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Ecology of Mediterranean lichens and plants: application of species distribution models.

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Summary

Preface

Naming things has always been a primordial need of the human being. Categorizing, *sensu* giving names to things, is natural and instinctual in human kind, and soon became a philosophical issue. Languages evolved, and are based on the mechanism of classification. Also, naturalistic longstanding disciplines, such as systematics and taxonomy, directly deal with this need, bringing into focus the problem of defining the boundaries between two adjacent categories – the taxa – and consequently of the sense of a categorical approach in investigating continuous systems, such as biological variability (morphology and anatomy, but also physiology, ecology, etc.).

Decades of theoretic studies focused on the environment as a complex and interconnected multi-level system have led to the formalization of methods, and algorithms, in forms which are usable by researchers. These tools can nowadays be coupled with modern technology, and high computing power. Hence, today it is possible to *classify* (i.e. traduce in discrete categories), and *quantify* (i.e. define the impact on other components of the environment) dynamics which are proper of complex systems. This view makes even more interesting the investigation of peculiar lifestyles and strategies, such as symbiotic associations.

The use of ecological niche modelling methods applied to the ecology of species is a powerful tool, which can lead, in the first place, to an improvement of the knowledge of poorly known taxa, which adopt peculiar life strategies. Secondly, in a perspective of conservation, they can be helpful in understanding the diversity of the environment, fundamental for its stability, hence for planning efficient policies, and for optimizing and focusing efforts.

The niche: the word, its history and visions.

The ecological thinking originates from Greek philosophers and naturalists and deeply roots back to 4th century B.C. The concept of ecological niche is detectable in Aristotle (*Historia Animālium*), who expressed it as a multiplicity of life forms with accurate descriptions of their habits, distribution, seasonal, climatic and abiotic factors. Later it is present in the work of Theophrastus (*Historia Plantarum*), whom describes relationships between organisms and environment. During the 18th century, Linnaeus merged the Christian tradition with coeval naturalists' work, defining the theory of the "economy of nature" (1949), which depicts nature as balanced, rational, and ordered by divine laws, and organisms as members of species, with well defined roles in the maintenance of order in the world. During the 19th century, the idea of interdependent relationships between elements in the environment arose in a variety of embryonal forms, such as the observation of plant-climate dependence, and the consequent description of plants distribution areas using latitude and longitude by Alexander von Humbolt, the father of biogeography (Silvertown et al., 2006). Other novel ideas were the definition of biotic relation types (van Beneden, 1876), the concept of biocoenosis (Möbius, 1877), the study of food web dynamics (Forbes, 1880), the study of vegetal (then ecological) successions (Thoreau, 1860), the notion of limiting factor (Liebig, 1840), and, influenced by the investigation on population dynamics (Malthus, 1798), the concept of adaptation to environment (Darwin, 1859).

The term "niche", intended as the place of a species in the environment, was used for the first time by the naturalist Roswell Hill Johnson (1910), but it was Joseph Grinnell that included, for the first time, this concept in his research framework (Grinnell, 1917). With the term "niche" he intended all the factors, biotic and abiotic, which influence the presence of a species in a given place. In order to explain the features of a species, he elaborated the ecological hierarchy, in which he placed biotic and biotic factors at different levels (from realms to niches). In this view, a niche is considered as the smallest unit of a system, which is defined by the characteristics and relationships of a species with regard to surrounding environment and organisms. Grinnell also focused on the comparison of communities living in different environments, elaborating the concept of ecological equivalents, i.e. species or associations which share the same ecological traits and strategies, in different geographic areas and environments. The mainspring that moved Grinnel towards these investigations is the same which prompted Charles Sutherland Elton's research in a perfectly opposite but complementary view (Elton, 1927): his research focused on the invariance of community structure across environments. Elton investigated the common traits of associations which occur in different environments or areas. Naturally, this lead him to study mainly trophic relationships, and to view the niche of a species essentially as its trophic position, i.e. "[the] *place in the biotic environment, its relations to food and enemies*". Grinnel and Elton visions are the baseline for the following formalization of the difference between the concepts of fundamental and realized niche, by George Evelyn Hutchinson (1957). In his synthesis, he took into account also the results from the validation test of Lotka-Volterra equation by Georgy Gause (1930), proving what now is known as the competitive exclusion principle. Hutchinson's definition of the niche as a n-dimensional space, where dimensions are functions of availability of resources and environmental factors (the *fundamental* niche) allowed contingent dynamics, based on trophic competition, which tend to reduce species' ecological space (*realized* niche). Hence, there is a shift of the concept "niche" towards a characteristic of the species, with an emphasis on ecological similarity. From this point onwards, the fundamentals of ecological niche concept basically remain the same, but are better implemented thanks to new statistical methods. From the "limiting similarity" (MacArthur and Levins, 1967), to the overlap index (Schoener, 1968), until latest algorithms integrations, and synthesis of these methods.

Nowadays, plenty of statistical methods have been developed to quantify and formalize ecological space occupied by a species, from regression models (Austin, 2007), including classification and regression trees (Massey et al., 2008), to random forests (Prasad et al., 2006), to ordination techniques (Ter Braak and Prentice, 1988), and Bayesian models (Termansen et al., 2006). Machine learning approaches, such as maximum entropy model (Maxent) have also became very popular (Phillips and Dudik, 2008). All these methods are involved in what is called "environmental niche modelling", "ecological niche modelling", "species distribution modelling", or "climate envelope modelling". These definitions can be incompatible, complementary, or coexistent depending on the object of study.

These views and tools make even more interesting the investigation of peculiar life strategies, such as strict associations, adopted by pioneer symbiotic organisms (lichens), and plant-fungus mycorrhizal organization (orchids).

Lichens and orchids.

The studies in this work face with lichens and orchids, two groups with peculiar life strategies, and adaptations to environmental conditions. They are both symbiotic entities, composed by a fungus and one or more algae the former, and a plant the latter (at least in one life phase).

Lichenized fungi show a peculiar life strategy. They constitute a self-sustaining system, since the algae, by mean of photosynthesis, provides nutrients for the fungus (Kappen, 1988; Campbell et al., 1998). Thus, generally lichens are heliophilous fungi. Furthermore, they are poikilohydric organisms: their hydration status depends on environmental water availability (Palmqvist and Sundberg, 2000). They are capable of dehydration, until they reach a dormancy-like phase, in which metabolism drops down at minimal levels. On the contrary, if there is an excess of water, the risk is the dissociation of the two partners. For these peculiarities, different lichen species show different degree of tolerance to dehydration and radiation. Thus, considering sun radiation as a constant for earth surface, abundance of water is one of the most important factors which shape lichen species niche (Topham, 1977).

Hence, in studying lichen ecology from the biogeographical point of view, we can assume that, at least in the broad sense, the concepts of “environmental niche model” and “climatic niche model” are mostly equivalent. Thanks to their capacity for adaptation, which allow them to adapt also to extremely severe conditions, lichens are present practically in any environment on earth, even those most extreme, hence foreclosed to colonization for other organisms. Lichens are globally distributed, and different groups are adapted to different climate types, from Antarctic to deserts, from mountains peaks to rainforests (Barreno et al., 1998). The Mediterranean is one of the most relevant centers of distribution of lichen taxa from a biogeographical point of view (Galloway, 2008). In fact, in species having the wide distributional ranges, a strong affinity to the Mediterranean climate can be observed, hence demonstrating the importance of this area as a major center of distribution. However, often little is known about the infra-specific variability of lichen species along climatic gradients within the Mediterranean area.

The Mediterranean is also a major diversity hotspot for the family of Orchidaceae. Among plants, orchids are probably one of the groups with more rare and endangered taxa (Brigham and Swartz

2003, Pitman and Jørgensen 2002). Orchids are blooming epiphytes, commonly known for their coloured and fragrant flowers, and one of the biggest vascular plant families, counting ca. 28000 accepted species (Christenhusz and Byng, 2016). Orchids have the peculiarity of living at least one phase of their life cycle, usually that of seed germination, in symbiosis with mycorrhizal fungi. Their seeds do not have nutrients storage structures, since they evolved a symbiotic relationship with soil fungi, which are able to provide them of the nutrients in the germination phase. Furthermore, a number of orchids are achlorophyllous, and remain in symbiosis with the fungus for their entire life. In the last years, this quite unique group of plants has been targeted by several conservation efforts to prevent diversity loss in consequence of global changes (Sletvold et al. 2013).

Species distribution modelling

Species distribution models aim at predicting where organisms do occur on the basis of the pattern of biophysical conditions of the study area (Drew et al., 2011). This is possible thanks to the creation of statistical models of the relationship between environmental variables and known occurrences of specimens of a taxon.

In distribution models, environmental data in gridded format (rasters) are interpolated with georeferenced occurrence locations. For every occurrence point, values of each environmental predictor are extracted. Then, an algorithm elaborates the mathematical relationship between presence (the response variable) and environmental features (the predictors). Years of systematic recording of meteorological data allowed their temporal and spatial organizations in time series and georeferenced raster maps, which can be easily implemented in computation software. In the same way, remote sensing data can be used to obtain synthetic landscape profiles, to be included in modelling procedures (Daly, 2006). Today one of the major application of these types of data are studies about climate change ecology, mostly facing issue of biodiversity conservation. However, while there exist a lot of environmental data at global or national scales, is not very simple to obtain data at finer scales (regional, or local). The latter are mostly fragmented and inhomogeneous, since often environmental monitoring and data gathering competences are spread among different institutions and administrations.

As far as modelling is concerned, several algorithms have been developed in the last 20 years. In the studies collected here, the focus is mostly centered on the integration of some of them. In particular, four algorithms were used: Generalized Linear Model, classic linear regression model (GLM; Elith et al. 2006, Guisan et al. 2006), Generalized Additive Model, linear regression model allowing interdependence of predictors (GAM; Hastie and Tibshirani 1990), Random Forest, a regression method which uses classification trees (RF; Cutler et al., 2007), and MaxEnt, a machine learning method based on the principle of maximum entropy, (Phillips et al. 2006).

These statistical methods have been integrated by mean of an ensemble modelling approach, which combines the results from different models in a final ensemble model, averaging them on the basis of individual model performance scores, for obtaining more robust predictions (Araújo and New, 2007; Merow et al., 2013). Among distribution modelling techniques, the ensemble approach is the more prudent, and is especially suitable for studying poorly know taxa, and when the number of occurrences is limited.

Three different applications

Many studies have included climatic niche modelling techniques to address biogeographical issues, such as quantifying potential distribution, species richness and turnover in specific sites, to define spatial geographic patterns of species. Recently, an increasing number of studies about fungi makes use of modelling approaches for exploring ecological variability (e. g. Bendiksby et al. 2014, Ellis et al. 2007, Wiersma and Skinner 2011).

In the first section, a study on the ecology of the infrageneric taxa of genus *Solenopsora* is presented (accepted for publication on *The Lichenologist*). *Solenopsora* A. Massal. (Leprocaulaceae, cf. Lendemer and Hodkinson 2013) is a genus of small foliose lichens, growing on rocks, in semi- natural areas. The genus includes up to 25 species, mostly occurring in temperate and subtropical regions, with the exclusion of South America (Gilbert et al. 2009, Ryan and Timdal 2002). In Europe, while some of the taxa have a wide geographical distribution, ranging from central Europe (with continental or Atlantic climate) to the Mediterranean, all the others are more restricted to Mediterranean area. The aim of this study was to explore the ecological variability of the different species of the genus that show diverse distribution pattern, for understanding whether the responses to environmental factors are species-specific.

Species distribution models can be used for forecasting the future distribution of a taxon when using future climatic scenarios, developed taking into account current knowledge on the possible effects of climate change. It is a fact that climate trends in the last century are anomalous if compared with previous climatic oscillations of the Earth (Dawson et al., 2011). The main differences from past trends can be summarized in three widespread phenomena: the global warming, which is predicted to hit, in some locations, an increase of more than 5°C (Intergovernmental Panel on Climate-Change, 2001a [IPCC]); the nature of precipitation events, which are becoming more localized, and abundant (Hannah et al. 2002); the occurring of catastrophic and extreme meteorological events (Easterling et al., 2005). Climate change already generated distributional range shiftings for several species, and an increased risk of extinction, or of invasion (Jump and Peñuelas 2005). Species distribution models can be a useful tool for estimating future species distributions, and hence the effects of global change on ecosystem dynamics and services.

In this view, policy and decision-making can be supported by developing species distribution models, thus improving the effectiveness of global change adaptation and mitigation strategies, especially as far as conservation efforts are concerned. In particular, since conservation efforts can be expensive, and time consuming, species distribution modelling can provide a way for optimizing resources, and for better addressing efforts.

The second section host a study addressing the modelling of current distribution, and the forecasting of distribution under future scenario (Hadley Global Environment Model 2 - Earth System, RCP 4.5 greenhouse gas emission scenario for 2070), of several Sardinian orchids (accepted for publication on *Community Ecology*). 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 was strongly influenced by its complex geological and climatic history. In this area, climate changes 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), thus leading to the extinction of endemic taxa, and to a reduced resistance and resilience of ecosystems (Jump and Peñuelas, 2005). While 529 orchid taxa are known to occur in Europe (Delforge, 2006), Sardinia is one of their biodiversity hotspots (Mittermeier et al., 2004), with 60 recorded taxa (Lai, 2009). However, Sardinian ecosystems are changing in consequence of climate change, and while some species are reducing their habitat, others are colonizing the island, and/or widening their distribution. Future climate change scenarios for Sardinia depict a situation in which the average monthly temperatures could increase of a 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 of 20–50% during the rest of the year (Gritti et al., 2006).

The third section of this work hosts a study on the use of distribution models for investigating taxonomic and evolutionary questions. Some previous works addressed similar questions, combining the use of species distribution models with morphological, chemical or molecular data (Martellos et al., 2014, Mereďa et al., 2016). In this study, the case of *Pterygiopsis affinis*, a rare crustose cyanolichen, adapted to the Mediterranean climate, is investigated (in submission). *P. affinis* s.str. is known to reproduce by apothecia (Massalongo, 1853; Henssen, 1963; 1979). However, a sorediate morphotype was discovered in Southern Italy twenty years ago, whose identity was never deeply investigated before. Species distribution models, together with morphological analysis, are used in this study to understand whether this morphotype is an ecological variation of the species, or a new taxonomic entity.

Most primitive lichens had a crustose, unorganized thallus, without an actual stratification, with blue algae as photosintetic partners (Dal Forno et al., 2013). These primitive lichens, still occurring in many environments, are normally crustose pioneer cyanolichens. They have an extreme phenotypic plasticity, ranging from “typical” to very uncommon forms, such as chimeras (Henskens et al., 2012). This variability can also affect the reproductive strategies: some lichens can switch to asexual reproductive strategies, especially when driven by a limited availability of free-living photobionts (Belinchón et al., 2015). Taxonomic classification of lichens is traditionally based on anatomy and morphology of the fruiting bodies. Thus, taxa which reproduce by vegetative structures only are normally treated separately from sexually reproducing taxa. However, according to the hypothesis of species pairs (Poelt, 1970; 1972), it is possible that the same taxon could adopt different reproductive strategies in different ecological conditions. For all these reasons, the taxonomic collocation of some taxa of cyanolichens is difficult, and species distribution modelling could be helpful in depicting their niche, and supporting taxonomical delimitation in particularly complex situations.

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Section 1

Ecological specialization of lichen congeners with a strong link to Mediterranean-type climate: a case study of the genus *Solenopsora* in the Apennine Peninsula

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Abstract: An ecological biogeographic perspective provides a better understanding of the factors that shape the geographical distribution of organisms, their biodiversity, and ecological speciation. Focusing on members of the lichen genus *Solenopsora*, which are strongly linked to a Mediterranean-type climate, we aimed to depict their environmental niches in the Apennine Peninsula. This area represents their ecological optima, as well as the biogeographical centre of distribution. On the basis of occurrences of *Solenopsora* congeners, we identified the key ecological factors that shape their environmental niches. Applying an ensemble approach, which merges the results of Random Forest, GLM, and MaxEnt algorithms, suitability maps were developed. These are mainly influenced by geological substrate, temperature, and precipitation. Occurrence of *Solenopsora* taxa seem to be mainly explained by low variability in diurnal temperature, tolerance to dryness, with an amount of precipitation in the range of 0–20 mm in the driest month, and a minimum temperature of the coldest month >5°C. The sensitivity to diurnal temperature, an important indicator for climate change, suggests that the taxa confined to Mediterranean bioclimatic types, i.e. *S. grisea*, *S. marina*, *S. olivacea* subsp. *olbiensis* and *S. olivacea* subsp. *olivacea* may be good indicators for climatic stability. The geological substrate was a strong limiting factor, and separated the taxa into three groups, which grow on calcareous, siliceous and ultramafic substrates, respectively. Scarce co-occurrence of species confined to one of the three categories of geological substrate suggests, that the level of niche differentiation is on a microhabitat level. Accounting for ecological requirements, the taxa differ in their tolerance to sub-optimal conditions. The ecological niches of sister subspecies pair with different reproduction strategy – fertile *S. olivacea* subsp. *olivacea,* and sorediate *S. olivacea* subsp. *olbiensis* overlaps strongly. However, suitability for *S. olivacea* subsp. *olbiensis* is greater in habitats with higher amounts of precipitations in the driest month, whereas *S. olivacea* subsp. *olivacea* is more restricted to warmer and drier areas. We also report new regional records for Italy; the first records of the occurrence of *S. cesatii* in Serbia and Ukraine, and *S. liparina* in Serbia.

Keywords: climate envelope, climate change, distribution modelling, ecological biogeography, ensemble climatic modelling, symbiotic organisms

Introduction

Understanding the factors that influence the spatial distribution of species in the present time is a key challenge of ecological biogeography (Monge-Nájera 2008, Leavitt & Lumbsch 2016). A prominent biogeographical patterns is linked to the Mediterranean-type climate, 80% of which is located the Mediterranean Basin – one of the world´s biodiversity hotspots with a rich biota and high proportion of endemic species (Myers et al. 2000, Fady-Welterlen 2005, Nieto Feliner 2014). Several studies have explored species-climate relationships for a wide variety of organisms in this area (e. g. Petit et al. 2005, Youssef et al. 2011, Planas et al. 2014, Santiso et al. 2016), as well as the ecological specialization of Mediterranean elements (Thompson et al. 2005). The Mediterranean biogeographical pattern is also one of the sixteen major patterns identified in lichens (Galloway 2008). Many lichens favour the Mediterranean climate (mild rainy winters, hot dry summers with nocturnal hydration by dew or fog during the drier seasons), but a Mediterranean element analogous to steno- or eurymediterranean vascular plants, has been difficult to define among lichens (Incerti & Nimis 2006). According to current knowledge an example of species restricted to this geographical area are e.g. *Physconia servitii*, *P. petraea* or *Physconia venusta* (Otte et al. 2002). Although in lichen genera with widely distributed species we may find some taxa with a strong affinity to the Mediterranean climate (e.g. *Leptogium ferax*, Guttová & Lőkös 2011; *Squamarina concrescens*, Poelt & Krüger 1970), little is known about closely related lichens (e.g. members of the same genus) and their ecological variation along climatic gradients within the Mediterranean.

An increasing number of studies on lichenized fungi have included the use of climatic niche modelling techniques to understand their biogeographical patterns (e. g. Bendiksby et al. 2014, Ellis et al. 2007, Wiersma & Skinner 2011). However, a need to extend ecological biogeographical studies to wider spectrum of lichen diversity has been raised (Leavitt & Lumbsch 2016). The lichen genus *Solenopsora* A. Massal. (Leprocaulaceae, cf. Lendemer & Hodkinson 2013, Miadlikowska et al. 2014) currently includes up to 25 species, mostly occurring in temperate and subtropical regions except for South America (Gilbert et al. 2009, Ryan & Timdal 2002). So far, they have been reported from three of the five Mediterranean-type ecosystems – the Mediterranean Basin (e. g. *S. grisea*, *S. olivacea* subsp. *olivacea*, *S. olivacea* subsp. *olbiensis*, *S. marina*, Nimis 2017, Guttová et al. 2014), California (e. g. *S. crenata*, *S. chihuahuana*, *S. cladonioides*, and *S. cyathiformis*, Ryan & Timdal 2002), and Australia (*S. holophaea*, *S. vulturiensis*, Cranfield 2004, Elix 2009, McCarthy 2013, McCarthy & Elix 2017, Sammy 1989). In view of this, eight species and two subspecies of the genus *Solenopsora* concentrated in the Mediterranean Basin were selected for study both for ecological as well as taxonomical reasons.

The distribution of the majority of the European taxa of the genus *Solenopsora* is restricted to the Mediterranean basin. Some of these species have wider biogeographical amplitude, extending to European areas with more continental or Atlantic climate (Guttová et al. 2014, Fačkovcová et al.

2017). They mostly inhabit substrates with fewer competitive interactions (rocks) in extreme or azonal habitats, unsuitable for cultivation, i. e. barely accessible gorges, cliffs, steep slopes, which are thus relatively stable with respect to vegetation succession, or human-induced landscape modifications. Here, environmental constraints limit the aboveground competition, and constrain succession. Some taxa grow in more sheltered, humid situations in woodlands (e. g. *S. olivacea* subsp. *olbiensis*), while others are able to tolerate direct sun in open habitats (e. g. *S. holophaea*).

Distribution models have been used to investigate taxonomic or evolutionary questions, when combined with morphological, chemical or molecular data (Martellos et al. 2014, Mereďa et al. 2016). The two closely-related intraspecific taxa within *Solenopsora olivacea,* with different modes of reproduction, feature peculiar ecological preferences: *S. olivacea* subsp. *olivacea* (forming apothecia) grows on rock faces in shaded and open habitats, whereas *S. olivacea* subsp. *olbiensis* (forming soredia) is an obligatory chasmophyte, when it occurs on perpendicular rock faces these are in humid and shaded forests (Guttová et al. 2014).

In this study, we aimed to investigate whether the species responses to environmental factors are taxon specific, and can shed more light on the differentiation between closely related entities of the two major lineages within the genus *Solenopsora* under the current generic concept (see Guttová et al. 2014). Employing a modelling approach, we used occurrence data of members of the genus from the Apennine Peninsula, aiming to 1) identify the environmental factors that shape the species ecological niches; 2) understand the flexibility of multiple *Solenopsora* taxa to inhabit different geographical and bioclimatic spaces; and 3) depict the degree of overlap/differentiation of ecological niches between the studied species, though with a special focus on two subspecies of *S. olivacea* with different reproductive strategies.

Materials and Methods

Study area

The Apennine Peninsula is a well-structured landscape of the Mediterranean Basin. Compared to the Iberian and Balkan Peninsulas, it features the fewest bioclimatic variants (cf. Rivas-Martínez et al. 2011), having the 1) Mediterranean pluviseasonal oceanic, 2) temperate continental, 3) temperate oceanic submediterranean, and 4) temperate oceanic variants. It had a limited contribution to the postglacial colonization of Central and North Europe due to stronger geographical barriers, such as the Alps (Nieto Feliner 2014). The study area includes the Apennine Peninsula with the southern Prealps (Prealpi Bresciane e Gardesane, Prealpi Bergamasche, Prealpi Venete, Alpi and Prealpi Giulie), and islands (Sicily and adjacent islands, Sardinia, and Elba). The area hosts all of the *Solenopsora* taxa known from the Mediterranean Basin and adjacent areas, such as North Africa, continental and Atlantic Europe, and Asia Minor. Furthermore, a higher number of occurrence data are available from this area, than from the Iberian and Balkan Peninsulas (Guttová et al. 2014, Fačkovcová et al. 2017, Supplementary Information 1 & 2), permitting a more reliable use of modelling algorithms.

Study species and occurrence records

We focused on nine *Solenopsora* taxa reported so far from the Apennine Peninsula (Nimis 2016): *S. candicans* (Dicks.) J. Steiner, *S. cesatii* (A. Massal.) Zahlbr., *S. grisea* (Bagl.) Kotlov, *S. holophaea* (Mont.) Samp., *S. liparina* (Nyl.) Zahlbr., *S. marina* (Zahlbr.) Zahlbr., *S. olivacea* subsp. *olbiensis* (Nyl.) Clauzade & Cl. Roux, *S. olivacea* (Fr.) H. Kilias subsp. *olivacea*, and S. *vulturiensis* A. Massal.

In order to gather data on the occurrence of the taxa in the study area (Supplementary Information 1), and to explore their geographical ranges (Supplementary Information 2), we revised specimens archived in the following collections: BC, BM, BP, BR, BRA, BRNU, CANB, CLU, FH, FI, G, GZU, H, LISU, O, PRA, PRC, PRM, SAV, TO, TSB, VBI, VER, W, ZA, herbaria of H. Komposch, I. Pišút, J. Vondrák and Linda in Arcadia. The revision of older material was necessary to prevent misidentifications, the most common of which are for *Solenopsora cesatii* (as *S. liparina*), *S. grisea* (as *S. cesatii*), *Lecanora pruinosa* Chaub. (as *S. candicans*), *Lecania spadicea* (Flot.) Zahlbr. (as *S. cesatii* var. *grisea* or *S. grisea*). Revisions of archived specimens, as well as recent records of field surveys conducted from 1999 to 2016 were also used (Fačkovcová et al. 2017, Guttová et al. 2014, 2015, Komposch & Breuss 2013). Occurrences were georeferenced using Q-Gis (QGIS Development Team 2009). Geographic biases (cf. Boakes et al. 2010), i.e. uneven spatial cover of the area of the

Apennine Peninsula and focus on some areas, were often present in historical and recent collections in particular areas (e.g. Liguria, Friuli-Venezia Giulia, Sicilia). To avoid spatial autocorrelation, we excluded repetitions from our dataset: in the computational step, occurrences that fell in the same cell (duplicate records) were automatically counted as one. The final dataset contained 94 records of *S. candicans*, 34 of *S. cesatii*, 23 of *S. grisea*, 12 of *S. holophaea*, 8 of *S. liparina*, 29 of *S. olivacea* subsp. *olivacea*, 8 of *S. olivacea* subsp. *olbiensis*, and 12 of *S. vulturiensis* from the study area. Since only a single record is known for *S. marina*, this taxon was excluded from further analyses.

Environmental variables and their contribution to characterization of Principal Component Analysis space

Nineteen bioclimatic variables (Supplementary Information 3) at 30 sec spatial resolution (ca. 1 km) were obtained from WorldClim (http://www.worldclim.org/; Hijmans et al., 2005). The variables are derived from measurements of monthly precipitation and temperature. Spearman correlation tests was used to exclude from further analyses the most correlated variables, hence reducing background noise ("Hmisc" R package; Harrell et al. 2016, R Core Team 2016), and targeting those that were expected to be significant for the biology of the species (Supplementary Information 4). Eight climatic variables remained for analyses in the dataset: BIO2 – mean diurnal range (mean of monthly (max temp – min temp)), BIO5 – maximum temperature of the warmest month, BIO6 – minimum temperature of the coldest month, BIO8 – mean temperature of the wettest quarter, BIO13 – precipitation of the wettest month, BIO14 – precipitation of the driest month, BIO15 – precipitation seasonality, and BIO19 – precipitation of the coldest quarter. Furthermore, the variable "altitude" and geological substrate was added as a categorical predictor (Supplementary Information 5). The raster was created from the Geological Map of Italy at scale 1: 1,000,000 provided by Servizio Geologico d'Italia (OneGeology Portal, ISPRA). We selected the units within the main lithological types including conglomerate (number 1), dolomite (number 2) and limestone (number 3), which are suitable substrates for *S. candicans*, *S. cesatii*, *S. grisea*, *S. olivacea* subsp. *olbiensis* and *S. olivacea* subsp. *olivacea*; mica- schists (number 4), phyllite (number 6), and sandstone (number 7), which are suitable for *S. vulturiensis* and *S. holophaea*, and peridotite (number 5; including ophiolites – serpentinites, gabbros and ophiolitic breccias) for *S. liparina*. These were converted into a raster with suitable categories numbered from 1 to 7 in alphabetical order, and another one including all "other substrates" (number 8). The rasters of predictors were at the same resolution of 30 sec, processed and cropped to the study area using the "raster" R package (Hijmans & van Etten 2012), and Q-Gis (QGIS Development Team 2016).

As well as evaluating geology as a categorical predictor we also tested the alternative of using this parameter as an environmental filter. After the ensemble modelling process, the climatic suitability maps were filtered for suitable geological substrate units, covering three groups – calcareous, ultramafic and siliceous substrates, hence masking and narrowing the suitability range. Out of the complete list of 101 units acquired from Geological Map of Italy at scale 1:1,000,000 provided by Servizio Geologico d'Italia (OneGeology Portal, ISPRA (Supplementary Information 6 & 7), we selected only the relevant units for analysing *Solenopsora* taxa with respect to their suitable substrates, converted into rasters using Q-Gis (QGIS Development Team 2016).

Habitat suitability maps in geographical space and calculating niche overlap

Models at 30 sec spatial resolution (ca 1 km) were produced by using three algorithms: Random Forest (a regression method which uses classification trees; Attorre et al. 2013, Barbet-Massin et al. 2012, Cutler et al. 2007), MaxEnt (a machine learning method based on the principle of maximum entropy; Phyllips et al. 2006), and GLM (Generalized Linear Model; Elith et al. 2006, Guisan et al. 2006, Serra-Diaz et al. 2012, Thuiller et al. 2009, Williams et al. 2009). Models were merged following an ensemble approach (Araùjo & New 2007, Merow et al. 2013), and using the "Biomod2" package in R (Thuiller et al. 2016, R Core Team 2016, van der Wal et al. 2014). The ensemble approach allowed us to use different algorithms for training initial models, and eventually merging them to an averaged model, weighted on their performance score. There was a performance threshold, below which models were not considered for building the ensemble. The performance of the models was assessed using the True Skill Statistic (TSS, Allouche et al. 2006), a validation metric based on the measures of sensitivity (proportion of correctly predicted presences) and specificity (proportion of correctly predicted absences) of the model. TSS value practically measures the ability of the prediction to discriminate whether the occurrence of an event happened or not. A model is considered good when TSS>0.6. Thus the threshold for building the ensemble was set at 0.7. In order to overcome sampling bias, we chose to sample pseudo-absences randomly from the study area, with a proportion presence/ pseudo-absences of 1:10, as suggested by Barbet-Massin et al. (2012). Parameters were set as follows: 80% of presence data were used for training, and 20% for testing; 10 replication runs; Beta multiplier adjusted to 2. Other parameters were set to default values.

A principal component analysis (PCA) was performed to assess the relationship between presence data and bioclimatic features, and how the taxa are distributed in the bioclimatic space by mean of “FactoMineR” (Le et al. 2008) and “Factoextra” (Kassambara & Mundt 2017) packages developed for R software (R Core Team 2016).

Since we scarcely recorded sympatric occurrence of the taxa confined to calcareous habitats (e. g. one site in Basilicata hosting *S. candicans*, *S. cesatii*, *S. marina*, *S. olivacea* subsp. *olbiensis*, and *S. olivacea* subsp. *olivacea*; several sites along the peninsula hosting *S. candicans* with *S. grisea*, *S. candicans* with *S. olivacea* subsp. *olbiensis*; *S. candicans* and *S. cesatii*), we further explored overlap of their niches in the geographical space. We assessed the niche overlap with an ‘I similarity statistic’, which was chosen for its simplicity, comparability and good performance (Warren et al. 2008, Rödder & Engler 2011). The ‘I similarity statistic’ is derived from the traditional D overlap index (Schoener 1968) integrated with the Hellinger distance measure (I), used to measure difference between two probability distributions. I similarity statistic measures the overall match between two species occupancies across all cells in the gridded environmental space, and ranges from 0 (no overlap) to 1 (complete overlap) (Warren et al. 2008). We calculated the I similarity statistic using the modelled species probability grids.

Results

Key environmental factors shaping ecological niches

The PCA analysis depicted the pattern of variation of the ten selected environmental variables (Supplementary Information 8A), and the position of the environmental niches of the taxa in PCA space (Supplementary Information 8B). The first two PCs explain 65.9 % of the variation in the data (Supplementary Information 8A, 9). The variability along PC 1 was mainly correlated with maximum temperature of the warmest month, precipitation of the driest month, altitude and precipitation of the wettest month, explaining 48.7 % of the total variation (Supplementary Information 8A, 9–11). PC 2 was correlated by precipitation seasonality, precipitation of the coldest quarter, minimum temperature of the coldest month and mean temperature of the wettest quarter, explaining 17.2 % of the variation (Supplementary Information 8A, 9, 10 & 12). Environmental range of the taxa in the study area as inferred by PCA is mostly placed along the PC 2 (Supplementary Information 8A).

The results of the climatic niches overlap tests (Tab. 1) showed very high I similarity statistics values (i.e. > 0.77), showing low variability in the climatic space of the studied taxa. Scarce co-occurrence of species confined to one of the three categories of geological substrate suggest, that the level of niche differentiation is on very fine, microhabitat level. In the study area representing climatic optimum of *Solenopsora* species, different parts of rock formations (e. g. open or shaded perpendicular faces or fissures of outcrops, cliffs, walls) facilitate the presence of more congeners.

Potentially inhabited geographical space in the study area

The modelled individualistic occurrences of *Solenopsora* taxa were shaped by their responses to the environment (Tab. 2, Supplementary Information 5 & 14). Geology generally constrained the probability of occurrence of all the taxa (Supplementary Information 6) best explaining the probability occurrence of seven of them – *S. candicans*, *S. grisea*, *S. holophaea*, *S. liparina*, *S. olivacea* subsp. *olbiensis*, *S. olivacea* subsp. *olivacea*, and *S. vulturiensis* (Tab. 2, Supplementary Information 5 & 14). Additional to geology however, one of the three most important drivers for the occurrence of *S. cesatii*, *S. grisea*, *S. olivacea* subsp. *olbiensis* and *S. olivacea* subsp. *olivacea* was mean diurnal temperature range, which quantified the day-to-night variation over a given year, based on the mean of the monthly temperature ranges. Maximum day-to-night variation of temperature of highly suitable habitats for these species (probability occurrence higher than 0.8) reaches up to 4–8 °C (Tab. 2, Supplementary Information 14 & 15). Minimum temperature of the coldest month lower than 5 °C decreased the probability of the occurrence of *S. candicans*, *S. grisea*, *S. liparina*, *S. olivacea* subsp. *olivacea* and *S. vulturiensis* (Tab. 2, Supplementary Information 14 & 15).

To explore the extent of the flexibility of *Solenopsora* taxa to colonize different geographical spaces within the Apennine Peninsula, we developed environmental niche models by an ensemble approach (Figs 1–4). The models, which take into account the areas with probability scores of occurrence higher than 0.7, suggested that within the group of taxa growing on calcareous substrates we can recognize two types of geographical distribution corresponding to high environmental suitability habitats. The first type included areas in mid-altitudes across the peninsula along the western coasts, coastal Molise, and the Gargano promontory (*S. candicans*, Fig. 1A), including Pre-Alpine territories in the north, and the mountains of Umbria, Campania, Basilicata, and Abruzzo at higher altitudes with limits from 900 to 1500 m a.s.l. (in case of *S. cesatii*, Fig. 1B). The second type was shifted towards the south part of the peninsula, e.g. the extreme south of Puglia, southern Campania and Sicily (*S. grisea*, *S. olivacea* subsp. *olbiensis*, *S. olivacea* subsp. *olivacea*, Figs 2A, 3B & 4A), in the case of *S. olivacea* subsp. *olbiensis* this included Sardinia (Fig. 3B). Alternative models based on climate (Supplementary Information 16A–C & F–G) with subsequent geological filtering (Supplementary Information 17A–C & F–G) confirmed these trends and the narrow suitability of habitats.

The centres of high suitability for *S. holophaea* and *S. vulturiensis* – two species confined to siliceous habitats, were situated at lower altitudes along Thyrrhenian coastline, Sicily and to the extreme south of Puglia (Figs 2B & 4B). The presence of serpentine and other types of ultramafic outcrops limited the occurrence of *S. liparina* (Fig. 3A), which is so far restricted to the Tyrrhenian coast, Tuscany and Calabria. The results of alternative approaches with suitable climate (Supplementary Information 16D, H & E), but filtered geological requirements (Supplementary Information 17D, H & E) again supported this trend.

Ecological specialization of S. olivacea subspecies with different reproduction strategy

Regularly fertile, apothecia forming *S. olivacea* subsp. *olivacea* was more frequent in our dataset (34 specimens; Supplementary Information 1), and is known to occur in nine administrative regions in the study area. Obligatory sorediate subspecies *olbiensis* was documented by 9 specimens from four administrative regions. Their environmental niches highly overlap (Tab. 1). The subspecies share two key environmental variables best explaining their habitat suitability (Tab. 2, Supplementary Information 5, 14 & 15), the mean diurnal range and geology, though *Solenopsora olivacea* subsp. *olivacea* occurrence is supported by a wider spectrum of suitable geological substrates (Tab. 2). The third most important variable for *S. olivacea* subsp. *olbiensis* was precipitation of the driest month, whereas for *Solenopsora olivacea* subsp. *olivacea* it was minimum temperature of the coldest month. Both modelling approaches, including the alternative based on geology filtering showed that the subspecies *olivacea* tended to occupy warmer and coastal areas (Fig. 4A, Supplementary Information 16G & 17G), whereas subsp. *olbiensis* preferentially occurred in temperate areas in hilly and mountain zones of the peninsula (Fig. 3B, Supplementary Information 16F & 17F).

Distribution of the treated taxa in the study area and their overall geographical range

We report new regional records (cf. Nimis 2016, Fačkovcová et al. 2017) for Abruzzo (*S. grisea*), Calabria (*S. vulturiensis*), Friuli (*S. grisea*), Marche (*S. cesatii*, *S. olivacea* subsp. *olivacea*), and Trentino-Alto Adige (*S. cesatii*) (Supplementary Information 1). We also report the first records on the occurrence of *S. cesatii* in Serbia and Ukraine, and *S. liparina* in Serbia as well (Supplementary Information 2). Based on the revised specimens, maps showing the extent of geographical ranges were developed (cf. Gaston 1996), in which the area within a polygon depicted the limits to the occurrence of taxa (Supplementary Information 18). *Solenopsora holophaea*, *S. vulturiensis* and *S. candicans* had the widest geographical ranges, respectively. Based on current knowledge, *Solenopsora olivacea* subsp. *olbiensis is* the taxon with the smallest geographical range (Tab. 3). We could recognize the following distribution patterns: 1) the Mediterranean Basin (*S. marina*, *S. olivacea* subsp. *olbiensis* and subsp. o*livacea*); 2) the Mediterranean Basin plus the Atlantic in the west and the Black sea region in the east (*S. holophaea*, *S. candicans* and *S. vulturiensis*); 3) the Mediterranean Basin and outposts in the Black sea coast (*S. grisea*); 4) the Mediterranean Basin and foothills of European high mountain ranges (*S. cesatii*); the Mediterranean Basin and Atlantic, the Hercynian massif in Central Europe and south-central Turkey (*Solenopsora liparina*).

Discussion

Ecological factors, e.g. geology and climate, have a strong influence on biodiversity patterns (Planas et al. 2014). In the present study, we aimed to explore the drivers shaping ecological niches and distribution of European taxa of the lichen genus *Solenopsora* with a strong link to Mediterranean-type climates, using a modelling approach. As evident in several genera representing rock-dwelling species (e.g. *Acarospora*, *Caloplaca*, *Lecanora*), the studied members of the genus *Solenopsora* were confined to a wide range of rock types, which can be assigned to one of the three groups – calcareous, siliceous, and ultramafic. Preference of a particular geological substrate is one of the key environmental predictors for species/taxon occurrence. Worthy to note is *S. liparina*, an example of an ecological vicariant specific to ultramafic (serpentinised ultramafites) substrates across its known distribution range. However, having accounted for geology, another important driver, shaping the predictive distribution of this species in ultramafic areas, is climate of the geographical area, which is in line with observations of Favero-Longo et al. (2018). Of the available localities in central Europe (the Hercynian mountains, the Western Carpathians) that represent sub-mediterranean or sub-atlantic conditions the species was recorded only at one site in Raškov, Bohemian-Moravian Highlands (Guttová et al. 2014).

In the study area, the climatic optima of *Solenopsora* taxa ranged from the cooler and drier to warmer and more humid conditions, as follows: temperate climate (*S. candicans*, *S. holophaea* and *S. liparina*), temperate warm climate (*S. grisea*), warm continental climate (*S. cesatii*), mediterranean climate (*S. olivacea* subsp. *olbiensis*, *S. vulturiensis*), and hot mediterranean climate (*S. olivacea* subsp. *olivacea*). Warm winters are important for *S. candicans*, *S. grisea*, *S. liparina*, *S. olivacea* subsp. *olivacea* and *S. vulturiensis*. Cooler summers were not limiting for *S. cesatii* occurrence, and environmental suitability for its occurrence has shifted to a temperate continental bioclimate.

