Distributional pattern of Sardinian orchids under a climate change scenario

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Abstract: The Mediterranean is one of the major biodiversity hotspots of the world. It has been identified as the "core" of the speciation process for many groups of organisms. It hosts an impressive number of species, many of which are classified as endangered taxa. Climate change in such a diverse context could heavily influence community composition, reducing ecosystems resistance and resilience. This study aims at depicting the distribution of nine orchid species in the island of Sardinia (Italy), and at forecasting their future distribution in consequence of climate change. The models were produced by following an "ensemble" approach. We analysed present and future (2070) niche for the nine species, using Land Use and Soil Type, as well as 8 bioclimatic variables as predictors, selected because of their influence on the fitness of these orchids. Climate change in the next years, at Mediterranean latitudes, is predicted to results mainly in an increase of temperature and a decrease of precipitation. In 2070, the general trend for almost all modelled taxa is the widening of the suitable areas. However, not always the newly gained areas have high probability of presence. A correct interpretation of environmental changes is needed for developing effective conservation strategies.

Abbreviations: GAM–Generalized Additive Model, GLM–Generalized Linear Model, GPS–Global Positioning System, HadGEM–Hadley Global Environment Model, IPCC–Inter-Governmental Panel for Climate Change, IUCN–International Union for Conservation of Nature, N–North, NW–North-West/Western, RCP–Representative Concentration Pathway, RF–Random Forest, SE–South-East, SW–South-West/Western, TSS–True Skill Statistic.

Nomenclature: Cronquist (1981).

Introduction

The Mediterranean basin is one of the most important biodiversity hot-spots in the world, and has been labelled as a climate change hot spot by the Inter-Governmental Panel for Climate Change (IPCC; Loizidou et al. 2016). The distribution of vascular flora in the Mediterranean basin was strongly influenced by a complex geological and climatic history, and especially by the Mediterranean Messinian salinity crisis, and the fluctuation of sea level during the Quaternary glacial periods (Mansion et al. 2008). Climate changes in such a complex ecological context could heavily influence communities composition, and the most relevant effect could be an increasing occurrence of taxa adapted to more dry and hot conditions (Reid et al. 2007, Vacchi et al. 2001, Walther et al. 2007, 2009), leading to the disappearance of local, endemic taxa, as well as to a reduced resistance and resilience of ecosystems (Jump and Peñuelas 2005).

Among plants, orchids are probably one of the families with more rare and endangered taxa (Brigham and Swartz 2003, Pitman and Jørgensen 2002, Wilcove et al. 1998), and have been targeted by several conservation efforts to prevent the effects of global changes (Sletvold et al. 2013). Out of the

25000-35000 taxa of the family Orchidaceae (Christenhusz and Byng 2016), 529 are known to occur in Europe (Delforge 2006), and one of their biodiversity hotspots is the Sardinia island (Mittermeier et al. 2004), which is known to host 60 taxa (Lai 2009). Thanks to its position, Sardinia has a very diverse climate (Fois et al. 2017), which, coupled with a complex geomorphology (Fois et al. 2017), produces a relevant number of different habitats. However, because of climate changes, its ecosystems are changing, and while some species are disappearing, others are colonising the island, and/or increasing their distribution. Future climate change scenarios (IPCC$_5$ global climate models, RCP 4.5 greenhouse gas emission scenario for 2070) for Sardinia depict a situation in which the average monthly temperatures could increase by 10–20% (even 50% during the cold season) with respect to the means of the 1961–1990 period. Furthermore, precipitations could increase by 20–50% during the cold season, and decrease by 20–50% during the rest of the year (Gritti et al. 2006) with respect to the 1961–1990 period. Climate change can affect orchids in several ways. A deficiency of precipitation during the coldest months could prevent a correct root development, and limit the storage of nutrients to sustain the vegetative phase of the life cycle (Rasmussen 1995, Wells

and Cox, 1989). An increased temperature seasonality could expose the seedlings to freezing during the cold period, and to heat shock, if the hot season will not be preceded by a mild spring as acclimatization period. Furthermore, too high temperatures during the hottest months could limit several orchids in closing their seasonal vegetative cycle in an optimal way (Hutchings 2010).

