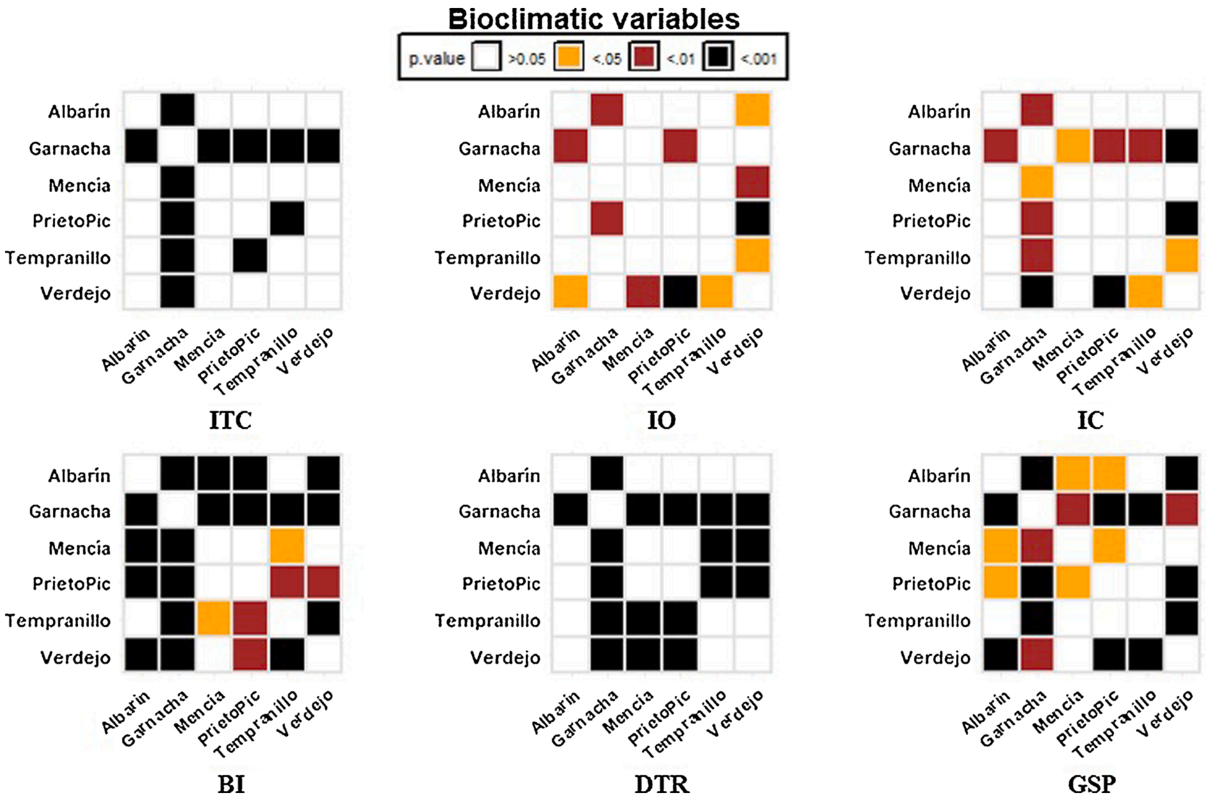

Fig. 9. Results of the Wilcoxon analysis for the bioclimatic variables.