The habitats of *Solenopsora* taxa are thus structured around three major ecological gradients, mainly determined by geology, temperature and precipitation. Considering climatic variables, one of the key factors that appeared to be structuring the study taxa is mean diurnal temperature range. This parameter, highly sensitive to small changes in maximum and minimum temperatures, is strongly affected by climate change (Braganza et al. 2004). Recent studies show that, during the past decades, a large global trend due to larger increases in minimum than maximum temperatures were observed (Braganza et al. 2004, Qu et al. 2014), whereas exceptional increases in diurnal temperature, due to decreased precipitation, fewer clouds, and land degradation, as in the case of Italy were also demonstrated (Peralta-Hernandez et al. 2009). Under certain scenarios in the future, Mediterranean basin ecosystems sensitive to warming and water availability may undergo changes never experienced yet in the Holocene (Guiot & Cramer 2016). In this respect, the occurrence of *Solenopsora* taxa confined to Mediterranean bioclimatic types, i. e. *S. grisea*, *S. marina*, *S. olivacea* subsp. *olbiensis* and *S. olivacea* subsp. *olivacea* may represent indicators of climatic stability. However, Rubio-Salcedo et al. (2017) compared variability in *S. holophaea* distribution in the Iberian Peninsula under current and future conditions, and found that climate change could have a positive effect on bioclimatic range of this taxon with a Mediterranean Atlantic distribution, with a considerable gain in projected potential area expected. However, these results were based on a different set of climatic variables, and none of them corresponded either to the first three best explanatory variables in our study (for both approaches, with geology included among climatic variables and as a filter). In our study we show that the distribution of *S. holophaea* is best explained by precipitation of the driest month, and in the case of an alternative model, by mean diurnal range, precipitation of the wettest month and precipitation of the driest month.

The studied *Solenopsora* taxa have significantly overlapping climatic niches. The biggest difference in occupied climatic niche space is between *S. cesatii*, which has a niche shifted to temperate continental bioclimatic types and higher altitudes, and the three ancestral, strictly Mediterranean taxa – *S. grisea*, *S. olivacea* subsp. *olivacea* and *S. olivacea* subsp. *olbiensis*. Despite occurrence records that are generally spread along the Apennine Peninsula, predicted suitable habitats for *S. grisea*, *S. holophaea*, *S. olivacea* subsp. *olbiensis*, *S. olivacea* subsp. *olivacea* and *S. vulturiensis* are restricted to smaller areas. When the two closely related species *S. candicans* and *S. cesatii* were analysed using a dataset from the centre and the margin of their distribution range in the Western Carpathians and Pannonia, tests of niche equivalency and similarity revealed that they colonize similar habitats in both (Fačkovcová et al. 2017). However, it is worth emphasizing that a strong limiting factor is geology, which splits the taxa of the genus into three groups: those growing on calcareous, siliceous and ultramafic substrates.

The role of ecology in speciation is not fully understood yet. Ecological speciation may be relatively more important in organisms with a sessile nature, which may be more sensitive to fine scale environmental heterogeneity (Anacker & Strauss 2014). Testing explicit predictions originating from the hypothesis of ecological specialization connects biogeography, evolutionary and functional ecology (Devictor et al. 2010). Martellos et al. (2014) investigated differences in the distribution of two intraspecific taxa within *Squamarina cartilaginea* (With.) P. James. They showed that spatial distribution models of those taxa are determined by similar climatic variables, and underlined the usefulness of a modelling approach for the delimitation of taxonomic entities. *Solenopsora* taxa evolved different reproductive strategies – through sexual (ascospores, produces either usually – e.g. *S. candicans*, *S. cesatii*, *S. holophaea*, *S. marina*, *S. olivacea* subsp. *olivacea*; or rarely – e.g. *S. grisea*, *S. vulturiensis*) and vegetative propagules (soredia – *S. olivacea* subsp. *olbiensis*, blastidia – *S. grisea*, *S. vulturiensis*). In our study, we focused on the distribution of two subspecies of *Solenopsora olivacea*, of which the more frequent subsp. *olivacea* reproduces sexually, while subsp. *olbiensis* through soredia. Although their ecological niches do overlap, the vegetatively dispersing subspecies occurs preferentially in habitats with a higher variation in temperature during the day, and more precipitation in the driest month. The sexually reproducing subspecies tends to occur in slightly warmer and drier areas. As Leavitt & Lumbsch (2016) summarized, species with a vegetative reproductive strategy often have a larger distribution range than their fertile counterparts. Our distribution models confirm this observation for the two sister subspecies. Regarding range overlap in sister species, it will be interesting to focus in future on species pairs with significantly different overall range sizes (Tab. 3), e.g. *S. grisea* (not confirmed yet from the Western Mediterranean, absent from the Atlantic), and *S. vulturiensis* (extending to the Atlantic up to Iceland). *S. vulturiensis* occurs in different biomes, and its ecological niche is much wider than that of its sister species.

An important factor determining the distribution of taxa of any group is the distribution of their ancestor, since it often represents inherited constraints (Heads 2015). According to our current knowledge, we consider *S. holophaea* as the ancestor (Guttová et al. 2014), featuring the largest extent of its geographical range (Tab. 3, Supplementary Information 17D). After colonization of new environments, the ancestral group split and descendants underwent adaptations in terms of evolution of morphological and anatomical characters responding to site-specific conditions, resulting in establishment of their ranges (shifts and/or contractions with respect to the ancestor) and ecological requirements.

The reconstruction of ecological requirements, and the modelling of habitat suitabilities of lichen congeners strongly linked to Mediterranean-type climate in their ecological optima within the Apennine Peninsula showed, that six of eight studied taxa respond to geology as a key environmental factor. Climate represented mainly by maximum temperature of the warmest month, mean diurnal range, precipitation of the driest month, minimum temperature of the coldest month and precipitation seasonality additionally contributes to distribution of the studied *Solenopsora* species (Tab. 2). A good example of specificity in response to the above mentioned environmental factors is connected to *S. liparina*, which is confined to ultramaphic rocks (Tab. 3). The ecological niches of the species strongly overlap in the study area. *S. cesatii*, shifted towards higher precipitation seasonality and higher values for precipitation of the coldest quarter and minimum temperature of the coldest month. Environmental space of *S. vulturiensis* forms a narrower subset of relative to its sister species *S. grisea*. Apart from sharing a common trait position with respect to minimum temperature of the coldest month, they differ in their requirements for geological substrate. The overall ranges of the taxa suggest that they differ in tolerance to sub-optimal conditions. Overall, we conclude that the flexibility of studied *Solenopsora* taxa to inhabit different geographical and bioclimatic spaces is limited to submediterranean bioclimates and some of the taxa can be considered indicators for climatic stability.

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Figures and Tables

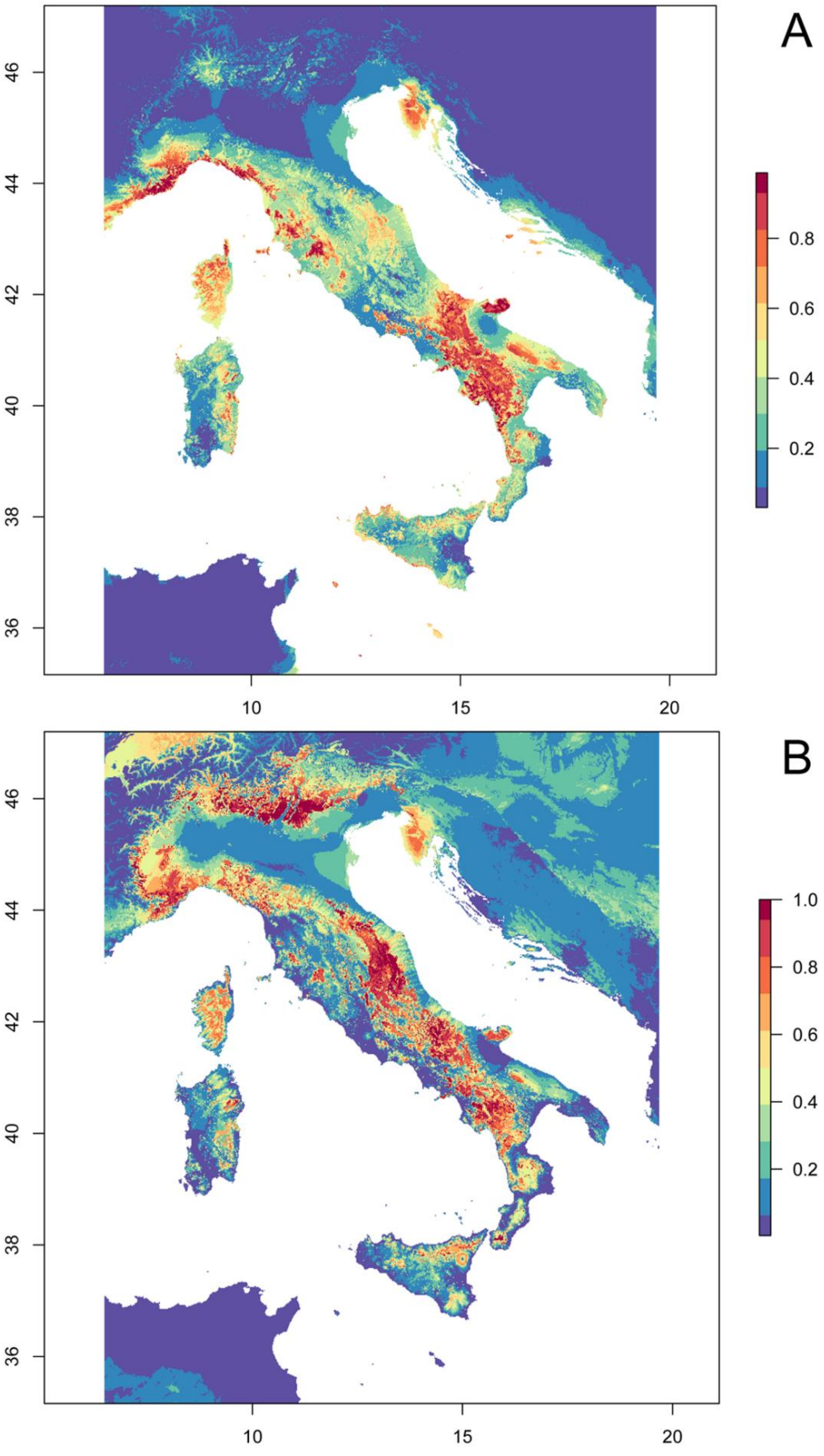


Fig. 1. Habitat suitability maps (HSMs) of *Solenopsora* taxa along the Apennine Peninsula, predicting suitable areas under current climatic and geological conditions from 0 (blue) – not suitable, to 1 (red)

– high habitat suitability. The scale on the right refers to the probability distribution scores. A – *S. candicans*, B – *S. cesatii*.

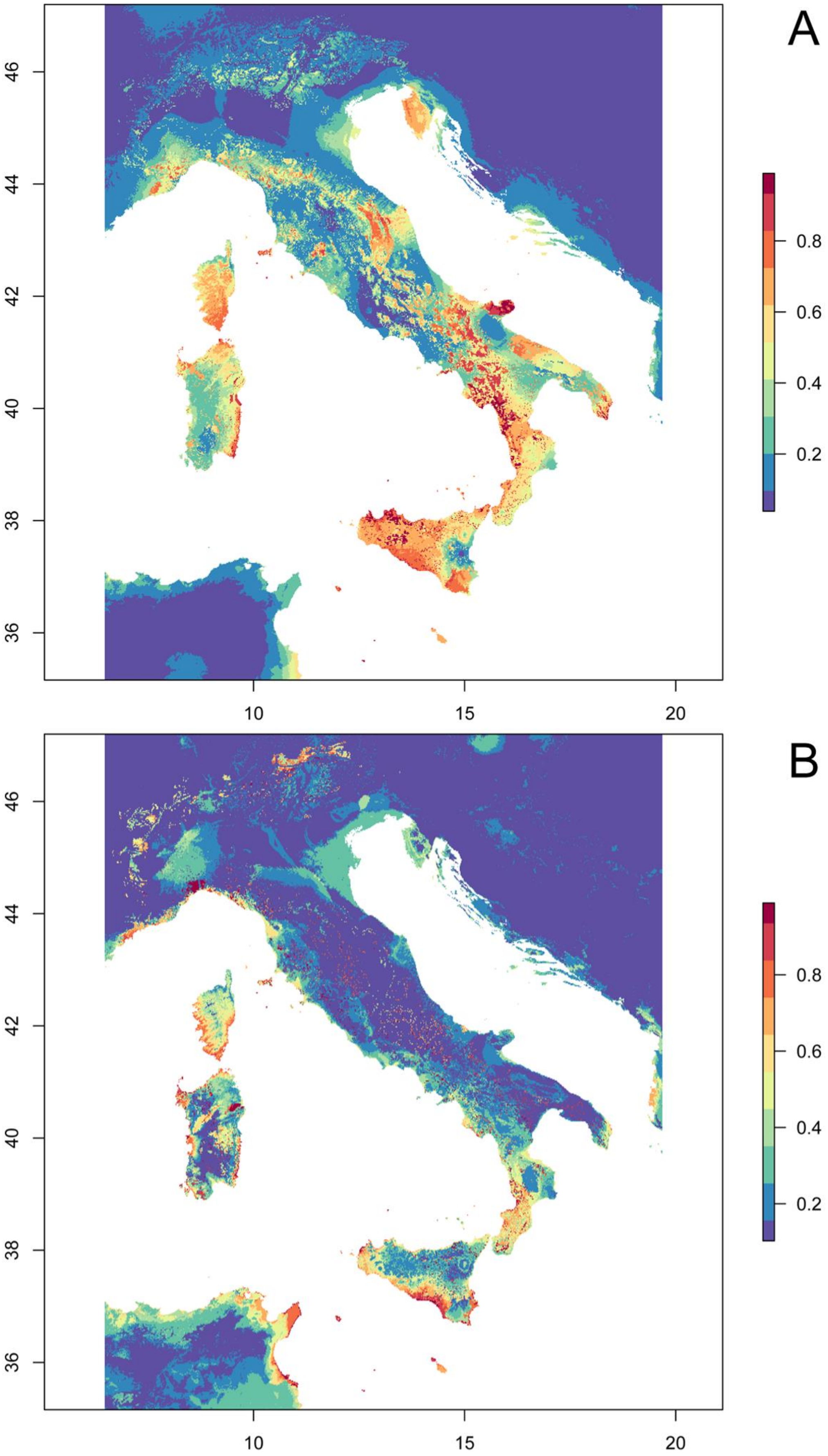


Fig. 2. Habitat suitability maps (HSMs) of *Solenopsora* taxa along the Apennine Peninsula, predicting suitable areas under current climatic and geological conditions from 0 (blue) – not suitable, to 1 (red)

– high habitat suitability. The scale on the right refers to the probability distribution scores. A – *S. grisea*, B – *S. holophaea*.

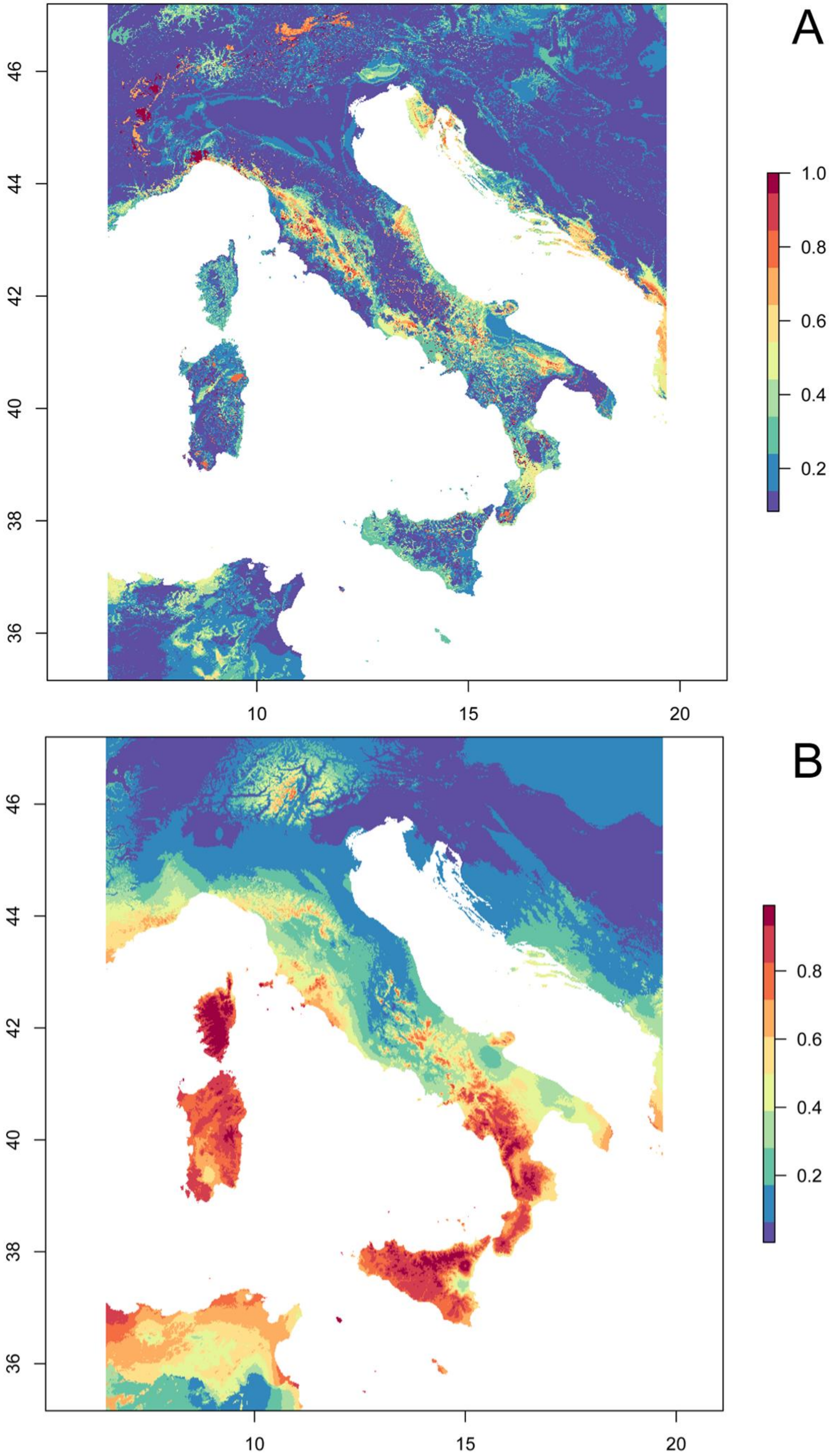


Fig. 3. Habitat suitability maps (HSMs) of *Solenopsora* taxa along the Apennine Peninsula, predicting suitable areas under current climatic and geological conditions from 0 (blue) – not suitable, to 1 (red)

– high habitat suitability. The scale on the right refers to the probability distribution scores. A – *S. liparina*, B – *S. olivacea* subsp. *olbiensis*.

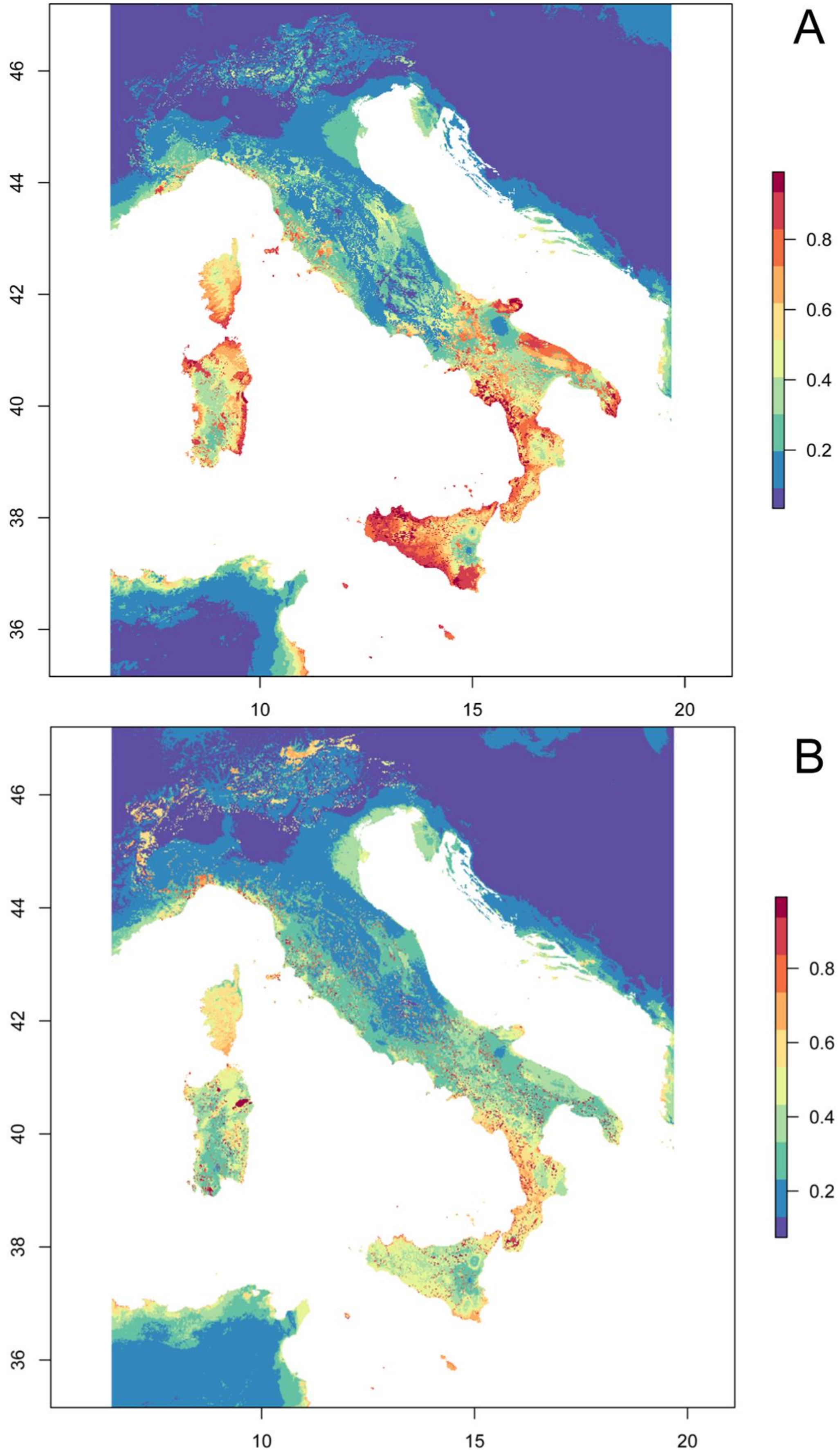


Fig. 4. Habitat suitability maps (HSMs) of *Solenopsora* taxa along the Apennine Peninsula, predicting suitable areas under current climatic and geological conditions from 0 (blue) – not suitable, to 1 (red)

– high habitat suitability. The scale on the right refers to the probability distribution scores. A – *S. olivacea* subsp. *olivacea*, B – *S. vulturiensis*.

Tab. 1. Assessment of climatic niche overlap between studied *Solenopsora* taxa based on I similarity statistics (Warren et al. 2008, Rödder & Engler 2011).

species 1	species 2	I overlap
candicans	*cesatii*	0.886
	grisea	0.963
	olivacea	0.945
	olbiensis	0.895
	holophaea	0.878
	liparina	0.881
	vulturiensis	0.928
cesatii	*grisea*	0.883
	olivacea	0.837
	olbiensis	0.774
	holophaea	0.822
	liparina	0.837
	vulturiensis	0.859
grisea	*olivacea*	0.985
	olbiensis	0.930
	holophaea	0.916
	liparina	0.886
	vulturiensis	0.958
olivacea	*olbiensis*	0.950
	holophaea	0.934
	liparina	0.895
	vulturiensis	0.970
olbiensis	*holophaea*	0.919
	liparina	0.877
	vulturiensis	0.946
holophaea	*liparina*	0.948
	vulturiensis	0.977
liparina	*vulturiensis*	0.953

Tab. 2. Key environmental factors best explaining the habitat suitability maps of analysed *Solenopsora* taxa. Abbreviations: bio2 – mean diurnal range, bio5 – maximum temperature of the warmest month, bio6 – minimum temperature of the coldest month, bio8 – mean temperature of the wettest quarter, bio14 – precipitation of the driest month, bio15 – precipitation seasonality, alt – altitude, geo – geology. Geological categories: 1 conglomerate, 2 dolomite, 3 limestone, 4 mica-schist, 5 peridotite, 6 phyllite, 7 sandstone, 8 other substrates.

Taxon	bio6 (°C)	bio14 (mm)	bio15 (mm)	bio2 (°C)	alt (m asl)	geo	bio5 (°C)
S. candicans	> 5	< 20	< 20	–	–	–	–
S. cesatii	–	–	–	< 4–6	> 1200	–	< 25
S. grisea	> 5	–	–	< 4–8	–	1, 3	–
S. holophaea	–	< 10	–		0	4, 5	–
S. olbiensis	–	< 15	–	< 4–6	–	3	–
S. olivacea	> 8	–	–	< 5	–	1, 2, 3	–
S. liparina	> 5	–	–	–	> 350	4, 5	–
S. vulturiensis	> 10	–	–	–	0	1, 2, 4, 5, 7	–

Tab. 3. Information about the extent of geographical ranges (cf. Gaston 1996) of the studied taxa. Size of the area where occurrences are distributed according to the polygon areas depicted in Supplementary Information 18, and their link to bioclimatic types or variants according to the given resources. Bioclimatic types and variants (Rivas-Martínez et al. 2011): Mpo – Mediterranean pluviseasonal oceanic, Toc – temperate oceanic, Tco – temperate continental, Tocsm – temperate oceanic submediterranean. Bioclimatic areas (Nimis 2016): SmedD – dry submediterranean, SmedH – humid submediterranean, MedH – humid Mediterranean.

Taxon	Area covered by occurrences distributions (km^2)	Geology	Bioclimatic types / variants	Bioclimatic areas
S. candicans	554 327	calcareous/ mafic igneous	Mpo, Toc, Tocsm	SmedD, SmedH, MedH
S. cesatii	184 147	calcareous	Mpo, Toc, Tocsm, Tco	SmedD, SmedH
S. grisea	253 181	calcareous	Mpo, Tocsm	SmedH
S. olivacea subsp. *olbiensis*	82 702	calcareous	Mpo, Tocsm	SmedH
S. olivacea subsp. *olivacea*	229 019	calcareous	Mpo, Tocsm	SmedH
S. vulturiensis	921 325	siliceous	Mpo, Tocsm	SmedH
S. liparina	161 912	ultramaphic	Tocsm	SmedH
S. holophaea	1 129 945	siliceous	Mpo, Tocsm	SmedH
S. marina	190 211	calcareous	Mpo	SmedH

Supplementary Information

Supplementary Information 1. List of revised herbarium specimens documenting the occurrence of *Solenopsora* congeners in the Apennine peninsula.

The collections are sorted according to the regions, which are listed in alphabetical order. Regions are abbreviated as follows: Abr – Abruzzo, Bas – Basilicata, Cal – Calabria, Camp – Campania, Fr – Friuli, Vg – Venezia Giulia, Laz – Lazio, Lig – Liguria, Lomb – Lombardia, Marc – Marche, Mol – Molise, Pugl – Puglia, Sar – Sardegna, Si – Sicilia, Tosc – Toscana, TAA – Trentino-Alto Adige, Ven – Veneto. With each herbarium specimen we cite complete information given in original label. Collectors´ names of recent material are abbreviated as follows: AG – Anna Guttová, AGr – Alice Grassi, LP – Luca Paoli, MS – Marek Slovák, SM – Silvana Munzi, SR – Sonia Ravera, ZF – Zuzana Fačkovcová. In brackets at the end of each entry, the herbarium acronym with a specimen number or barcode, if available, is given.

SOLENOPSORA CANDICANS (DICKS.) J. STEINER

Abr

Bussi and Popoli, between the villages, rocky slopes (W–NW, calcareous rocks) in forest (*Quercus* spp, *Fraxinus* spp) along the road E80, on rock, 269 m, 7.7.2015, 42°11'39"N 13°51'09"E, leg. MS & A. Pleceníková (SAV).

Bas

Val d´Agri: Grumento Nova, municipal park, NE slope of the town, limestone outcrops in the forest park (*Pinus* sp., *Cupressus* sp.), on perpendicular rock face, alt. 742 m, 8. 10. 2013 leg. ZF, AG & LP, N40° 16.984´ E15° 53.198´ (SAV); ibid., E slope of the town hill, secondarily wooded area along the road (*Pinus* sp., *Cupressus* sp.) with shaded limestone outcrops (hard, carstic forms), extremely scarce, alt. 618 m, 7. 4. 2014 leg. AG, LP N40° 16.667´ E15° 55.171´ (SAV); ibid., Strada comunale di Monserrato, limestone outcrops in the pasture, on rocks, alt. 724 m, 6. 10. 2013 leg. ZF, AG & LP, N40° 17.329´ E15° 51.282´ (SAV); ibid., strada comunale di Monserrato, humid mixed forest on a slope facing capella/chiesa di Monserrato, on shaded limesto rock, alt. 805 m, 6. 10. 2013, leg. ZF & AG, N40° 17.276´ E15° 51.612´ (SAV); ibid., Strada provinciale Grumento – Tramutola, S exposed xerotherm slope, limestone outcrops, alt. 644 m, 11. 10. 2013 leg. AG, AGr, ZF, LP & SR, N40° 18.305´ E15° 50.455´ (SAV); banks of the Lago di Pertusillo, open xerotherm with karst formations, on limestone rock, alt. 618 m, 7. 4. 2014 leg. AG, AGr, LP & SR, N40° 16.667´ E15° 55.171´ (SAV); Viggiano, forested hilltop above the cemetery (*Pinus* sp., *Cupressus* sp.), N facing slope, on limestone rocks, alt. 953 m, 22. 8. 2013 leg. AG & LP, N40° 20.434´ E15° 53.722´ (SAV); ibid. 10. 10. 2013 leg. ZF, AG & LP, N40° 20.434´ E15° 53.722´ (SAV); Viggiano, along the road SS276 between Agriturismo Casteluccio and junction of SS276 and SP11bis, oak forest, on shaded limestone rock, perpendicular face, alt. 708 m, 23. 8. 2013 leg. AG & LP, N40° 20.391´ E15° 52.997´ (SAV); Marsicovetere, NW slopes of the Sacro Monte di Viggiano, in fissures of limestone outcrops and towers, alt. 1179 m, 7. 12. 2013 leg. AG & LP, N40° 22.610´ E15° 50.025´ (SAV); Pollino Mt.: Castelluccio superiore, sentiero Bosco difesa, open limestone rocks in macchia type of vegetation, on rock faces, alt. ca 736 m, 1. 2. 2015, leg. AG & LP, N40° 00.774´ E15° 58.607´ (SAV); ibid., humid *Quercus cerris* forest, shaded hard limestone outcrops and towers, on rock faces, alt. ca 779 m, 1. 2. 2015, leg. AG & LP, N40° 00.726´ E15° 59.042´ (SAV); ibid., humid *Quercus* sp. div. forest, shaded hard limestone outcrops and horizontal forms, on rock, alt. ca 910 m, 1. 2. 2015, leg. AG & LP, N40° 01.813´ E15° 59.137´ (SAV); Viggianello, località "Torno", shaded limestone outcrops among *Quercus* trees on pasture, on rock faces, alt. ca 855 m, 1. 2. 2015, leg. AG & LP, N39° 58.854´ E16° 06.709´ (SAV); La Rotonda, rocca – rocky hilltop in the centre of the town, open limestone rocks, on rock faces, alt. ca 627 m, 1. 2. 2015, leg. AG & LP, N39° 57.402´ E16° 02.426´ (SAV).

Cal

Fiume Caronte (Dipignano CS), 21. 12. 1985, leg. Puntillo Domenico, alt. 500 m (TSB 7024); Valle Fiume Caronte (Mendicino – CS): substrato – calcareous, 460 m, 12. 2. 1986, leg. Puntillo (CLU 1660).

Camp

Prov. Salerno: Amalfi coast, between Ravello and Valico di Chiunzi on M. Cerreto, ca 3 km before the pass, narow gorge with *Castanea*, limestone, ca 600 m, 18. 4. 2000 leg. P. L. Nimis & M. Tretiach (TSB 31803); Monti Lattari Mt.: Tramonti, Valico di Chiunzi – mountain pass, limestone cliffs, sheltered, humid rock faces, alt. ca 722 m, 6. 2. 2015, N40° 43.143´ E14° 37.161´ leg. AG & LP (SAV).

Fr

Carso Triestino: M. Lanaro, 500 m, su calcare, leg. Nimis, 9. 10. 1985 (TSB 6546); Malchina, 170 m, su calcare, 25. 3. 1985, leg. Nimis (TSB 5496); Trieste: Val Rosandra, substrato calc., 7. 9. 1987, leg. & Puntillo, herb. D. Puntillo (CLU 4414); ibid. leg. & Puntillo, herb. D. Puntillo (CLU 4418).

Laz

Prov. Latina: Monti Arunci, M. S. Angelo, near Gaeta, road to the top, at ca. 1200 m, *Fagus* forest, dry calcareous grasslands, limestone rocks, 5. 4. 2000, leg. P. L. Nimis & M. Tretiach (TSB 32370).

Lig

Erbar. Crittogam. Ital. no 68 (1068), sulle rupi calcaree in diverse località dei dintorni di Genova. Baglietto (FI, TO, as *Ricasolia candicans*); Lichenes Alpium. No. 139. Alpi liguri, Liguria: presso di Colla Micheri al di sopra da Laigueglia, ca 160 m, su roccie esposte. 5. 1958. Leg. M. Steiner (BM, LISU, W 1962–6356); Cryptogamae exsiccatae Edit. a Museo Hist. Natur. Vindobonensi. No. 4234. Italien: Ligurien, SE-Hang des Monte Bellenda gegen San Bartolomeo bei

Ventimiglia, auf kalkältigem Sandstein einer Bruchsteinmauer der Ölgärten, ca 250 m, 26. 4. 1958, leg. M. Steiner (H, O – L58279, PRA, W 1962–09021); Riviera dei Fiori, San Bartolomeo al Mare, au-dessus de l´église, route au-dessus du camping La Rosa, affleurements rocheux, exp. plein Est, alt. 50 m, 25.8.1982, 43°55´17´´N 8°5´51´´E, leg. et det. P. Clerc (FH 00377486, H, G 00295670, 00272808a, b); Noli – Finale Ligure, olive growths, the walls of calcareous rocks along the road, on rock, alt. 103 m, 11. 7. 2012 leg. AG & LP, N 44° 11.504´ E 8° 21.608´ (SAV) TLC; Genova, Luarto, 1936, C. Sbarbaro, Cat. Lich. Univ. No. 10960 (H); Liguria, in valle Bisagno, loco Pontecarrega, 1934, C. Sbarbaro (H, as *Placolecania candicans*).

Lomb

In calcarei supra Laveno ad Larium lacum, leg. et det. Garovaglio (BM, as *Parmelia candicans*, VER, TO, as *Ricasolia/Lecanora candicans*); Ad saxa jurassica umbrosa domorum in monte Piatto supra Larium lacum, 500 m, Anzi (as *Gyalolechia candicans* var. *cesatii* f. *dealbata*, BM, O – L58248, PRA-V-01984, W).

Marc

Prov. Pesaro: Montefeltro, S. Leo, calcareous outcrops just east of the village, *Quercus*, *Robinia*, 540 m, 19. 8. 1996, leg. P. L. Nimis (TSB 23522).

Mol

Pozzilli – Santa Maria Oliveto, mixed light *Quercus-Carpinus* forests, a clearing with limestone rocks and boulders, on rock, 579 m, 7. 4. 2011 leg. AG & SM, N41° 31.919´ E14° 05.604´ (SAV); Roccaravindola (alta), old rock terraces in the mixed *Quercus-Carpinus* forest, humid and sheltered place with *Ceterach* sp., on limestone rocks, alt. 347 m, 8. 4. 2011 leg. AG & SM, N41° 31.901´ E14° 07.131´ (SAV); ibid. mixed light *Quercus-Carpinus* forest above the quarry, on shaded calcareous rock and boulders along the path, alt. 389 m, 9. 4. 2011 leg. AG & SM, N41° 32.013´ E14° 06.979´ (SAV); ibid. borgo in via Boticelli/graveyard, mixed light *Quercus-Carpinus* forest above the quarry, on shaded calcareaous rock and boulders along the path, alt. 389 m, 9. 4. 2011, 21. 6. 2010, leg. AG & SM, N41°32.013′ E14°06.979′ (SAV); Pozzilli, the plateau above the village mixed *Quercus-Carpinus* forest along the dirty road near the pasture, sheltered limestone boulders and rocks, on perpendicular faces, alt. 526 m, 11. 4. 2011, leg. AG & SM, N41° 31.415´ E14° 04.734´ (SAV).

Pugl

Prov. Foggia: Daunia, presso Ponte 13 Archi sul Lago di Catola below Calenza, calc. sandstone, cement, 245 m, 13. 4. 1998, leg. Nimis & Tretiach (TSB 30056); Gargano, P.so del Lupo, 530 m, *Quercus*, limestone, 5. 4. 1996, leg. P. L. Nimis & M. Tretiach (TSB 22841); Martina Franca: Bosco delle Pianelle, 400 m, Querce decidue, muri di pietre calcaree in ombra, 8. 4. 1996, leg. P. L. Nimis & M. Tretiach (TSB 22275); Isole Tremiti: Isola di S. Domino, su calcare, 50 m, 4. 7. 1986, leg. Nimis (TSB 7632).

Sar

Nuoro: Barbágia Seoúl, ca 2.5 km S der Bahnstation Esterzili SVV seui, Kalk. Sh. 670–680 m. An Kalkfels. Leg. W. Brunnbauer 3. 5. 1986 (W 1999-01159); M. Arcueri, 1000 m, on limestone, 5/1986, leg. Nimis (TSB 7465); M. Albo, P.ta Cupetti, 950 m, on limestone, 25. 7. 1985, leg. Nimis et Poelt (TSB 6128); Sotto P. Corongiu (Jerzu), ca. 900 m, su calcare, 8/1989, leg. Nimis, Roux, Tretiach, Vězda (TSB 13 165).

Si

Prov. Trapani: Riserva Nat. Dello Zingaro, 200–550 m, 11. 12. 1995, kalk. macchia, leg. P. L. Nimis & M. Tretiach (TSB 21523); Marettimo (Égadi Islands-TP), Buccerie, 260 m, kalk, Excursion S.L.I., 24-31. 3. 1991, det. P. L. Nimis (TSB 15713, 18698, 15714 ut *S. cesatii*); ibid. sopra Marettimo, 50 m, calcareous rocks, excursion S.L.I., 24–31. 3. 1991, det P. L. Nimis (TSB 18705 with *Solenopsora olivacea*); Insula Marettimo: Égadi insulae, supra vicum Marettimo, 100 m, 24. – 31. 3. 1991, leg. et det. A. Vězda (PRA-V-01978); ibid., Isole Égadi – TP, loc. Case Romane, substr. roccia calcarea, 260 m, 27. 3. 1991, 38°N 12°E, leg. Puntillo (as *S. cesatii*, CLU 7707).