In order to prevent loss of biodiversity, and for developing effective conservation strategies, it is relevant to understand the effects of climate change on the future distribution of each species. Climatic niche modelling, which is a useful approach for understanding the current distribution of a taxon, and forecasting its future distribution, is often used for developing more effective conservation strategies (Attorre et. al. 2013). Especially when applied in the field of conservation ecology, since conservation efforts can be expensive and time consuming, climatic niche modelling can provide a way for optimising resources and better addressing efforts. An interesting example is the case of the conservation of wild potato relatives, which were lacking from germplasm collections. Hence, species distribution modelling was used to establish high suitability habitats for collecting wild specimens (Castañeda-Álvarez et al. 2015). Niche models have also been used to understand distributional patterns, to forecast future distribution of species and to plan effective conservation strategies on several groups of organisms. In a study from Wang et al. (2016), they were used not only to assess the niches of several forest trees in a climate change scenario, and their shifts, but also to identify species which could be suitable for reforestation. As far as orchids are concerned, there are several studies which make use of species distribution models. Kolanowska (2013) and Kolanowska and Konowalik (2014) analysed the climatic niches of *Epipactis helleborine* and *Arundina graminifolia*, two invasive orchids, and their potential modification in future scenarios both in native and invasive ranges. Other studies aimed at quantifying potential distribution, species richness, and turnover, in specific sites, in order to define which phytogeographical regions are more important for conservation (e.g., Vollering et al. 2015). The same approach is also used to identify areas which are suitable for a given taxon, but in which the taxon was not reported yet, hence potentially discovering new populations. Furthermore, since biodiversity also affects human welfare, it is urgent to quantify and understand it loss, in order to adapt to its consequences (habitats and ecosystems loss and fragmentation, species endangerment and extinction). Since spatial and ecological differences across the globe are too wide, and of the number of endangered organisms and ecosystems is increasing steadily, niche modelling can be more useful at regional scale.

In this paper, we applied an ensemble niche modelling approach to occurrence records of nine orchid taxa known to occur in Sardinia, aiming at:

a) depicting their current distribution, and

b) understanding whether and how their distribution will change in future climate scenarios.

These two questions could be the starting point for developing proper conservation strategies.

Materials and methods

Study area

The Island of Sardinia has an area of 241,00 km², with an elevation range from 0 to 1834 m a.s.l. (Punta la Marmora, Gennargentu Massif).

Its geological structure is made of several stratified layers, which are: a) "Hercynian Basement" (schistore rocks variously metamorphosed and refolded during the Hercynian Orogenesis), of sedimentary origin, with an age ranging from Lower Cambrian to Lower Carboniferous (SE Sardinia). b) thick marine carbonatic sediments (dolomites, limestones), from Triassic to Cretaceous (Supramonte); c) a very thick Cenozoic succession made by continental and marine sediments (conglomerates, sandstones, clayes), marles and limestones, from Eocene to Pliocene, (area around Cagliari); d) detritic deposits, mostly continental (alluvional, aeolian, lacustric etc) of the Quaternary (conglomerates, grainstones, silt, clay), generally of limited thickness, discontiously covering the previous geological formations (Campidano valley) (Carmignani et al. 2008).

Climate is characterized by two main seasons, hot-dry and a cold-humid (Arrigoni 2006). The former has its higher intensity at high latitudes and altitudes. Annual mean temperature rages from 17-18 °C on the coast, to 10-12 °C on the mountains. Annual precipitation varies greatly from the coast to the inland. The average minimum is recorded in the South-West (e.g., Cagliari, 433 mm/y), while the maximum in the montane areas in the North (with a peak in Mount Limbara, 1412 mm/y). In general, Nurra (NW) and Campidano plain (SW) together with the Coghinas basin (N), are the driest zones, while the most rainy regions are the central part of Gallura (Mount Limbara), Barbagia and west Ogliastra (Gennargentu massif) (Camarda et al. 2015).

However, a summer period of aridity (at least 3 months), with very low precipitation, characterizes the whole island, marking Sardinian climate as typical eutemperate-dry Mediterranean (Rivas-Martinez 2008).

Response variables

For this study, we selected nine taxa for which at least 15 occurrence records were available. Occurrence data were obtained from both herbaria (Detailed list in supplementary materials S1), and field surveys, carried out between 02/2012 and 06/2017. As far as herbarium specimens are concerned, georeferencing was made *a posteriori* by using QGIS (QGIS 2016) software (2.18.6 "Las Palmas" version 2016). Field observations were georeferenced by means of a portable GPS (Garmin GPS 12CX™).

The dataset contains data for nine species: *Anacamptis longicornu* (36 records), *A. papilionacea* var. *grandiflora*

Table 1. Predictor variables selected for developing the models after a Spearman correlation test (correlation plot is shown in Supplementary Materials, Fig. S0).

Variable	Description
BIO1	Annual Mean Temperature
BIO4	Temperature Seasonality
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO15	Precipitation Seasonality
BIO19	Precipitation of Coldest Quarter

(19 records), *A. papilionacea* var. *papilionacea* (29 records), *Ophrys bombyliflora* (17 records), *O. morisii* (21 records), *O. tenthredinifera* (27 records)*, O. speculum* (20 records), *Serapias lingua* (22 records), *S. parviflora* (16 records). The full dataset is reported as supplementary material (Electronic Supplement, Table S0). To avoid autocorrelation, two records of *Ophrys speculum* were excluded from the initial dataset.

Predictor variables

19 bioclimatic variables were obtained from the WorldClim dataset (Hijmans et al. 2005, O'Donnel and Ignizio 2012), with a spatial resolution of 30 arcsec (0.83 × 0.83 = 0.69 km^2 ca. at our latitude), in the form of raster layers.

