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Modelling the potential effects of climate change in the distribution of *Xylotrechus arvicola* in Spain

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Abstract: *Xylotrechus arvicola* is an emerging grape pest that generates serious sanitary problems in vineyards and is currently expanding its range throughout Spain. The increasing prevalence of this pest in Spanish vineyards has been detected since 1990. In this study, the relationship between the climate and the actual distribution of the beetle was analysed, as well as how this distribution might change in the future according to several climate change models. The methodology was based on predictive models (SDM; species distribution modelling) using climate variables as explanatory factors, although the relationships were not necessarily causal. Maxent was used as the SDM method. The current climatic niche was calculated, and the actual potential distribution area was estimated. The relationships between the climate variables and the species probability of the presence were projected to various future climate change scenarios. The main conclusions reached were that climate change will favour the expansion of X. arvicola and that the potential infestation zones will be extended significantly. Although the results, because they were based on hypothetical climate frameworks that are under constant revision, were not conclusive, they should be taken into consideration when defining future strategies in the wine industry.

Keywords: species distribution models; vineyard; pest mapping; maximum entropy

Xylotrechus arvicola (Olivier 1795) (Coleoptera: Cerambycidae) is an emerging grape pest that generates serious sanitary problems in important Spanish vineyards. In some locations, this beetle has been identified as a pest for more than 25 years. The beetle's global distribution includes Europe, Asia and North Africa (Villiers 1978). In Spain, this beetle has been found in the vineyards of La Rioja, Álava (Ocet, del Tío 1996), Castilla-La Mancha (Rodríguez et al. 1997), Castilla, León (Peláez et al. 2001) and Navarra (EVENA 2005).

The damage caused by the beetle infestations is a consequence of the gallery excavation during the *Xylotrechus* larval stage. These galleries weaken the plants and facilitate branch breakage and death (Armendáriz et al. 2008; Ocete et al. 2002), infestation by pathogenic fungi, and reduced grape production yield and quality (Ocete et al. 2009).

Available studies on the biology of *X. arvicola* have focused on the parameters of the fertility, viability and mortality of the eggs, rather than on the period in which the larvae develop within the plant and become inaccessible. It is now known that the longevity of female adults is between 23 and 36 days. The females start to lay eggs during the 1st week of adult life, but are able to lay eggs a dozen times. The fecundity and viability are highest in the first egg laying cycle and decrease during

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the subsequent reproductive events (Rodríguez-González et al. 2017).

Monitoring the biological cycle is very difficult and requires intensive field study and direct sampling and examination by sawing fine cuts of the strains. According to these data, the cycle of *X arvicola* is biannual, and the flight of adults corresponding to the eggs laid two years previously takes place in the third weeks of May and June (Calleja 2007) or at the end of March and at the end of July (García-Ruiz et al. 2011). The eggs are laid in the cracks of the bark, and the emerging larvae rapidly penetrate the plant, making prophylactic treatments much more difficult.

Laboratory tests have shown that the eggs are capable of complete development in a very wide range of temperatures between 15 and 35 °C (García-Ruiz et al. 2011), but there do not appear to be any data on the bi- or multi-variable effects or on the other developmental stages of the species.

There is currently no effective solution to the problem of the beetle infestation. In Spain, no chemical substance has been approved for the treatment of grapevines. One preventive cultural technique is the elimination of timber rests during vine pruning. If an infestation is established, however, it is necessary to eliminate the pest sources by cutting back the trunks of the vines and covering the wounds with sealing paste (Ocete et al. 2002). Unfortunately, the continuous renewal of vineyards complicates the crop management because a single vineyard contains plants of many different ages and management requirements (Calleja 2007).

A heavy increase in *Xylotrechus arvicola* symptoms in Spanish vineyards has been detected since 1990. Currently, the causes of this expansion remain unknown. It is, therefore, advisable to conduct further studies on the biology of this beetle and the possible environmental factors influencing its spread. Other studies have reported climate variables as influencing factors on the health of some species (Gregorová et al. 2010). In our case, it is reasonable to assume that the climate conditions are influencing factors that can facilitate the expansion of the beetle's range.