Tosc

Giugliano, Toscana, agosto 1884 (Herbarium U. Martelli as *Lecanora candicans*, FI); Lichenes rariores Etruriae, no. 12, ad rupes calcareas montis S. Juliani, supra hujus nomini pagum, 250 m (O – L58264, W 19373 both as *Gyalolechia candicans*); E. Marcucci Piante dell´Isola dell´ Elba, Portoferraio, 8. 5. 1880 (Erbario O. Beccari as *Ricasolia candicans*, FI); A S. Margherita in Monticci presso Firenze, 24. 4. 1805 (Erbario O. Beccari as *Ricasolia cesatii*, FI); Colline Metallifere Mts., Gerfalco, le Cornate Mt., open or shaded calcareous outcrops, perpendicular rock faces, alt. 740 m, 8. 3. 2010 leg. AG, LP & T. Pisani, N43° 08.843´ E10° 58.399´ (SAV); ibid., alt. 834 m, 8. 3. 2010 leg. AG, LP & T. Pisani, N43° 08.955´ E10° 58.188´ (SAV); ibid., alt. 871 m, 8. 3. 2010 leg. AG, LP & T. Pisani, N43° 09.013´ E10° 58.120´ (SAV); ibid., alt. 904 m, 8. 3. 2010 leg. AG, LP & T. Pisani, N43° 09.080´ E10° 57.996´ (SAV); ibid., alt. 1020 m, 8. 3. 2010 leg. AG, LP & T. Pisani, N43° 09.274´ E10° 57.561´ (SAV); Castell´Azzara, Mt. Civitella – Mt. Penna, the foot of the massive – Sorgente del carpino, shaded calcareous rock faces around the cave, alt. 889 m, 10. 4. 2010 leg. AG & LP, N42° 46.339´ E11° 41.590´ (SAV); ibid., a transmitting station, limestone outcrops on a grazed slope, alt. 1078 m, 10. 4. 2010 leg. AG & LP, N42° 45.986´ E11° 40.516´ (SAV); ibid. the foot of the Mt. Penna, slope with small karst formations, on limestone karren, alt. 1024 m, 10. 4. 2010 leg. AG & LP, N42° 46.368´ E11° 39.956´ (SAV); ibid. Mt. Penna summit, open limestone cliffs, alt. 1074 m, 10. 4. 2010 leg. AG & LP, N42° 46.406´ E11° 40.081´ (SAV); Cetona, Mt. Cetona, open calcareous outcrops alt. ca 1000 m, 05/2010 leg. LP, UTM E735028 N4756833 (SAV); Roccalbegna, Rocca – the foot of the castle hill, on limestone rock, alt. ca 540 m, 16. 8. 2014, leg. LP, N42° 47´ 12,27´´ E11° 30´ 25,21´´ (SAV); Mt. Labbro, open limestone outcrops on SW slopes, on limestone rock, alt. ca 1100 m, 16. 8. 2014, leg. LP, N42° 49´ 17,57´´ E11° 31´ 21,22´´ (SAV); Maremma, provincia di Grosseto, Scansano, località „Sasseta“, agriculture land/pastures, schistose calcareous outcrops, semi-shaded by scarce oak trees, alt. 556 m, 10. 10. 2010, leg. AG & LP, N42° 42.199´ E11° 20.474´ (SAV); Convento del Petreto, limestone rocks and outcrops in oak forest, alt. 546 m, 13. 4. 2014, leg. AG

& LP, N42° 41´ 37.37´´ E11° 20´15.95´´ (SAV); località „Convento del Petreto – sassicaia“, oak wood on the SW facing slope with *Lobaria pulmonaria*, on shaded mossy calcareous rock, alt. 445 m, 25.2.2012, leg. AG & LP, N42° 41´ 24,78´´ E11° 20´ 11,97´´ (SAV); Buonconvento, località Bibbiano, basamento in calcare di una croce, alt. ca 215 m, 19. 9. 2013 leg. LP, UTM E 699460 N 4777210 (SAV); Rocca d´Orcia, limestone rock outcrops on the top of the hill in the centre of the village and outcrops within the castle area, alt. 524 m, 27. 8. 2013, leg. AG & LP, N43° 00.611´ E11° 36.825´ (SAV); Montagnola Senese, Casanova di Colle Ciupi, frammento di roccia prelevato da un muretto, alt. 427 m, 20. 10. 2013, leg. LP, N 43° 21´ 18,36´´ E 11° 13´ 48,85´´ (SAV); Ancaiano, along the road between Passo degli Incrociati and Ancaiano, on hard limestone rocks along the road, alt. 505 m, 27. 8. 2013, leg. AG & LP, N43° 17 39,34´ E 11° 11 0,35´ (SAV); ibid. 12. 10. 2013, leg. ZF, AG & LP, N43° 17.544´ E11° 11.410´ (SAV); Provincia di Siena, Montalcino, La Fortezza, NW facing brick wall at the main gate, alt. 551 m, 16.8.2015, leg. AG & LP, N 43°03'22.06" E 11°29'22.07" (SAV).

TAA
Prealpi Bresciane e Gardesane: Nago – Torbole, locality Malga Zures, open limestone outcrops on the top of the hill, alt. 655 m, 28. 4. 2012, leg. AG & MS, N45° 51´ 35,65´´ E 10° 53´ 53,57´´ (SAV).

Specimens without detailed lables:
Lichenes exsiccati Italiae, Auctore A. Massalongo. N. 210, leg. Anzi (O – L58250, TO, W all as *Ricasolia candicans*); Erbar. Crittogam. Ital. no. 68 (TO, as *Ricasolia candicans*); Italy, herb. Körber (O – L58252 as *Ricasolia candicans*).

***SOLENOPSORA CESATII* (A. MASSAL.) ZAHLBR.**
Abr
Prov. Chieti, Borrello, Riserva Cascate del Rio Verde, open calcareous outcrops above humid valley with stream, on overhanged faces of rocks, 755 m, 9.9.2015, 41.917010°N 14.321165°E, leg. Z. Fačkovcová, L. Paoli & A. Vannini (SAV).
Bas
Prov. Potenza: Viggiano, above the village on the road to Madonna di Viggiano, 1000 m, *Quercus pubescens* open woodland on limestone, 11. 4. 1995, leg. P. L. Nimis & M. Tretiach (TSB 22002 ut *S. candicans*); Val d´Agri, Grumento Nova, municipal park, NE slope of the town, limestone outcrops in the forest park (*Pinus* sp., *Cupressus* sp.), on perpendicular rock face, alt. 742 m, 8. 10. 2013, leg. ZF, AG & LP, N40° 16.984´ E15° 53.198´ (SAV); ibid., strada comunale di Monserrato, humid mixed forest on a slope facing capella/chiesa di Monserrato, on shaded limesto rock, alt. 805 m, 6. 10. 2013, leg. ZF & AG, (SAV); ibid. 7. 4. 2014, leg. AG & LP, N40° 17.134´ E15° 51.627´ (SAV).
Camp
Prov. Caserta: Lago del Matese, 3 km before Passo di Miralago, calcareous rocks, ca 1020 m, 15. 4. 2000, leg. P. L. Nimis & M. Tretiach (TSB 32002 ut *S. candicans*).
Fr
Alpi Carniche: Creta Grauzaria (UD), gola del Rio Forchia, ca. 650 m, in fessura di una parete calcarea. 25. 7. 1993, leg. M. Tretiach (TSB 17375 ut *S. candicans*); Trieste: Karst, Val Rosandra bei Bagnoli della Rosandra SE Trieste, ca 100–150 m, Kalk, 19.7.1979, leg. M. & M. Mayrhofer, P. L. Nimis, Nr. 1249 (GZU 21-2015); Val Rosandra, Au-dessus de St. Maria, Standort: parois calcaires verticales en exposition nord-ouest, 100 m, 1. 7. 1982, leg. et det. Ph. Clerck, Inventar–Nr. 2433–2434 (BM); Val Rosandra, Au dessous de Monte Stena, 29.6.1982, 250 m, Standort: Paroi verticale ombragée par la végétation, exp. SSW, leg. et det. P. Clerc, Inventar – Nr. 4632-4633 (G 00295723); Au-dessus de Santa Maria, sous le monument Cippo Comici, 1.7.1982, 300 m, Standort: Parois verticales calcaires en exp. NW., leg. et det. Ph. Clerc, Inventar – Nr. 4770-4771 (G 00295724); Carso Triestino: presso l´abisso Plutone di Gropada (TS), c. 370 m, su roccia calcarea, 25. 12. 1992, leg. Tretiach (TSB 16715 as *S. candicans*); Borgo Grotta Gigante: 220 m, su calcare, 27. 5. 1985, leg. Poelt et Nimis (TSB 5567 ut *S. candicans*).
Lomb
Ad saxa jurassica umbrosa domorum in monte Piatto supra Larium lacum, 500 m (as *Gyalolechia candicans* var. *cesatii* f. *dealbata*, BM); Alpi Bergamasche: provincia di Bergamo, commune di Castione della Presolana, Bratto – Donico, S slopes of the Presolana Mt., massif of the Mt. Sarradone, open calcareous cliffs and outcrops, in fissures and perpendicular E – SE faces, alt. 1377 m, 5. 10. 2010, leg. AG, N45° 55´ 46.77´´ E 10° 03´ 59.97´´ (SAV); ibid. S slopes of the Presolana Mt., S slopes of Pizzo Plagna above Cantoniera, open calcareous cliffs and outcrops, in fissures and perpendicular E faces, alt. 1539 m, 6. 10. 2010, leg. AG, N45° 56.070´´ E10° 05.570´´ (SAV); provincia di Bergamo, Dosso, Val di Scalve, limestone crest along the road SP59, on sheltered limestone rock fissures, alt. 970 m, 10. 4. 2015, leg. AG, N45° 56.903´ E10° 06.729´ (SAV); Prealpi Bresciane e Gardesane: Gargnano, area of Lago di Valvestino (valle di torrente Toscolane), side valley Val di Sas (ca 300 m from the junction Molino di Bollone – Turano – Vantone, S slope with relic *Pinus silvestris*, on perpendicular limestone rock faces and fissures, alt. 573 m, 29. 4. 2012, leg. AG & MS, N45° 45´ 2.82´´ E 10° 35´ 48.51´´ (SAV); Tignale, limestone crest covered by vegetation along the road to Oldesio – Tignale, on sheltered limestone rock, alt. 345 m, 14. 4. 2015, leg. AG, N45° 43.629´ E10° 42.009´ (SAV); Tremosine, limestone outcrops along the road Tremosine – Vesio (SP 38) with *Amelanchier ovalis*, in sheltered limestone rock fissures, alt. 540 m a.s.l., 14. 4. 2015, leg. AG, N45° 47´ 20.37´´ E10° 45´ 05.40´´ (SAV).
Marc

Prov. Teramo: below Pascellata – Rocca S. Maria, comune di Vella Castellana, *Populus*, *Fraxinus*, along a river, limestone 800 m, 8. 8. 1996, leg. P. L. Nimis & M. Tretiach (TSB 25010 ut *S. candicans*).

Mol

Prov. Campobasso: below Lupara along river Biferno, dry calcareous rocks, cultivations, 280 m, 41° 44´36´´ N, 14° 44´32´´, leg. Nimis & Tretiach 4. 4. 1997 (TSB 27025 ut *S. candicans*); Tufara: Toppo Castagnite (CB), 600 m, 1995, leg. R. Garofalo (TSB 21783 ut *S. candicans*); Prov. Isernia: M. Caraceno (Pietrabbontante), calcareous outcrops just above the Sannitic Theater, 1150 m, leg. Nimis & Tretiach, 4. 4. 1997 (TSB 26612 ut *S. candicans*).

Ven

Massalongo Lichenes Italici Exsiccati No. 141, Ad saxa jurasica in prov. Veronensi (M. Baldo, Grezzana etc.) [VER, W as *Ricasolia cesatii*]; Ad saxa calcarea in montibus supra Lecco, Garovaglio (VER, as *Parmelia cesatii*); Herb. Massal. R. 37, vidis Cl. Roux 1982.10 (VER, as *Solenopsora cesatii*); Aûf dem Monte Baldo (G 00295722 as *Ricasolia cesatii*); Prealpi Bresciane e Gardesane: Magugnano, Valle di Trovai, area of the cave Grotta di Val Trovai, SW slopes of Malga Trovai, open limestone outcrops in the light mixed forest, in shaded fissures, alt. 1100 m, 28. 4. 2012, leg. AG & MS, N 45° 41´ 54.32´´ E 10° 47´ 38.65´´ (SAV as *S. carpatica*); Altopiano di Asiago-Valle del Brenta-Massiccio del Grappa (Dolomiti Feltrine e Bellunesi): San Nazario, the mouth of the valley opening to Via Monte Asolone (Localita Campagna), limestone outcrops, alt. 250 m, 30. 4. 2012, leg. AG & MS, N45° 50´ 23.96´´ E 11° 41´ 48.79´´ (SAV).

Vg

Prealpi Giulie: alta valle del Torre (UD), presso Tanataviele (staz. 1), 660 m, su massi calcarei, su muschi epilitici, in ombra sotto gli alberi. Det. Tretiach, esempl. Poco svilup., 21. 3. 1992, leg. Castello / Tretiach (TSB 16804 as *S. candicans*); Prov. UD, M.te Musi, Sentiero CAI 740, versante sud M.te Musi, Tanataviele, su roccia calcarea – staz. 15, alt. ca 750 m, 9. 3. 2003, leg. C. Molaro (TSB 36166 as *S. candicans*).

Sar

Prov. Di Nuoro: presso Jerzu, sotto P.ta Corongius, 750 m, su calcare, 2. 9. 1989, leg. Nimis, Roux, Tretiach, Vězda (TSB 13476 ut *S. candicans*); M. Albo, P.ta Cupetti, 950 m, on limestone, 25. 7. 1985, leg. Nimis et Poelt (TSB 6099 ut *S. candicans*); Isola di Tavolara, on fissures of dolomitic rock, ca 20 m, 17. 5. 1987, leg. G. Brizzi (TSB 8458).

Tosc

Provincia di Siena: Ancaiano, along the road between Passo degli Incrociati and Ancaiano, on hard limestone rocks along the road, alt. 505 m, 27. 8. 2013, leg. AG & LP, N43° 17´ 39.34´´ E 11° 11´ 0.35´´ (SAV); ibid. on hard limestone rocks along the road and in the humid oak forest, alt. 505 m, 12. 10. 2013 leg. ZF, AG & LP, N43° 17.544´ E11° 11.410´ (SAV).

TAA

Prealpi Bresciane e Gardesane: Nago – Torbole, W facing foot of M.te Altissimo, locality Daine – carst dolomitic formations behind the chapel with Madonnina, in fissures of rock, alt. 325 m, 28. 4. 2012, leg. AG & MS, N45° 51´ 58.82´´ E 10° 53´ 16.07´´ (SAV).

Specimens without detailed lables:

Herb. Massal. R. 37, vidis Cl. Roux 1982.10 (VER, as *Solenopsora cesatii*).

***SOLENOPSORA GRISEA* (BAGL.) KOTLOV**

Abr

Prov. L´Aquila: Gole del Sagittario below Villalago, limestone, 685 m, 11. 8. 1996, leg. P. L. Nimis & M. Tretiach (TSB 25238 ut *S. candicans*).

Cal

Valle de Fiume Caronte, Piano della chiesa, 680 m, on limestone, 5. 4. 1986, leg. Puntillo (TSB 7212 as *S. bagliettoana*); ibid. Mendicine – CS, substrato calc, alt. 485 m, esp. E, 12. 2. 1986, leg. Puntillo (TSB 6994 as *S. cesatii*); ibid. loc. Pantano Lungo, 480 m, su calcare, 13. 7. 1988, leg. Nimis, Tretiach, Castello (TSB 10563 as *S. cesatii*); ibid. substrato calc., alt. 460 m, 12. 2. 1986, leg. Puntillo (CLU 1633 as *S. candicans*); ibid. substrato calc., alt. 510 m, 26. 2. 1986, leg. Puntillo, no 1633 herb. D. Puntillo (CLU 1677 as *Solenopsora bagliettoana*).

Camp

Prov. Salerno: Amalfi coast, narrow gorge just above Positano near the main road ca 90 m, 18. 4. 2000 leg. P. L. Nimis & M. Tretiach (TSB 32344 ut *S. cesatii*); Scala (Amalfi), rupi calcaree presso l´antica torre sopra Atrani, ca 200 m, calcare, *Cupressus*, *Fraxinus ornus*, 18. 4. 2000, leg. P. L. Nimis & M. Tretiach (TSB 31674 ut *S. cesatii* var. *grisea*).

Fr

Trieste: Val Rosandra, fondovalle presso il ruscello, esposta a nord, 25. 5. 1981, leg. Loi & Nimis (TSB 1416).

Laz

Prov. Latina: Monti Arunci, M. S. Angelo, near Gaeta, road to the top, at ca. 1200 m, *Fagus* forest, dry calcareous grasslands, limestone rocks, 5. 4. 2000, leg. P. L. Nimis & M. Tretiach (TSB 32423).

Lig

Lichenes Italici, Rapallo (Genova), 6.1949, Sbarbaro, Herb. Dr. Ed. Frey, Bern, Nr. 15.685 (G 00295727 as *Placolecania cesatii* var. *olivacea*); in Liguria orientali, loco Ruta, ad maceriam sub oleis, 1934 C. Sbarbaro (LISU as *Diphratora cesatii* var. *olivacea*); Lich. Italica. Ruta, ad maceries. 1930 leg. C. Sbarbaro (H, as *Placolecania cesatii* var. *olivacea*); Riviera di Ponente: Noli – Finale Ligure, strada per Verzi (via Iulia Augusta), olivetti, the walls of calcareous rocks along the road, on rock, alt. 103 m, 11. 7. 2012 leg. AG & LP N 44° 11.504´ E 8° 21.608´ (SAV); Lich. Italiae. Paraggi, Portofino, 1932, leg. C. Sbarbaro (H, PRM 639454, as *Placolecania cesatii* v. *olivacea*); Portofino, ad muros et rupes conglomeraticas, 1934, leg. C. Sbarbaro (BC 955749, BC 955750, as *S. olivacea*).

Marc

Prov. Pesaro: Montefeltro: S. Leo, calcareous outcrops just east of the village, Quercus, Robinia, 540 m, 19. 8. 1996, leg. P. L. Nimis (TSB 23512).

Pugl

Prov. Bari: Gravina di Puglia: Necropolis, soft calcareous rocks, ca 330 m, 7. 4. 1996, leg. P. L. Nimis & M. Tretiach (TSB 22692); Prov. Foggia: Isole Tremiti, Isola di S. Nicola, 55 m, on limestone, 6. 7. 1996 leg. Nimis (TSB 7550 as *S. bagliettoana*); ibid. ca. 50–60 m, leg. Nimis & Tretiach, 3. 4. 1997 (fertile, TSB 26249 as *Solenopsora bagliettoana* v. *grisea*).

Sar

Provinz Nuoro, Sopramonte über Oliena, beschatteter Kalkfelsblock, 750 m, 16. 4. 1971, leg. H. Wunder (GZU 10-86 as *Solenopsora*); Prov. Nuoro: M. Albo, P.ta Cupetti, 950 m, on subvertical limestone walls, 25. 7. 1985, leg. Nimis & Poelt (TSB 6093 as *S. cesatii*); Strand, südl. Cala Gonone, Kalksteinblöcke, 27.3.1988, herb. Werner Repetzky, det. W. Brunnbauer (W 1999-01148, as *S. bagliettoana*).

Si

Agrigento, bei den Tempelruinen von Agrigent. (ex herb. Poelt), 27. 12. 1954 leg. J. Poelt (LISU as *Solenopsora bagliettoana* f. *cinerascens*); Prov. Palermo: Rocca Busambra, Bosco della Ficuzza, 1200 m, su calcare, 6. 1988, leg. Nimis/Poelt (TSB 11008 ut *S. candicans*); Prov. Trapani: Riserva Nat. dello Zingaro, 200–550 m, 11. 12. 1995, Kalk, macchia, leg. P. L. Nimis & M. Tretiach (TSB 21503); Erice, su roccia calcarea in parte decalcificata, sotto il castello, versante NW, 24. 3. 1991, leg. Tretiach (TSB 15451 as *S. cesatii*); Égadi Islands: Marettimo, Selle di M. Falcone, 500 m, kalk, Excursion S.L.I., 24–31. 3. 1991, det. P. L. Nimis (TSB 15715 as *S. cesatii*); Marettimo, Buccerie, 240 m, kalk, Excursion S.L.I., 24-31. 3. 1991, det. P. L. Nimis (TSB 15714 as *S. cesatii*); ibid., loc. Case Romane, rocc. Calcaree, alt. 260 m, 27. 3. 1991, leg. D. Puntillo herb. D. Puntillo (CLU 7707 as *S. cesatii*, with intermixed *S. candicans* and *S. olivacea* subsp. *olivacea*); Isole Pelagie: Linosa, Rocce laviche tra il Faro di Scalo Vecchio ed il Paese, 10–15 m, 16. 4. 1992, leg. J. Poelt (escursione della SLI) (GZU 62-92, as *Solenopsora*).

Tosc

Castell´Azzara: Mt. Civitella – Mt. Penna, the foot of the massive – Sorgente del carpino, calcareous rock faces around the cave, shaded foot, alt. 889 m, 10. 4. 2010, leg. AG & LP, N42° 46.339´ E11° 41.590´ (SAV); ibid. the summit of Mt. Penna, open limestone rocks/cliffs, alt. 1074 m, 10. 4. 2010, leg. AG & LP, N42 46.406 E11 40.081 (SAV).

SOLENOPSORA HOLOPHAEA (MONT.) SAMP.

Lig

Rabenhorst, Licheni Europaei. No. 432. In murorum et rupium fissuris inter Voltri et Arenzano (Liguria occidua), leg. F. Baglietto (BR-LICH, PRA-V-01994, PRM 862950, PRM 19.332, as *S. Requeinii*); Erb. Critt. Ital. No. 36. Sui muri campestri e tra le screpolature delle rupi tra Voltri ed Arenzano, nella Liguria occidentale, 1857, Baglietto (FI, as *S. Requienii*); V. Köfaragó-Gyelnik, Lichenotheca. No. 61. Italia, in Liguria occidentali, Arenzano, ad ripam. 26. 12. 1934 leg. C. Sbarbaro (BM, H, PRA-V-01993, VBI 20430, as *S. requienii*); Arenzano, in Liguria occid., ad ripam siccam argillaceam, 1941, leg. C. Sbarbaro (LISU, as *S. Requenii*); Varazze, loco dicto Cantalupo, leg. C. Sbarbaro, 10.1925 (O – L58288 as *Psoroma holophaeum*); ibid., 10.1930 (H, as *Candelariella (Solenopsora) holophaea*, *S. Requienii*, LISU, as *S. Requienii*); Varazze, un muretto a Casanova, 22.2.1924, leg. G. Gresino (FI – Herbarium Gavioli No. 12397, as *Psoroma holophaeum*); Erbar. Crittogam. Ital. No. 368. Su rupi ombreggiate nella valle della Cerusa sopra Voltri, Liguria occidentale, leg. Baglietto (BM, FI, as *Ricasolia cesatii olivacea*); Liguria, Baglietto, 1879 (G 00295730, as *S. requienii*, *S. holophaea*).

Sar

distr. Cagliari: reservatum nature „Monte Arcosu“, ad latera montis „Lattias“, alt. 950 m. In fissurium rupium silicearum. 30. VIII. 1989. Leg. P. L. Nimis, C. Roux, M. Tretjak et A. Vězda (BM 2369, H, PRA-V-07969, SAV, TSB 13701, A. Vězda: Lichenes selecti exsiccati, no. 2369); Prov. di Cagliari: costa orientale, Capo Ferrato, fessure di roccia silicea, 60 m, 1. 9. 1989, leg. Nimis, Roux, Tretiach, Vězda (TSB 13200); M. Arcosu, salita a M. Leties, 750 m, in fessure, roccia silicea, 8/1989, leg. Nimis, Roux, Tretiach, Vězda (TSB 13243); Prov. Sassari: M. Russu, on the road between S. Teresa and Castelsardo, in fissures of acid rock along the coast. 10 m. 5/1986 leg. Nimis (TSB 7323).

Si

Isola di Linosa: 16. 4. 1992, leg. D. Puntillo, herb. D. Puntillo (CLU 11313); Linosa (AG), P.ta Calcarella, 10–30 m, su roccia, 15. 4. 1992, leg. P. L. Nimis (TSB 17233); Prov. Messina: Taormina, M. Petraro, ca 450 m, filliti, conglomer. (con calc.), 28. 2. 1995 leg. P. L. Nimis & M. Tretiach (TSB 20069 TSB); Isola di Pantelleria: loc. Montagne Grende, 5. 5. 1981, leg. Loi (TSB 15828).

Tosc

Isola di Capraia: Archipelago Toscano, su roccia sil. presso il porto, 19. 4. 1988, leg. Nimis & Tretiach (TSB 11220 with *S. vulturiensis*); E. Marcucci Piante dell´Isola dell´ Elba, Dintorni di Portoferraio, 1871 (Erbario O. Beccari in FI, as *S. Requienii*).

Specimens without detailed lables:

Lichenes exsiccati Italiae. Auctore A. Massalongo. N. 324 (O – L58289, W, both as *S. Requienii*).

SOLENOPSORA LIPARINA (NYL.) ZAHLBR.

Lig

Erbar. Crittogam. Ital. No 368. *Ricasolia cesatii olivacea*, su rupi ombreggiate nella valle della Cerusa sopra Voltri, Liguria occidentale, Baglietto; lectotype (TO); ibid. syntype designated by Y. Kotlov 2004 (BP 82928).
Savona: Varazze, loco Rianello, 2. X. 1930 leg. C. Sbarbaro (BP71242 as *Placolecania olivacea*); ibid., ad rupem praerutam sub Cypressis (H, as *S. cesatii* f. *olivacea*).
Gavi – Bosio: Parco Naturale delle Capanne di Marcarolo, serpentine outcrops along la strada provinciale 165 Bosio – Capanne di Marcarolo, in rock fissures, alt. 616 m, 27. 4. 2013 leg. AG, MS, J. Kučera & K. Olšavská N36° 57.164´ W4° 07.415´ (SAV).

Tosc

Pievescola: strada per Querceto 1B e Castello di Casole, serpentine outcrops, in fissures of rocks and perpendicular faces, alt. 250 m a.s.l., 6. 9. 2013, leg. LP, E. Guerrini & S. Landi, UTM E 671000 N 4798688 (SAV); ibid. in fissures of rocks and perpendicular faces, alt. 250 m, 12. 10. 2013, leg. ZF, AG & LP, N43° 19.635´ E11° 05.632´ (SAV); località Le Gabbra, serpentine outcrops, in fissures of rocks and perpendicular faces, alt. 250 m, 6. 9. 2013, leg. LP, E. Guerrini & S. Landi, UTM E 670977 N 4798733 (SAV); ibid. in fissures of rocks and perpendicular faces, alt. 270 m, 12. 10. 2013, leg. ZF, AG & LP, N43° 19.317´ E11° 06.505´ (SAV); Casciano di Murlo: Riserva Naturale Basso Merse, serpentine outcrops along the road between Casciano di Murlo and Capella Orsa, in fissures of serpentine rocks and perpendicular shaded faces, alt. 460 m, 17. 8. 2013, leg. AG & LP, N43° 08.431´ E11° 20.613´ (SAV); Vescovado di Murlo: serpentine outcrops along the road between Vescovado di Murlo and Rocca di Crevole, on faces of larger rocks, alt. 295 m, 28. 11. 2013, leg. AG & LP, N43° 11.078´ E11° 21.278´ (SAV).

SOLENOPSORA MARINA (ZAHLBR.) ZAHLBR.

Bas

Val d´Agri: Grumento Nova, strada comunale di Monserrato, humid mixed forest on a slope facing capella/chiesa di Monserrato, on shaded limesto rock, alt. 805 m, 9. 4. 2014, leg. AG & LP, N40° 16.984 E15° 53.198 (SAV).

SOLENOPSORA OLIVACEA (DUFOUR EX FR.) KILIAS SUBSP. *OLBIENSIS* (NYL.) CLAUZADE ET CL. ROUX

Bas

Val d´Agri: Grumento Nova, parco municipale, NE slope of the town, limestone outcrops in the forest park (*Pinus* sp., *Cupressus* sp.), on perpendicular rock face, alt. 742 m, 9. 4. 2014, leg. AG & LP, N40° 16.984´ E15° 53.198´ (SAV); Pollino Mt.: Castelluccio superiore, humid *Quercus cerris* forest, shaded hard limestone outcrops and towers, on rock faces, alt. ca 779 m, 1. 2. 2015, leg. AG & LP, N40° 00.726´ E15° 59.042´ (SAV).

Lig

Ruta, in Liguria orientale (prope Genuam) ad maceriam. 1930. Leg. C. Sbarbaro (BP66379, as *Placodiella olivacea* var. *sorediifera*); ibid., 8.1931 (H, as *Catillaria (Placodiella) olivacea* var. *sorediifera*); ibid., 1934 (H, as *Placodiella olivacea* var. *sorediifera*).

Tosc

Maremma: provincia di Grosseto, Scansano, località „Convento del Petreto – sassicaia“, oak wood on the SW facing slope with *Lobaria pulmonaria*, on shaded mossy calcareous rock, alt. 445 m, 25. 2. 2012, leg. AG & LP, N42° 41´ 24,78´´ E11° 20´ 11,97´´ (SAV); ibid. Convento del Petreto, limestone rocks and outcrops in oak forest near the convent, alt. 546 m, 13. 4. 2014, leg. AG & LP, N42° 41´ 37,37´´ E11° 20´15,95´´ (SAV); Provincia di Siena: Ancaiano, along the road between Passo degli Incrociati and Ancaiano, on hard limestone rocks along the road and in the humid oak forest, alt. 505 m, 12. 10. 2013, leg. ZF, AG & LP, N43° 17.544´ E11° 11.410´ (SAV).

Si

Prov. Messina – Taormina: M. Ziretto ca 400 m, calcari, *Q. pubescens*, 28. 2. 1995, leg. P. L. Nimis & M. Tretiach (TSB 20137); ibid. leg. P. L. Nimis & M. Tretiach (TSB 20135); ibid. leg. P. L. Nimis & M. Tretiach (TSB 20136).

*SOLENOPSORA OLIVACEA (*DUFOUR EX FR.) KILIAS SUBSP. *OLIVACEA*

Bas

Potenza: Marina di Maratea, substr. calc., 28. 4. 1996 herb. D. Puntillo (TSB 11312); ibid. 18. 5. 1996, leg. Bartoli & Puntillo herb. D. Puntillo (CLU 10090 as *Solenopsora*); ibid. 28. 4. 1996, leg. Puntillo herb. D. Puntillo (CLU 11311 as *Solenopsora*).

Camp

Prov. Salerno: Scala (Amalfi), rupi calcaree presso l´antica torre sopra Atrani, ca 200 m, calcare, *Cupressus*, *Fraxinus ornus*, 18. 4. 2000. Leg. P. L. Nimis & M. Tretiach (TSB 31660); road between Vibonati and Sicili (NW of Sapri), bridge on the river Bussento just below Sicili, deep calcareous gorge along the river, ca 180 m, 17. 4. 2000, leg. P. L. Nimis, D. Puntillo & M. Tretiach (TSB 31875); Amalfi coast, narrow gorge just above Positano near the main road, ca 90 m, 18. 4.

2000, leg. P. L. Nimis & M. Tretiach (TSB 32340); Capo Palinuro, near the Lighthouse, ca 150 m, limestone rocks, *Olea*, 17. 4. 2000, leg. P. L. Nimis & M. Tretiach (TSB 31552).

Laz

Prov. Latina: Maranolo sopra Pormio, ca 300 m, 5. 4. 2000 leg. M. Tretiach (TSB 32550).

Lig

Lichenotheca parva No. 70. Italia – in Liguria occidentali, Varigotti, rupicola sub oleis prope Castrum Saracinum. 5. 1937. Leg. C. Sbarbaro (BP75677, H, O – L58300, PRA-V-01975, as *Placolecania cesatii* var. *olivacea*); Spotorno, Savona, 16. 3. 1954, leg. Sbarbaro (BM, O – L115259).

Marc

Prov. Pesaro: Montefeltro: S. Leo, calcareous outcrops just east of the village, *Quercus*, *Robinia*, 540 m, 19. 8. 1996 leg. P. L. Nimis (TSB 23510).

Pugl

Prov. Foggia: Gargano: Torre di Porticello, near Vieste, 10–30 m, coastal calcareous hills, 5. 4. 1996, leg. P. L. Nimis & M. Tretiach (TSB 22753); Isole Tremiti, Isola di S. Nicola, ca 50–60 m, leg. Nimis & Tretiach, 3. 4. 1997 (TSB 26231); Gargano peninsula, below M. S. Angelo – road to S. Maria di Pulsano, ca 500 m. calcareous grassland, *Q. ilex* woodland. 5. 4. 1996, leg. P. L. Nimis & M. Tretiach (TSB 22550); P.so del Lupo, 530 m, limestone, 5. 4. 1996, leg. P. L. Nimis & M. Tretiach (TSB 22847); Prov. Brindisi: Selva di Fasano, above S. Lucia, 390 m, shaded calcareous rocks, isolated old oaks, 8. 4. 1996, leg. P. L. Nimis & M. Tretiach (TSB 23140); Prov. Lecce: between S. Gagliano del Capo and Marina di Novaglie, coastal N-exposed calcareous cliffs, 60 m, 9. 4. 1996, leg. P. L. Nimis & M. Tretiach (TSB 22611).

Sard

Province of Nuoro: M. Arcueri near Seui, 1100 m, on limestone, 5/1986, leg. Nimis (TSB 7357); Prov. Cagliari: Felsküste ca 1.5 km N von Buggeru. Sh. 30–50 m. An Kalkfels. Leg. W. Brunnbauer 2. 5. 1986 (W 1999–01157); Strand, südl. Cala Gonone, Kalksteinblöcke, 27. 3. 1988 leg. W. Brunnbauer (W 1999–01148).

Sic

Marettimo (Égadi Islands TP): 450 m, kalk, excursion S.L.I., 24–31. 3. 1991, leg. P. L. Nimis (TSB 18699); sopra Cala Marino, 150 m, calcareous rock, excursion S.L.I., 24–31. 3. 1991, leg. P. L. Nimis (TSB 39881); loc. Case Romane, rocc. Calcaree, alt. 260 m, 27. 3. 1991, leg. D. Puntillo herb. D. Puntillo (CLU 7707 ut *S. cesatii*, mixture with *S. candicans* and *S. grisea*); ibid. Buccerie, 240 m, calcareous rocks, Excursion S.L.I., 24–31. 3. 1991, leg. Castello, Nimis, Tretiach (TSB 15716); ibid. Buccerie, 260 m, limestone, Excursion S.L.I., 24–31. 3. 1991, leg. SLI (TSB 15717); ibid. Ficerella, 200 m, calcareous rocks, Excursion S.L.I., 24-31. 3. 1991, leg. P. L. Nimis (TSB 18700); ibid. Ficerella, 200 m, calcareous rocks, Excursion S.L.I., 24-31. 3. 1991, leg. P. L. Nimis (TSB 18703); Prov. Trapani: Riserva Nat. dello Zingaro, 200–550 m, 11. 12. 1995, kalk, macchia. Leg. P. L. Nimis & M. Tretiach (TSB 21467); Lampedusa: 60 m, kalk, 12. 4. 1982 leg. Nimis (TSB 17246).

Tosc

Parco Nazionale Archipelago Toscano: isola di Pianosa (LI), escursione del GdL di Floristica e Sistematica della S.L.I., 0–28 m s.l.m., 22–26 marzo 2005, Stazione Cala dell´Alga, leg. L. Muggia (TSB 38357); ibid. leg. L. Muggia (TSB 38356); ibid. leg. L. Muggia (TSB 38355); Insula Dianum (Giannutri), sulla rupi, 6.3.1897 (FI, as *Diphratora (Ricasolina) olivacea*); E. Marcucci Piante dell´Isola dell´ Elba, 14. 7. 1870 (Erbario O. Beccari in FI, as *Ricasolia olivacea*).

SOLENOPSORA VULTURIENSIS A. MASSAL.

Cal

Catanzaro Cortale, 2. 3. 1992, alt. 380 m,. leg. D. Puntillo (CLU 8245 as *Solenopsora*; CLU 8240 as *Solenopsora*).

Lig

H. Lojka: Lichenotheca universalis, Fsc. II (1885) Nr. 73, Super muros campestres circum Voltri Liguriae occidentalis, leg. Dr. F. Baglietto, Comm. Dr. F. Arnold (BP 85498, G 00295735, H, as *Lecanora vulturiensis*); Arenzano, loco rerrerasse, 4. 1947, leg. C. Sbarbaro (LISU); Arenzano, loco olivetta, ad maceriem. XI. 1936. Leg. C. Sbarbaro (H); Arenzano, 9.1948, C. Sbarbaro (PRM 31.223); Voltri, loco classic, 1/1930, leg. et det. C. Sbarbaro (H, PRM 639460); Voltri (= Vulturis) prope Genuam, ad maceriam loco Santuario delle Grazie, 21.3.195, leg. C. Sbarbaro (BC 955745); Erb. Critt. Ital. No. 367. Sopra un vecchio muro ombreggiato tra Voltri ed Arenzano, Liguria occidentale, 1858, Baglietto (FI, H); Cinque Terre – Riomaggiore, a harbour, brick wall lining the starcase, in fissures between bricks, alt. 18 m, 12. 4. 2015, N44° 05´ 53.58´´ E09° 44´ 15.07´´ leg. AG (SAV); Ruta (Camogli), ad maceries sub olei, 1934, C. Sbarbaro (H, in envelope with *Placodiella olivacea* subsp. *sorediifera*).

Tosc

Murlo – Miniere di Murlo: the valley Valle del Crevole, along the path Sentiero delle Miniere, gabbri, diaspri, on sheltered rocks, alt. 216 m, 16. 4. 2014 leg. AG & LP, N43° 09´ 26.39´´ E11° 22´59.95´´ (SAV); Montalcino, La Fortezza, NW facing brick wall at the main gate, alt. 551 m, 16.8.2015, leg. AG & LP, N 43°03'22.06" E 11°29'22.07" (SAV).

Sar

Prov. Cagliari: oasi WWF di M. Arcosu, salita al M. Lattias ca. 750 m, su parete subverticale silicea, 8/1989 leg. Nimis, Roux, Tretiach, Vězda (TSB 13386).

Si

Isole Pelagie: Linosa, Ascensione al. M. Nero, 20–107 m, 14. 4. 1992, leg. J. Poelt (escursione della SLI) (GZU 62-92 as *Solenopsora*); ibid. verso M.re Nero, 40–80 m, su tufi, 14. 4. 1992, leg. M. Tretiach (TSB 17177); ibid., Costa da

Faraglione a Calla Mannarazzo, 2–10 m, 16. 4. 1992, leg. J. Poelt (escursione della SLI) (GZU 62-92 as *Solenopsora*); Isola di Alicudi: roccia vulcanica, alt. 50 m, 25–29. 7. 1994, leg. Otonello & Puntillo, herb. D. Puntillo (CLU 9854). Prov. Messina: Taormina, M. Petraro, ca 450 m, filliti, conglomer. (con calc.), 28. 2. 1995 leg. P. L. Nimis & M. Tretiach (TSB 20063).

Supplementary Information 2. List of revised herbarium specimens documenting the distribution range of *Solenopsora* congeners outside the Apennine Peninsula. The collections are sorted according to the countries and the regions, within which are listed in alphabetical order. With each herbarium specimen we cite the complete information given in the original label. Collector´ names of recent material are abbreviated as follows: AG – Anna Guttová, JK – Jaromír Kučera, MS – Marek Slovák, SM – Silvana Munzi, ZF – Zuzana Fačkovcová. In the brackets at the end of each entry, the herbarium acronym with a specimen number or barcode if available is given. The list contains only unpublished records which were not included in Guttová et al. (2014, 2015) and Fačkovcová et al. (2017).

SOLENOPSORA CANDICANS (DICKS.) J. STEINER

Croatia

Split distr., prope pagum Rogoznica, alt. 10 m, 3.6.1968, ad muros e lapidibus calcareis compositos, A. Vězda: Lich. Sel. Exs. No. 742., leg. A. Vězda (H); Istria, ad saxa dolomitica murorum ad viam publicam inter Hosti et Sv. Matije, 200–250 m, Schuler Kryptogamae exsiccatae, No. 1364, leg. J. Schuler (BRNU, H, as *Placolecania candicans*); Cres: walls of limestone rocks along the road no. 100 between the junctions for Orlec and Stanič, shaded limestone rocks, 225 m, 9.8.2016, 44°50.131'N 14°24.716'E, leg. AG & H. Béreš (SAV); Dalmatien: Gravosa [Gruž], Alte Manes auf Lapad, ca 60 m, 23.9.1907, leg. A. Latzel (Herb. Mus. Palat. Vindob. in W 1907–18727, as *Placolecania cesatii*); Kalničko gorje Mts: Kalnik village, calcareous outcrops on the ridge near Stari grad Veliki Kalnik, on the vertical flat rock surface with E exposition, 512 m, 30.9.2016, 46.133387°N 16.464947°E, leg. ZF, M. Maslać & M. Doboš (SAV, ZA); Hvar: Pitve, foothill of the mountain near tunnel between the villages Pitve – Zavala, shaded limestone outcrops in the mixed *Pinus* – *Quercus* wood, alt. 200 m a.s.l., N43°08'31.9" E16°40'27.3", 2. 7. 2017 leg. A. Bérešová (SAV); Nord Dalmatien: Sekanović, 1908, M. Servit (Herb. Mus. Palat. Vindob. in W 1918–257, as *Placolecania candicans*); Southern Dalmatia: Opuzen, delta of Neretva river, SW facing slopes along E65 road between Ladište and Klačni, limestone rocks, alt. 128 m a.s.l., N42°58'43.0" E17°32'11.4", 6. 7. 2017 leg. A. Bérešová (SAV); Ragusa [Dubrovnik]: Lapad, saxa calc., alt. 60 m, 2.2.1908, leg. A. Latzel, Flora Dalmatica (H, as *Placolecania cesatii*); Ragusa, Žarkovica, 180 m, leg. A. Latzel, det. Zahlbruckner (ZA, as *Placolecania cesatii*); Ražanj: macchia (*Quercus* sp., *Olea* sp., *Pistacia* sp.) along the road between Ražanj and Kanica, calcareous outcrops, on rock faces, 35 m, 30.8.2016, 43°30'24.08"N 15°59'24.54"E, leg. MS (SAV).