Spearman correlation was applied to identify the variables which were significantly correlated ("corrplot" R package, Wei and Simko 2017). Variables were considered collinear when $\rho > 0.8$ with a p-value < 0.01. Thus, they were ranked on the basis of the number of significant correlations, and redundant variables (those correlated with the highest number of other predictors) were excluded from further computation, in order to avoid multicollinearity in the set of predictors. Furthermore, the selection of redundant variables to exclude was also based upon the expert-based knowledge on the general physiology and ecology of orchids, and on the autecology of the investigated taxa. Thus, the total number of bioclimatic predictors was reduced to 8, in Table 1 codes for bioclimatic variables refer to WorldClim classification (correlation plot in Electronic Supplement, Figure S0).

In order to predict the evolution of orchid populations in the future, bioclimatic variables were retrieved also for year 2070. These rasters have been produced by using the global circulation model HadGEM2-ES (Hadley Global Environment Model 2 - Earth System, Collins et al. 2008), with representative concentration pathway (RCPs) 4.5 (Thomson et al. 2011).

Other three predictors were added, namely altitude (obtained from WorldClim as well), soil type and land use (both obtained from the Ecopedological Map of Italy; ISPRA 2005). These categoric predictors were transformed into ras-

ters with the same extent and resolution as the bioclimatic predictors starting from the raw data maps, and extracting the corresponding attributes, cell by cell, using the category value of the polygon which occupies the centre of the cell.

The rasters of all predictors were cropped to the study area ("raster" R package, Hijmans and Etten 2012), which extent ranges from 7.691667 to 9.983333 DD longitude, and 38.675 to 41.33333 DD latitude (SR WGS84).

Data analysis

Environmental niche models

The spatial distribution of each species was analysed with three well established algorithms: Random Forest, a regression method which uses classification trees (RF; Cutler et al. 2007), Generalized Linear Model, a classic linear regression model (GLM; Elith et al. 2006, Guisan et al. 2006), and Generalized Additive Model (GAM; Hastie and Tibshirani 1990). Since different algorithms can provide similar predictions, with slight (but sometimes relevant) differences, the resulting models were combined in an ensemble, which averages their results on the basis of individual model performance scores, for obtaining a more reliable prediction (Araújo and New 2007, Merow et al. 2013).

Since the use of presence-only data can bias the analysis and lead to unrealistic predictions, pseudo-absences (i.e., inferred absence data based on the information available about the presence locations of the species; Chefaoui and Lobo 2008, Phillips et al. 2009) were generated for informing models about locations in which species do not occur: a simple random sampling was chosen, with a ratio of 10 to 1 pseudo-absence / presence data (Barbet-Massin et al. 2012).

True Skill Statistic (TSS) was adopted as validation metric (Allouche et al. 2006). TSS is based on the measures of sensitivity and specificity of the model. Sensitivity is the proportion of real occurrences predicted by the model, while specificity is the proportion of real absences predicted by the model. TSS value (Sensitivity + Specificity − 1) substantially measures the ability of the model to discriminate between occurrence and non-occurrence of an event. A model is considered good with TSS > 0.6. Models were generated using 80% of presence data for training, and 20% for testing. Hence, in each of the 20 replication runs which were executed for each model, 80% of presence data were used to develop the model, and 20% for testing its sensitivity. Pseudo-absences ratio was set at 10:1 to presence data (Barbet- Massin et al. 2012). Beta multiplier was adjusted to 2 (Moreno-Amat et al. 2015, Shcheglovitova and Anderson 2013).

Models were merged by using an ensemble approach (Araújo and New 2007, Merow et al. 2013). Since there are no specific guidelines for selecting the models for the ensemble (i.e., which models to exclude from the averaging process in order to obtain a reliable output), the performance threshold was used as selection method. All the models with a true skill statistics (TSS) value lower than 0.6 (the threshold sug-

Table 2. Predictor variables ordered for importance for each taxon, scored from 1 (more influencing) to 11 (less influencing).

Species	BIO12	Alt	BIO5	BIO19	BIO1	BIO4	BIO6	BIO13	BIO15	Soil	Land use
A. papilionacea var. *grandiflora*	1	4	9	2	3	7	8	5	6	10	11
A. longicornu	1	3	5	2	6	7	6	4	5	10	11
A. papilionacea var. *papilionacea*	4	2	3	5	8	1	7	6	9	10	11
O. bombyliflora	1	6	2	5	3	8	7	4	9	11	10
O. morisii	1	3	2	4	8	5	7	6	9	10	11
O. neglecta	1	5	6	3	7	4	2	8	9	11	10
O. speculum	1	3	6	2	4	9	5	8	7	11	10
S. lingua	2	5	1	6	7	3	4	8	9	10	11
S. parviflora	1	2	5	4	8	3	7	6	9	11	10

gested in previous works, e.g., Araújo et al. 2005, Engler et al. 2011) were excluded from further computations.