In this study, the climate data were analysed as explanatory variables of the actual distribution of the beetle, as well as how this distribution might change in the future according to several climate change models.

Species distribution models (SDMs) were used to facilitate these analyses. SDMs are tools that allow a "climatic niche" to be defined from the actual presence data and a set of climatic variables. The empirical relationships between climate and the presence are used to construct a statistical model that can be applied to the whole study area. The model produces a map in which each location has a suitability value (interpreted as the probability of the presence). The statistical model can be applied to different climate scenarios to evaluate the induced or potential spatial distribution changes. The results can detect the zones that might become infested under new climate conditions, as well as those that might become incompatible or remain susceptible.

SDMs have increased in importance during recent years (Guisan, Zimmermann 2000; Booth et al. 2014; Hao et al. 2020). These models have a broad relevance across conservation biology, biogeography, reserve design and climate change. SDMs can provide valuable information regarding the trend of the *X. arvicola* evolution under future climate change scenarios. The same SDM-based methods have been used to model other notable pests in southern Spain: (Joaquín Duque-Lazo et al. 2018) modelled the oak decline caused by *Phytophthora cinnamomi* in Andalusia, and (Navarro-Cerrillo et al. 2004) analysed the current and future distribution of *Cerambyx sp.* assuming similar bases to those used in this study.

The aim of this study was to model the potential distribution of *X. arvicola* under the actual climate conditions and to compare this distribution with the potential distributions under future climate change conditions. SDM and cartographic techniques were applied to a study area consisting of the Spanish territories of the Iberian Peninsula (492 000 km^2).

MATERIAL AND METHODS

***Xylotrechus* data.** The data on the presence of *X. arvicola* in Spanish vineyards were compiled from a literature review. Only part of the record was georeferenced, but all the data were checked to assign location values of latitude and longitude from the maps and place names. The final map included 84 presence locations (Figure 1). These data were gathered from nine publications (Ocete, del Tío 1996; Ocete et al. 2002, 2004; Moreno et al. 2004; EVENA 2005; Moreno 2005; Calleja 2007; Armendáriz et al. 2008).

Environmental variables. The models were built using 36 climatic variables to represent the period from 1961–1990 and consisted of the monthly rainfall, mean monthly minimum temperature and mean monthly maximum temperatures.

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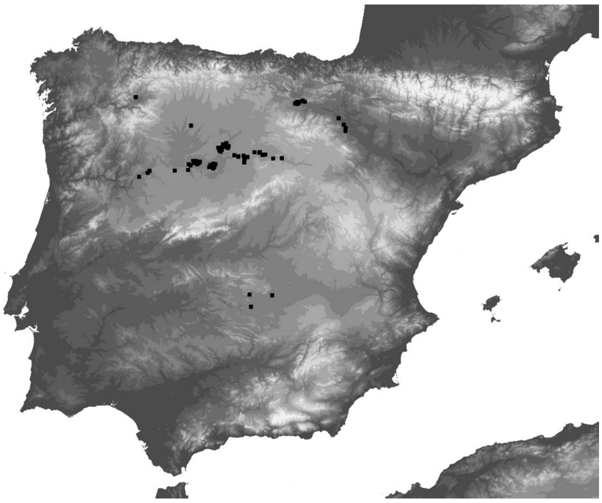

Figure 1. Presences of *Xylotrechus arvicola* in vineyards (in black). The background is the digital elevation model of the Iberian Peninsula

Climatic maps were created for the authors from the raw data from meteorological stations provided by the Spanish Agency of Meteorology, AEMET (http://www.aemet.es/). These maps were made on behalf of the OECC (Oficina Española de Cambio Climático, Spanish Office for Climate Change, https://tinyurl.com/us6p6ye) in a research project (2009–2011) on the impact of climate change on the flora and vegetation of Spain (Felicísimo et al. 2011).