France

Tresnay sur Sarthe, calcaire, 1907, Monguillon (H, as *Squamaria candicans*).

Germany

An Dolomitfelsen der Kemitzen-Steine westlich von Weissmain im Frankenjura, Arnold no. 1221, 4.9.1887 (H, as *Ricasolia candicans*); Auf Kalkblocken bei Trier, Rabenhorst Lichenes europaei No. 748, leg. A. Metzler (BM, H, as *Ricasolia candicans*); Rheinthal, Eifel, dolomit, 16.7.1951, leg. A. Henssen, det. V. Räsänen (H).

Greece

Insel Kerkyra (Korfu): Sokrati – Zigos road, semi-exposed limestone outcrop in olive groove, 370 m, 16.7.2014, 39.7221°N 19.8003°E, leg. S. Rui & E. Timdal (O-L196253); Insel Kreta: Chania, along road from Voukolies ro Paleochora, near Floria, under overhanging rock, 550 m, 7.9.1998, 35.355°N 23.74°E, leg. S. Rui & E. Timdal (O-L204416); Vilandredo, Kollita Farangia Gorge, on calcareous rocks, alt. 275 m, N35°16'11.2" E24°20'44.7", 8. 4. 2017, leg. J. Kučera & M. Slovák (SAV); Spili, plateu above the village, calcareous crest above the road Spili – Gerakari, alt. 796 m, N35°12'58.3" E24°34'04.0", 4. 4. 2017 leg. J. Kučera & M. Slovák (SAV); Moni, ca 0.5 km from the village, above the road between Moni and Sougia villages, on calcareous rocks, N35°16'47.7" E23°48'53.1", 5. 4. 2017 leg. J. Kučera & M. Slovák (SAV); Insel Paximadhia: kalk., 1904, leg. J. Dörfler (Herb. Musei Palt. Vindob. in W 798, as *Placolecania candicans*).

Portugal

Estremadura, Praia da Ribeira de Ilhas, ad ripas calcarias abruptas orientem spectantes, circ. 10 m, 22.12.1955, Tavares: Lichenes Lusitaniae selecti exsiccati no 94, leg. C. N. Tavares (H); Lavalette, 4.2.1845 (G 00295701, as *Parmelia candicans*, *Lichen candicans* – note: most probably, damaged thallus!).

Specimens without detailed lables:

Erb. O. Beccari, 1862 (FI, as *Ricasolia candicans*)

SOLENOPSORA CESATII **(A. MASSAL.) ZAHLBR.**

Austria

Kärnten, Gailtaler Alpen: Dobratsch-Südabfall, Schütt, zw. Oberfederaun und Unterschütt, 750 m, 46°34'34"N 13°47'55"E, *Ostrya carpinifolia-Fraxinus ornus*-dominierter Wald vereinzelt *Pinus sylvestris*, *P. nigra* auf südexponierten, nich sehr steilen Kalkneigungsflächen, 13. 10. 1996, leg. H. Komposch (herb. H. Komposch, as *S. carpatica*); ibid. 46°34'28"N 13°47'55"E, 13. 10. 1996, leg. H. Komposch (herb. H. Komposch, as *S. carpatica*); Steiermark, Grazer Bergland: Gamskogel 1.78 km WNW von der Ortskapelle in Kleinstübing, 180 m, 47°11'14"N 15°18'8"E, senkrechte, WSW-exponierte, ca 5 m hohe Dolomitfelsfläche in schütterem Föhren-Rotbuchen-wald, 04. 02. 2007, leg. H. Komposch & B. Emmerer (herb. H. Komposch 7996, 7999).

Greece

Dodekanes: Insel Simi (Symi, Symä), kalkfelsen am Kloster Panormitis, ± 5 m, N-exponiert, 7.9.1983, leg. J. Poelt (GZU 106-83, as *Solenopsora* sp. – note: cf. *cesatii*, very small specimen!).

Romania

Apuseni Mts – Muntele Mare: Poşaga de Sus, Scarita Belioara Mt., south feet of the calcareous hills with *Juniperus sabina*, in fissures of rocks, 866 m, 1.10.2016, 46°29'17.78"N 23°22'8.33"E, leg. MS & E. Gbúrová Štubňová (SAV); Munţii Şureanu Mts: Hunedoara, Crivadia, calcareous outcrops near the quarry, on rock, 613 m, 28.6.2014, 45°27.924'N 23°12.362'E, leg. et det. ZF & MS (SAV).

Serbia

Suva planina Mts: Bela Palanka, the valley between the villages Bežište and Gorna Koritnica, limestone crest above the road, on perpendicular shaded faces of limestone rock, 529 m, 15.6.2016, 43°08.21'N 22°19.893'E, leg. AG, MS, JK & E. Štubňová (SAV); ibid., Crvena Reka, the valley of the river Nišava, side valley along the road A4, on perpendicular shaded faces of limestone rock, 344 m, 43°19.467'N 22°09.971'E, leg. AG, MS, JK & E. Štubňová (SAV).

Slovakia

Malé Karpaty Mts: Smolenice, the valley Hlboča, a crest with limestone outcrops and cliffs above the valley between the waterfall and elevation point Molpír, on sheltered calcareous rocks, in fissures on perpendicular face, alt. 371 m a.s.l., N48°30.670´ E17°24.684´, 11. 4. 2017 leg. A. Guttová, Z. Fačkovcová, A. Lackovičová, A. Košuthová, V. Kučera & G. Kozárová (SAV); Strážovské vrchy Mts: Nitrianske Rudno, a rocky crest “Biele skaly” near touristic path to “Košútova skala” from Nitrianske Rudno village, beech forest with relict pine stands (*Pinus silvestris*), in fissures on perpendicular face of calcareous rocks, S-exposed, alt. 572 m, N48.78795° E18.45105°, 8.7.2017 leg. Z. Fačkovcová & L. Paoli (SAV); Uhrovské Podhradie, a rocky crest along touristic path from Uhrovský hrad castle to point “Kňažinové lúky”, beech forest with relict pine stands (*Pinus silvestris*), on partially shaded perpendicular face of calcareous rock, N-exposed, alt. 600 m, N48.751639° E18.395078°, 9.7.2017 leg. Z. Fačkovcová & L. Paoli (SAV); Muránska planina Mts: Muráň, National Nature Reserve Cigánka, exposed limestone cliffs on NW slopes of the castle hill, shaded rock face, alt. 884 m, N48°45.563´ E20°3.415´, 31. 5. 2017 leg. A. Bérešová & Z. Palice (SAV).

Ukraine

Eastern Carpathians, Zakarpatska Oblast Region: Khust, Velyka Uhol'ka, above the valley of Kamenskyi strumok, E-ESE descending crest, ENE of the point 'Pogar' and 0.4–0.5 km NW-WNW of the rock “Molochnyi kamen” [Молочний Камінь], in fissures of ESE and SW facing limestone rock outcrop, partly shaded by a lime-tree, 770 m, 15.5.2015, 48°15'19.6"N 23°39'58.8"E, leg. F. Berger, Z. Palice & N. Sanderson, det. Z. Palice (herb. Z. Palice Nr. 19040 in PRA, SAV); ibid., the top part of the rock-point “Molochnyi kamen”, on more-less vertical limestone rock below overhang (SW exposition), 720 m, 18.5.2015, 48°15'10.2"N 23°40'27.9"E, leg. et det. Z. Palice (herb. Z. Palice Nr. 19045 in PRA, SAV); ibid., in fissures of WSW exposed limestone overhang and on exposed, E-facing overhang, 725 m, 18.5.2015, 48°15'09.9"N 23°40'28.8"E, leg. et det. Z. Palice (herb. Z. Palice Nr. 19046, 19047 in PRA, SAV).

SOLENOPSORA GRISEA **(BAGL.) KOTLOV**

Algeria

C. Flagey. Lichenes Algerienses. A. C. à la base des rochers calcaires humides de Constantine et Azeba (W 1899–1581 as *Ricasolia liparina*; H as *Ricasolia liparina*).

Croatia

Bukovica gebirge in Dalmatien: Höhle Pržun, 1908, leg. M. Servít (W 311, as *Placolecania cesatii* var. *olivacea*); Dalmatia: Gebiet von Zara [Zadar], Südostufer des Lago di Vrana, kalkfelsen in der Sonlucht am au sliege nach Banjevac, c. 100 m, 29.3.1913, J. Baumgartner (W 4401, as *Placolecania liparina*); Hercegnovi, Pločica, 280 m, calc., leg. M. Servít (PRM 13.014, as *Placolecania liparina*); Insel Arbe, Tigna, Valle di S. Pietro, Kalk, 2–300 m, leg. J. Baumgartner (PRM 639458, as *S. liparina*); Island Krk, road between the town of Krk and Baška, the point Prijevoj Treskavec, limestone cliffs near the monument to Glagolitic alphabet, on perpendicular faces and in fissures, alt. 264 m a.s.l., 10.8.2016, leg.

AG & H. Béreš, N45°01.672' E14°40.689' (SAV); Isola Cherso [Cres], sopra la discarica sopra la cittadina d Cherso, ca 600 m s.l.m, Aprile 1998, leg. Tretiach (TSB 30712, as *S. cesatii* var. *grisea*); pr. Kupari, in rup. calcar. 1917, leg. R. Dvořák (PRM 639457, as *S. liparina* – note: cf. *grisea*!); Hvar: Sveta Nedjelja, foothil of the Sv. Nikola massive,between the village and the bay Dubovica, limestone outcrops in dry *Pinus* wood, on shaded rock faces and fissures, alt. 118 m a.s.l., N43°08'29.2" E16°34'33.0", 5. 7. 2017 leg. A. Bérešová (SAV); Ražanj, macchia (*Quercus* sp., *Olea* sp., *Pistacia* sp.) along the road between Ražanj and Kanica, calcareous outcrops, on rock faces, 35 m a.s.l., 30.8.2016, leg. MS, N43°30'24.08" E15°59'24.54" (SAV); župa Dubrovečka, calcicola prope Čelopeči, ca 20 m, 1917, leg. R. Dvořák (PRM 639456, as *S. liparina*); Istrien: Insel Veglia, kalkfelsen, 4.4.1907, c. 3–400 m, leg. J. Baumgartner (W 7162, as *Placolecania liparina*); Jablanac, 120 m, calc., 1.7.1927, leg. M. Servít (PRM 7715, PRM 7716, as *S. liparina*).

Cyprus

Larnaca, Pyla, prope vicum Oroclini, in vicinitate litoris, alt. 5–10 m, ad saxa conglomerata p. max. parte calcarea, 25.6.1987, A. Vězda: Lich. Sel. Exs. No. 2349, leg. A. Vězda (H, TSB 13659, as *S. cesatii*).

France

Bouches-du-Rhône: Saing-Rémy-de-Provence, prope Glanum, alt. 100 m s. m. 17.4.1965, ad parietes rupium calcarearum, septentrionem spectantium, A. Vězda: Lich. Sel. Exs., No. 391, leg. G. Clauzade, J. Lambinon & A. Vězda (BM, G 00295718, H, LISU, as *S. liparina*); Montpellier, Schaer. 1855 (G 00295720, as *Lecanora Montagnei* β *calcaria*); Nice, Mont Alban, ad saxa calcarea, Reliquiae Suzaianae 1966, No. 74, leg. J. Suza 4.1927, det. A. Vězda 1.1966 (BM, H, PRM 916720, PRM 866151, as *S. liparina*); ibid. (PRM 639463, PRM 639464, as *Placolecania* sp.); Nice, Villefranche, Vinaigrier, ad rupes calcareas, 300 m, 5.1927, leg. J. Suza (PRM 639462, as *Placolecania* sp.); Gorges de Régalon, 12.4.1968, leg. Z. Černohorský, det. G. Clauzade (PRC 1402, as *S. liparina*); Pic St. Loup: sommet, surfaces frontales 110/6, expos. N, 630 m, leg. E. Frey, 8.10., aus Herbar Dr. Ed. Frey, Bern, Nr. 5215, collectionnés en sept.-oct. 1931 dans les environs de Montpellier et sur le Mont Aigoual (G 00295726, as *S. cesatii*); Rochers de Tabason (400 m), Saignon (Vaucluse), sur paroi de molasses burdigalienne, exp. NW, 2.10.1954, leg. et det. G. Clauzade (LISU, as *S. cesatii* f. *grisea*); Vaucluse, Apt, Rocsaliére, Rochers de St. marguerite (400 m d´alt.), parois non ensoleilleé de molase paléomiocéne, 22.5.1952, leg. G. Clauzade (LISU, as *S. cesatii*); St. Guilhem le Désert murs et rochers, le long du chemin à la l. terasse, expos. N, 200 m, leg. E. Frey 14.4.1934, D. ex Herb. D´E. Frey, Berne, Nr. 5216, coll. dans les environs de Montpellier et sur l´Espinouze (Dép. Hérault) (G 00295725, as *S. cesatii* var. *grisea*); ibid., parois calcarire argileuse, expos. N, 250 m, Nr. 5217 (G 00295728, as *S. cesatii*); Vallon de l´Amandier, Allanch (Bouches de Rhone), calc. urgonien exp. nord, sur la roche même ou sur la terre à la surf. de la roche, 27.12.1954 leg. G. Clauzade (LISU, as *Solenopsora* sp.); ibid., sur la terre à la surface du calc. (LISU, as *Solenopsora* sp.).

Greece

Astypaläa: M. Athymadari, auf Kalkfelsen, K. H. Rechinger, Iter Aegaeum IV, 26.5.1935, det. Szatala (W 9503, as *S. liparina*); Creta: Sphakia, Insel Gavdos, K. H. Rechinger, Iter Aegaeum VI, 6.6.1942, det. Szatala 1943 (W 18603, as *S. cesatii*); Pinienwald auf der Paßhöhe zwischen Katharos und Mallaes in O. Kreta. Kalkstein. 22.6.1904, leg. Dr. Sturany, det. A. Zahlbruckner (W 1997-00802, as *Lecanora cesatii*); Ost Kreta, Neapolis, kalkstein, 5.6.1904, leg. Sturany (W 724, as *Placolecania cesatii*); Chania, along the road just E of Asfendos, alt. 790 m, N35°14.33' E24°13.11', 29.5.2009, leg. S. Rui & E. Timdal (O – L156009, as *S. cesatii*); Chania, along road Vrisses – Amoudari, on rock, alt. 450 m, N35°19.81' E24°12.14', 29.5.2009, leg. S. Rui & E. Timdal (O – L156001, as *S. cesatii*); Iraklion, 300-400 m WSW of Odigitrias monastery, on rocks, alt. 260 m, N34°58.36' E24°47.72', 26.5.2009, leg. S. Rui & E. Timdal (O – L155989, as *S. cesatii*); Iráklion, between Avdhou and Tzermiádhes, c. 1.8 km N of Kera, on vertical face and under overhang on boulder in *Olea* grove, rather shady, alt. 520 m, N35°13.9' E25°27.9', 29.5.2009, leg. S. Rui & E. Timdal (O – L, as *S. cesatii*); Iráklion, Mt Ioúhtas (c. 10 km S of Iráklion), vertical face of limestone rock, in hillside, alt. 550 m, N35°13.3' E25°8.7', 5.6.2000, leg. S. Rui & E. Timdal (O – L15193, as *S. cesatii*); Spili, plateu above the village, calcareous crest above the road Spili – Gerakari, alt. 796 m, N35°12'57.4" E24°34'02.4", 4. 4. 2017 leg. J. Kučera & M. Slovák (SAV); Moni, ca 0.5 km from the village, above the road between Moni and Sougia villages, on calcareous rocks, alt. 166 m, N35°16'47.7" E23°48'53.1", 5. 4. 2017 leg. J. Kučera & M. Slovák (SAV); Corfu: Sokrati – Zigos road, rather shady limestone boulders in olive grove, alt. 370 m, N39°43.33' E19°48.02', 16.7.2014, leg. S. Rui & E. Timdal (O – L196254); hill above Troumetas, exposed limestone outcrops, alt. 420 m, N39°42.55 E19°44.96', 16.7.2014, leg. S. Rui & E. Timdal (O – L196247); Insel Kerkyra (Korfu), Akrotirion Kassiopis bei Kassiopi, nordseitige Abbrüche an der Küste, 8.1970, leg. J. Poelt, Vergleichsherbar J. Poelt Nr. 9194 (GZU 3-92, as *S. bagliettoana*); Kaválla, Thassos: along dirt road from Maries to Theologos, near Vatos, E-facing limestone wall in/above steep pine forest, alt. 590 m, N40°42.1' E24°39.7', 31.5.2000, leg. E. Timdal (O – L59264, as *S. cesatii*); between Potos and Psiloammos beach, coastal *Quercus ilex* shrub, on limestone in small canyon, alt. 10-20 m, N40°35.5' E27°37.3', 6.6.2000, leg. S. Rui & E. Timdal (O – L59286, as *S. cesatii*); dirt road off main road from Potos to Theologos, near Stavri, E-facing limestone wall in cayon in open pine forest, alt . 300 m, N40°37.6' E24°42.8', 6.6.2000, leg. S. Rui & E. Timdal (O – L59298, as *S. cesatii*); ibid.,limestone wall facing S an olive grove to the south, alt. 80 m, N40°37.2' E24°39.6', 6.6.2000, leg. S. Rui & E. Timdal (O – L59292, as *S. cesatii*); Konitsa: Ioanina, near the bridge above the river Aoos, on limestone rock, 450 m a.s.l., 14.6.2015, N40°02'11.7" E20°44'42.6", leg. MS & E. Štubňová (SAV); Pelion Mts: Agria, in the vicinity of a water management point construction site, on limestone rock, alt. 98 m a.s.l., 13.6.2015, N39°20.545' E23°01.505', leg. MS & E. Štubňová (SAV).

Israel
Northern Region – Golan: Ein Kinya, limestone outcrops, alt. 680 m, 8.3.2014, N33°13'43.68" E35°43'51.75", leg. AG, MS & JK (SAV); Northern Region – Lower Galilee: Beit She´an, Gan HaShlosha (Sachne) National park, along the road no 669 between the kibbutzim Beit Alfa and Nir David, natural limestone rock, in fissures, alt. -84 m b.s.l., 9.3.2014, N32°30.342' E35°26.820', leg. AG, MS & JK (SAV); Gilboa Mt.: Beit She´an, the massif of the Mt. Gilboa, N slope, pine forest along the road no 667, camping site, on limestone rock, alt. 255 m a.s.l., 9.3.2014, N32°31.566' E35°22.346', leg. AG, MS & JK (SAV); Tiberias, limestone outcrops in the city limits along the road no. 90, in fissures of limestone rock, alt. -173 m b.s.l., 8.3.2014, N32°48.427' E35°31.576', leg. AG, MS & JK (SAV); Yemin Ord, Mt. Carmel, S foothills, limestone rocks in the forest along Finger cave trail, alt. 80 m a.s.l., 7.3.2014, N32°42.794' E34°58.567', leg. AG, MS & JK (SAV).

Romania
A. Vězda: Lich. Sel. Exs. No. 1266. Romania, Dobrogea, Tirguşor, in valle fluminis Casimcea inter pagos Casian et Cheia, alt. 80 m, ad saxa calcarea, 1.5.1974, leg. A. Vězda (BM, G00295716, H, as *S. liparina*); Podişul Dobrogei: Tirguşor, limestone outcrops and xerotherm slopes above the lake on the river Casimcea between the villages Cheila and Casian, on limestone rocks, alt. 96 m, 3.9.2013, N44°29.461' E28°27.395', leg. AG & MS (SAV).

Spain
Mallorca: Sa Molita, near the road at alt. 620 m, N39°50' E2°49', 10.3.1985, leg. E. Timdal (O – L15063, as *S. cesatii*); San Vicente, alt. 20 m, N39°55' E3°3', 14.3.1985, leg. E. Timdal (O – L15064, as *S. cesatii*).

Tunisia
Djebel Zaghouan (NW Flanke): Felspartien abseits der Strße zur Relaisstation bei 700–780 m, 19.4.1982, leg. J. Poelt (GZU 41-82, as *Solenopsora* sp.).

Turkey
Province Aydin: S of Kuşadasi, coastal rocks and sea cliffs, ca 10 m, 28.7. & 30.7.1971, N37°50' E27°16', leg. J. R. Bell, det. M.R.D. Seaward (BM 000500895, as *S. candicans*); Alharan, Alanya: growing on vertical conglomerate rock, very sheltered habitat, 5.5.1971, leg. J. R. Bell (BM 000500909, as *S. liparina*); ibid., sheltered vertical rock face, on rocky crevices, 5.5.1971, leg. J. R. Bell (BM 000500910, as *S. vulturiensis*).

Specimens without detailed label:
Bas in rocher humides de sud Moem In Monsourah, n. 308, Anzi, Herb. Muller Arg. 1896 (G00295712, as *Lecanora liparina*); hb. Hepp 1868 (G 00295721, as *Lecanora Montagnei* β *calcaria*); PRC 1401, as *Lecanora cesatii* v. *grisea*.

SOLENOPSORA HOLOPHAEA (MONT.) SAMP.

Cape Verde
Kapverden, Fogo, N15°00' W24°21', Mt. Velha, oberhalb des MDR-Gebäudes, an Fels und über Feinerde in Spalten, substrat: Fels, Erde, 1500 m NN, expos. NNE, leg. Bruno Mies, 2.11.1988, Coll. B. Mies (G 00295729).

France
J. Harmand: Lichenes gallici rariores exsiccate, No. 118. Supra terram saxorum prope mare. Pornic (Loire-Inférieure). Abbé Bioret. (H, as *Psoroma holophaeum*); H. Des Abbayes: Lichenes Gallici et Nonnulli alii exsiccate, No. 38. Gallia: Piriac (Loire-Inférieure), ad terram et arenas inter saxa maritima, leg. ipse, Augusto 1936 (G 00295733, O – L58291, as *Candelariella holophaea*); Corsica: Ajaccio, terricola, 12.1877, leg. J.P. Norrlin, det. W. Nylander (H, as *Lecanora holophaea*); Bretanha-Erquy: sôbre a terra nas fendas da rocha, 17.7.1954, leg. et det. C. Tavares (LISU); Cap de Erguy, 17.7.1954, leg. Eilif Dahl (O – L58290, as *Psoroma holophaeum*).

Greece
Piraeus – Methana peninsula, above Agios Nikolaos, site:71-06-B, on rock volcanic, alt. 200 m, 10.12.2005/L96H, UTM: 707076E 4167480N; 37°37´52´´N 23°20´48´´E (Abbott´s lichens from Peloponnese; herb. Linda in Arcadia).

Morocco
Oued Yquem, próximo de Rabat, sôbre as rochas schistosas, 23.1.1936, leg. R. Werner, det. C. Tavares (LISU).

Portugal
C. N. Tavares: Lich. Lusitaniae selecti exsiccate, No. 115. Alto Alentejo: prope Évora, ad cementum in fissuris muri septentrionem spectantis, circ. 300 m s. m., 19. 5. 1957, leg. C. N. Tavares (LISU 199220, O – L58293, PRA-V-01990); Alentejo: Vila Nova de Milfontes, margem Sul do rio Mira, sôbre a terra dos rochedos, 24.5.1951, leg. et det. C. Tavares (LISU 199169); Alto Alentejo, próx. De Évora, sôbre a argamassa de um muro, 19.5.1957, leg. et det. C. Tavares (LISU 199174); Algarve: Bordeira, pr. Al jezur, sôbre a terra dos taludes, 31.3.1951, leg. et det. C. Tavares (LISU 199173); Azores, Faial: Praia do Norte Porto da Fajã, found growing on stone walls, rock outcrops and boulders, alt. 45m, 13.3.1976, coll. P.W. James (BM); Baixo Alentejo: Próx. de Évora, sôbre a terra de um muro, 1.12.1955, leg. et det. C.

Tavares (LISU 199170); Mina da Somincor, campo de futebol, sobre *Q. ilex*, 25.5.2000, UTM x-590.77, y-4159.95, leg. P. Carvalho, M. Jones & C. Branquinho, det. P. Carvalho (LISU 252183); Próx. de Mourão, margem direita do Guadiana, sôbre a terra nas fendas da rocha, 1.12.1955, leg. et det. C. Tavares (LISU 199168); Estremadura: Berlenga, próx. Do Carreiro do Mosteiro, sôbre os detritus, no granite, 14.6.1951, leg. et det. C. Tavares (LISU 199171); ibid., sôbre o granito, 17.7.1951, leg. et det. C. Tavares (LISU 199172); Serra de Sintra, Azoia, sôbre a terra musgosa dum muro, 4.5.1951, leg. et det. C. Tavares (LISU 199221).

Spain

Vězda: Lich. Rar. Exs., No. 70. Insulae Canarienses. Gran Canaria: distr. Mogán, in declivibus occidentalibus montis Guirre supra urbem Mogán, alt. 500-600 m, ad terram in fissuris rupium basalticarum. 15.2.1993, leg. A. Vězda (BM, H, TSB 18192); H. T. Lumbsch et G. B. Feige: lecanoroid lichens. Distributed by the University of Essen, No. 98. Spain, Canary Island, La Palma, SE part of the island, La Caldereta, 6.7 km on road between Las Indias and Fuencaliente, old lava flow near Las Indias, 160 m, 13.3.1995, leg. G. B. Feige, N28°30' W17°51' (BM, H); Almeña: Nijar, Sierra del Cabo de Gata, Barranco del Sabinar, roca nitrofila, 150 m, 18.4.1987, Herbarium Patricia Geissler, det. Ph. Clerc (G 00295732); Insulae Canarienses, Gran Canaria: Distr. San Bartolome, Ayacata, in valle „Barranco de Ayacata“, 900 m, in fissuris, ad terram et ad rupes basalticas. 10.2.1993, leg. A. Vězda (PRA-V-01989); Canary Islands, Tenerife: 2.3 km up road TF375 from Santiago del Teide to Guía de Isora (1.0 km from turnoff to Las Manchas), lava field, vertical rock wall, alt. 1100 m, N28°16.8' E16° 47.8', 15.1.2001, leg. S. Rui & E. Timdal (O – L73355); lower xerophilous zone, narrow ridge between two small cultivated valleys, between Icor and Arico Viejo, alt. 350 m, 30.1.1964, leg. H. A. Imsaug & F. H. Imshaug No. 34998 (H); road Arano-Inzana, 1400 m, on soil in SW exposed slope within a *Pinus canariensis* open wood, 1.1986, leg. Nimis (TSB 6888); top of the road between Santiago del Teide and Masca (Masca side), rock outcrops in steep hillside, alt. 1100 m, 11.1.2001, N28°18' E16°49.4', leg. S. Rui & E. Timdal (O – L73324); Barranco de Masca, just near the village of Masca, 600–700 m, vertical cliffs, open *Euphorbia* scrub with *Opuntia*, 7.1.1995, leg. P.L. Nimis (TSB 20293); Macizo de Anaga, along San Andres – Taganana road, upper part, steep rock wall by the road, Erica arborea zone, alt. 500 m, N28°32.7' E16°12.0', 14.1.2001, leg. S. Rui & E. Timdal (O – L73350); Mirador de La Sentinela, open soil in abandoned *Opuntia* plantation, 21.12.1984, leg. Nimis (TSB 4766, as *Lecania holophaea*); Puerto de S. Marco under Icod de los Vinos, ca 80 m, on soil in Juniperus-Cistus Monspeliensis stand, 1.1986, leg. Nimis (TSB 6940); Canary Islands, La Palma: Los Llanos de Aridane, 1.2 km SE of Todoque, lava outcrop by the road, agricultural land near village, alt. 380 m, N28°36.5' E17°53.8', 8.1.2002, leg. S. Rui & E. Timdal (O – L101891); Canary Islands, Gomera: Ancon de las Palomas, about 2 km from Equito, alt. 1050 m, 21.3.1972, leg. H. Østhagen (O – L148533, as *S.* cf. *holophaea*); Iles Canaries, El Hierro: Frontera, El Golfo, Chemin reliant le Paso de Jinama â Frontera, 1.10.1986, 1100–1200 m, standort: paroi verticale au bord du chemin, en exp. SW, sur *Erica arborea* en bordure de chemin dans la pente, leg. et det. Ph. Clerc, Flore des Iles Canaries, Inventar – Nr. 11778–11780 (G 00111051).

Specimens without detailed lables:
Lich. Mader., ex herb W. Nylander, 1874 (BM, as *Lecanora holophaea*); No. 324, Fram. Pag. 20, n. 40 (G00295731, as *S. requienii*).

SOLENOPSORA LIPARINA (NYL.) ZAHLBR.

France

Haute Vienne: 1882, E. Lamy (G00295713, as *Lecanora liparina*); Rocher de serpentine de la Haute Vienne, 1882, E. Lamy (G00295714, as *Lecanora liparina*).

Great Britain

West Cornwall, Lizard: valley above Kynance Cove, from settlement to the sea (10/688134), on sunny serpentine rocks near stream above Cove, 19.4.1986, leg. P.W. James (BM); ibid., from settlement to the sea (10/686135), on sunny, vertical rocks – serpentine (BM); Kynance, Gew-graze Valley from coast to Kynance Farm and above (10/676144), near Soap Rock, on serpentine outcrop near sea at Gew-graze, 21.4.1986, leg. P.W. James (BM).

Greece

Crete: Kissou Kampos, E-exposed slope above a curve of the road between Kissou Kampos and Aktounta, on serpentine rocks, alt. 546 m a.s.l., N35°11'13.8" E24°32'51.4", 4. 4. 2017, leg. J. Kučera & M. Slovák (SAV).

Serbia

Foothills of Kopaonik Mts: Vlajkovci (municipality of Brus), the valley of the river between the villages Vlajkovci and Kočije, serpentine outcrops along the road 212, shaded and shaltered fissures and rock faces, 670 m a.s.l., 15.6.2016, N43°20.303' E20°56.548', leg. AG, MS, JK & E. Štubňová (SAV).

Turkey

Hatay region: Gaziantep, Nurdagı, Terken Köyü civarı, on vertical side of volcanic outcrop in steppe valley, alt. 950 m, 2. 9. 2014, N37°06'13" E37°02'05", leg. M. Candan & J. Vondrák (herb. J. Vondrák, Nr12581).

SOLENOPSORA MARINA (ZAHLBR.) ZAHLBR.

Croatia

Veglia: au kalkfelsen den Meerestrande bei der Haupt Veglia, leg. Baumgartner (PRM 639459).

Greece

Konitsa: Ioanina, near the bridge above the river Aoos, on limestone rock, 450 m a.s.l., 14.6.2015, N40°02'11.7" E20°44'42.6", leg. MS & E. Štubňová (SAV); Rhodos: Rücken eines Hügels etwa 2 km N Phaliraki, S der Stadt Rhodos; Konglomeratfelsen in Phrygana-Vegetation, um 50 m, 5.9.1983, leg. J. Poelt (GZU 106-83, as *Solenopsora* sp.); Voiotia: Felsblöcke an der Strße von Livadia nach Arahova S der Ortschaft Tsoukalades, ca. 420 m, 16.9.1989, leg. H. Mayrhofer, Nr. 9892 (GZU 48-90, as *Solenopsora* sp.).

Jordan

Ajloun: Alkalia-Al-Icherbeh road, on rocks, facing east, shady place under forest, protected from the light, 31.10.1985, leg. A. El-Oglah (BM, as *Solenopsora* sp. – note: cf. *marina*!).

Montenegro

A. Vězda: Lich. Sel. Exs., No. 710. Jugoslavia – Montenegro, Petrovac distr., supra vicum Buljarica, alt. 30 m, ad cementum in fissuris muri, loco opaco sub Oleis, 12.7.1968, leg. A. Vězda (BM, G 00295705, H, LISU, PRA-V-06310); Kotor: ca 10 m S of the S gate of the old town of Kotor, vertical rock wall, facing S, alt. 134 m, 22.7.2010, N42°25.37' E18°46.28', leg. S. Rui & E. Timdal (O – L163458).

Portugal

Algarve: serra da Gralheira, próx. De Albufeira, sôbre o calcáreo, duma gruta, 29.3.1951, leg. C. Tavares (LISU 3988, as *Dermatocarpon* sp.).

Specimens without detailed lables:
Da A. Fiori VI. 1927, leg. L. Senni (FI, as *Placolecania spadicea*).

SOLENOPSORA OLIVACEA (DUFOUR EX FR.) KILIAS SUBSP. *OLBIENSIS* (NYL.) CLAUZADE ET CL. ROUX

France

Région Provence – Alpes – Cote d´Azur: Vaucluse, Gorges du Lioux, alt. 300–600 m, N43°56'51" E5°18'10', 29.5.2003, leg. et det. Ph. Clerc (G00295711).

SOLENOPSORA OLIVACEA (DUFOUR EX FR.) KILIAS SUBSP. *OLIVACEA*

Croatia

Anzi: Lichenes rariores Veneti, No. 65. Ad muros calcareos eorumque cementum in Dalmatia (porto di Gravosa vicino a Ragusa) leg. Micheletti, ex Herb. Massal. (G00295708, O – L58301, as *Biatorina Michelettiana*); Schuler Kryptogamae exsiccatae, No. 864. Hungaria: ad saxa calcarea prope Fiume, usque 200 m, adscendens, leg. J. Schuler (FI, H, as *Catillaria olivacea*); Dalmatia: alt. 40 m, 13.1.1907, leg. A. Latzel (H, as *Catillaria olivacea*); Insel Rab (Arbe), flysch, c. 50 m, 8.4.1926, leg. J. Baumgartner (O – L115236, as *Catillaria olivacea*); Jugoslawien, Leicht beschattete Kalkblöcke am St. Antonius-Hügel südlich Korcula auf der Insel Korcula, August 1969, leg. J. Poelt, Vergleichsherbar J. Poelt Nr. 7371 (GZU 62-88); Ražanj, macchia (*Quercus* sp., *Olea* sp., *Pistacia* sp.) along the road between Ražanj and Kanica, calcareous outcrops, on rock faces, 35 m a.s.l., leg. MS 30.8.2016, N43°30'24.08" E15°59'24.54" (SAV); Gebiet von Zara [Zadar]: Südostufer des Lago di Vrana, an kalkfelsen i. d. Sonlucht am Wege nach Banjevac, c. 100 m, 29.3.1913, leg. J. Baumgartner (W 1916–4469, as *Catillaria olivacea* var. *soredifera*); Zara, c. 50 m, 8.4.1913, leg. J. Baumgartner, det. A. Zahlbruckner (O – L115249, as *Catillaria olivacea*); Uljan, c. 50–75 m, 19.3.2013, leg. J. Baumgartner, det. A. Zahlbruckner (O – L115245, as *Catillaria olivacea*); Insel Pašman, Kloster S. Francesco, c. 10 m, 24.3.1913, leg. J. Baumgartner (O – L115250, as *Catillaria olivacea*); Insel Selve (=Silba), *Quercus* – Ilex Walde, Kalkgestein, c. 40 m, 1.4.1913, leg. J. Baumgartner, det. A. Zahlbruckner (O – L115235, as *Catillaria olivacea*); Island Krk: road between the town of Krk and Baška, the point Prijevoj Treskavec, limestone cliffs near the monument to Glagolitic alphabet, on perpendicular faces and in fissures, 264 m a.s.l., 10.8.2016, N45°01.672' E14°40.689', leg. AG & H. Béreš (SAV); Vrbnik, limestone rock in the pine wood along the parking place in the village, 19 m a.s.l., 10.8.2016, N45°04'31.22" E14°40'50.38", leg. AG & H. Béreš (SAV); Hvar: Sveta Nedjelja, foothil of the Sv. Nikola massive,between the village and the bay Dubovica, limestone outcrops in dry *Pinus* wood, on shaded rock faces and fissures, alt. 118 m a.s.l., N43°08'29.2" E16°34'33.0", 5. 7. 2017 leg. A. Bérešová (SAV); Istria: Canale di Leme bei Rovigno, Kalkfelsen, c. 80 m, 26.3.1924, leg. J. Baumgartner (O – L58297, as *Lecania olivacea*); Castelnuovo, c. 120 m, 13.4.1925, leg. J. Baumgartner (O – L115239, as *Catillaria olivacea*); Insel Lussino (=Lošinj), Weg mauern am Fusse des Mte. Assero gegen die Stadt Assero, ca 25 m, 10.4.1914, leg. J. Baumgartner (O – L115251, as *Catillaria olivacea*); ibid., ca 100 m (W 1916–3423, as *Catillaria olivacea*); V. Vignole, zwischen Altura n. Krnice (=Carnizza), kalk, 9.4.1925, leg. J. Baumgartner (O – L115255, as *Catillaria olivacea*); Ragusa [Dubrovnik]: Lapad, saxa calc., 60 m, 11.2.1908, leg. A. Latzel, Flora dalmatica, (FI, as *Catillaria olivacea*).

France
A. Vězda: Lich. Sel. Exs., No 334. Gallia – Provence, Bouches-du-Rhône: Marseille, in collibus Marseilleveyre, prope Fontaine d'Ivoire, alt. 150 m, ad saxa calcarea septentrionem spectantia, leg. G. Clauzade & Y. Rondon (H, as *Catillaria olivacea*); Gallia: Nizza, Metzler 1866 (H, as *Biatorina michelettiana*); Nizza, an Kalkfelsen, 1866, leg. A. Metzler (G 00295706, O – L115258, as *Biatorina michelettiana*); Brando: Marine – de Sisco, in litore maris , ad lapides magnos calcareos, 26.6.1969, leg. G. Clauzade, J. Lambinon, Y. Rondon & A. Vězda, Lichenes Corsicani (G00295710, as *Placodiella olivacea*).

Greece
K. H. Rechinger fil., Iter Graecum II., 1932, Ikaria: Hag. Kirykos, 50 m, auf Kalkfelsen, 24.6.1932, det. Szatala (W 1960–9083, as *Solenopsora cesatii* f. *olivacea*); K. H. Rechinger fil., Iter Aegaeum VI., 1942, Creta, Selinos, zwischen Paleochora und Vutas, 2.6.1942, det. Dr. Oe. Szatala (W 1959–18099); K. H. Rechinger fil., Iter Aegaeum VI., 1942, Creta, Herakleion: Insel Dia, 23.6.1942, det. Dr. Oe. Szatala (W 1960–8664); K. H. Rechinger, Reise nach Korfu 1912, mit *Verrucaria murina*, leg. Rechinger (W 1915–11649, as *Catillaria olivacea*); Crete: Iráklion, between Kastélion and Khersónisos, bottom of gorge of river Apossolemis, on boulder by a dray brook, shady, alt. 250 m, 5.9.1995, N35°14.2' E25°21.6', leg. S. Rui & E. Timdal (O – L15174); Sternes, in SE direction from the village, in the valley, on calcareous rocks, alt. 330 m, 6. 4. 2017, N35°00'20.6" E25°05'27.1", leg. J. Kučera & M. Slovák (SAV); Moni, ca 0.5 km from the village, above the road between Moni and Sougia villages, on calcareous rocks, alt. 166 m, N35°16'47.7" E23°48'53.1", 5. 4. 2017 leg. J. Kučera & M. Slovák (SAV); Argolid – small valley just north of road between Drepano and Kantia, site: 61-75-A, on rock limestone, alt. 80 m, 26.2.2003/L25H, UTM: 671746E 4156255N; 37°32´14´´N 22°56´38´´E (Abbott´s lichens from Peloponnese; herb. Linda in Arcadia); Lakonia – summit of limestone hill just east of road going east from Neapoli, site: 60-84-A, on rock limestone, alt. 503 m, 18.9.2000/L30H, UTM: 689502E 4045824N; 36°32´27´´N 23°06´34´´E (Abbott´s lichens from Peloponnese; herb. Linda in Arcadia; Insel Samos: Umgebung von Pythagorion Schlucht NW Pythagorion, August 1984, leg. J. Poelt, Flora von Giechenland (GZU 99-84).

Montenegro
A. Vězda: Lich. Sel. Exs., No. 707. Montenegro: Petrovac distr., supra vicum Buljarica, alt. 30 m, ad macerias calcareas sub *Oleis*, 12.7.1968, leg. A. Vězda (H, as *Placodiella olivacea*); Budva: along road E65 between Petrovac and Bukovic, at the crest, limestone rock outcrop, alt. 747 m, 21.7.2010, N42°13.02' E18°58.39', leg. S. Rui & E. Timdal (O – L163447).