R software (R Core Team 2016) was used for all analyses. The final ensemble was obtained by using the Biomod2 R package (Thullier et al. 2016).

Results

The variables, ordered according to the importance score for each taxon, are listed in Table 2.

Annual precipitation (BIO12) is the most influencing variable for most species (which require a total precipitation of at most 500 mm/year) but *Anacamptis papilionacea* var. *papilionacea*; altitude scores second, strongly influencing 5 out of nine taxa. The maximum temperature of warmest month (BIO5), and the precipitation of coldest quarter (BIO19) scores third. As detailed in Table 3, these variables depict an environmental limit for the distribution of taxa.

Altitude is a relevant predictor for 5 taxa (*Anacamptis longicornu*, *A. papilionacea* var. *papilionacea*, *Ophrys morisii*, *O. speculum*, *Serapias parviflora*), which seem to have a higher suitability at altitudes higher than 500 meters. As far as the other 4 taxa are concerned, they are normally restricted to lower altitudes, even if records above 1000 m are reported.

While all the taxa do require high temperature in the summer, *Anacamptis papilionacea* var. *grandiflora*, *A. longicornu*, *Ophrys tenthredinifera*, *O. speculum* and *Serapias lingua* differ from the other taxa since they are not much influenced by the maximum temperature of the warmest month; at the same time, they do require an amount of precipitation in the coldest quarter higher than 250-300 mm, while other taxa are not much influenced by this variable.

Explanation of model output

The models for *Anacamptis papilionacea* var. *grandiflora*, *A. longicornu* and *Ophrys speculum* project a climatic niche defined by limited precipitations (lower than 600 mm), occurring mostly during the cold season (more than 150 mm). *Anacamptis papilionacea var. grandiflora* seems to occur in areas with 13-15°C annual mean temperature, while *A. longicornu* and *Ophrys speculum* niche is more influenced by altitude (Figure 1).

Table 3. Limits to the distribution of each taxon as depicted by the most influencing predictor variables. These values were obtained from response curves built during the modelling procedure, they show the probability of presence against the variation of a specific variable.

Species	BIO12 (mm)	Alt (m a.s.l.)	BIO5 (°C)	BIO19 (mm)
A. papilionacea var. *grandiflora*	< 500			> 300
A. longicornu	< 500	> 500		> 300
A. papilionacea var. *papilionacea*	< 500	> 500	> 29	
O. bombyliflora	< 500		> 29	
O. morisii	< 500	> 500	> 29	
O. neglecta	< 500		> 29	> 250
O. speculum	< 500	> 500	> 29	> 300
S. lingua	< 500		> 29	
S. parviflora	< 500	> 500	> 29	

Table 4. Percentual gain and loss of climatic niche, and net gain, with respect to current conditions.

Species	Loss %	Gain %	Change %
A. papilionacea var. *grandiflora*	47.57	67.68	20.12
A. longicornu	13.59	228.05	214.46
A. papilionacea var. *papilionacea*	14.68	229.11	214.43
O. bombyliflora	13.00	231.08	218.09
O. morisii	5.54	274.62	269.08
O. neglecta	34.84	129.86	95.02
O. speculum	23.89	132.20	108.31
S. lingua	10.26	222.43	212.17
S. parviflora	20.76	169.66	148.90

Ophrys bombyliflora and *Serapias lingua* are projected to require high temperatures in summer (>28°C). However, *Ophrys bombyliflora* is also related to a mean annual temperature lower than 16°C, and hence differs from *Serapias lingua*, which does not tolerate high seasonal excursions. Both the

species are restricted to areas with a relatively limited amount of annual precipitation, with a maximum of ca. 500 mm. *Anacamptis papilionacea* var. *papilionacea* seems to have the same requirements as far as high temperature in summer is concerned, and has a similar response to temperature seasonality as *Serapias lingua* and *S. parviflora*. The latter seems to have the same requirement in terms of annual precipitation as *Ophrys bombyliflora* and *Serapias lingua.* Furthermore, *Serapias parviflora* shares with *Anacamptis papilionacea* var. *papilionacea* a reduced distribution at lower altitudes (< 150-200 m), with an optimum over 800 m (Figure 2).

Ophrys morisii is another species that requires high temperatures in the warmest months (>28°C), and which has a limited distribution at lower altitudes (<100 m). It has also a lim-

ited fitness when annual precipitation is higher than 500 mm, a feature it shares with the congeneric *O. tenthredinifera*. The latter however, does require a warm (mean temperature >7°C) and more rainy (300 mm) cold season (Figure 3).

### Distribution under a climate change scenario

The change in habitat suitability is projected to range from ca. 20% up to ca. 270% in future projections (Table 4).