Briefly, a total of 2 173 rainfall and 973 temperature stations were available with 36 climatic variables for each year: the mean maximum and minimum temperatures and monthly rainfall (3 variables × 12 months). The results of the processes carried out by AEMET were thousands of tables with climate data associated with georeferenced points.

To build the maps from the point data, ordinary kriging interpolation procedures were used (Boer et al. 2001; Attorre et al. 2007) and the application of empirical altitudinal temperature gradients in mountainous areas (which usually have few weather stations). This analysis resulted in gridded maps with a 1 × 1 km spatial resolution (for a more detailed methodology, see Felicisimo et al. 2011).

Climate data from the reference period 1960–1990 were used to develop the current SDMs. The future climate values were drawn from two IPCC (Intergovernmental Panel on Climate Change, https://www.ipcc.ch/) scenario families, A2 and B2 (Nakićenović et al. 2000), and two general models of circulation, the Canadian Global Coupled Model (CGCM2) from the Canadian Centre for Climate Modelling and Analysis (McFarlane et al. 1992) and ECHAM4 from the Max Planck Institute for Meteorology (Roeckner et al. 1996). ECHAM is a combined acronym where the EC comes from an atmospheric circulation model called ECMWF (European Centre for Medium-Range Weather Forecasts) and from HAMburg, the city where the parameterisation package was developed.

The coarse model data were downscaled and adapted to the meteorological station level by AEMET using a statistical downscaling method (Morata 2014). From the meteorological station data, future maps were interpolated from the current climate maps. In this study, we used future projections for the 2041–2070 period for two general models and two scenario families. All the digital maps are freely available in GeoTiff format (http://ide.unex.es).

SDM methods. Maxent (maximum entropy) was used as the SDM method (Phillips et al. 2006; Phillips, Dudík 2008), a well-known method in the SDM toolbox, (Muñoz, Felicísimo 2004; Elith et al. 2006; Leathwick et al. 2006). Maxent is a standalone tool that performs all the steps of the workflow without the use of other applications.

Maxent is designed to work with presence-background (pseudoabsence) data rather than presence-absence data (Phillips et al. 2009). This approach uses a probabilistic framework for estimating the environmental range of the species from a set of presence points and environmental variables. Maxent represents the potential distribution of the species as a probability distribution and assigns a non-negative value to every site in the study area. The main cartographic outputs of Maxent are maps where each pixel has a presence probability value. Maxent is a widely used and well-tested method in this type of study (Merow et al. 2013).

The model accuracy was evaluated using the AUC statistic (area under the ROC (receiver-operating characteristics) curve) (Hanley, McNeil 1982). The ROC curve does not merely summarise the performance at a single arbitrarily selected decision threshold. Instead, this curve examines the performance across all the possible decision thresholds (Fielding, Bell 1997). The ROC curve plots the sensitivity (i.e., true positives) vs. the 1-specificity (i.e., false positives). Hanley and McNeil (1983) have shown that when dealing with a single scoring model, the AUC is equal to the empirically observed probability of a class-1 observation attaining

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a higher score than a class-0 observation. The AUC has been widely used for testing the performance of potential distribution models in a variety of topics (Mateo et al. 2012; Felicísimo et al. 2013).

Like many classifiers, Maxent can use training and control samples. Two configurations were used to make the models. First, a random sample of 20% of the presence points was used for the cross validation, allowing the training and testing AUC values to be obtained. Once the fit of the model was checked with the independent sample, all the points were used in the final model.

Although the final model depended on several variables and their interactions, a jackknife procedure (Efron, Gong 1983) was used to estimate the importance of the variables in the model. The jackknife is performed internally by Maxent and provides a set of response curves that show how each environmental variable affected the Maxent prediction. These curves reflect the dependence of the predicted suitability both on the selected variable and on the dependencies induced by the correlations between the selected variable and the other variables.