Portugal
C. N. Tavares: Lichenes Lusitaniae selecti exs., No. 64. Portugal, Estremadura – Portela de Sintra, ad rupes calcarias umbrosas, septentrionen spectantes, circ. 130 m, 26.12.1953, leg. C. N. Tavares (H, LISU 199237, as *Catillaria olivacea*); Algarve: Serra da Gralheira, próx. de Albufeira, sôbre o calcáreo, 29.3.1951, leg. C. Tavares (LISU 191303); Estremadura: entre s Malveira da Serra e Aldeia de Juso, sôbre o calcáreo, 23.2.1951, leg. et det. C. Tavares (LISU 191300, as *Catillaria olivacea*); entre Barcarena e Caxias, sôbre o calcáreo, 14.3.1950, leg. C. Tavares (LISU 191296); entre T a jouce e Manique, sôbre o calcáreo, 8.3.1950, leg. et det. C. Tavares (LISU 191291, as *Catillaria olivacea*); entre a Malveira da Serra e Aldeia do Juso, sôbre o calcáreo, 23.2.1951, leg. C. Tavares (LISU 191292, as *Catillaria olivacea*); Cascais – Guia, sôbre o calcáreo, 29.4.1950, leg. et det. C. Tavares (LISU 191298, as *Catillaria olivacea*); entre Cascais e a Guia à beira da Estrada nova, sôbre o calcáreo, 1.3.1954, leg. et det. C. Tavares (LISU 191287, as *Catillaria olivacea*); prox. da Ericeira, junto à Foz da Ribeira do Porto, sôbre o calcáreo, 22.7.1955, leg. C. Tavares, det. C. Roux (LISU 191299, as *Catillaria olivacea*); Óbidos, nas muralhas do Castelo, sôbre o calcáreo, 29.12.1953, leg. C. Tavares (LISU 191295); Pedra Furada, sôbre o calcáreo, 16.7.1949, leg. et det. C. Tavares (LISU 191288, as *Catillaria olivacea*); próximo de Ponte de Louse (Arredores de Lisboa), sôbre o calcáreo, 4.2.1950, leg. et det. C. Tavares (LISU 191290, as *Catillaria olivacea*); Serra da Arrábida, próximo do Convento, sôbre o calcáreo, 18.3.1949, leg. C. Tavares (LISU 191286, as *Catillaria olivacea*); Sintra, the village Fontanelas, 1.5 km north from the village, calcareous outcrops on the plateau with macchia vegetation, on the vertical, shaded rock face with western exposition, alt. 100 m, 27.4.2016, N38.86100° W9.44253°, leg. AG, ZF & SM (SAV); Portela de Sintra, sôbre o calcáreo, 12.2.1950, leg. et det. C. Tavares (LISU 191285, as *Catillaria olivacea*); S. Martinho do Porto, sôbre a praia do Norte, sôbre o calcáreo, 23.3.1951, leg. C. Tavares (LISU 191301, as *Catillaria olivacea*); Tapada de Mafra, sôbre o reboco de um muro, 28.1.1950, leg. et det. C. Tavares (LISU 191289, as *Catillaria olivacea*); Portinho da Arrábida: sôbre o calcáreo, 6.4.1951, leg. et det. C. Tavares (LISU 191302, as *Catillaria olivacea*); Ribatejo: Nascente à beira da estrada antes de Rio Maior, sôbre o calcáreo, 17.12.1953, leg. et det. C. Tavares (LISU 191297, as *Catillaria olivacea*).

Spain
Mallorca: c. 2.5 km WNW of Caserio Massanella, alt. 250 m, 9.3.1985, N39°46' E2°51', leg. E. Timdal (O – L58295).

Specimens without detailed lables:
Givaod, 1836, herb. Reuter-Barbey (G 00295707, as *Biatora olivacea*).

***SOLENOPSORA VULTURIENSIS* A. MASSAL.**
Bulgaria

Pontus: Distr. Burgas, inter pagos Varvara et Mičurín, ad scopulus maritimum, 1–10 m, 22.8.1977, leg. A. Vězda (PRA-V-01995, PRA-V-01996).

France
A. Vězda: Lich. Sel. Exs., No. 839. Gallia, Corsica, Distr. Ste Marie-Sicche: scopulus La Castagna dictus prope Coti Chiavari, alt. 100 m, ad terram et supra rupem ipsam graniticam in fossis viae publicae. 5.7.1969, leg. Y. Rondon & A. Vězda (BM, H, LISU, PRA-V-06439);
Bretanha: Erquy, na terra entre as rochas, 17.7.1954, leg. C. Tavares (LISU, as *S. subdisparata*).

Great Britain
Channel Islands, Larbastier, Guernsey (G 00295734, as *Lecanora holophaea* var. *glaucospora*).

Greece
Insel Patmos: Felsige Hänge nördlich unterhalb des Klosters des Hl. Johannes, eruptivgestein, 8.8.1984, leg. J. Poelt, Flora von Griechenland (GZU 99-84, as *Solenopsora* sp.).

Iceland
Snæfellsnessýsla: Lóndrangar, maritime rocks, alt. 5–10 m, 21.7.2005, N64°143.9' E23°47.2', leg. S. Rui & E. Timdal (O – L).

Ireland
Howth: Co. Dublin (Maritime and Marine Lichens), leg. et det. M. C. Knowles, 1910–1913 (LISU, as *Lecania leucospeirea*).

Portugal
Alentejo: Vila Nova de Milfontes, na margem sul., sóbre rocha arenácea, 24.5.1951, leg. C. Tavares (LISU, as *Solenopsora* sp.); Algarve: Bordeira, pr. Al jezur, sôbre a terra dos taludes, 31.3.1951, leg. C. Tavares (LISU 3868, as *Solenopsora* sp.); Douro Litoral: Vila do Conde, sobre o granite, 21.4.1951, leg. C. Tavares (LISU 4162); Estremadura: Barril de Baixo, mouth of Lisandro river [Foz do Lizandro], sandstone rocks bordering the beach and coastal macchia, alt. 26 m, 27.4.2016, N38°56.182' W9°25.147', leg. AG, ZF & SM (SAV); Berlenga, próx. do Carreiro do Mosteiro, sôbre a terra no granito, 14.6.1951, leg. C. Tavares (LISU 4068, as *Solenopsora* sp.); ibid., sôbre o granito, 17.7.1951, leg. et det. C. Tavares (LISU 199172, in envelope with *S. holophaea*); ibid., à beira do caminho para o Carreiro do Mosteiro, sôbre o granite, 14.6.1951 leg. C. Tavares (LISU, 4118 as *Solenopsora* sp.); Ericeira, Praia de Ribeira d'Ilhas, siliceous sandstone rock on the top of cliff, E-exposed rock face, in fissures, alt. 15 m, 27.4.2016, N38°59.333' W9°25.197', leg. AG, ZF & SM (SAV); Serra de Sintra, próx. de Almocageme, sôbre o granite, 5.5.1952, leg. C. Tavares (LISU, 4806 as *Solenopsora* sp.); Serra de Sintra, Azóia, nas pedras dos muros divisórios, 7.1.1961, leg. C. Tavares (LISU, 6692 as Solenopsora sp.); ibid., sôbre a terra de muros, 4.5.1951, leg. C. Tavares (LISU 4213, as *Solenopsora* sp.); Vendas, próx. de Palmela, sôbre a argamassa dum muro, 31.1.1950, leg. C. Tavares (LISU, 3753 as *Solenopsora* sp.); Ponte do Lima, Sá (paredes), 11.9.1920, leg. G. Sampaio (LISU, PRM 639461); Tras os montes: Prox. De Moncorvo, na margem do Rio Sabor, sôbre a rocha, 15.6.1958, leg. C. Tavares (LISU 6363, as *Solenopsora* sp.; G 00295736); Vila do Conde (num muro), 9.2.1920 (W 2271, as *S. subdisparata*).

Spain
Canary Islands: Tenerife, Parque natural Teno, Masca, valley of Barranco de Masca, on volcanic outcrop in maritime scrub vegetation, alt. 100–600 m, 10.3.2013, N28°17'51" W16°50'40", leg. J. Vondrák (herb. J. Vondrák Nr. 12182, as *Solenopsora* sp.); Cantabria: Cordillera Cantabrica Mts, Las Carreras – Muskiz, forest park La Arboleda, siliceous schists along road bank, 505 m a.s.l., 24.5.2015, N43°16.982' W3°4.669', leg. AG, JK & MS (SAV); Pirineos Occidentales Mts, Puerto de Otsondo, dirty road towards the village Goramendi, siliceous schists along road bank, 641 m a.s.l., 29.5.2015, N43°14.366' W1°28.409', leg. AG, JK & MS (SAV); Gerona: along road Roses – Cadaques, on rock wall in the roadside, alt. 280 m, 24.7.2013, N42°17.20' E3°13.38', leg. S. Rui & E. Timdal (O – L184444).

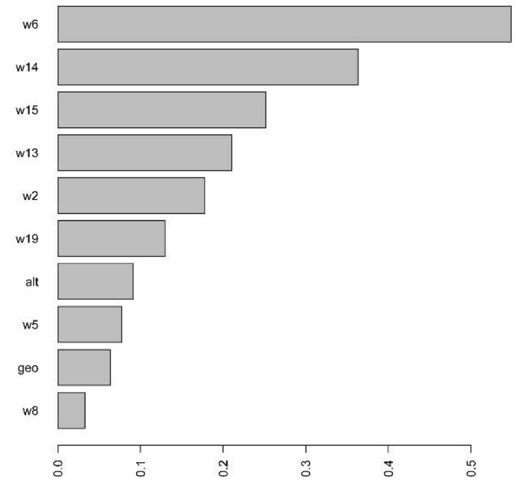
Supplementary Information 3. List of WorldClim 1.4 environmental variables derived from monthly mean, maximum, and minimum temperature and precipitation interpolations averaged for 1950 to 2000 at a spatial resolution of $1km^2$ and their codes used in this study.

bio1 = annual mean temperature (°C)
bio 2 = mean diurnal range (Mean of monthly (max temp - min temp)) (°C)
bio 3 = isothermality (BIO2/BIO7) (* 100)
bio 4 = temperature seasonality (standard deviation *100)
bio 5 = maximum temperature of the warmest month (°C)
bio 6 = minimum temperature of the coldest month (°C)
bio 7 = temperature annual range (BIO5-BIO6) (°C)
bio 8 = mean temperature of the wettest quarter (°C)
bio 9 = mean temperature of the driest quarter (°C)
bio 10 = mean temperature of the warmest quarter
bio 11 = mean temperature of the coldest quarter
bio 12 = annual precipitation (mm)
bio 13 = precipitation of the wettest month (mm)
bio 14 = precipitation of the driest month (mm)
bio 15 = precipitation seasonality (coefficient of variation)
bio 16 = precipitation of wettest quarter (mm)
bio 17 = precipitation of driest quarter (mm)
bio 18 = precipitation of warmest quarter (mm)
bio 19 = precipitation of coldest quarter (mm)

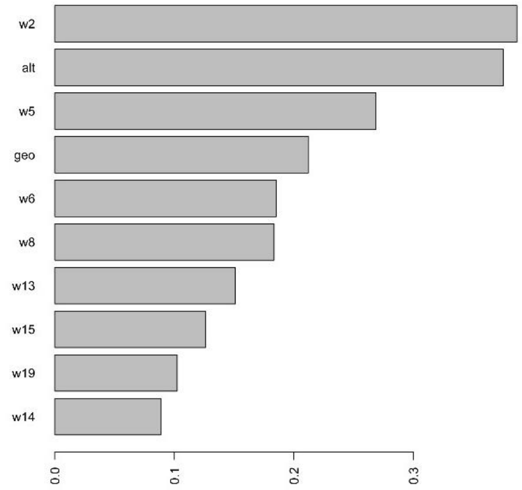
Supplementary Information 4. Correlation coefficients (Spearman) between bioclimatic variables. Strong correlations highlighted in bold.

	bio01	**bio02**	**bio03**	**bio04**	**bio05**	**bio06**	**bio07**	**bio08**	**bio09**	**bio10**	**bio11**	**bio12**	**bio13**	**bio14**	**bio15**	**bio16**	**bio17**	**bio18**	**bio19**
bio01	1																		
bio02	0.28	1																	
bio03	0.56	**0.72**	1																
bio04	-0.23	0.55	-0.09	1															
bio05	**0.93**	0.54	0.64	0.03	1														
bio06	**0.95**	0.04	0.45	-0.43	**0.79**	1													
bio07	0.03	**0.86**	0.32	**0.87**	0.33	-0.22	1												
bio08	0.2	0.35	0.15	0.42	0.26	0.07	0.4	1											
bio09	**0.88**	0.14	0.52	-0.4	**0.78**	**0.9**	-0.13	-0.12	1										
bio10	**0.98**	0.36	0.55	-0.09	**0.97**	**0.88**	0.16	0.26	**0.83**	1									
bio11	**0.98**	0.16	0.54	-0.37	**0.85**	**0.99**	-0.12	0.11	**0.91**	**0.92**	1								
bio12	-0.69	-0.3	-0.4	0.03	-0.67	-0.63	-0.18	-0.37	-0.57	-0.7	-0.65	1							
bio13	-0.52	-0.33	-0.28	-0.19	-0.56	-0.42	-0.33	-0.41	-0.38	-0.55	-0.46	**0.91**	1						
bio14	-**0.79**	-0.22	-0.5	0.31	-0.69	-**0.77**	0.02	-0.23	-0.7	-**0.74**	-**0.79**	**0.85**	0.61	1					
bio15	0.6	0.07	0.43	-0.45	0.47	0.64	-0.2	0.09	0.57	0.53	0.65	-0.53	-0.19	-**0.85**	1				
bio16	-0.54	-0.35	-0.29	-0.19	-0.59	-0.44	-0.34	-0.42	-0.4	-0.58	-0.48	**0.92**	**0.99**	0.62	-0.19	1			
bio17	-**0.76**	-0.24	-0.49	0.25	-0.68	-**0.73**	-0.02	-0.3	-0.65	-**0.73**	-**0.75**	**0.88**	0.65	**0.99**	-**0.83**	0.66	1		
bio18	-**0.87**	-0.15	-0.47	0.35	-**0.77**	**-0.9**	0.08	0.01	-**0.89**	-**0.83**	**-0.9**	**0.8**	0.6	**0.88**	-0.67	0.62	**0.85**	1	
bio19	-0.15	-0.35	-0.09	-0.44	-0.26	-0.01	-0.48	-0.64	0.08	-0.22	-0.05	0.65	**0.75**	0.37	-0.12	**0.75**	0.44	0.15	1

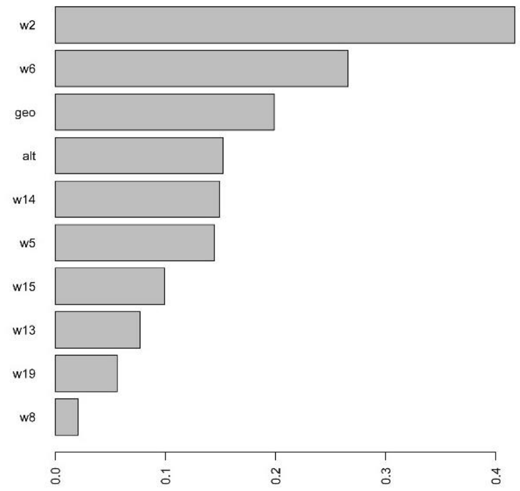
Supplementary Information 5. The reduced set of environmental variables used for modelling plotted according to their contribution to best explain the habitat suitability maps. For list of WorldClim 1.4 environmental variables see Supplementary Information 3; instead of prefix “bio” the letter “w” was used in the following graphs.



S. candicans

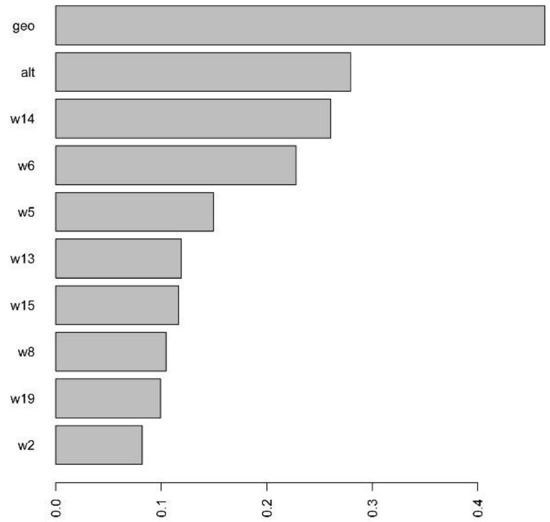


S. cesatii

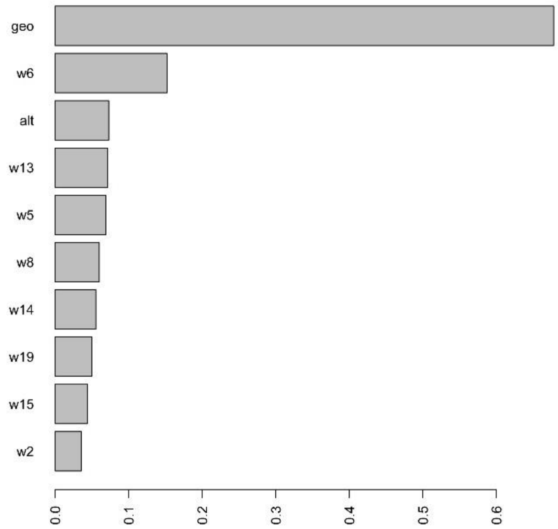


S. grisea

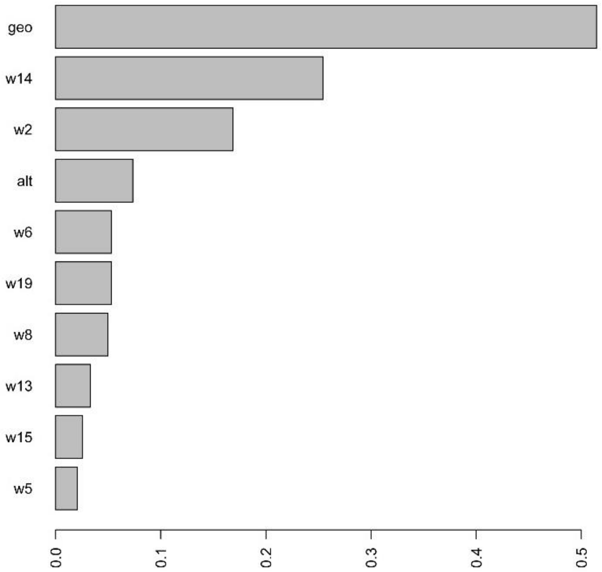
S. holophaea



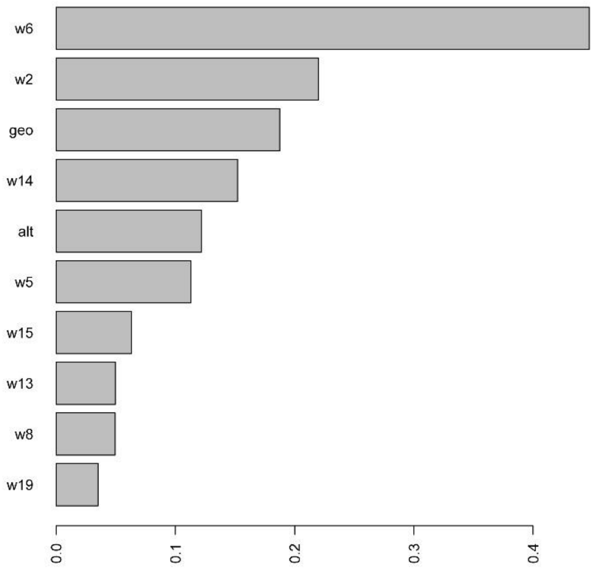
S. liparina



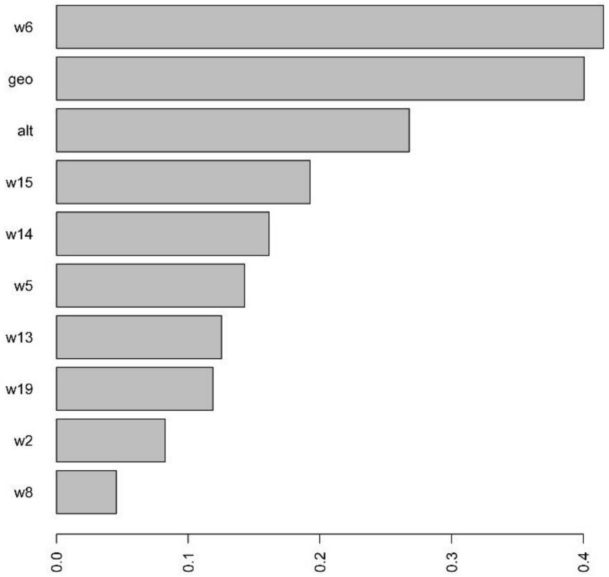
S. olivacea* subsp. *olbiensis



S. olivacea subsp. olivacea



S. vulturiensis



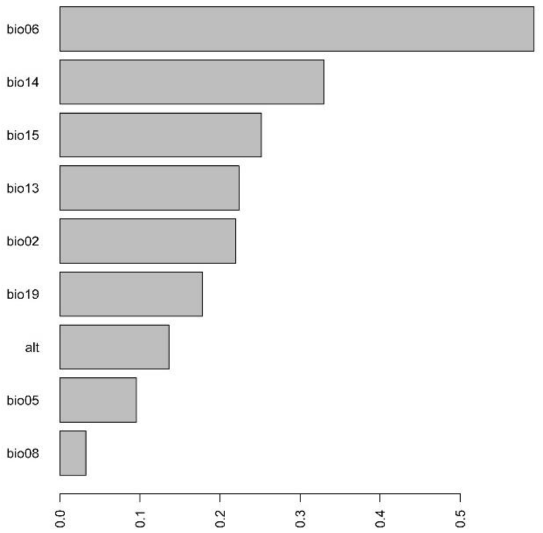
Supplementary Information 6. List of main lithological units according to the Geological Map of Italy, scale 1: 1,000,000 provided by Servizio Geologico d'Italia (OneGeology Portal, ISPRA) used for geological filtering.

ID	Main Lithological Unit	Correspondig Solenopsora taxa
1-2	Basalt	*S. candicans*
3	Andesite	-
4	sandstone	*S. vulturiensis*
5	mudstone	-
6	limestone	-
7	siltstone	-
8-9	Andesite	-
10-16	sandstone	*S. holophaea, S. vulturiensis*
17-18	Basalt	-
19-20	impure_limestone	-

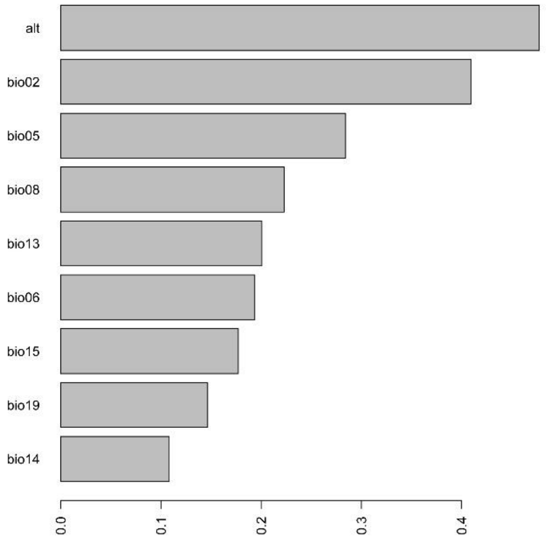
21	impure_carbonate_sediment	-
22	clastic_sedimentary_rock	-
23-26	conglomerate	*S. candicans*
27	Clastic Sediment	-
28-29	carbonate_sedimentary_rock	-
30	diorite	-
31-32	dolomite	*S. candicans*
33	diamicton	-
34	gneiss	-
35-36	granite	-
37	granulite	-
38	eclogite	-
39	granulite	-
40	quartzite	-
41-62	limestone	*S. candicans, S. cesatii, S. grisea, S. olivacea* subsp. *olivacea, S. olivacea* subsp. *olbiensis, S. marina*
63-66	impure_limestone	-
67	mudstone	-
68	impure_limestone	-
69-71	mica_schist	*S. holophaea, S. vulturiensis*
72	monzonite	-
73	limestone	*S. candicans*
74-75	peridotite	*S. liparina*
76	limestone	*S. candicans*
77-79	mudstone	-
80	phyllite	*S. vulturiensis*
81-88	rhyolite	-
89-90	sandstone	*S. vulturiensis*
91-93	shale	-
94	Basalt	-
95	slate	*S. vulturiensis*
96	clastic_sedimentary_rock	*S. holophaea*
97	tephrite	-
98	Clastic Sediment	-
99	tonalite	-
100-101	Andesite	-

Supplementary Information 7. The reduced set of environmental variables used for alternative modelling with geology filtering plotted according to their contribution to best explain the habitat suitability maps. For list of WorldClim 1.4 environmental variables see Supplementary Information 3.

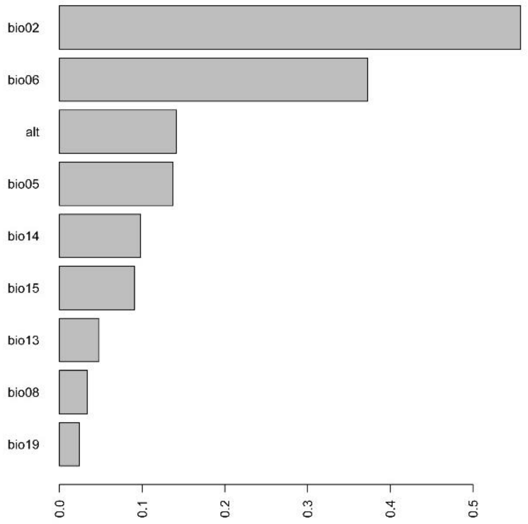
S. candicans



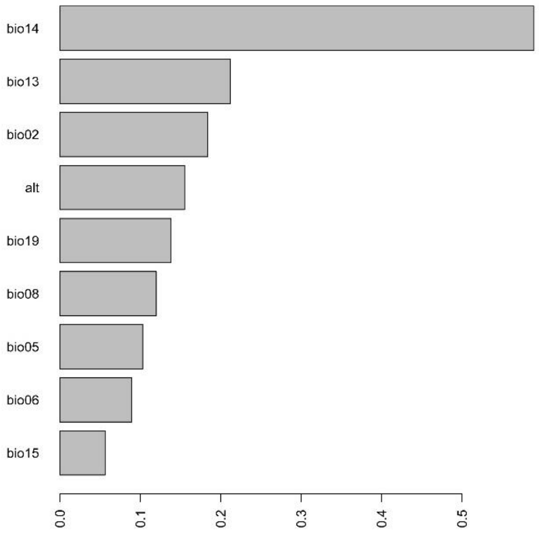
S. cesatii



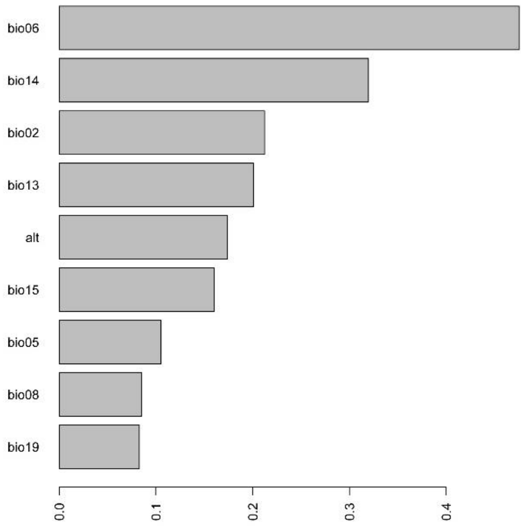
S. grisea



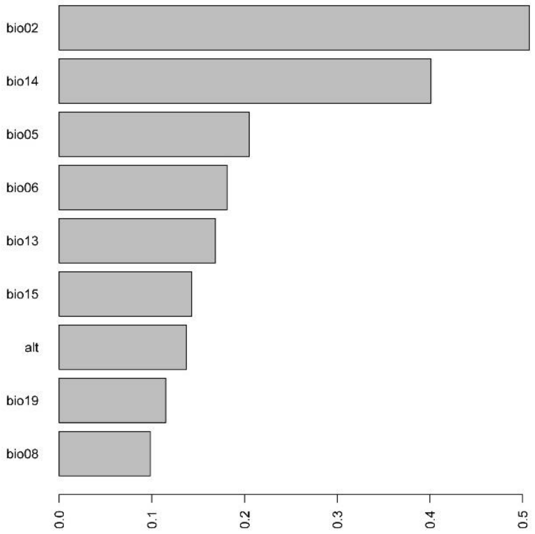
S. holophaea



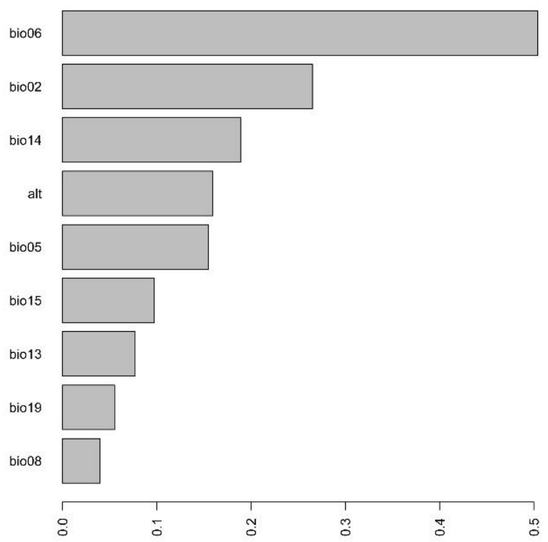
S. liparina



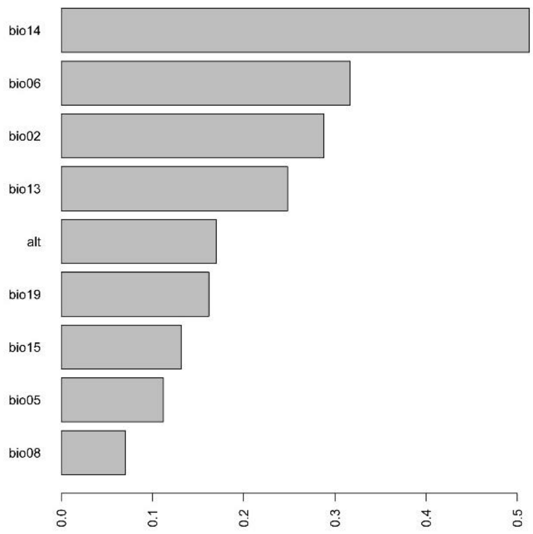
***S. olivacea* subsp.**
olbiensis



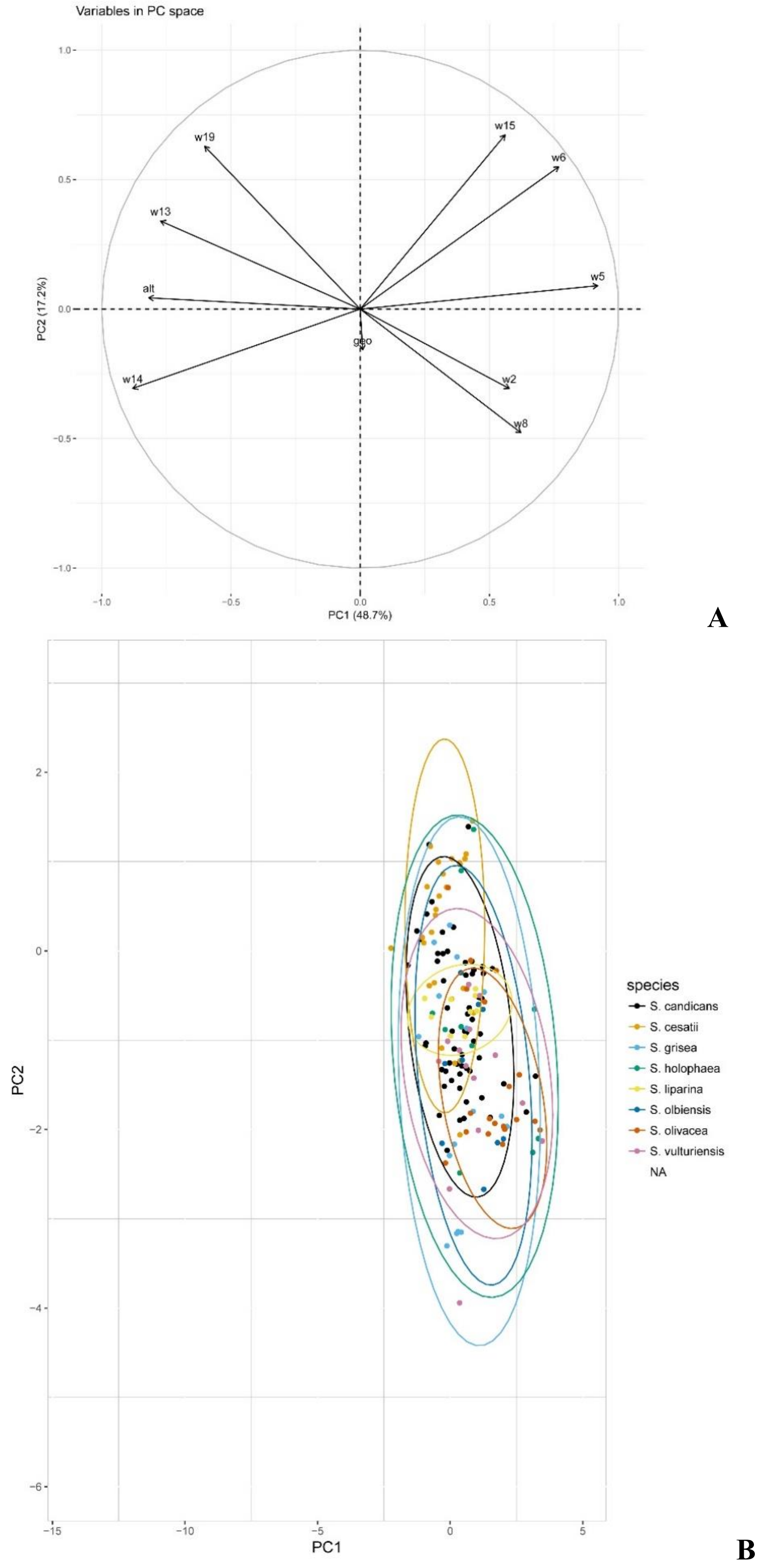
S. olivacea* subsp. *olivacea



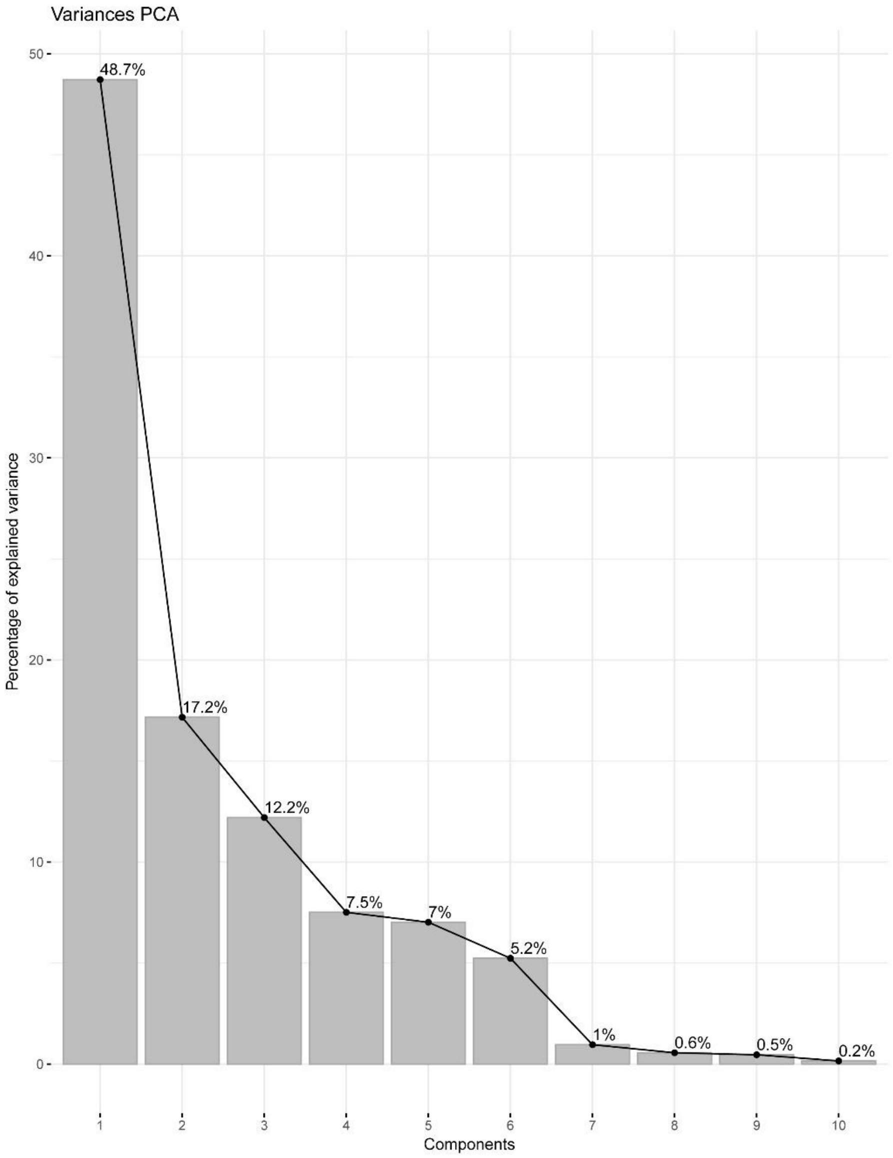
S. vulturiensis



Supplementary Information 8. Principal component analyses of reduced set of environmental variables (see Materials and Methods) and occurrences of *Solenopsora* taxa in the study area. **A:** Projection of the environmental variables in two-dimension PCA space. The variance explained by the components is given in parentheses. For list of WorldClim 1.4 environmental variables see Supplementary Information 3; instead of prefix “bio” the letter “w” was used in the following graphs. **B:** Ordination of the occurrences of *Solenopsora* taxa on first and second ecological PC axes (95% confidence ellipses) in the study area. For correlations of the environmental traits with component axes see Supplementary Information 10, 11 and 12.



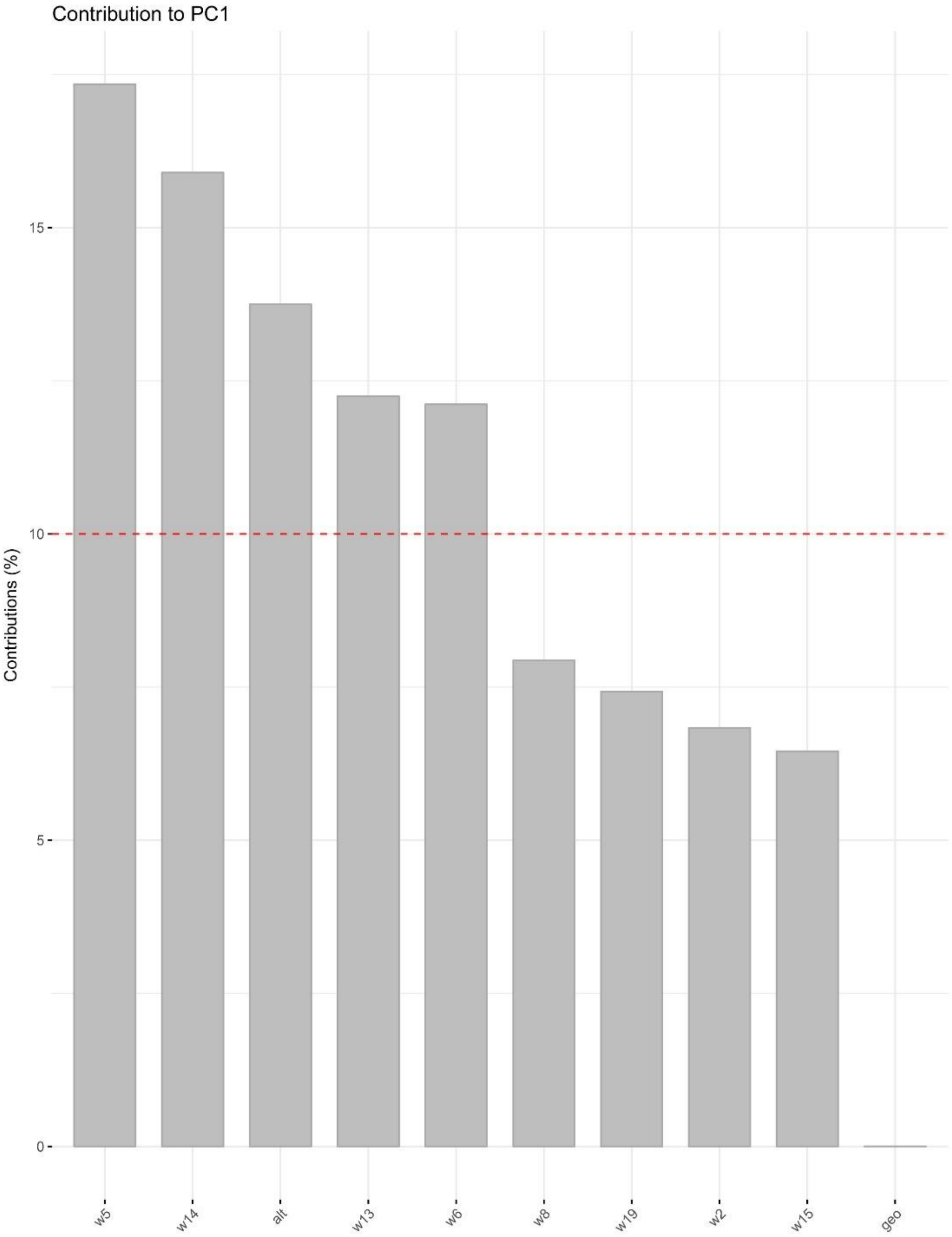
Supplementary Information 9. PCA analysis – percentage of variation explained by principal components (1–10).