The general trend is an increase of the size of the suitable area for the majority of the analysed species, even if with different probability of occurrence (see later). Except for *Anacamptis papilionacea* var. *grandiflora*, the percentage loss of occupied area is generally 10-fold lower than the gain.
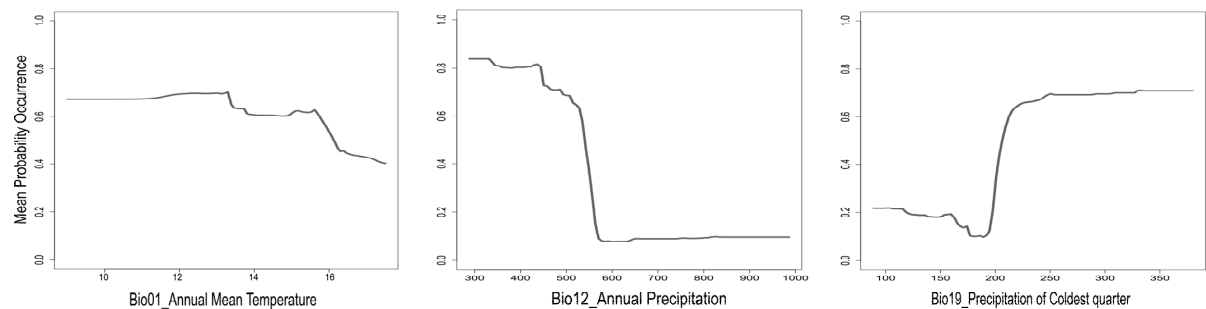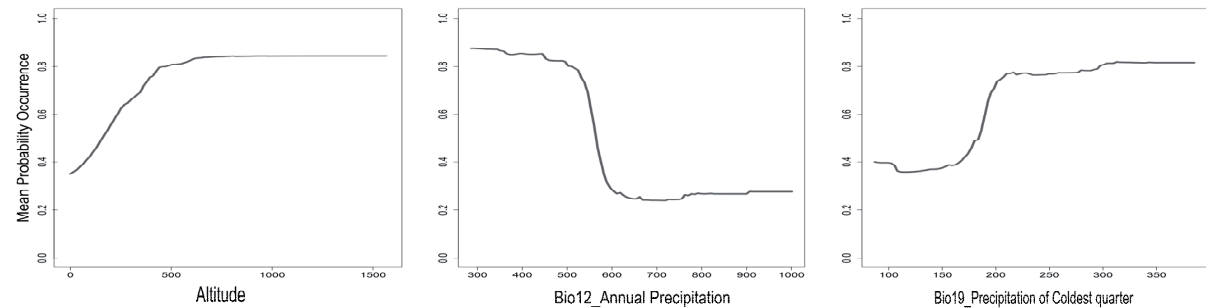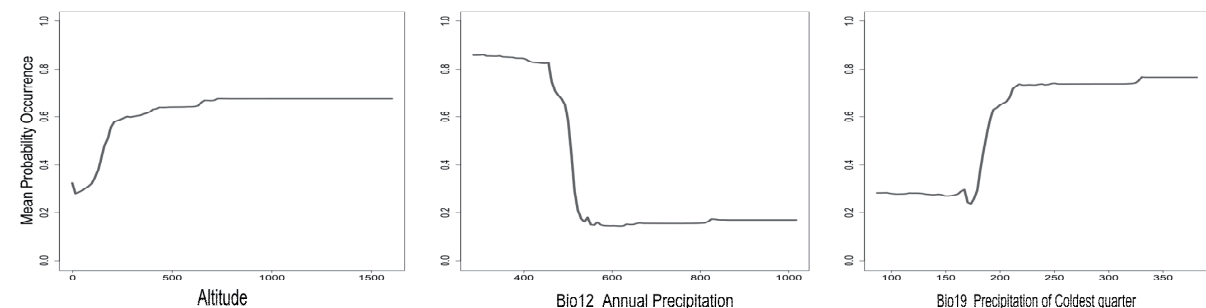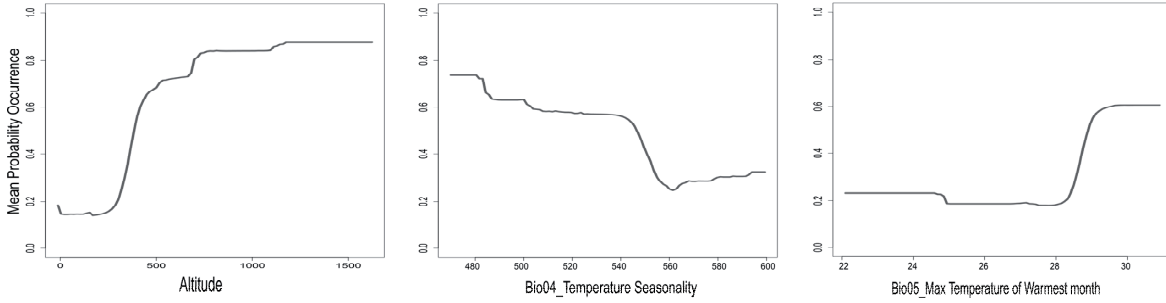

Figure 1. Response variables graphs for the three most important predictors as far as *Anacamptis papilionacea* var. *grandiflora, A. longicornu* and *Ophrys speculum* are concerned. The y-axis corresponds to mean probability of presence, the x-axis represents the variables values (mm for precipitation, °C for temperature, % for seasonality).