RESULTS

Reliability and model evaluation. Tests with 80% and 20% of the data for the training and cross validation testing, respectively, generated AUC values of 0.982 ± 0.001 and 0.955 ± 0.005. An AUC of 0.5 is equivalent to a random prediction, and 1.0 is equivalent to a perfect fit. The AUC value of the final model (100% sample size) was 0.985, which is a very good fit.

Climatic variable contributions. The four variables with contributions of 5% or more were PR10 (October rainfall: 51.5%), TX1 (January mean maximum temperature: 16.5%), TM7 (July mean minimum temperature: 6.7%), TX10 (October mean maximum temperature: 5.6%), and TM8 (August mean minimum temperature: 5.1%). Figure 2 displays the curves corresponding to these variables.

The rainfall in October ranged from a registered minimum of 20 L/m^2 to 45 L/m^2. Values above this value implied a very low probability of the *X. arvicola* presence. Similarly, the approximate range for the January mean maximum temperature was 7 to 10 °C, while that of the July mean minimum temperature was 11 to 16 °C.

Current potential distribution area. The maps generated by the Maxent model show the suitability value for each location in the study area from 0 (incompatible) to 1 (suitable), taking the local values of the climatic variables into account.

The continuous values were reclassified into two unique classes, suitable and incompatible, to create a binary map. Although this process is a simplification, it is necessary for comparing the potential surfaces between the actual and future scenarios. The selection of the threshold value for the construction of the binary map can be performed in several ways. In the present experiment, the criterion was the minimum value that included all the presences. The corresponding threshold value for this criterion was 0.140. Using this value, the actual suitable area for *X. arvicola* covered 90 547 km^2 (dark grey area in Figure 3), while the unsuitable area encompassed 401 668 km^2.

Future potential areas. The Maxent models were projected for the period from 2041 to 2070 for the combinations of scenarios (A2, B2) and models (CGCM2, ECHAM4). The suitability maps were "binarised" with the same threshold as the actual map, and the areas were compared. Figure 4 shows the suitable areas for each combination of scenario family and model.

All the scenario family/model combinations were geographically consistent, although with variations in extent. The CGCM2 maps showed areas that were similar to the current distribution, but the ECHAM4 models generated a strong expansion in the suitable area for *X. arvicola*. ECHAM4 was characterised by an increase in the summer temperatures and a moderate reduction in the annual rainfall. These circumstances seemed to favour the extension of *X. arvicola* into areas that are currently unsuitable. Table 1 shows the extent of the future potential areas and percentages in comparison with the current potential areas.

There were two types of changes in the spatial extent: either an incompatible zone became a suitable area, or a potential area became unsuitable. Similarly, there were two types of areas without change: suitable areas that remained suitable and unsuit-

Table 1. Future estimation of the suitable areas for *X. arvicola* in the period 2041–2070 (km^2)

	CGCM2	ECHAM4
A2	82 764 (91%)	18 9047 (209%)
B2	109 241 (121%)	192 261 (212%)

Percentage values are in comparison with the actual suitable areas (90 547 km^2)