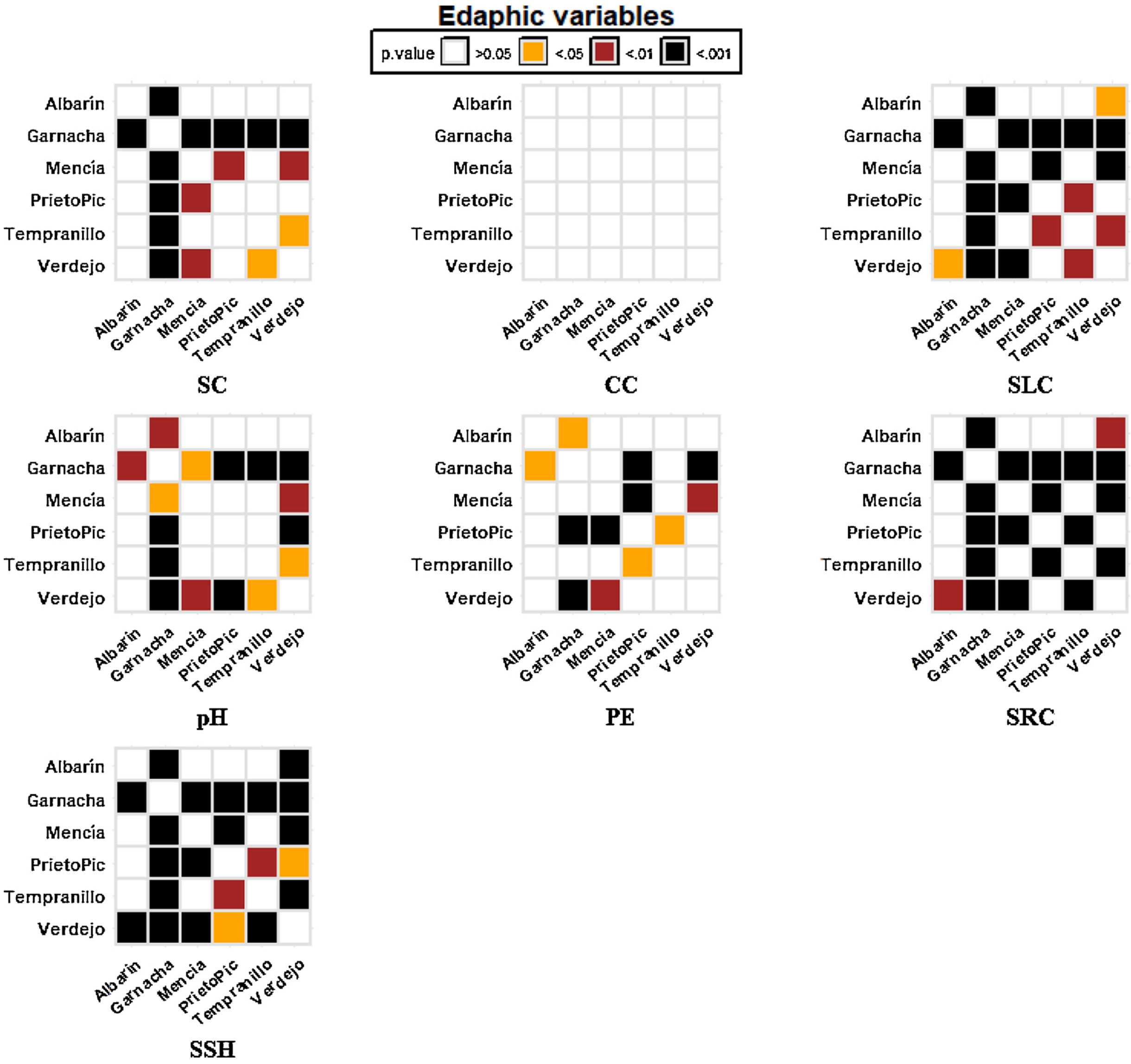

Fig. 10. Results of the Wilcoxon analysis for the soil variables.

The results from the inclusion of the 30 km buffer would allow the production zone to be extended by up to 6417.75 km^2 (Table 4), predominantly in the north of Zamora province. Some of these areas are at present included in the Los Valles de Benavente DO. The findings reported in this study could imply changes in the boundaries of the DO León.

Fig. 3 and Table 4 show the results for Albarín. According to the distribution models, new areas within the production zone, located mainly in the northern and western territories, are suitable for growing this variety. Its production zone could be increased (up to an additional 2000 km^2) by taking into account a buffer of 30 km around the DO.

The main cultivars of Garnacha are at present in the western territories of the study area. This research has revealed that the areas with suitable conditions for its cultivation could be increased up to about 500 km^2 in these municipalities and neighbouring areas, and up to 1000 km^2 if the territories to the north of these areas are also included (Fig. 4 and Table 4).

Prieto Picudo is the most important variety in the DO León, and is cultivated in 29 municipalities. Fig. 5 shows that these cultivars could be extended under the current conditions to most areas in the DO, only excluding the south-eastern and westernmost territories. These western areas are more adequate for the cultivation of Mencía and Garnacha. The production zone could be increased to 4300 km^2 (Table 4) by including zones in the north of Zamora province which are currently included in the Los Valles de Benavente DO.

As mentioned previously, Tempranillo and Verdejo are characterized by the same environmental variables. Today, these types of grapevine are planted in the Páramo and Esla Campos regions. Figs. 6 and 7 show that cultivars of these varieties could be expanded near these areas to cover an area of twice as many kilometres as at present (see Table 4).

The Mencía variety is mainly planted in the westernmost areas of the DO, and represents 75 % of the vineyards in the DO Bierzo, which is the other denomination in the León province and located to the west of it. Suitable areas for this variety can be expanded up to 3500 km^2, preferably to the north of these territories (Fig. 8, Table 4).

3.3. Understanding differences in suitable areas for each variety

After determining the six bioclimatic variables and the seven soil variables shown to be useful for identifying suitable areas, the ultimate goal is to understand whether these variables also contribute to an understanding of the differences in the maps for each of the six varieties.