A. papilionacea var. *grandiflora* is the taxon with lower net gain (ca. 20%) in comparison with the current distribution; *O. morisii* is the species with potentially the highest enlargement of climatically suitable area (269%).
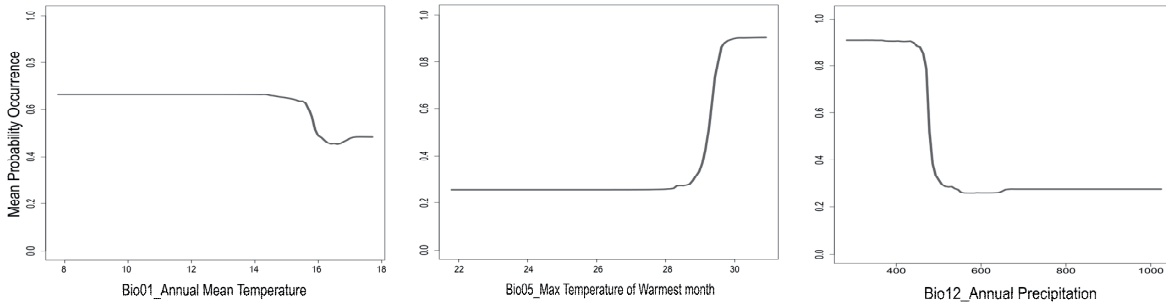
Suitability maps

Suitability maps (Supplementary material, Figures S1-3) are reported for current and future (2070) climatic conditions.
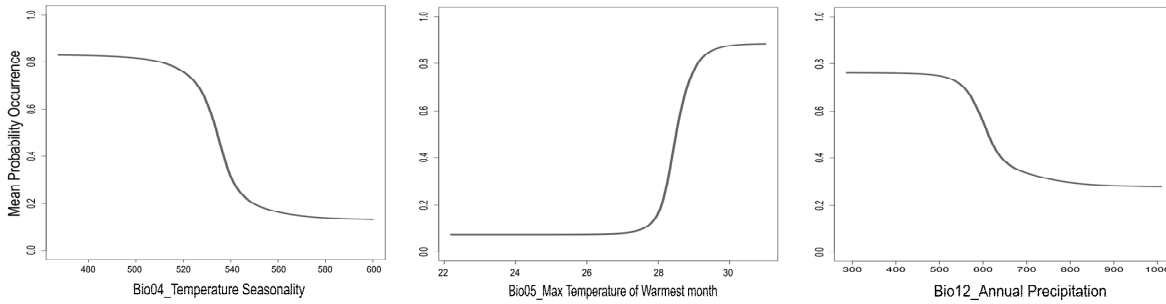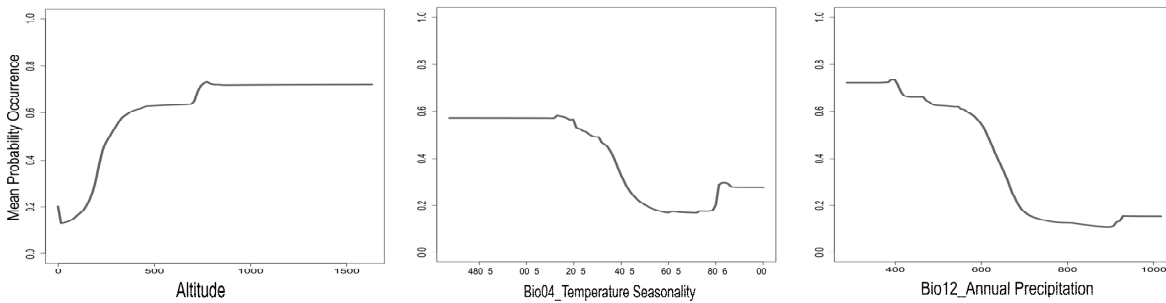
A. papilionacea

O. bombyliflora

S. lingua

S. parviflora

Figure 2. Response variables graphs for the three most important predictors as far as *Anacamptis papilionacea* var. *papilionacea, Ophrys bombyliflora, Serapias lingua* and *S. parviflora* are concerned. The y-axis corresponds to mean probability of presence, the x-axis represents the variables values (mm for precipitation, °C for temperature, % for seasonality).

Predicted suitability ranges from 0 (not suitable, blue) to 1 (highly suitable, red).