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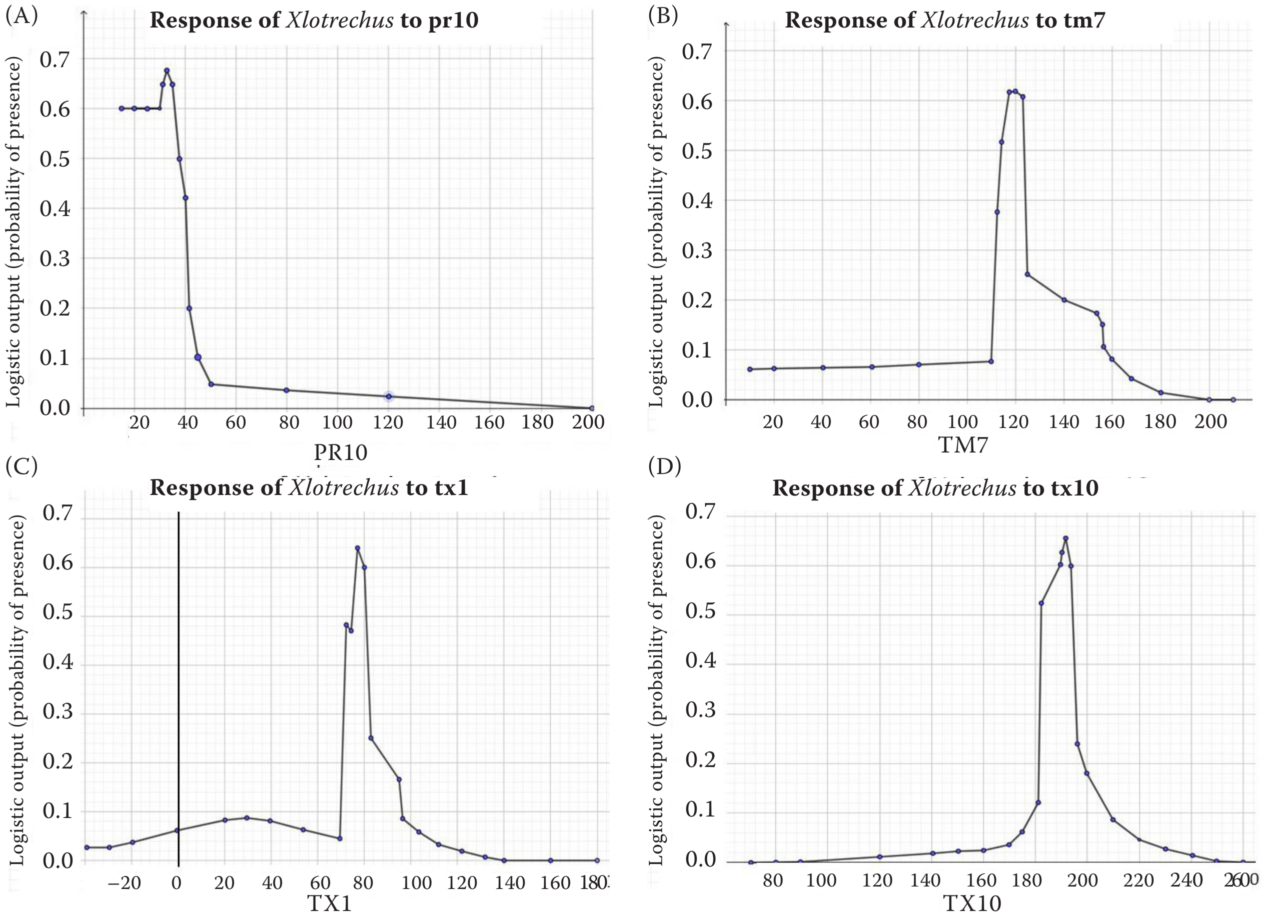

Figure 2. Response curves for the four most important variables in the Maxent model: (A) PR10: October rainfall, L/(m^2·month), (B) TX1: January mean maximum temperature, °C × 10, (C) TM7: July mean minimum temperature, (°C × 10), (D) TX10: October mean maximum temperature (°C × 10)

able areas that remained unsuitable. The cartography of these areas is an interesting issue. Figure 5 shows each scenario/model map with the four types of transitions indicated. The corresponding areas are shown in Table 2. There were major changes in the ECHAM4 models in which large areas became suitable for *X. arvicola*.

Figure 3. Suitable area (dark grey, 90 547 km^2) for the actual climate conditions

DISCUSSION

The main drawback of the SDM method is that it generates results based on correlations, not causal relationships. Indeed, it is theoretically possible that a distribution could be explained by variables unrelated to the actual limiting factors of the species. Therefore, to make projections to future scenarios from the climate data, it is necessary to accept the premise that the climate has a real influence on the distribution of the species. This is a reasonable hypothesis, at least on a "country" scale (hundreds of km), and has been accepted in numerous papers, always with the caveat of unproven causality (Seo et al. 2009; Dobrowski et al. 2011).