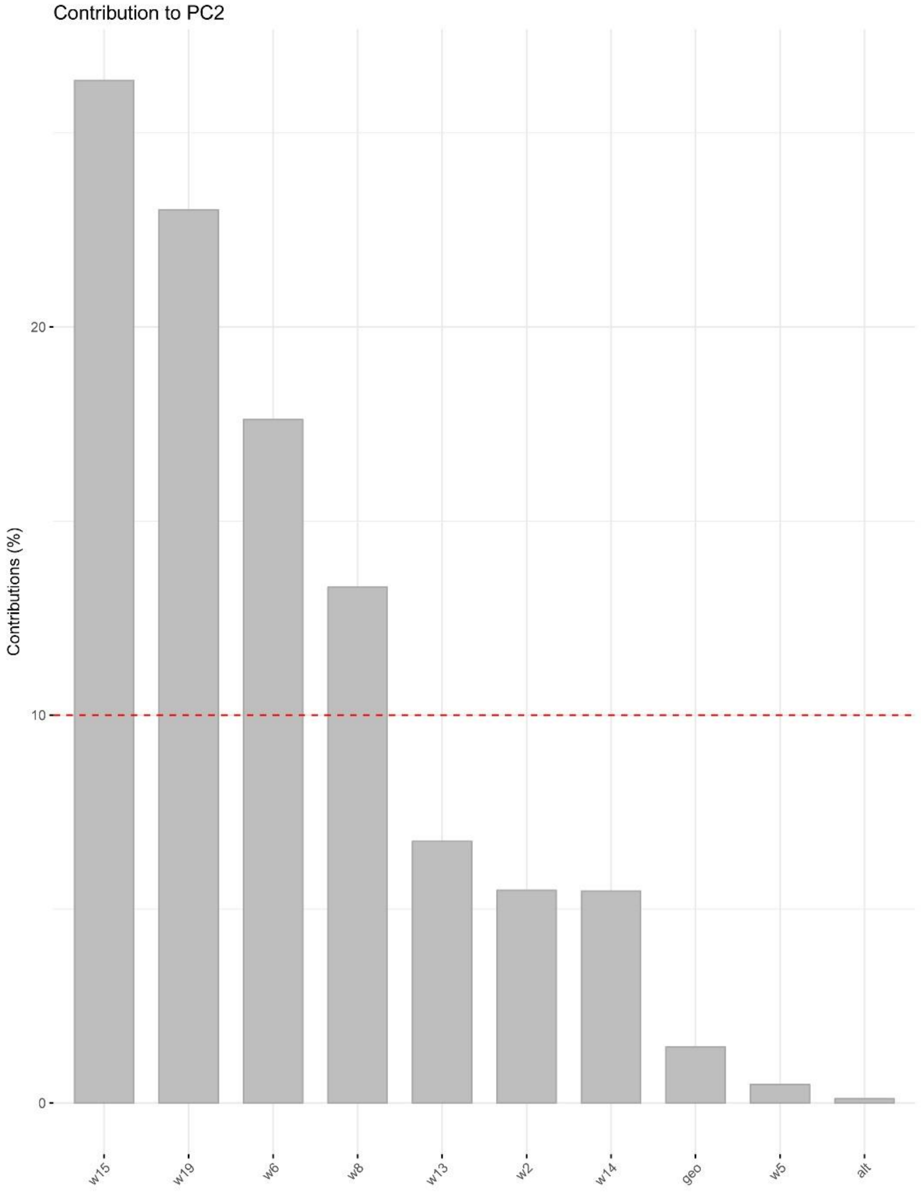
Supplementary Information 10. PCA analysis – contribution of environmental variables to principal components 1 – 5. For list of WorldClim 1.4 environmental variables see Supplementary Information 3.

Environmental variable	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**
bio5	17.34	0.48	4.93	1.20	8.55
bio14	15.90	5.46	2.43	1.24	7.09
alt	13.75	0.11	4.42	17.20	14.71
bio13	12.25	6.74	4.50	9.92	3.27
bio6	12.12	17.61	0.01	0.97	0.82
bio8	7.94	13.29	0.65	35.64	0.09
bio19	7.43	23.02	11.85	0.18	8.40
bio2	6.83	5.48	14.25	31.86	5.56
bio15	6.45	26.35	0.88	0.01	14.82
geo	0.00	1.44	56.09	1.76	36.69

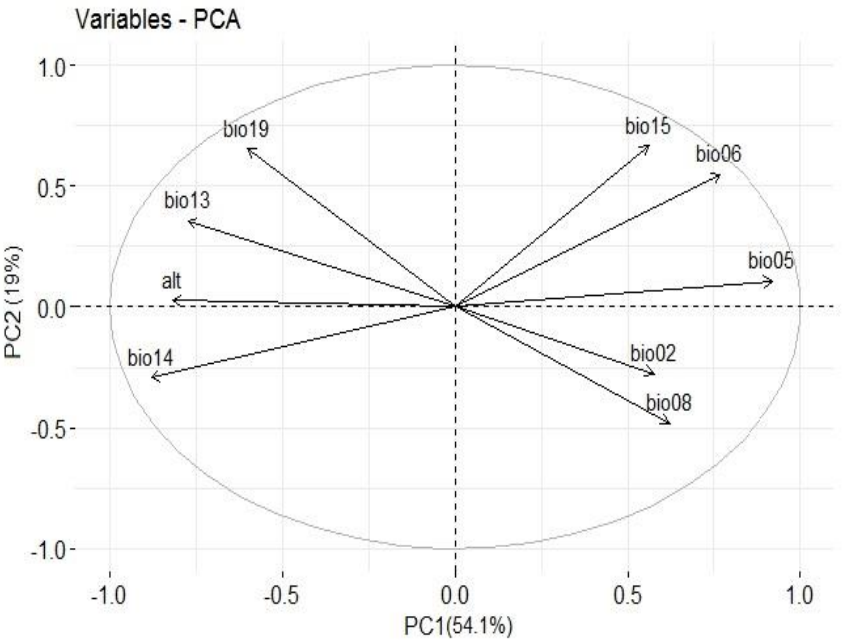
Supplementary Information 11. Contribution of variables to PC1. Red dashed line indicates the expected average contribution, if the contribution of the variables were uniform. A variable with a contribution larger than this cutoff (1/length = number of variables*100; 1/9 = 0.111 = 11%) could be considered as important in contributing to the component. For list of WorldClim 1.4 environmental variables see Supplementary Information 3; instead of prefix "bio" the letter "w" was used in the following graphs.



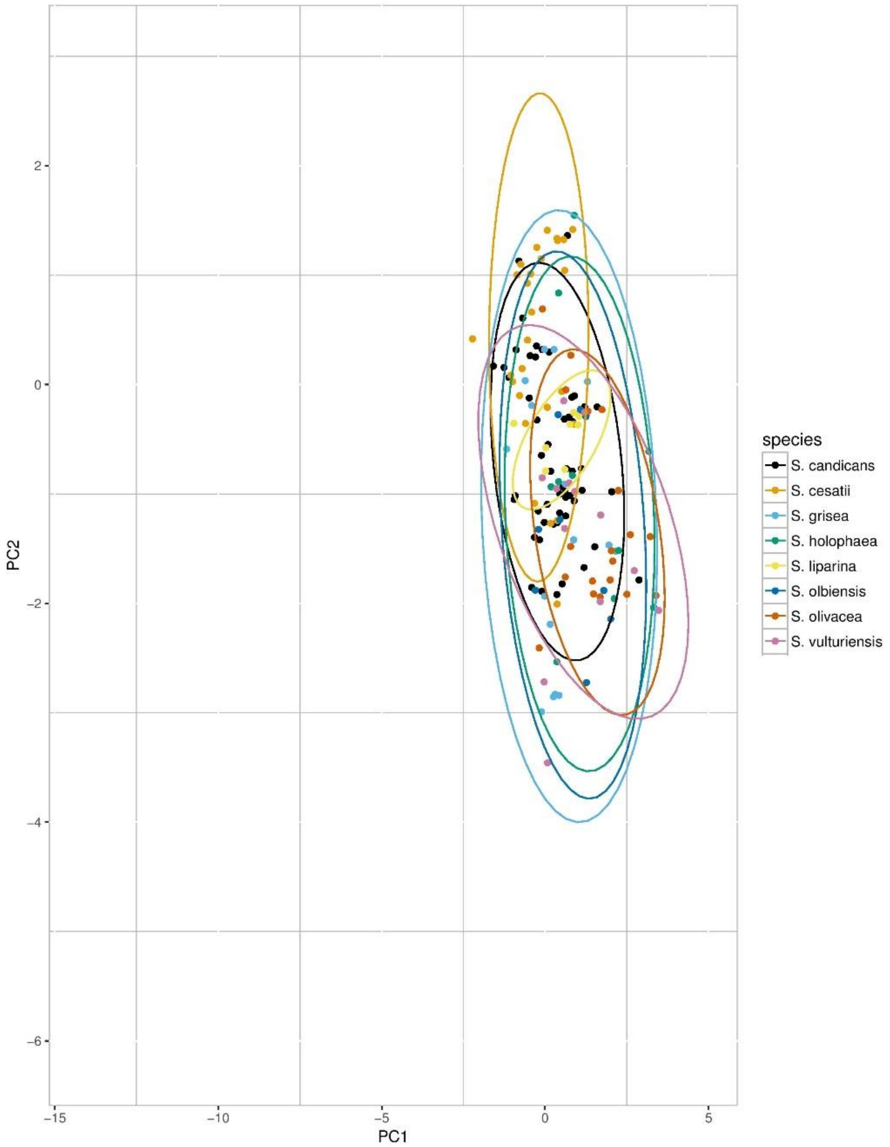
Supplementary Information 12. Contribution of variables to PC2. Red dashed line indicates the expected average contribution, if the contribution of the variables were uniform. A variable with a contribution larger than this cutoff (1/length = number of variables*100; 1/9 = 0.111 = 11%) could be considered as important in contributing to the component. For list of WorldClim 1.4 environmental variables see Supplementary Information 3; instead of prefix "bio" the letter "w" was used in the following graphs.



Supplementary Information 13. Alternative model approach with geology filtering. **A:** Principal component analyses of reduced set of environmental variables (see Materials and Methods) and occurrences of *Solenopsora* taxa in the study area – projection of the environmental variables in two-dimension PCA space. The variance explained by the components is given in parentheses. The abbreviations of the variables are given in Supplementary Information 3; **B:** Principal component analyses of reduced set of environmental variables (see Materials and Methods) and occurrences of *Solenopsora* taxa in the study area – ordination of the occurrences of *Solenopsora* taxa on first and second ecological PC axes (95% confidence ellipses) in the study area. For correlations of the environmental traits with component axes see F and G; **C:** PCA analysis – percentage of variation explained by principal components 1–9**; D:** PCA analysis – contribution of selected environmental variables to principal components 1–2; **E:** Contribution of variables to PC1. Red dashed line indicates the expected average contribution, if the contribution of the variables were uniform. A variable with a contribution larger than this cutoff (1/length = number of variables*100; 1/9 = 0.111 = 11%) could be considered as important in contributing to the component; **F:** Contribution of variables to PC2. Red dashed line indicates the expected average contribution, if the contribution of the variables were uniform. A variable with a contribution larger than this cutoff (1/length = number of variables*100; 1/9 = 0.111 = 11%) could be considered as important in contributing to the component.

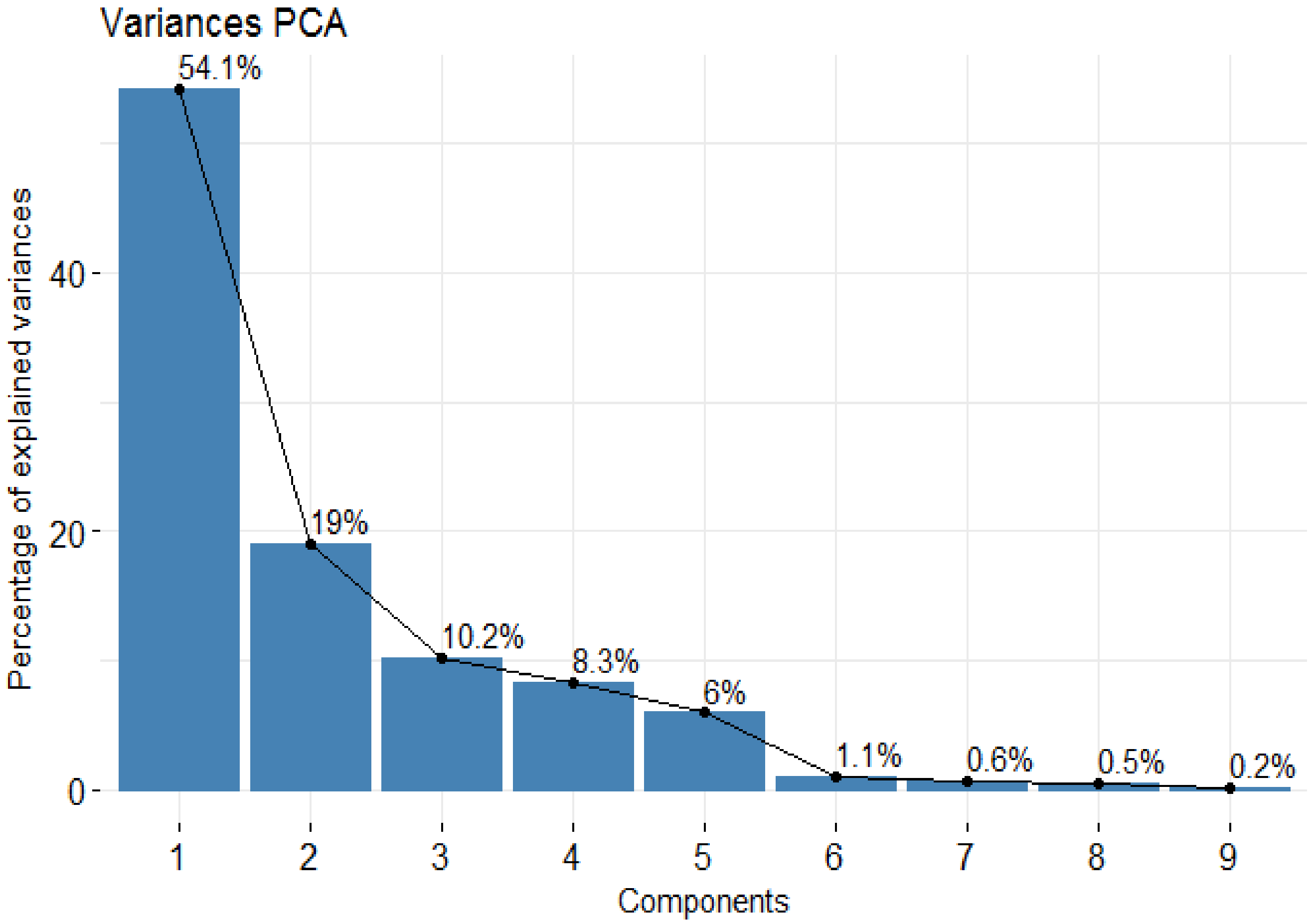


A



B

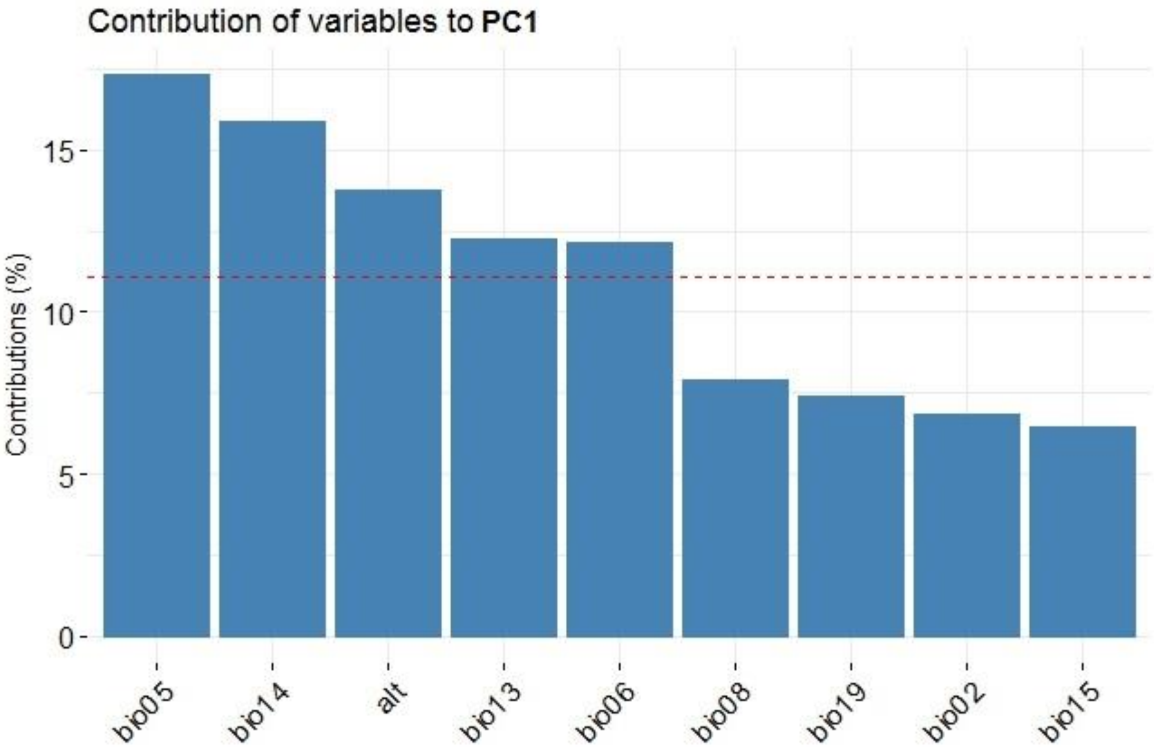
C



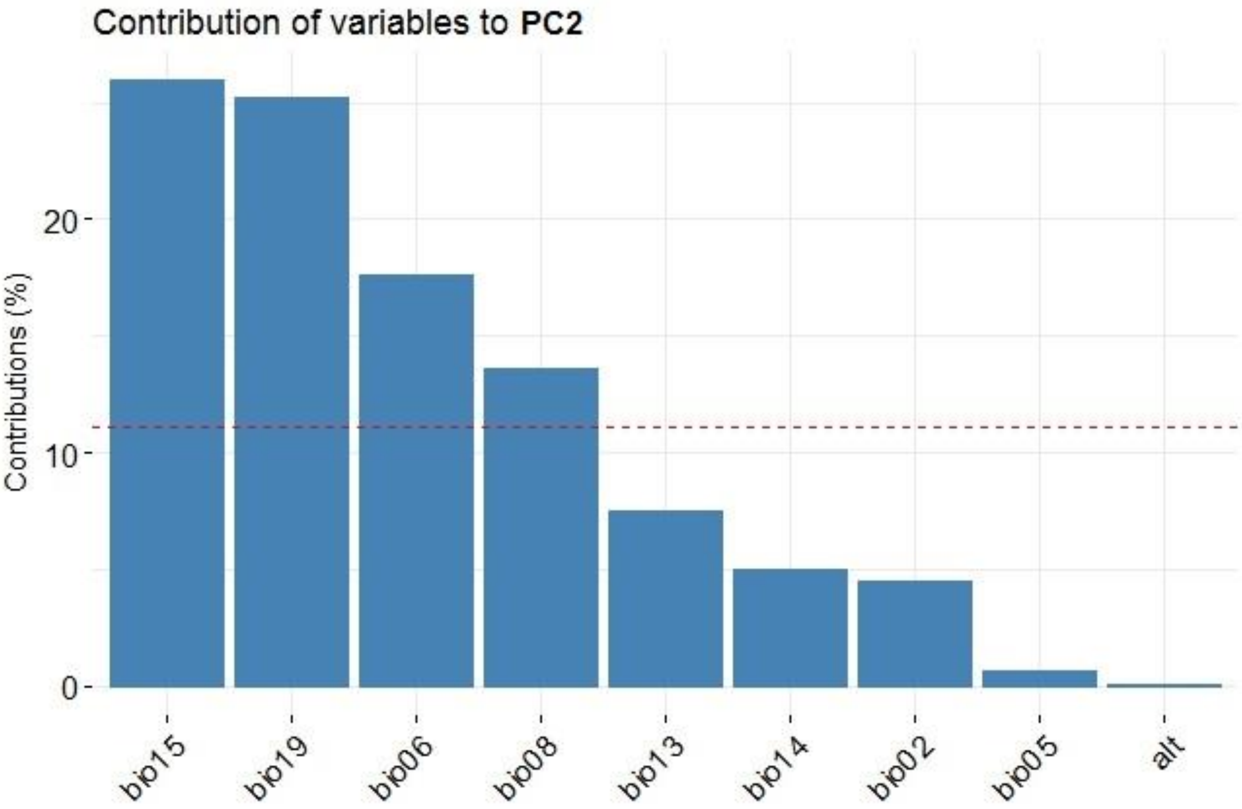
D

Environmental variable	**PC1**	**PC2**
alt	13.74	0.04
bio02	6.82	4.46
bio05	17.34	0.67
bio06	12.12	17.61
bio08	7.93	13.58
bio13	12.25	7.47
bio14	15.91	5.02
bio15	6.46	25.97
bio19	7.43	25.19

E

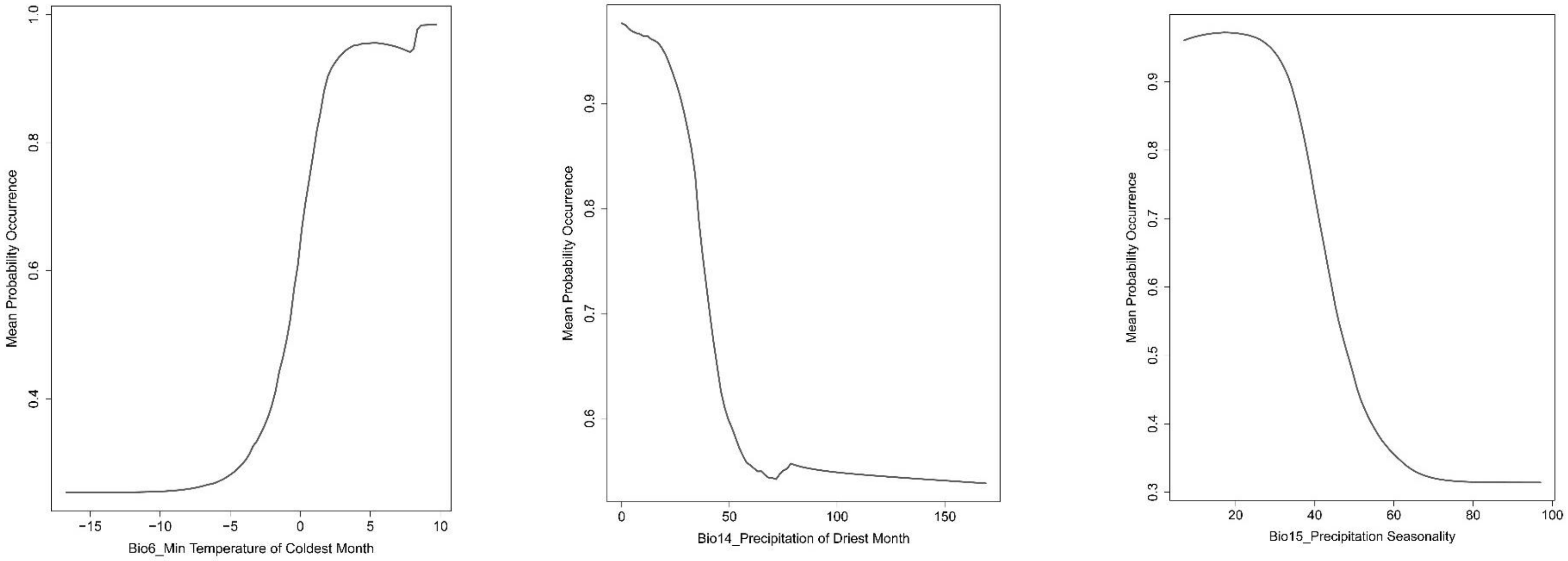

Contribution of variables to PC1
Contributions (%)
0
5
10
15
bio05
bio14
alt
bio13
bio06
bio08
bio19
bio02
bio15

F

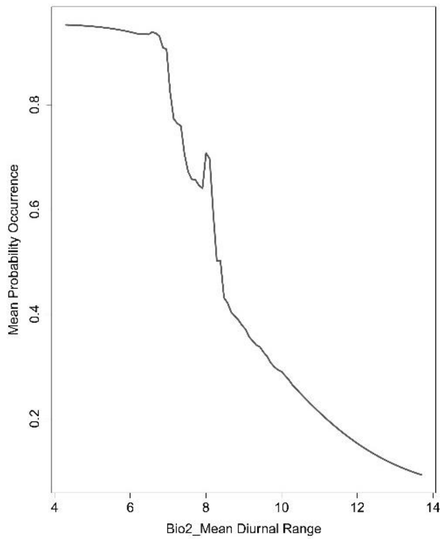

Contribution of variables to PC2
Contributions (%)
0
10
20
bio15
bio19
bio06
bio08
bio13
bio14
bio02
bio05
alt

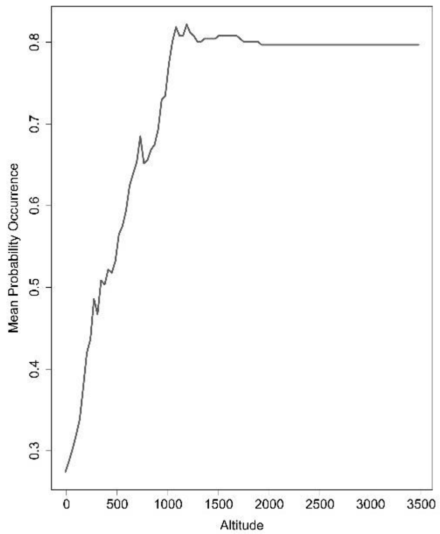
Supplementary Information 14. The response curves showing the ranges in environmental conditions that are most favourable for the distribution of the *Solenopsora* taxa, based on ensemble modellistic approach for the first three best explaining environmental variables with geology included as a categorical predictor. The x-axis represents variable range for the study area, the y-axis represents the mean probability of presence when all of the other variables are set to their average (mean probability occurrence).

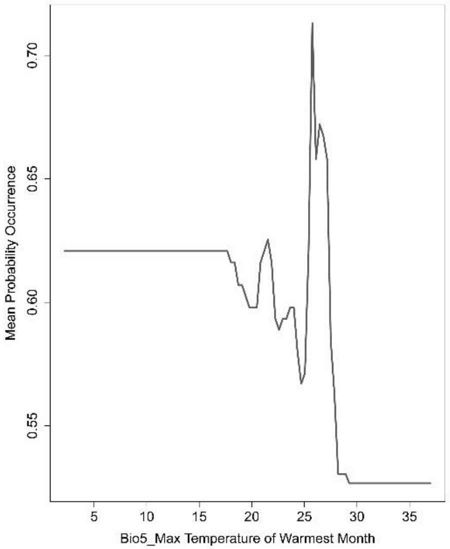
S. candicans



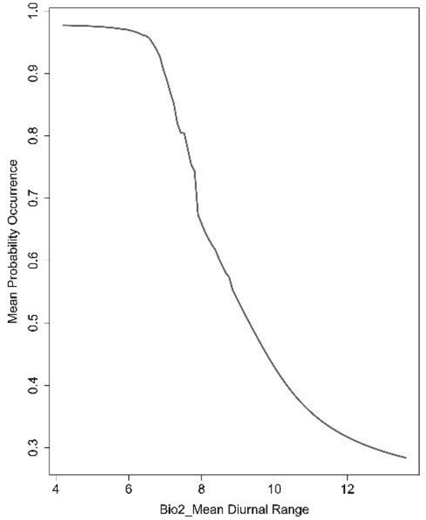
S. cesatii

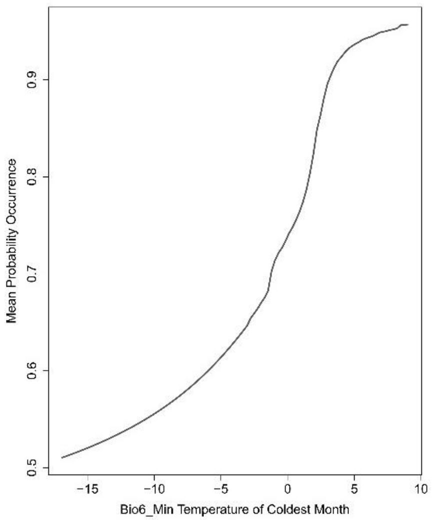


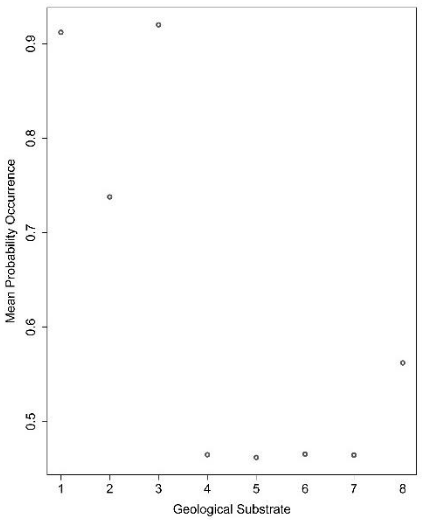




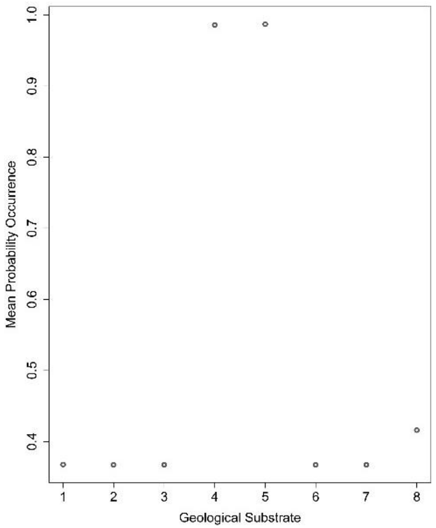
S. grisea

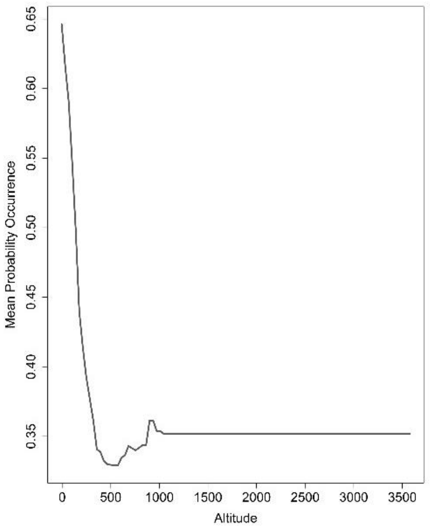


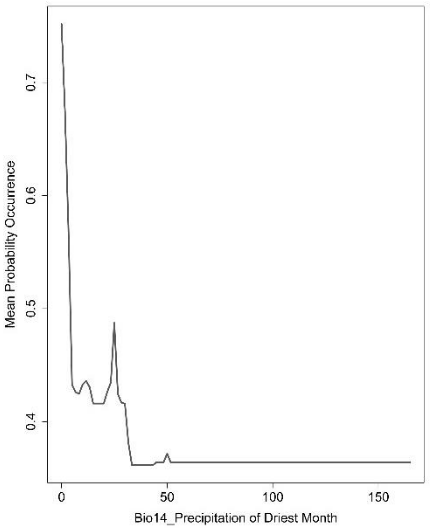




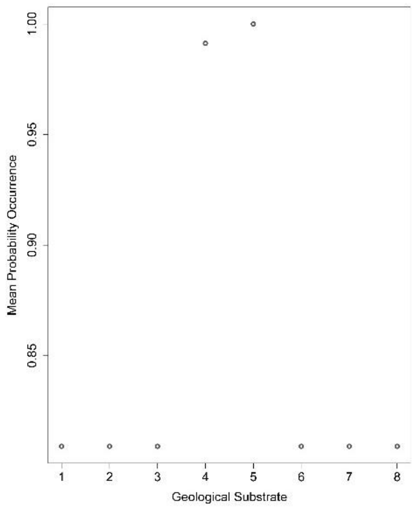
S. holophaea

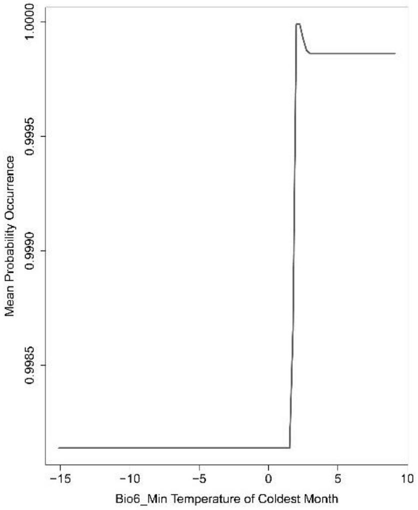


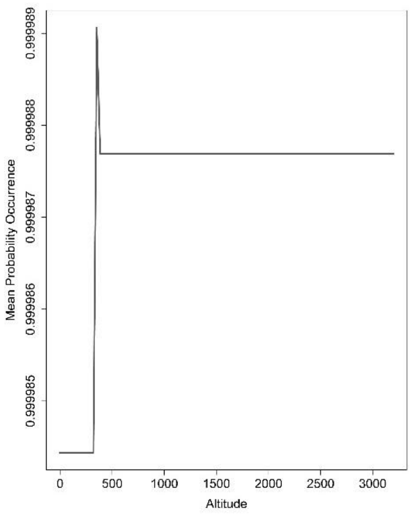




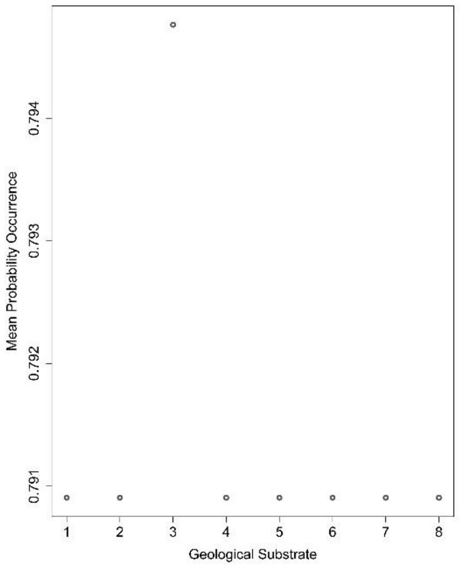
S. liparina

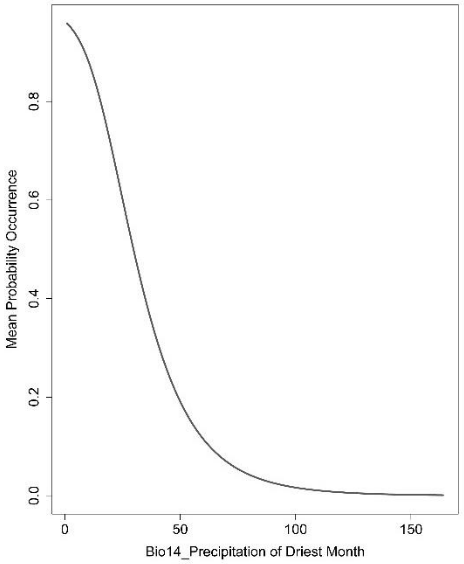


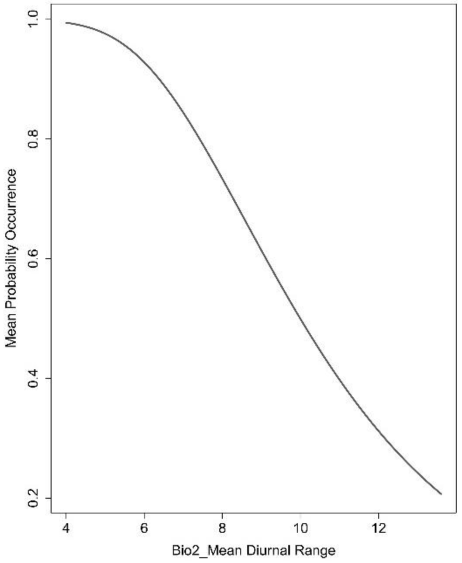




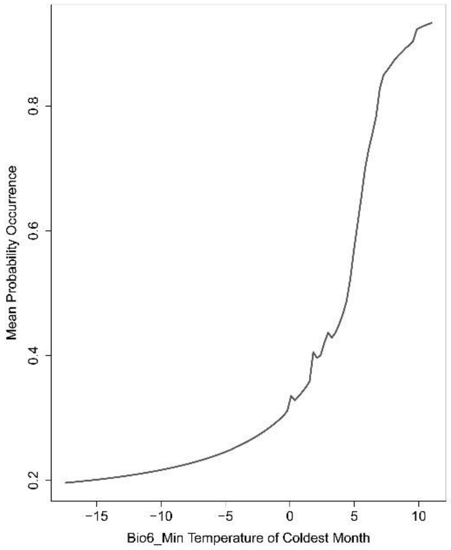
S. olivacea* subsp. *olbiensis

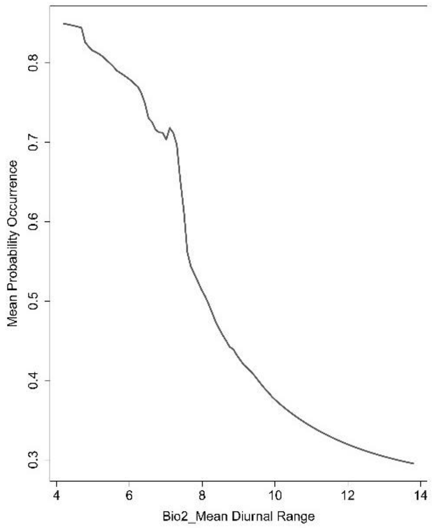


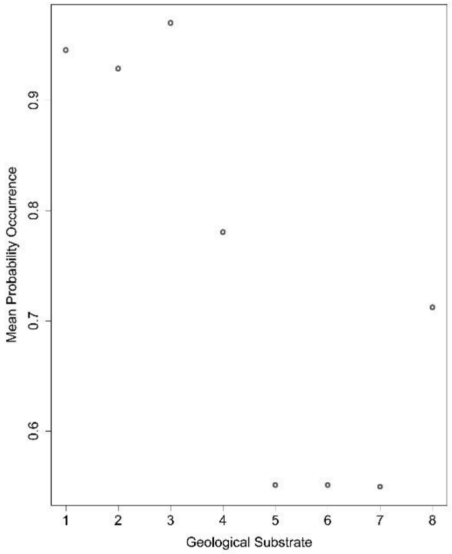




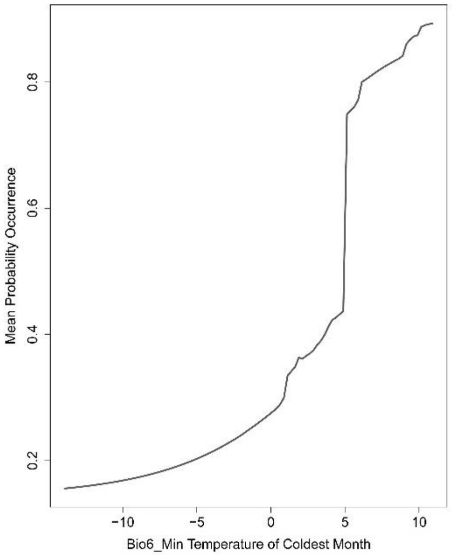
S. olivacea* subsp. *olivacea

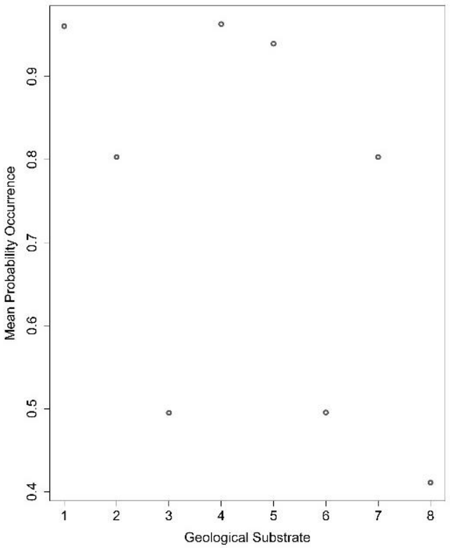


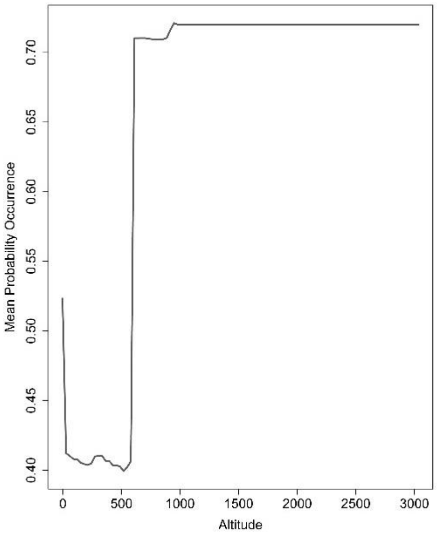




S. vulturiensis

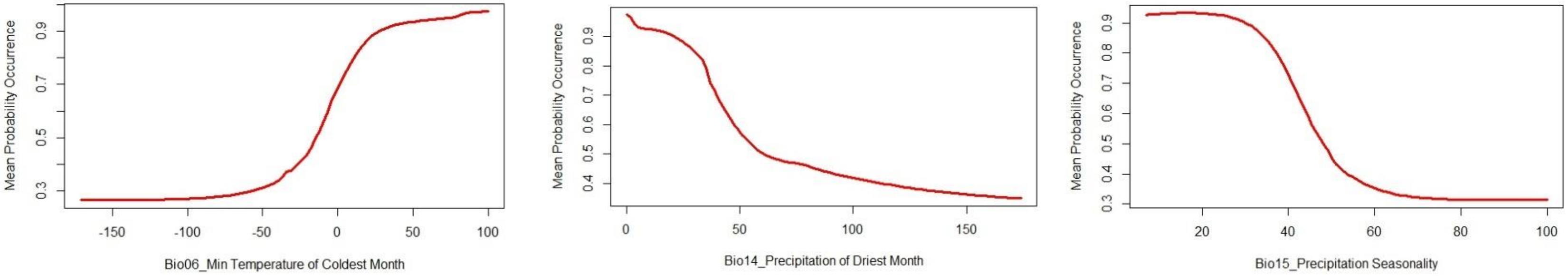




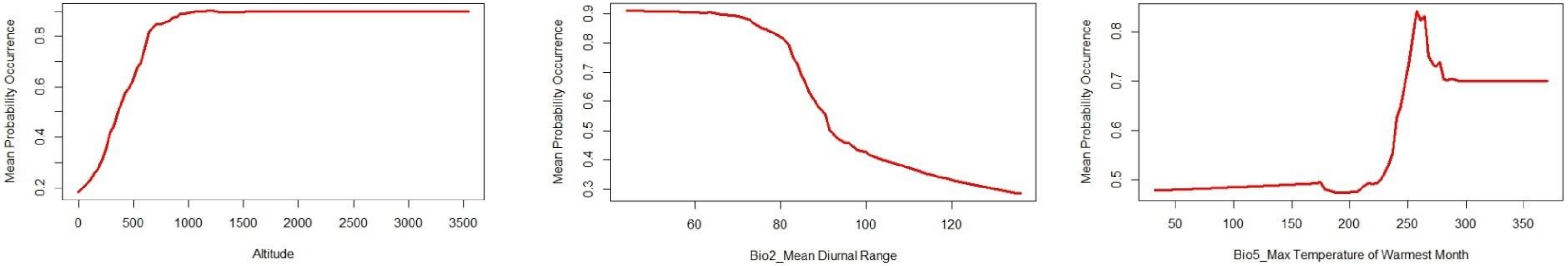


Supplementary Information 15. The response curves showing the ranges in environmental conditions that are most favourable for the distribution of the *Solenopsora* taxa, based on ensemble modellistic approach for the first three best explaining environmental variables (geology added later as environmental filter). The x-axis represents variable range for the study area, the y-axis represents the mean probability of presence when all of the other variables are set to their average (mean probability occurrence).