Anacamptis papilionacea var. *grandiflora* (Figure S1a) is depicted as occurring with high suitability mostly in the south-east and south westernmost part of the island. Another spot of high suitability is present in the north-western part of the island, immediately north of the town of Alghero. A. *longicornu* (Figure S1b) has a similar potential distribution, but has a high suitability only in the south-eastern part of the island. *Serapias lingua* (Figure S1c), on the contrary, has a high suitability also along the western coast. In the future scenario, all these species seem to widen their suitable area especially in the west side of the island. However, *Anacamptis papilionacea* var. *grandiflora* seems to have a reduced probability of occurrence, maintaining limited areas of high suitability only in the southernmost parts of the island.

Anacamptis papilionacea var. *papilionacea*, *Serapias parviflora*, *Ophrys bombyliflora* and *O. morisii* (Figures S2a-d) are depicted as occurring with high suitability mostly in the south-easternmost part of the island. In the future scenario, all these species are projected to expand their distribution to almost all the island, with high suitability especially in the north-western part.

Ophrys tenthredinifera and *O. speculum*, currently given as occurring with high suitability in the southern part of the island (Figures S3a,b), are projected to have a widening of the suitable area, but coupled with a decrease of suitability scores, with areas of high suitability limited to the southernmost parts of the island.

Discussion

From our analysis, all the nine orchid taxa are projected to have an expansion of their distributional range in the island. However, areas of high suitability (>0.8), indicating areas in which the taxa will almost certainly occur, will decrease for at least two of them.

Most of the species which have a high suitability in areas with low average yearly precipitation, *Anacamptis longicornu*, *Ophrys bombyliflora*, *O. morisii*, *O. speculum*, *Serapias lingua* and *S. parviflora*, are projected to have a widening of their areas of high suitability (>0.8).

Anacamptis papilionacea var. *papilionacea* is also projected to increase its area of high suitability, since it is positively influenced by high temperatures in the warmest month, which will increase in the future scenarios. However, interannual variability is foreseen to increase in future scenarios, with a deepening of differences between winter and spring. In the western parts of Sardinia the humid winds from the Mediterranean could mitigate this effect. Hence, *Anacamptis papilionacea* var. *papilionacea* is projected to increase its areas of high suitability in the western part of the island. *Anacamptis papilionacea* var. *grandiflora* is known to occur only in Sardinia and Sicily, and it is normally restricted to lower altitudes, even if records above 1000 m are reported.
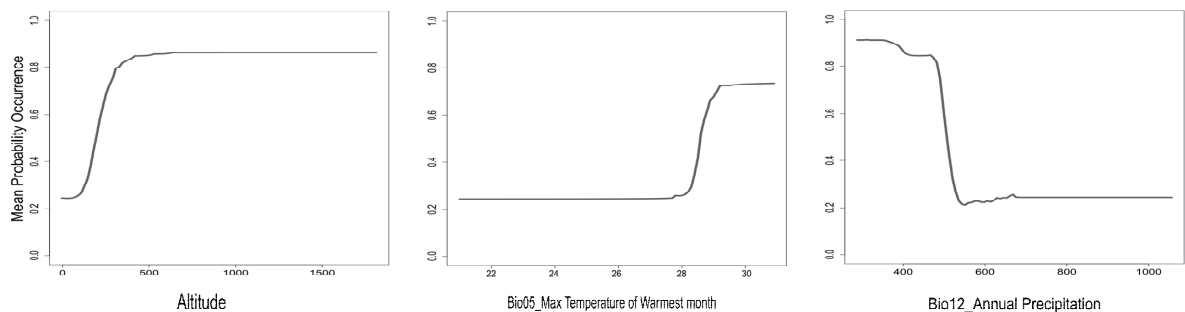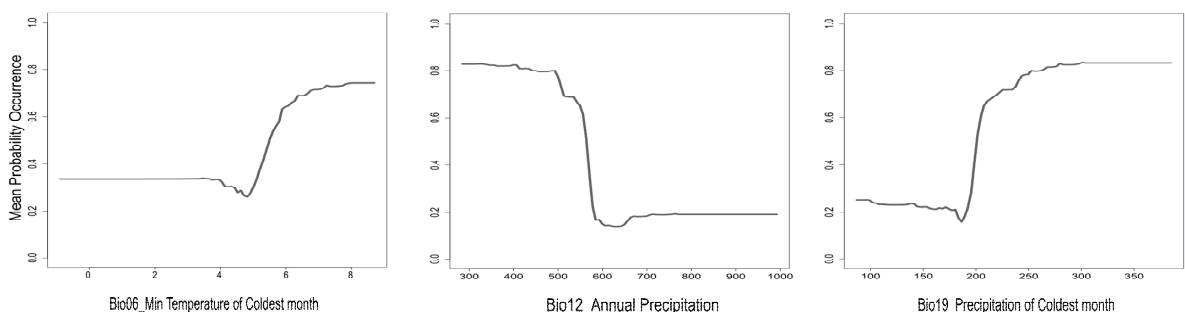
Figure 3. Response variables graphs for the three most important predictors as far as *Ophrys morisii* and *O. tenthredinifera* are concerned. The y-axis corresponds to mean probability of presence, the x-axis represents the variables values (mm for precipitation, °C for temperature, % for seasonality).