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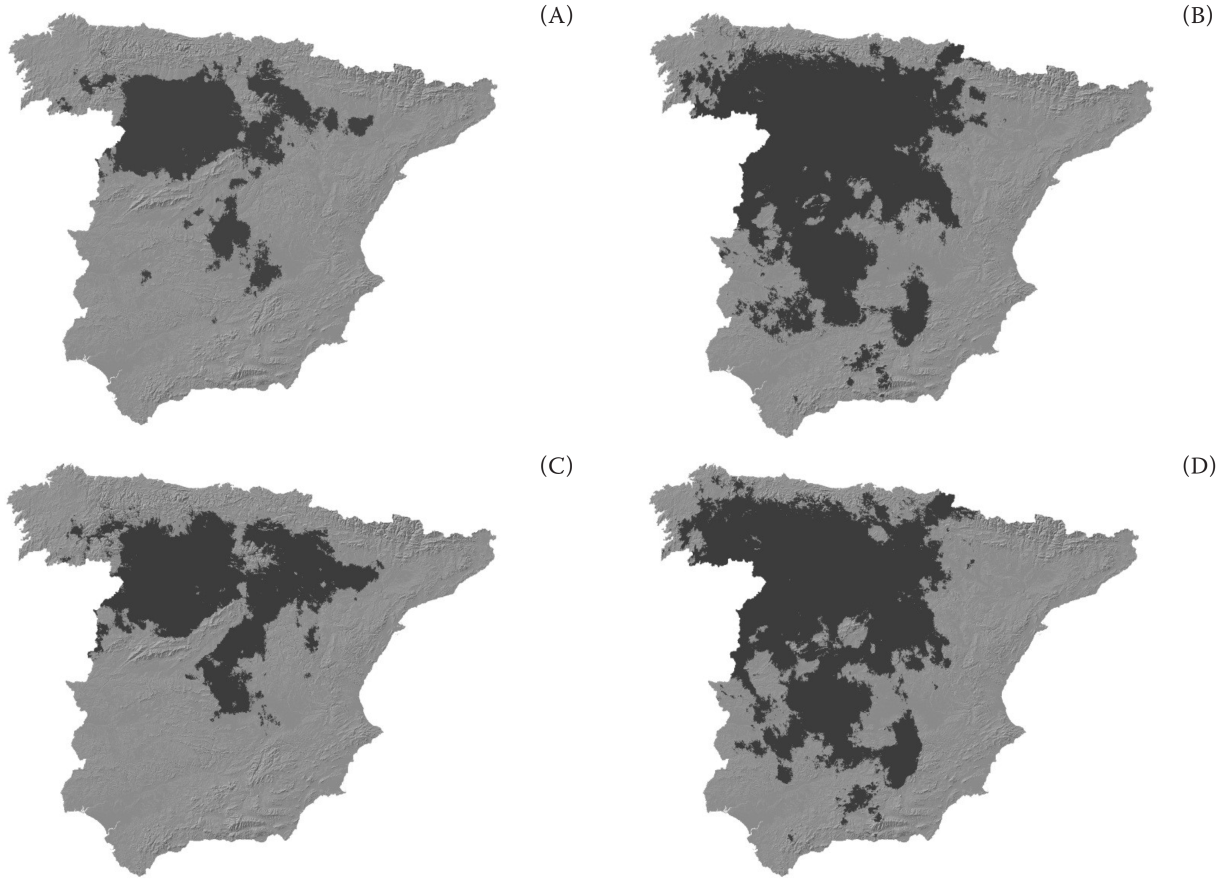

Figure 4. Suitable areas (dark grey) for each combination scenario/model (A) A2-CGCM2, (B) A2-ECHAM4, (C) B2-CGCM2, (D) B2-ECHAM4

With these caveats, climatic variables can be interpreted as limiting factors or as indicators of limiting factors that make up the climate niche that allows the development of *X. arvicola* in vineyards. Obviously, there are numerous potentially influential factors that were not introduced into the model. The reason was that there is usually no information about their current or future values (interspecific relationships, response to extreme values or unpredictable catastrophic events, humidity, etc.). However, if the model is able to adjust to the current distribution area, its explanatory capacity can be used and can provide useful information for future scenarios.