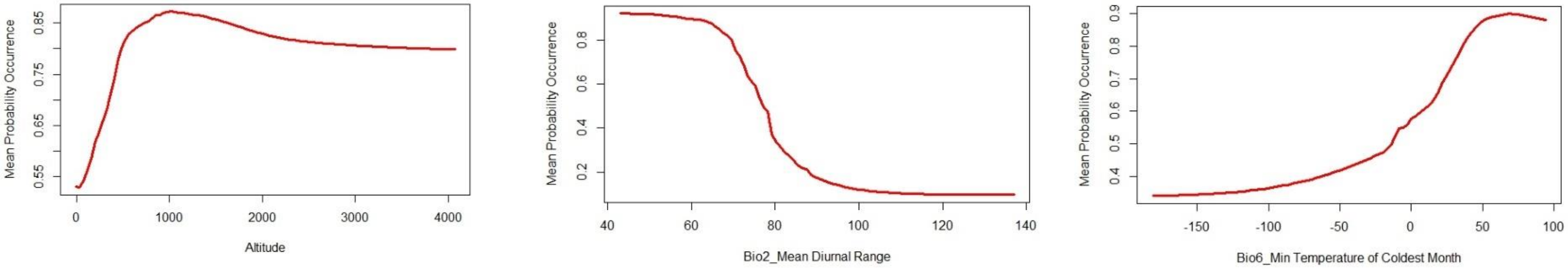
S. candicans



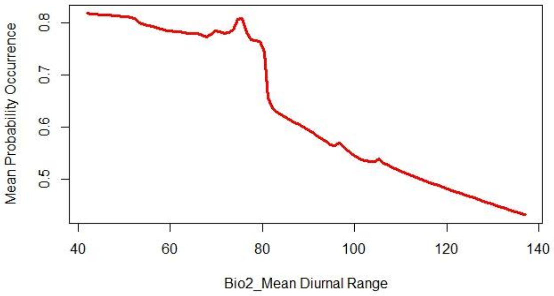
S. cesatii

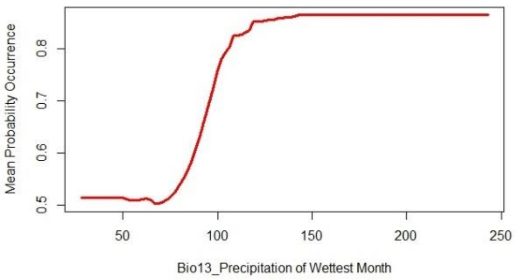


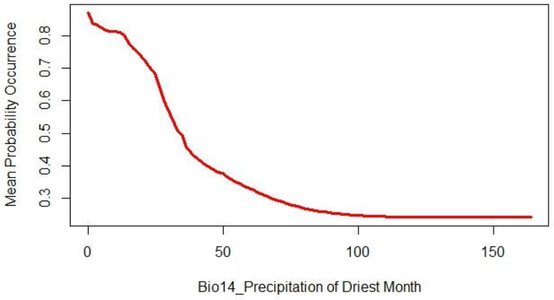
S. grisea



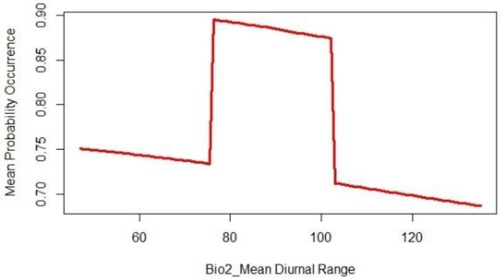
S. holophaea

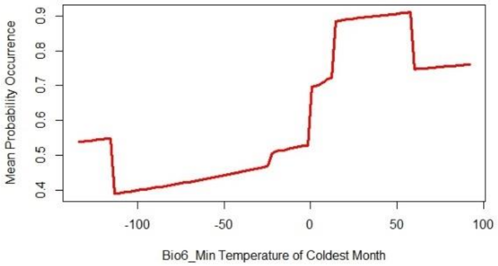


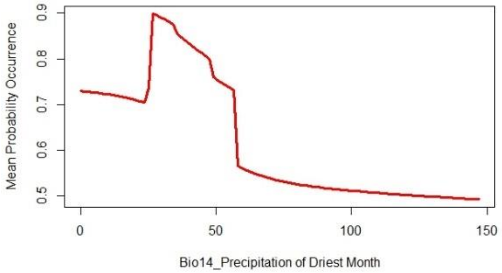




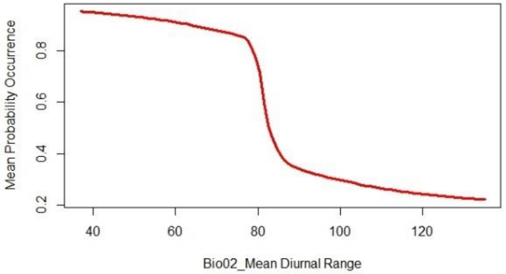
S. liparina

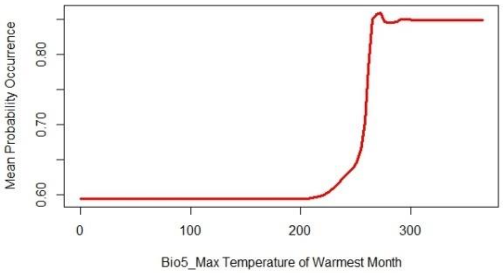


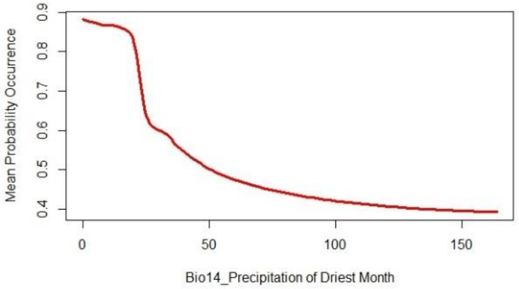




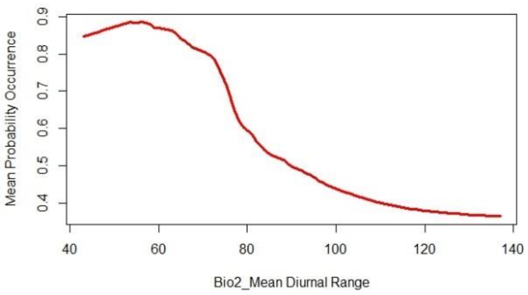
S. olivacea* subsp. *olbiensis

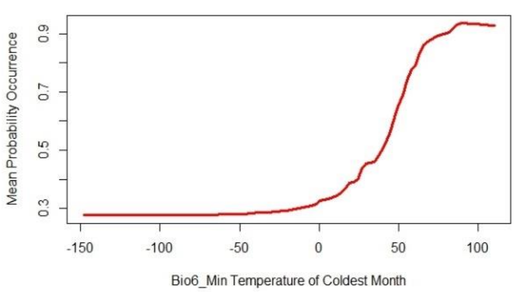


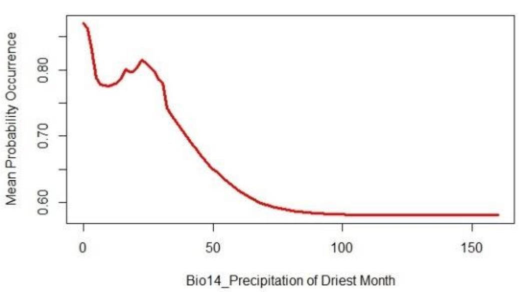




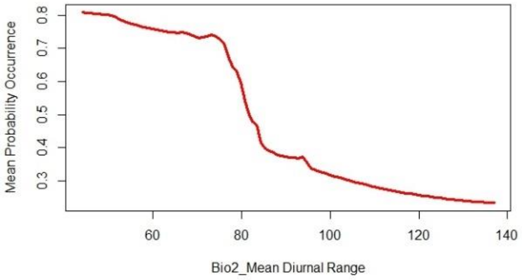
S. olivacea* subsp. *olivacea

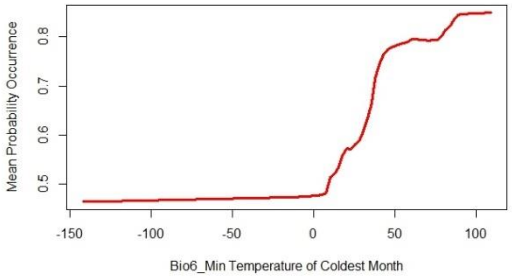


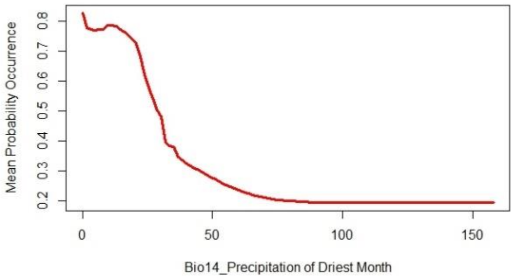




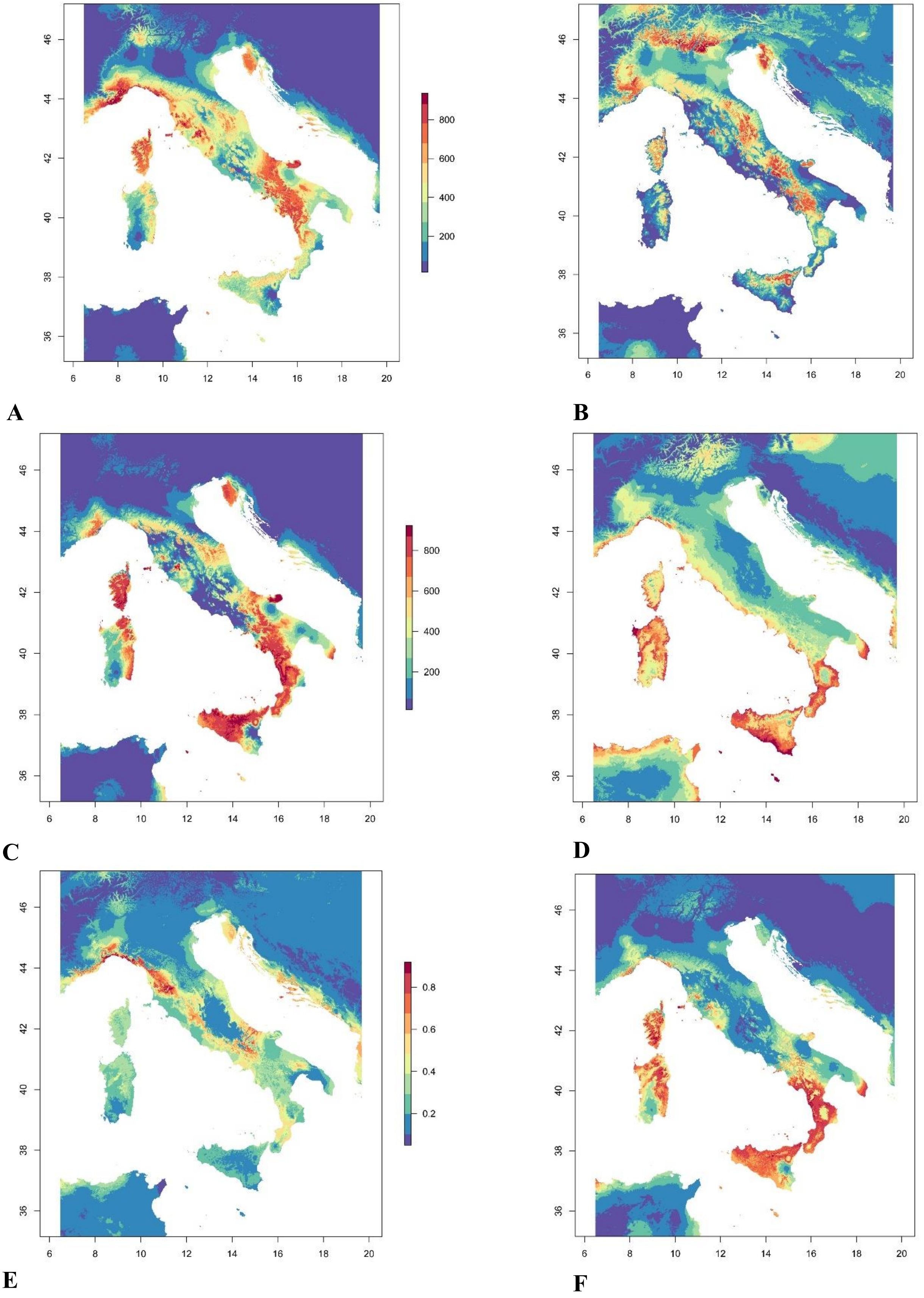
S. vulturiensis



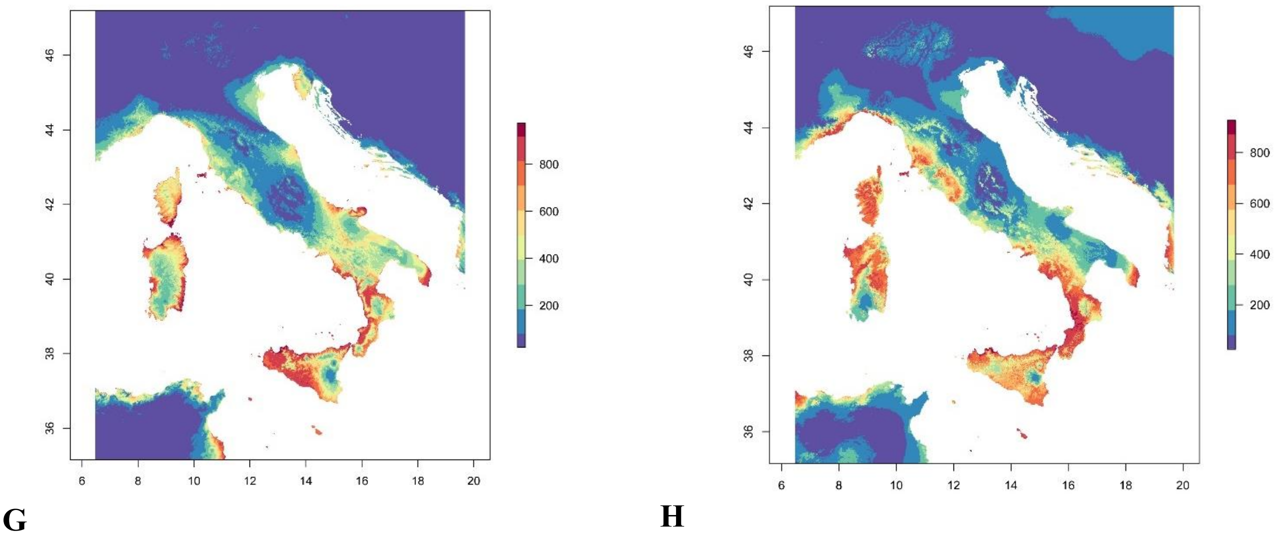




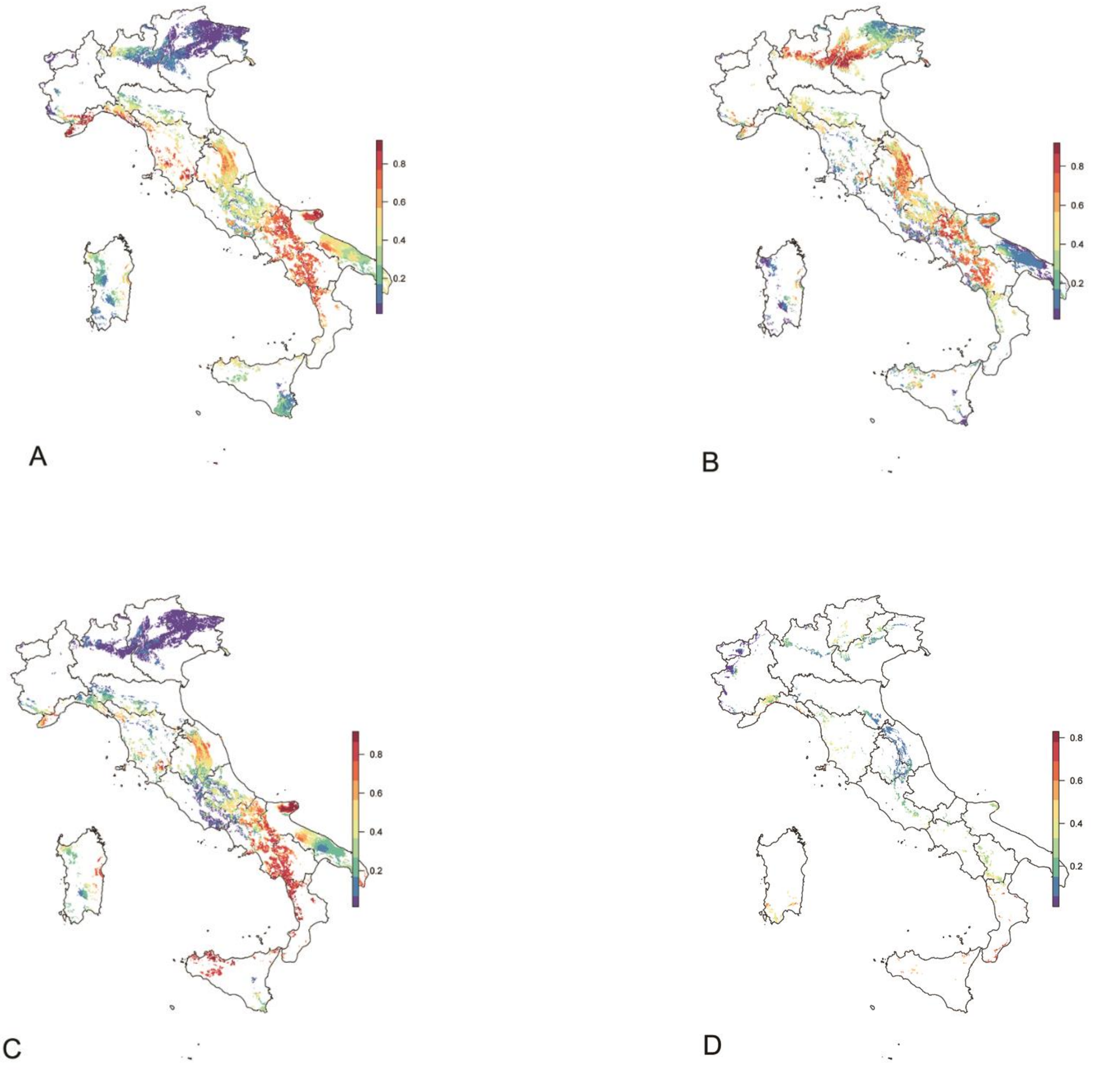
Supplementary Information 16. Habitat suitability maps (HSMs) of *Solenopsora* taxa along the Apennine peninsula, predicting suitable areas under current climatic conditions from 0 (blue) – not suitable, to 1 (red) – with high habitat suitability, based on climatic data. The scale on the right refers to the probability distribution scores. A – *S. candicans*, B – *S. cesatii*, C – *S. grisea*, D – *S. holophaea*, E – *S. liparina*, F – *S. olivacea* subsp. *olbiensis*, G – *S. olivacea* subsp. *olivacea*, H – *S. vulturiensis*.

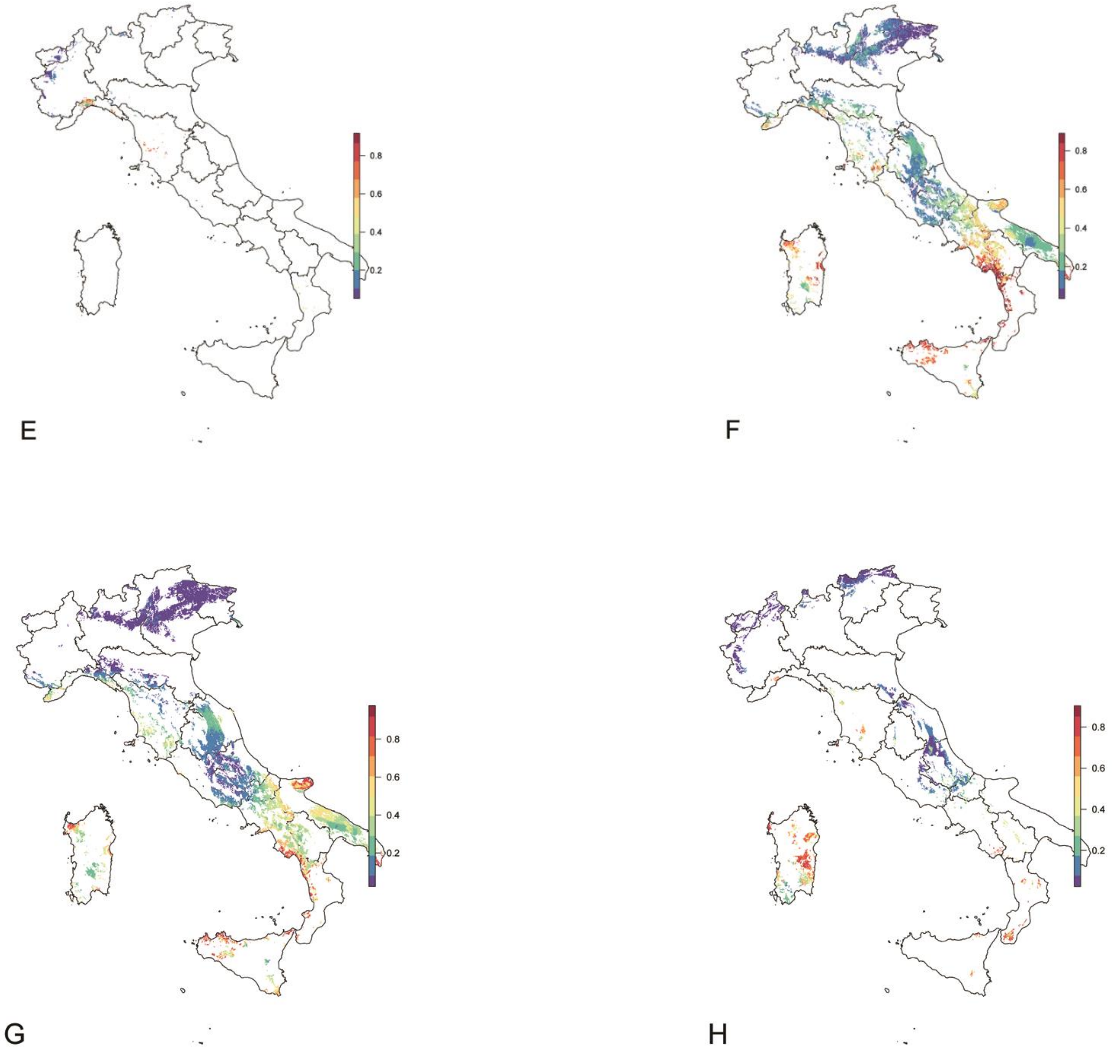


A B C D E F

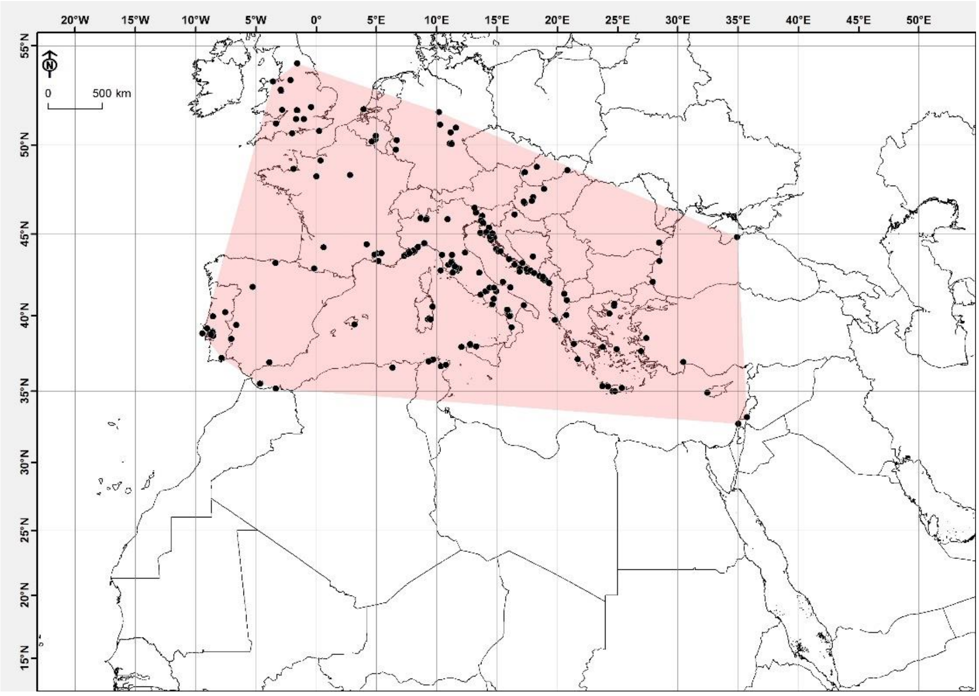


Supplementary Information 17. Habitat suitability maps (HSMs) of *Solenopsora* taxa along the Apennine peninsula as a result of alternative approach based on filtering geology from 0 (blue) – not suitable, to 1 (red) – high habitat suitability. The scale on the right refers to the probability distribution scores. A – *S. candicans*, B – *S. cesatii*, C – *S. grisea*, D – *S. holophaea*, E – *S. liparina*, F – *S. olivacea* subsp. *olbiensis*, G – *S. olivacea* subsp. *olivacea*, H – *S. vulturiensis*.

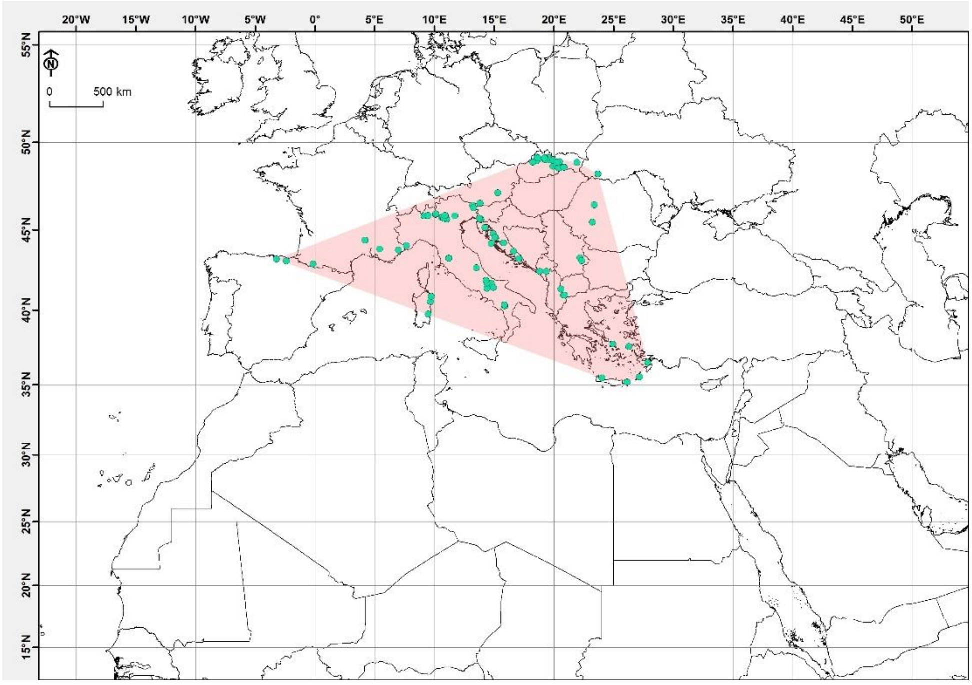



0.8
0.6
0.4
0.2
E
0.8
0.6
0.4
0.2
F
0.8
0.6
0.4
0.2
G
0.8
0.6
0.4
0.2
H

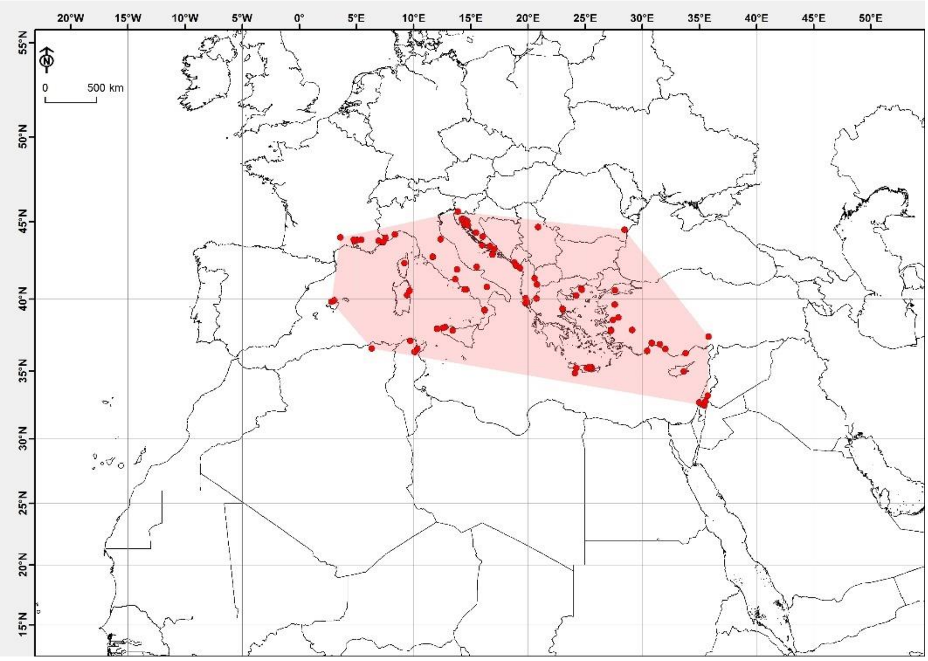
Supplementary Information 18. Maps showing the extent of geographical ranges (cf. Gaston 1996) of the studied *Solenopsora* taxa based on revised herbarium specimens and field work, where area within the polygons enclose the limits to the occurrence of distribution ranges of taxa. The most outlying points are connected in polygons. A – *S. candicans*, B – *S. cesatii*, C – *S. grisea*, D – *S. holophaea*, E – *S. marina*, F – *S. liparina*, G – *S. olivacea* subsp. *olbiensis*, H – *S. olivacea* subsp. *olivacea*, I – *S. vulturiensis*.