Ophrys bombyliflora, *O. tenthredinifera* and *Serapias lingua* have a similar ecology, and are known to sporadically occur up to ca. 1000 m, while the latter could sporadically grow up to 1500 m.

Anacamptis papilionacea var. *grandiflora* and *Ophrys tenthredinifera* are projected to have a relevant reduction of their areas of higher suitability, in spite of a widening of their potential distribution area in the island. The former is projected to reduce its suitability especially in the north-western part of the island, and, together with the latter, will maintain high suitability values only in the southern part of Sardinia. Both species are especially limited by the precipitation in the coldest season, if over 200 mm. *Anacamptis papilionacea* var. *grandiflora* is also projected to be limited by a general increase in yearly mean temperature, since it is projected to have a higher suitability in areas with an average yearly temperature lower than 16°C. On the contrary, an increase of average temperature should not affect particularly *Ophrys tenthredinifera*, which is projected to have a higher suitability in areas with warmer winters especially in South Sardinia, where summer is hotter and drier, and a small amount of rain is mostly occurring in autumn and winter. Hence, this area could remain suitable to this species also in future scenarios.

In fact, in future forecasts, climate change will lead to an increase of the average temperature, with an increase of seasonality, and to a decrease of precipitation, especially in the warm season (Giorgi and Lionello 2008). These changes will lead to possible climatic and ecological limitations to the distribution and survival of several orchid taxa.

Some of these limitations might be: a deficiency of precipitation during the coldest months, which can prevent the correct development of the roots, as well as the storage of enough nutrients to sustain the vegetative phase of the life cycle of several orchids (Tatarenko and Kondo 2003); an increased temperature seasonality, which could expose the seedlings to freezing during the cold period, and to heat shock, if the hot season will not be preceded by a mild spring as acclimatization period (Pfeifer et al. 2006); too high temperatures during the hottest months, which could limit several orchids in closing their seasonal vegetative cycle in an optimal way (Rasmussen 1995, Wells and Cox 1989).

A progressive establishment of such ecological and climatic conditions could thus cause a generalized change of distribution of orchid taxa towards areas in which suitable microclimatic conditions do occur. Furthermore, as a response to different climatic conditions, orchids could also anticipate all the phases of their vital cycle (dormancy, vegetative phase, blooming season and fructification). However, since orchids are almost exclusively entomogamous, this could lead to a non-optimal timing between the blooming season and the seasonal activity of pollinators.

Climate change is projected to have a strong influence on distribution and suitability in the Sardinian taxa we investigated: some species are projected to have a wider distribution, with increased suitability in several parts of the island, while some others will reduce their suitability, and will become restricted to smaller areas.

The effects of these changes are complex to forecast, however. Changes in ecological conditions could affect all those populations which will not be able to escape the new – hostile – ecological conditions. Furthermore, a "mass movement" of other orchid's populations following changed ecological conditions could eventually lead to a niche overlap in the future, which could lead to: competition among taxa, and the eventuality of the loss of less adapted ones; hybridization among sympatric taxa. Hybridization could increase local biodiversity, if it produces new, independent taxonomical entities, while maintaining the "parental taxa". On the other hand, it could decrease local biodiversity if, in the process that lead to the stabilization of the new hybrid entities, the "parental taxa" disappear.

The results of this work could be of interest when planning climate change adaptation strategies, especially when protection of biodiversity is concerned. In Italy, a national directive for the protection of plants is missing, while there are 10 orchids listed in the red list of the vascular flora (Rossi et al. 2013).

Nonetheless, analysed species are the commonest in the study area and they have not been evaluated by the IUCN Species Survival Commission. According to the IUCN red list criteria for evaluation of threatened species (mainly relied on expected population size reduction and geographic range compression in the next 10 years; IUCN Red List Categories and Criteria 3.1, 2012), these species are not to be considered as endangered. Despite their conservation status, however, this work represents an important starting point for an effective monitoring of the effect of future environmental disturbances. Sardinia, while being an important hotspot for the family (Mittermeier et al. 2004), is also missing proper directives as far as both flora and fauna are concerned. Since planning proper conservation frameworks require reliable scientific data, studies like the present could allow an optimal evaluation of the current and future status of these taxa, and hence to better address conservation and management efforts.

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Supplementary material

Table S0. Occurrence dataset of the nine species modelled.

Figure S0. Correlation plot of climatic predictor variables, colour intensity indicates high rho values.

Figure S1. Suitability maps for *Anacamptis papilionacea* var. *grandiflora* (a), *A. longicornu* (b) and *Serapias lingua* (c).

Figure S2. Suitability maps for *Anacamptis papilionacea* var. *papilionacea* (a), *Serapias parviflora* (b), *Ophrys bombyliflora* (c) and *O. morisii* (d).

Figure S3. Suitability maps for *Ophrys tenthredinifera* (a) and *O. speculum* (b).

The files may be downloaded from www.akademiai.com.