Table 2. Areas of the four classes of transition from the present to the future (km^2)

		Future (2041–2070)	
Present	A2/CGCM2	Unsuitable	Suitable
	Unsuitable	380 263	21 405
	Suitable	29 188	61 359
	A2/ECHAM4	Unsuitable	Suitable
	Unsuitable	285 830	115 838
	Suitable	17 328	73 219
	B2/CGCM2	Unsuitable	Suitable
	Unsuitable	370 613	31 055
	Suitable	12 361	78 186
	B2/ECHAM4	Unsuitable	Suitable
	Unsuitable	281 724	119 944
	Suitable	18 230	72 317

The main results of this study were that the climate change will affect the temporal evolution of areas with *X. arvicola* and that the area of the potential infestation zones will increase. Three of the four scenario/climate combination models predicted a significant expansion in range. In the A2/CGCM2 model, the susceptible area showed minor changes that mainly occurred along the margins of the current potential area, but the remaining models showed a 121 to 212% expansion in the *X. arvicola* suitable areas.

The differences could be due to two factors. The first is that the global circulation models CGCM2 and

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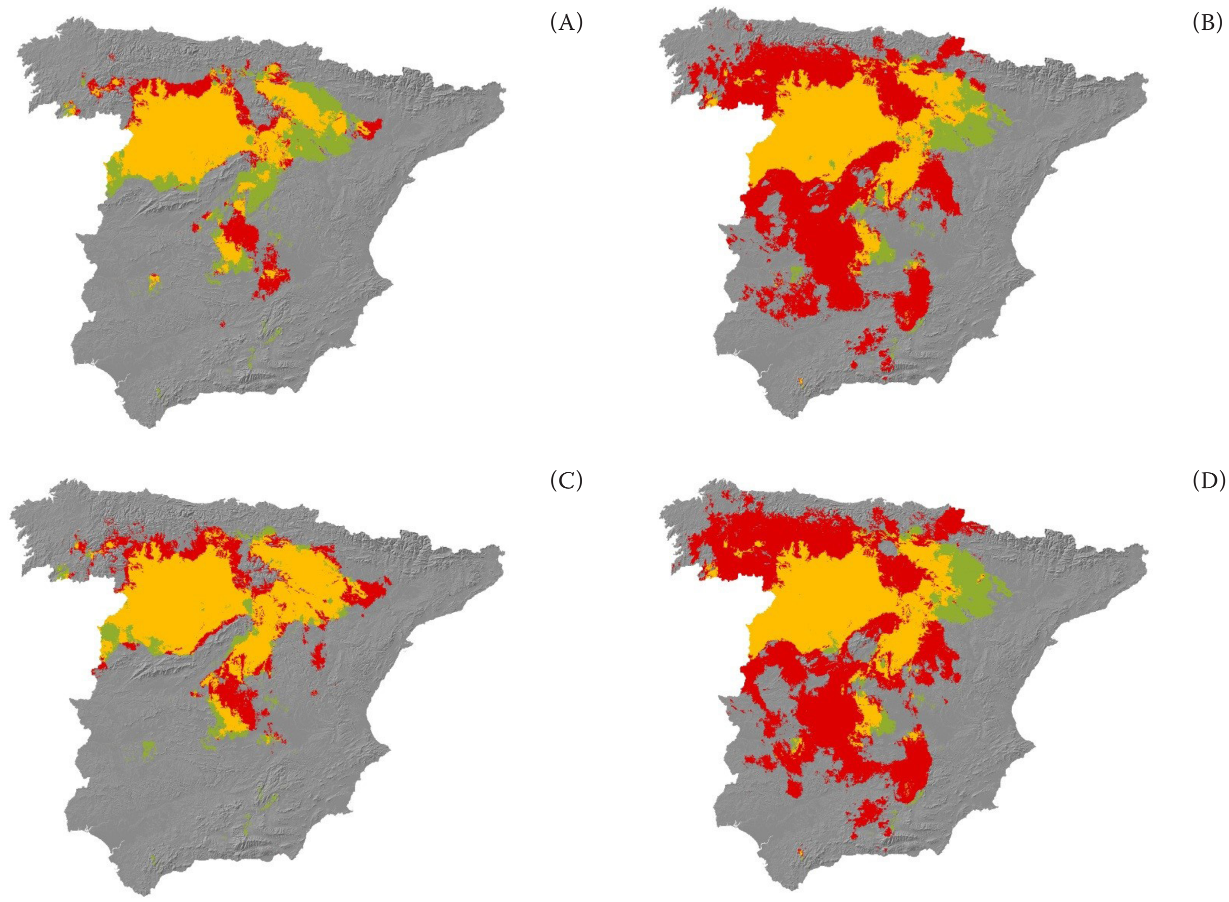