A Kruskal-Wallis test was computed in R using the current vineyards, establishing the null hypothesis that the location parameters of the distribution of the variables are the same in each group (variety). Significant statistical differences were observed between the varieties for all the variables (except clay) (p-values are shown at the bottom of Table S.1). This indicates that clay is useful for predicting suitable areas but in a generic form, without explaining the differences between the varieties.

We understand that an area may be suitable for a variety if the variables used in the prediction indicate that they are compatible with the new variety. The non-parametric Wilcoxon Rank Sum Test using the Bonferroni correction was applied across the previously selected variables to test whether two wine-grape varieties significantly differed in their climate and soil conditions. The analyses were run using R software.

Figs. 9 and 10 show the results for the Wilcoxon analysis with statistical significance (p value <0.05, 0.01 and 0.001). With regard to the bioclimatic predictors, Garnacha (as previously highlighted) is the variety with the most diverging requirements, differing in all the selected variables (except for the Annual Ombrothermic Index, IO) compared to the remaining varieties. The greatest differences were recorded for Temperature Range During Ripening (DTR), Compensated Thermicity Index (ITC) and the Branas Index (BI), with p values < 0.001 (shaded in black in Fig. 9). These last variables were predictors with a significant contribution in the MaxEnt models. The lowest values of ITC were recorded in the westernmost areas of the DO, the location of the Garnacha plots. It is worth mentioning that these plots are also situated in zones with the lowest BI and the highest DTR values.

Garnacha is also the variety with the most different requirements in terms of soil granulometry (sand and silt contents). Similar results were found for the rest of the soil variables, with statistical differences between Garnacha and the other varieties (except soil permeability). It should also be noted that Verdejo showed significant differences with the other grapevines for soil saturation humidity, soil retention capacity and pH (except Albarín).

The analysis of all the significant variables with a confidence level of 99 % shows that, as has already been mentioned, Garnacha is the wine-grape variety with the most different requirements, with the greatest differences observed with Prieto Picudo. In contrast, Tempranillo and Albarín have the same bioclimatic and soil needs.

4. Conclusions

The current study proposes an integrated methodology to optimize and delimit suitable areas for wine production. The new approach includes the combination of traditional climate parameters with new bioclimatic indices and soil variables that are essential for viticulture. The proposed approach also includes several statistical analyses for selecting the variables that best characterize the vineyards, as well as species distribution models integrated in GIS. The new methodology was tested on the Denomination of Origin León (DO León) located in northwest Spain.

The results show that the environmental factors in the area under study are quite homogeneous, which confirms its correct delimitation as a Denomination of Origin and its differentiation from other neighbouring producing areas (known as “terroir”). In addition, this methodology allowed us to distinguish zones inside the same viticultural area where conditions could be more favourable for some varieties in the DO.

Some parameters and bioclimatic indices not traditionally used in viticulture have emerged as being essential for discriminating and characterizing wine-grape varieties. The two bioclimatic variables with the highest contribution to the single models were the Compensated Thermicity Index (ITC) and Growing Season Precipitation (GSP) for Mencía, Tempranillo and Verdejo; ITC and the Annual Ombrothermic Index (IO) for Albarín and Prieto Picudo; and ITC and Branas Index (BI) for Garnacha. Based on these results, it can be confirmed that the bioclimatic indices proposed by Rivas-Martínez et al. (2011) (especially the ITC) are very useful for delimitating and characterizing vineyards.

Soil variables are also essential for accurately delimiting suitable areas for viticulture. Soil Saturation Humidity (SSH) and pH were among the soil variables with the highest contribution to single models in all the varieties analysed.

The maps of the suitable areas for each variety and for the three scenarios analysed show there is a large area (inside and around the DO) not currently under cultivation that can be used for planting vineyards. These results could lead to changes in the boundaries of the DO León.

The authors believe this new methodology is an useful tool for agronomic and oenological management, contributing to more effective site selection for new vineyards, improved vineyard management, and can even be used to protect territories with a historical and cultural wine-growing heritage. The control and optimization of vineyard location can play a part in revitalizing these areas and creating new opportunities to avoid the abandonment of rural areas, a priority objective in the EU’s and Spain’s territorial planning. In addition, a more detailed knowledge of the most discriminating variables for vineyards will be of great help in determining the possible effect of climate change in the sector and anticipating possible impacts.

CRediT authorship contribution statement

S. del Río: conceptualization, methodology, data curation, formal analysis, investigation, writing original draft, writing-review and editing, visualization, project administration, supervision. **R. Álvarez-Esteban**: methodology, formal analysis, software, statistics, writing-review and editing. **R. Alonso-Redondo**: formal analysis, visualization, writing-review and editing. **C. Hidalgo**: statistics, visualization, writing-review and editing. **A. Penas**: conceptualization, methodology, writing-review and editing.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could be seen to influence the work reported in this paper

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