Figure 5. The maps show the four classes of transitions from the present to the future. Green: suitable to unsuitable (future safe zones); red: unsuitable to suitable (potential *X. arvicola* new zones); orange: remain suitable (no changes); grey: remain unsuitable (no changes), (A) A2-CGCM2, (B) A2-ECHAM4, (C) B2-CGCM2, (D) B2-ECHAM4

ECHAM4 were built by different teams with different procedures and equations. Although the physical phenomena are the same, the methods for modelling them are different. These differences are a very specialised, and the authors of the SDMs are unable to analyse them and can only use the results. The second factor is better known and is due to the characteristics of the scenarios: the B2 scenarios are more optimistic and include some control of greenhouse gas emissions. The A2 scenarios include a greater increase in these emissions, which means that the effects on the climate change are greater (Nakićenović et al. 2000). It is difficult to interpret how these differences influence the results of the Maxent models because such models are complex and include several variables and interactions. However, (Felicísimo et al. 2011) showed that the most notable differences in climate change projections in the study area were a rise in temperature between 1 and 3 °C in January and between 2 and 6 °C in the May-October period and a significant reduction in rainfall in the autumn. The magnitude of these changes depended mainly on the scenario family (A2 or B2), but the trend was the same.

Specifically, the most influential variables according to the results were the October rainfall (strongly decreasing in all the climate change scenarios); TX1: January mean maximum temperature (increasing between 1 and 3 °C), July mean minimum temperature (increasing approximately 3 °C in all the scenarios), and October mean maximum temperature (increasing between 2 and 7 °C). These climate change data appeared in the extended report of (Felicísimo et al. 2011).

The results provide a discouraging forecast for the wine industry in Spain, which generates 4 800 M€/year (0.65% GDP). Although the results, which were based on hypothetical climate frameworks that are under constant revision, were not conclusive, we propose that they should be taken into consideration when defining future strategies for the industry.

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X. arvicola affects numerous species of trees and shrubs, i.e., *Prunus spinosa* (Vives 2000; Soria et al. 2013;) *Quercus*, *Carpinus*, *Castanea*, *Fagus* (Armendariz et al. 2008). It should be noted that these models are only applicable to vineyards, not to other cases, whose circumstances may be different.

The scenario family/model combinations employed in this study were only a subset of all the possible analyses. We suggest that future research should extend the analysis to the wider Mediterranean area, including France (Aquitania) and Portugal, and should use a wider range of scenario family/model combinations to contrast with the predictions of the current study.

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