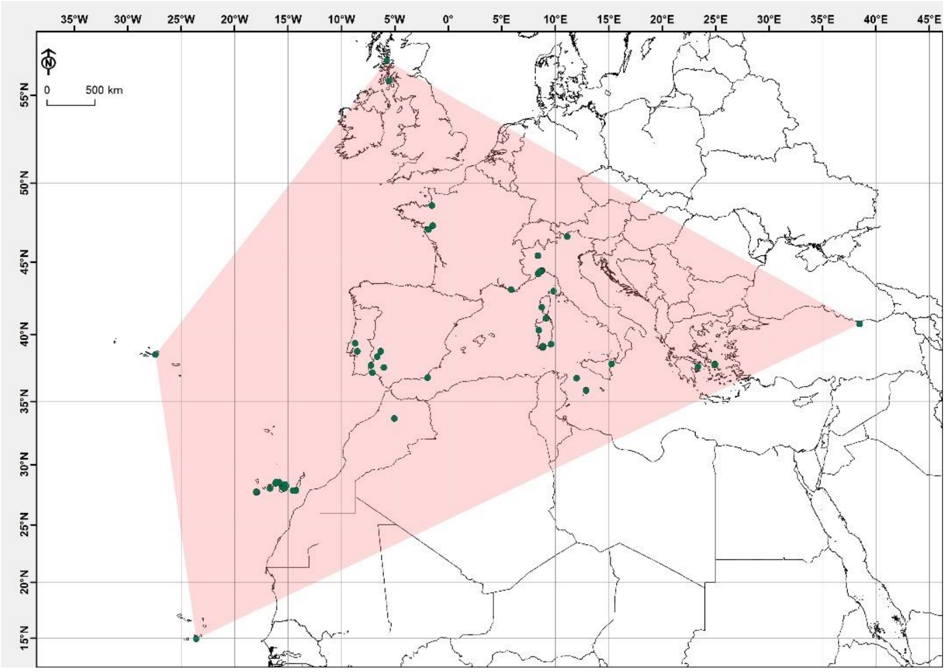
A



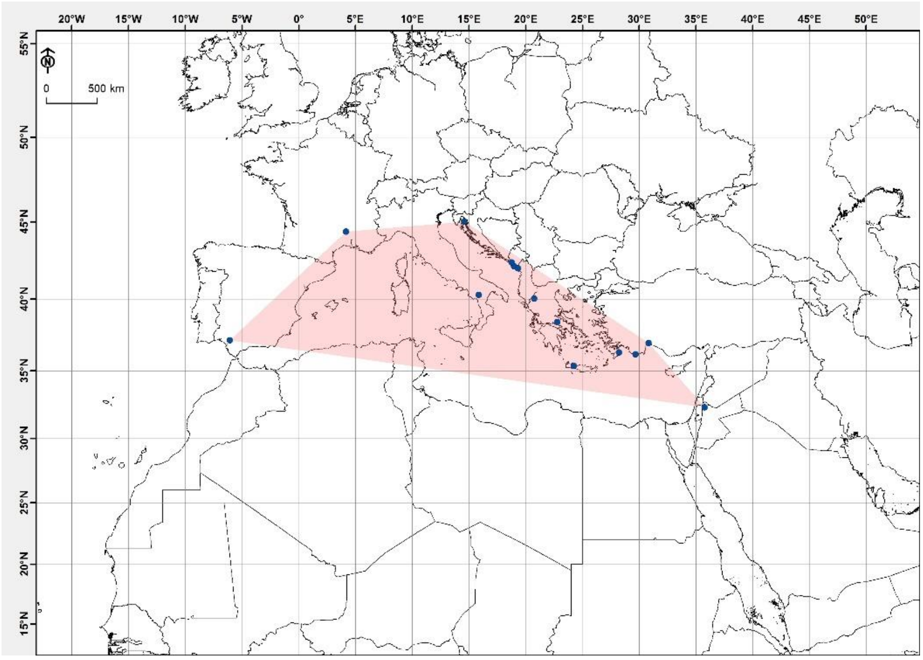
B


20°W
15°W
10°W
5°W
0°
5°E
10°E
15°E
20°E
25°E
30°E
35°E
40°E
45°E
50°E
55°N
50°N
45°N
40°N
35°N
30°N
25°N
20°N
15°N
N
0
500 km

C


35°W
30°W
25°W
20°W
15°W
10°W
5°W
0°
5°E
10°E
15°E
20°E
25°E
30°E
35°E
40°E
45°E
55°N
50°N
45°N
40°N
35°N
30°N
25°N
20°N
15°N
N
0
500 km

D


20°W
15°W
10°W
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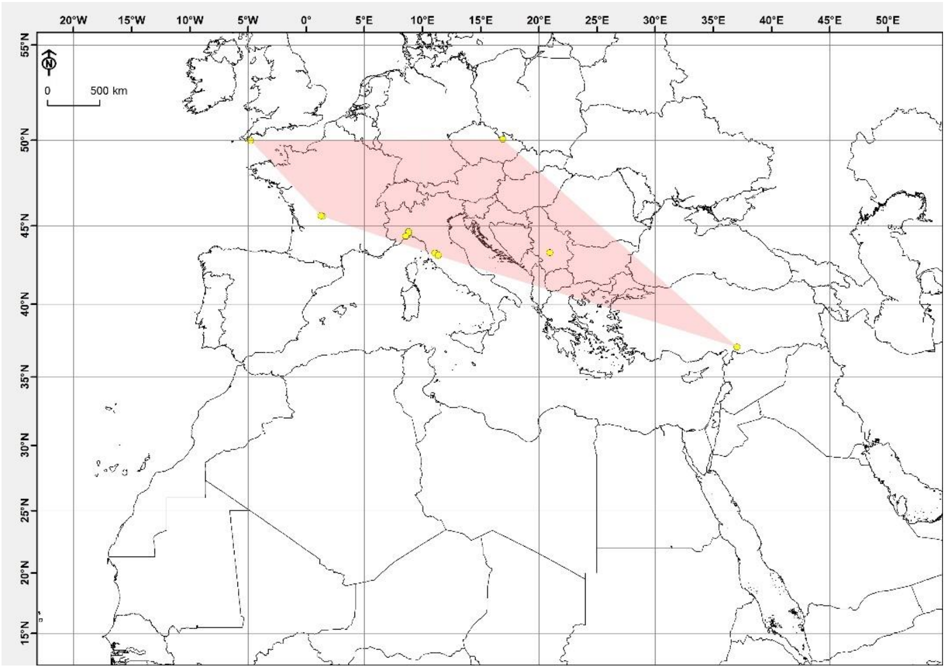
5°E
10°E
15°E
20°E
25°E
30°E
35°E
40°E
45°E
50°E
55°N
50°N
45°N
40°N
35°N
30°N
25°N
20°N
15°N
N
0
500 km

E


20°W
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15°E
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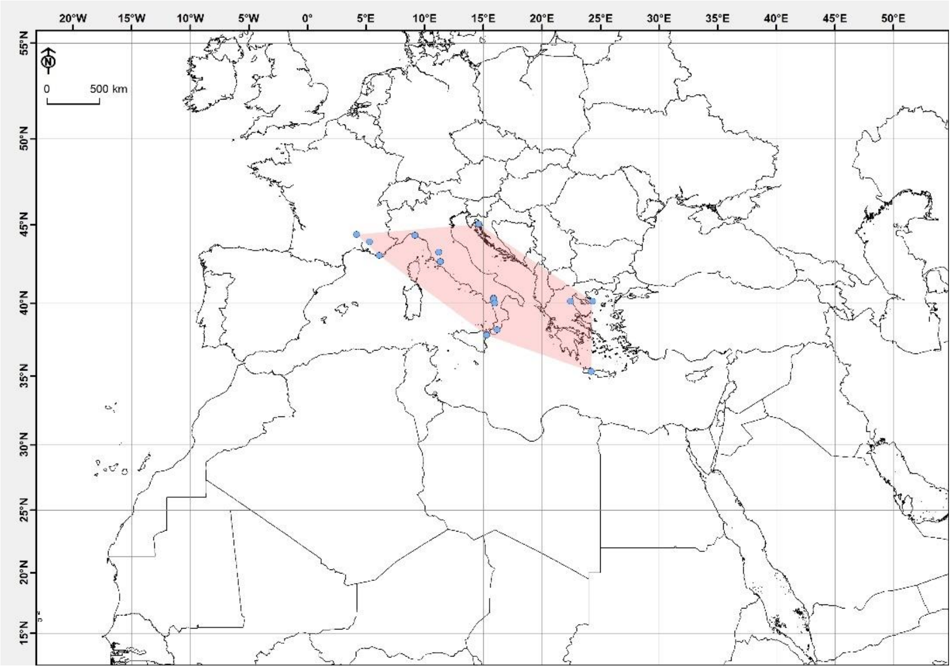
25°E
30°E
35°E
40°E
45°E
50°E
55°N
50°N
45°N
40°N
35°N
30°N
25°N
20°N
15°N
N
0
500 km

F


20°W
15°W
10°W
5°W
0°
5°E
10°E
15°E
20°E
25°E
30°E
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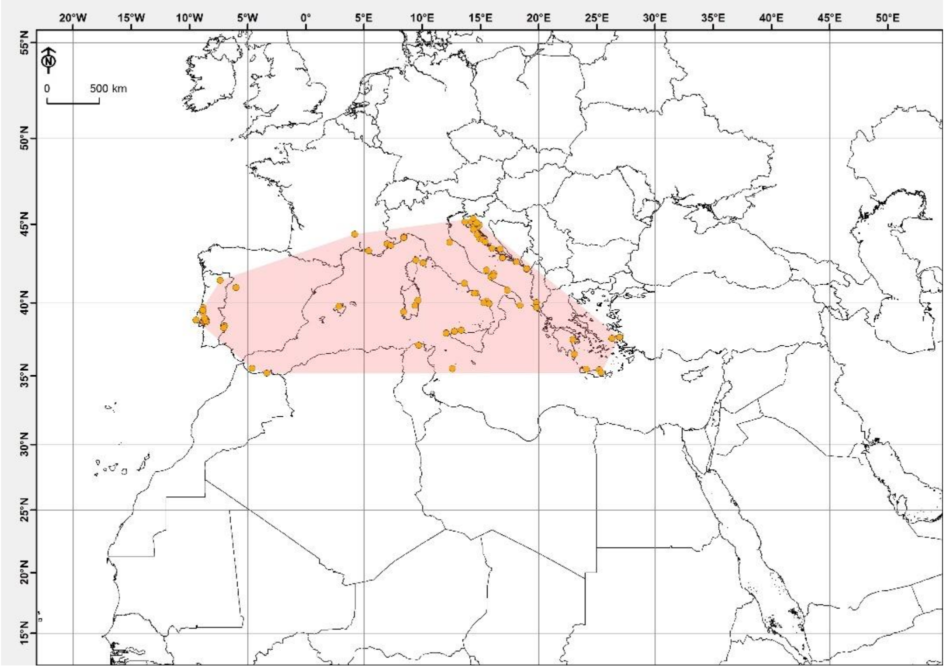
45°E
50°E
55°N
50°N
45°N
40°N
35°N
30°N
25°N
20°N
15°N
N
0
500 km

G


20°W
15°W
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5°E
10°E
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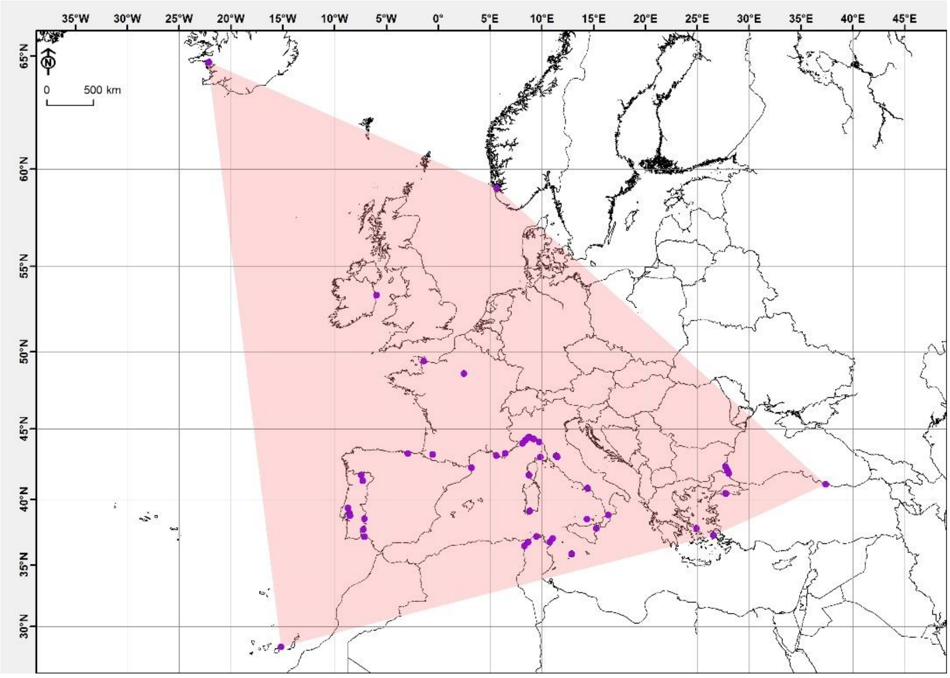
30°E
35°E
40°E
45°E
50°E
55°N
50°N
45°N
40°N
35°N
30°N
25°N
20°N
15°N
N
0
500 km

H


35°W
30°W
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5°W
0°
5°E
10°E
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20°E
25°E
30°E
35°E
40°E
45°E
65°N
60°N
55°N
50°N
45°N
40°N
35°N
30°N
N
0
500 km

I

Distributional pattern of Sardinian Orchids under a Climate Change Scenario

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Abstract

The Mediterranean is one of the major biodiversity hotspot 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 as predictors Land Use and Soil Type, as well as 8 bioclimatic variables, 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 temperatures and a decrease of precipitations. 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.

Keywords

Biodiversity, climatic niche, conservation, ensemble modelling, Mediterranean basin

List of 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 1984):

Anacamptis longicornu (Poir.) R. M. Bateman, Pridgeon & M. W. Chase

Anacamptis papilionacea var. *grandiflora* (L.) R. M. Bateman, Pridgeon & M. W. Chase

Anacamptis papilionacea var. *papilionacea* (L.) R. M. Bateman, Pridgeon & M. W. Chase

Arundina graminifolia (D.Don) Hochr.

Epipactis helleborine (L.) Crantz

Ophrys bombyliflora Link

Ophrys morisii (Martelli) Soò

Ophrys speculum Link

Ophrys tenthredinifera Willd.

Serapias lingua L.

Serapias parviflora Parl.

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 disappearing 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 of a 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 of 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 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 potatoes 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, forecast future distribution of species and purpose 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 fa as orchids are concerned, there are several studies which make use of species distribution models. In Two studies (Kolanowska 2013, Kolanowska and Konowalik 2014) analysed the climatic niches of *Epipactis elleborine* 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 extension of 24100 km^2, 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 precipitations, characterize 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 occurrences records were available. Occurrence data were obtained both from herbarium specimens (Detailed list in supplementary materials **Table S0**), and from field surveys, carried out between 02/2012 and 06/2017. As far as herbarium specimens are concerned, georeferencing was made *a posteriori* by using Q-Gis software (2.18.6 “Las Palmas” version 2016). Field observations were georeferenced by mean of a portable GPS (Garmin GPS 12CX^{TM}).

The dataset contains data for nine species: *Anacamptis longicornu* (36 records), *A. papilionacea* var. *grandiflora* (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 (S0). To avoid autocorrelation, two records of *Ophrys speculum* were excluded from the initial dataset (**Table S0**).

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 (0.83x0.83= 0.69 km^2 c. a. at our latitude), in the form of raster layers.

Among these variables, Spearman correlation was applied to identify the variables which were significantly correlated ("corrplot" R package). 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 auto ecology 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 **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 rasters 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), 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 suggested in previous works, e.g., Araújo et al. 2005, Engler et al. 2011) were excluded from further computations.

R software was used for all analyses. The final ensemble was obtained by using the Biomod2 R package.

Results

The variables, ordered according to the importance score for each taxon, are listed in **Table 2**. Annual Precipitation 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, and the precipitations of coldest quarter score 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**).

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 do 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* seem 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 seem 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 limited fitness when annual precipitations are higher than 500 mm, a feature it shares with the congeneric *O. tenthredinifera*. The latter however, do 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 of 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. *A. papilionacea* var. *grandiflora* is the taxon with the 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 (**Figures 4-6**) are reported for current and future (2070) climatic conditions. Predicted suitability ranges from 0 (not suitable, blue) to 1 (highly suitable, red).

Anacamptis papilionacea var. *grandiflora* (**Figure 4a**) 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 4b**) has a similar potential distribution, but has a high suitability only in the south-eastern part of the island. *Serapias lingua* (**Figure 4c**), 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* seem 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 5a- 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 6a, 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 a widening 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, inter- annual 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. *Ophrys bombyliflora*, *O. tenthredinifera* and *Serapias lingua* have a similar ecology, and are known to sporadically occur up to ca. 1000 meters, while the latter could sporadically grow up to 1500 meters.

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 these species are especially limited by the precipitations in the coldest season, if they are 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 precipitations, 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 Sardinia as far as the nine taxa we investigated: some species are projected to have a widening of their 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 however complex to forecast. 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 consider 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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Tables

Table 1. Predictor variables selected for developing the models after a Spearman correlation test (correlation plot is shown in 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

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

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.

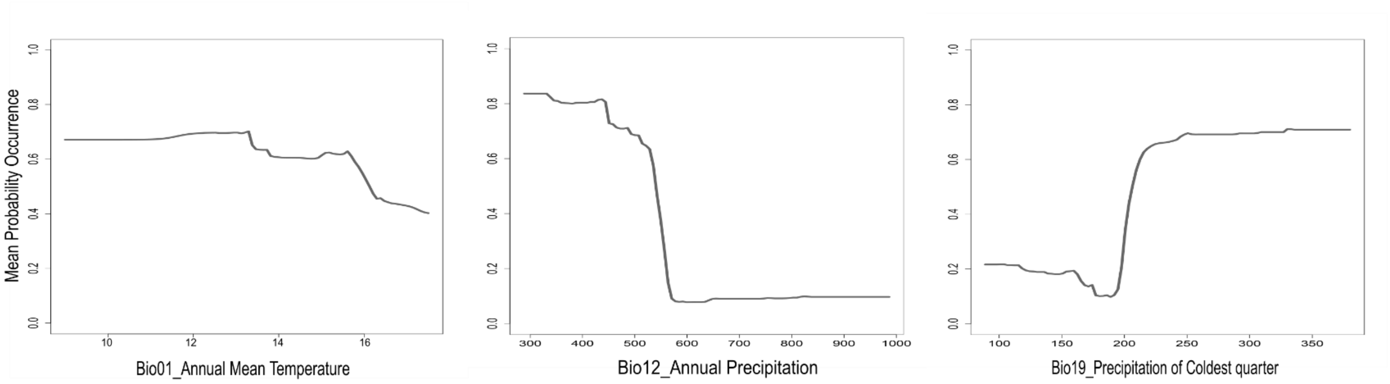
Species	BIO12 (mm)	Alt (m a.s.l.)	BIO5 (°C)	BIO19 (mm)
A. papilionacea var. *grandiflora*	< 500			> 300
A. longicornu	< 500	> 500		> 300
A. papilionacea var. *papilionacea*	< 500	> 500	> 29	
O. bombyliflora	< 500		> 29	
O. morisii	< 500	> 500	> 29	
O. neglecta	< 500		> 29	> 250
O. speculum	< 500	> 500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

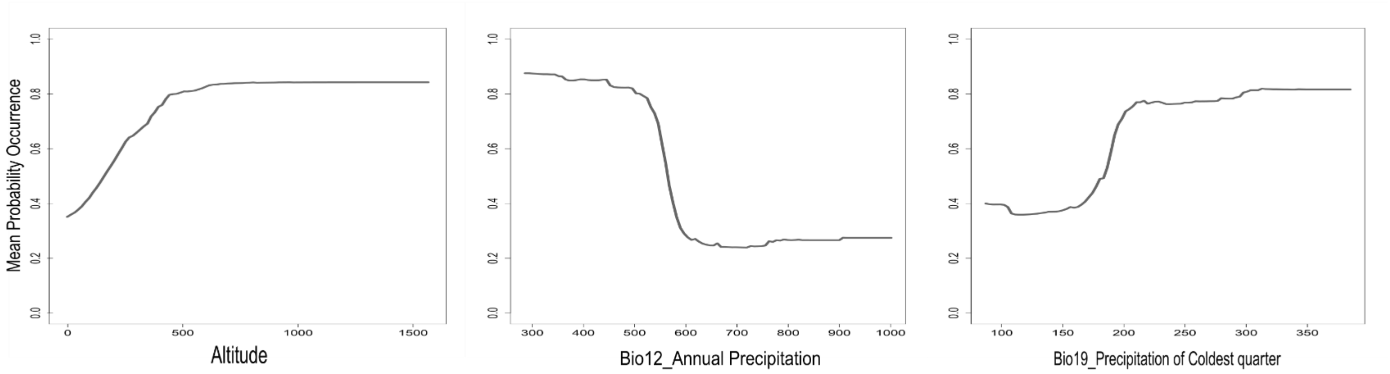
Species	Loss %	Gain %	Change %
A. papilionacea var. *grandiflora*	47.57	67.68	20.12
A. longicornu	13.59	228.05	214.46
A. papilionacea var. *papilionacea*	14.68	229.11	214.43
O. bombyliflora	13.00	231.08	218.09
O. morisii	5.54	274.62	269.08
O. neglecta	34.84	129.86	95.02
O. speculum	23.89	132.20	108.31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

Figures

A. grandiflora



A. longicornu



O. speculum

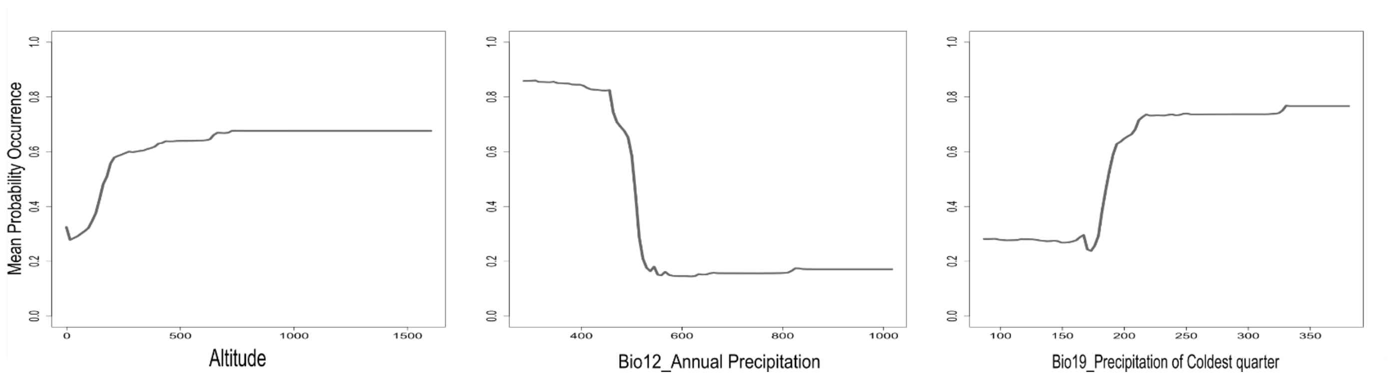
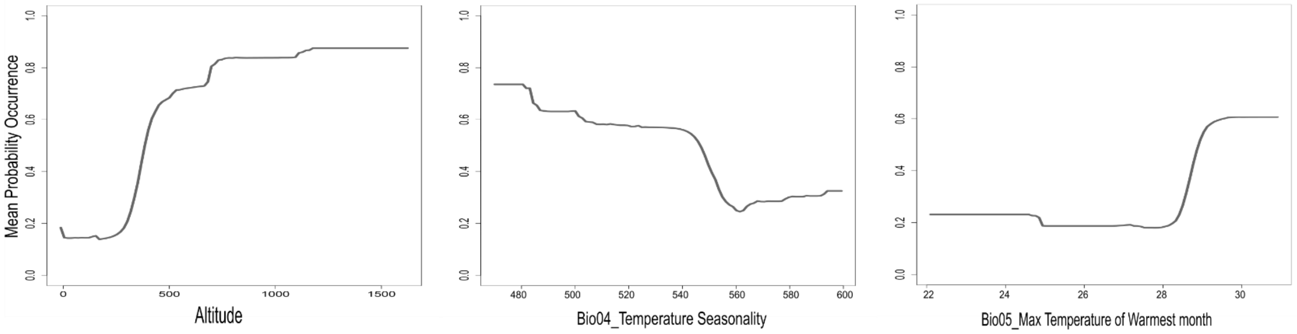
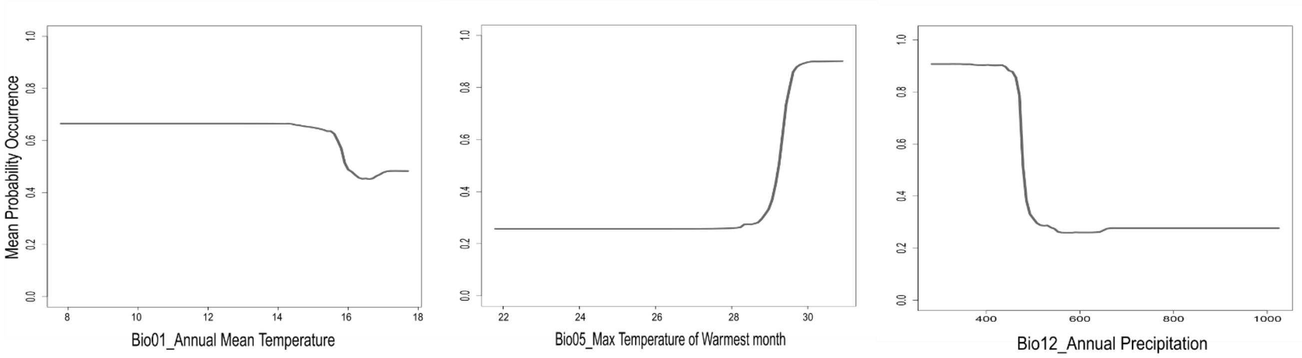


Figure 1. Response variables graphs for the three most important predictors as far as *Anacamptis papilionacea* var. *grandiflora*, *A. longicornu* and *Ophrys speculum* are concerned. The y- axis correspond to mean probability of presence, x- axis represent the variables values (mm for precipitation,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

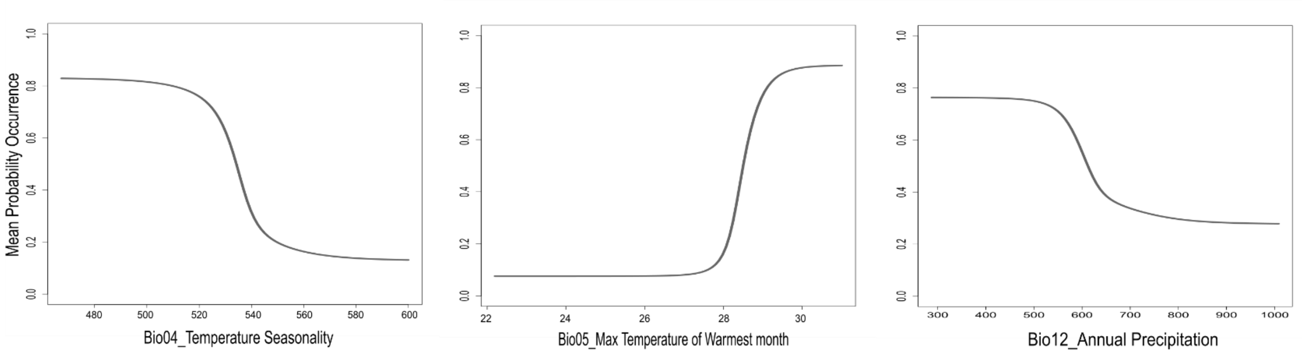
A. papilionacea



O. bombyliflora



S. lingua



S. parviflora

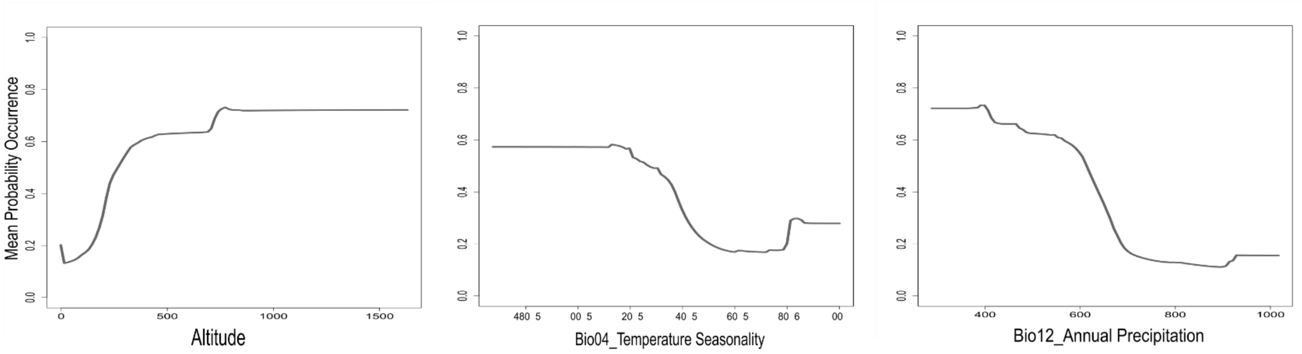
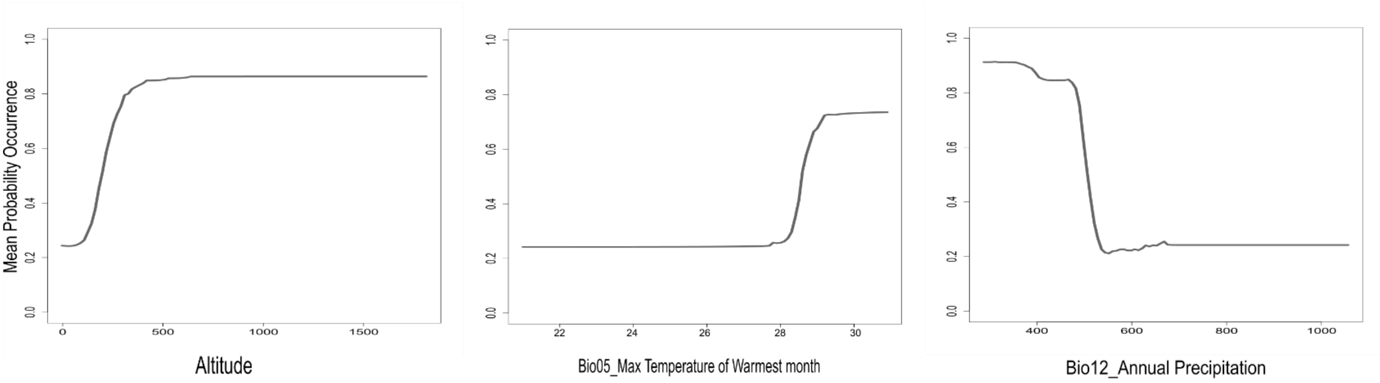


Figure 2. Response variables graphs for the three most important predictors as far as *Anacamptis papilionacea* var. *papilionacea*, *Ophrys bombyliflora*, *Serapias lingua* and *S. parviflora* are concerned. The y- axis correspond to mean probability of presence, x- axis represent the variables values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

O. morisii



O. tenthredinifera

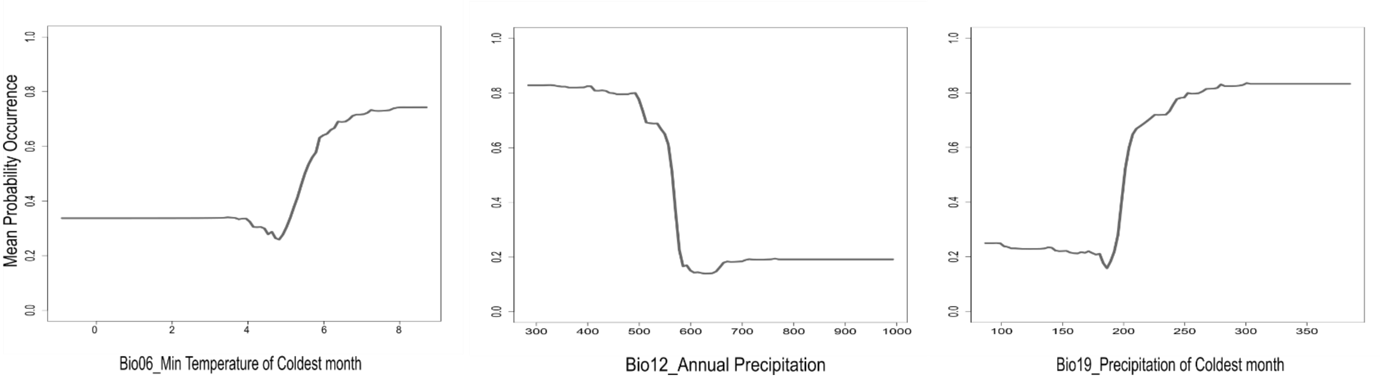
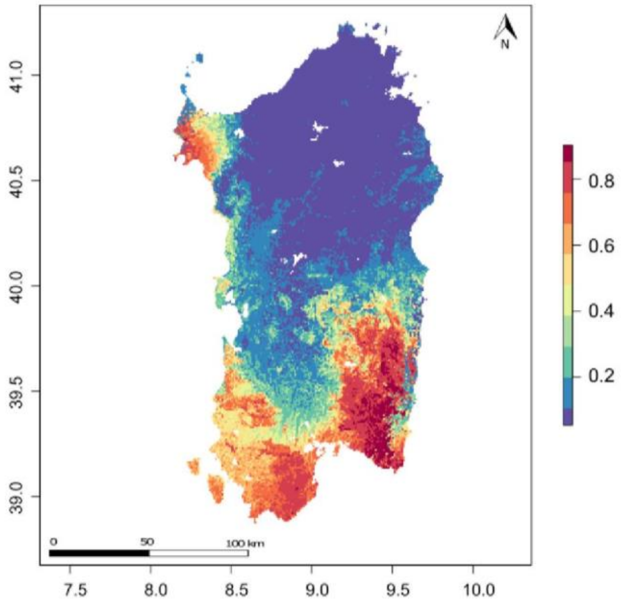


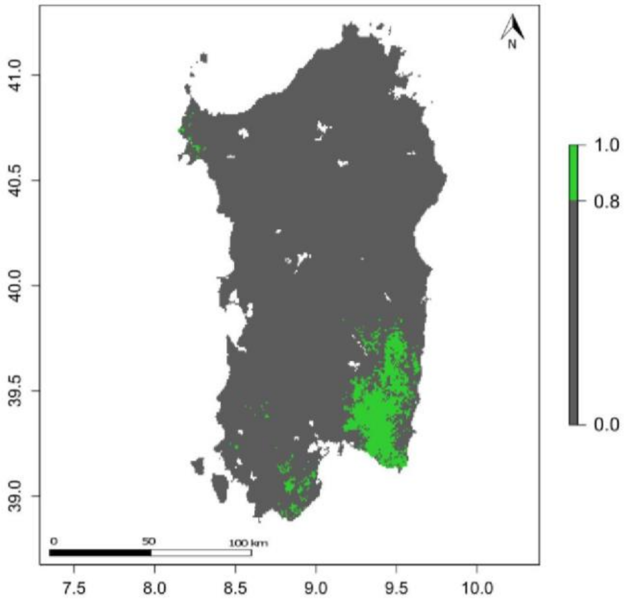
Figure 3. Response variables graphs for the three most important predictors as far as *Ophrys morisii* and *O. tenthredinifera* are concerned. The y- axis correspond to mean probability of presence, x- axis represent the variables values (mm for precipitation, °C for temperatures, % for seasonality).

a)

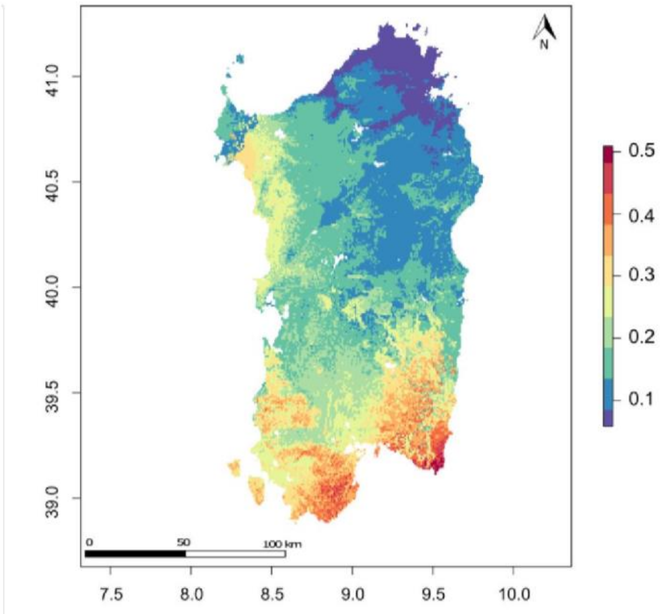
A. grandiflora

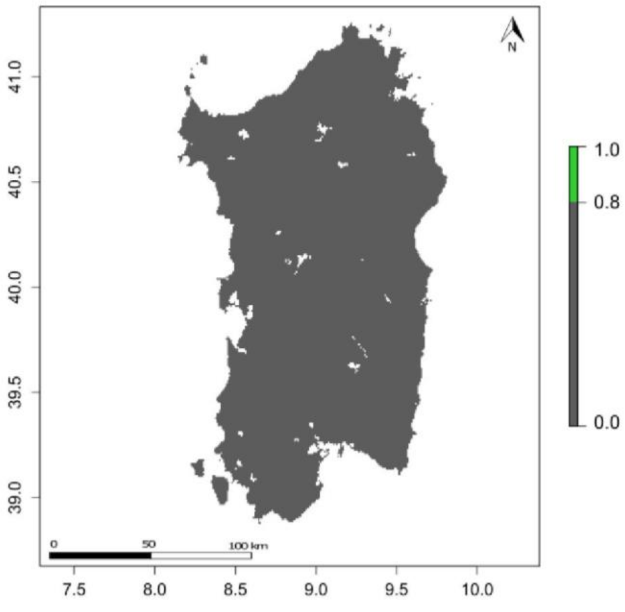
Present





Future

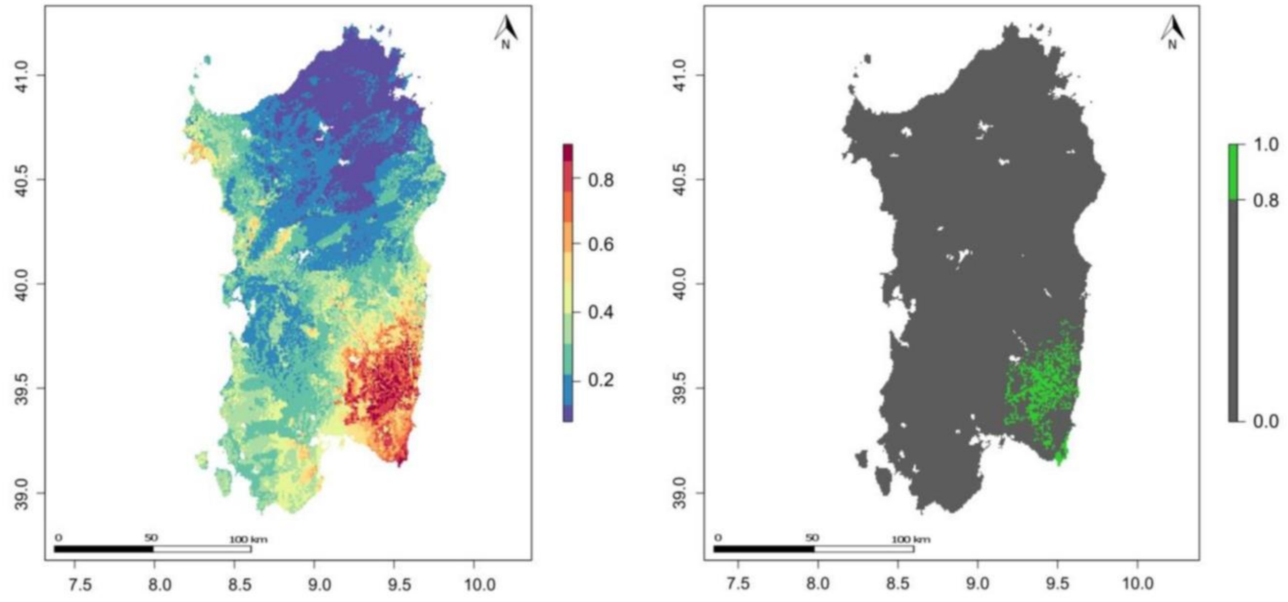




b)

A. longicornu

Present



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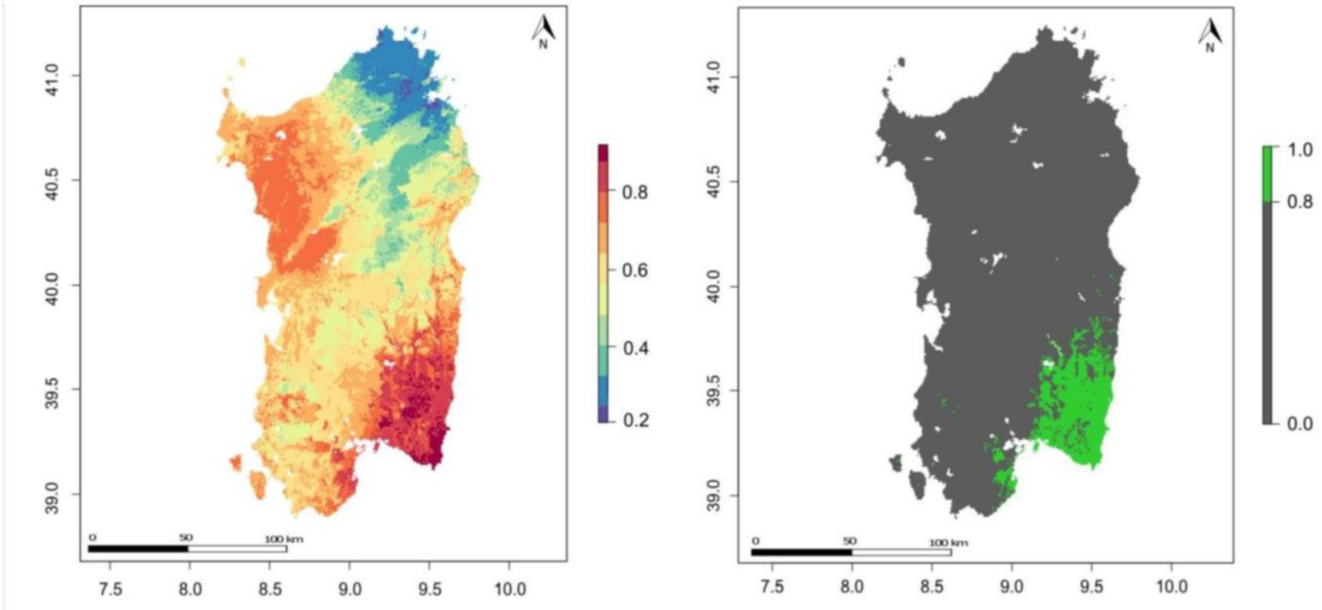
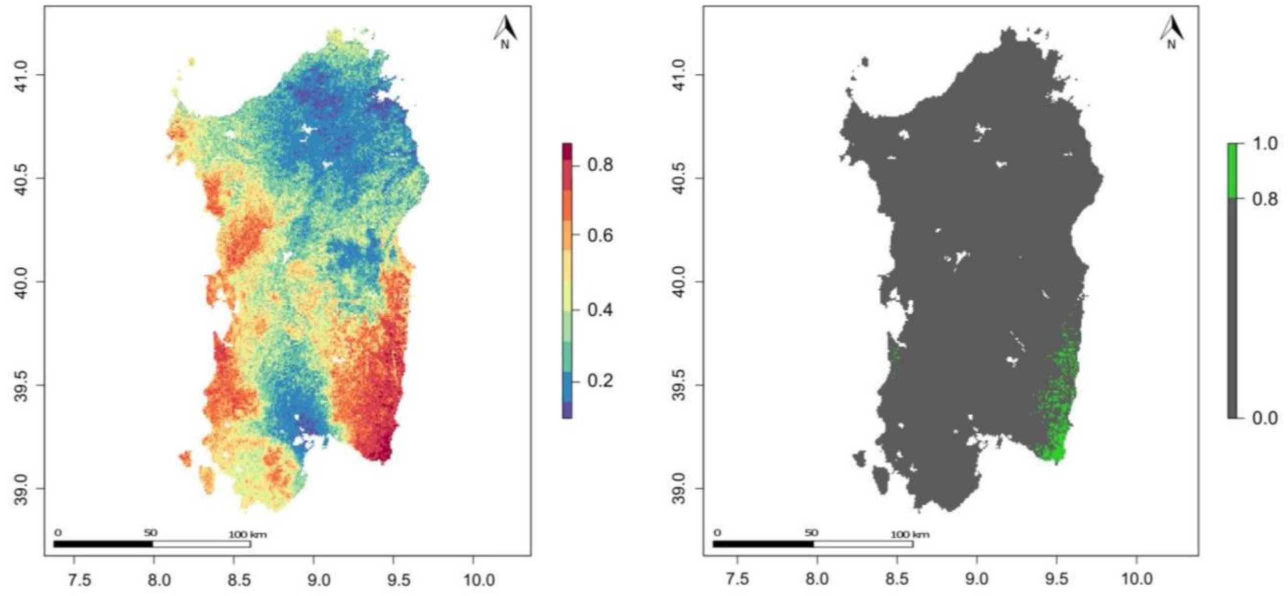


c)

S. lingua

Present



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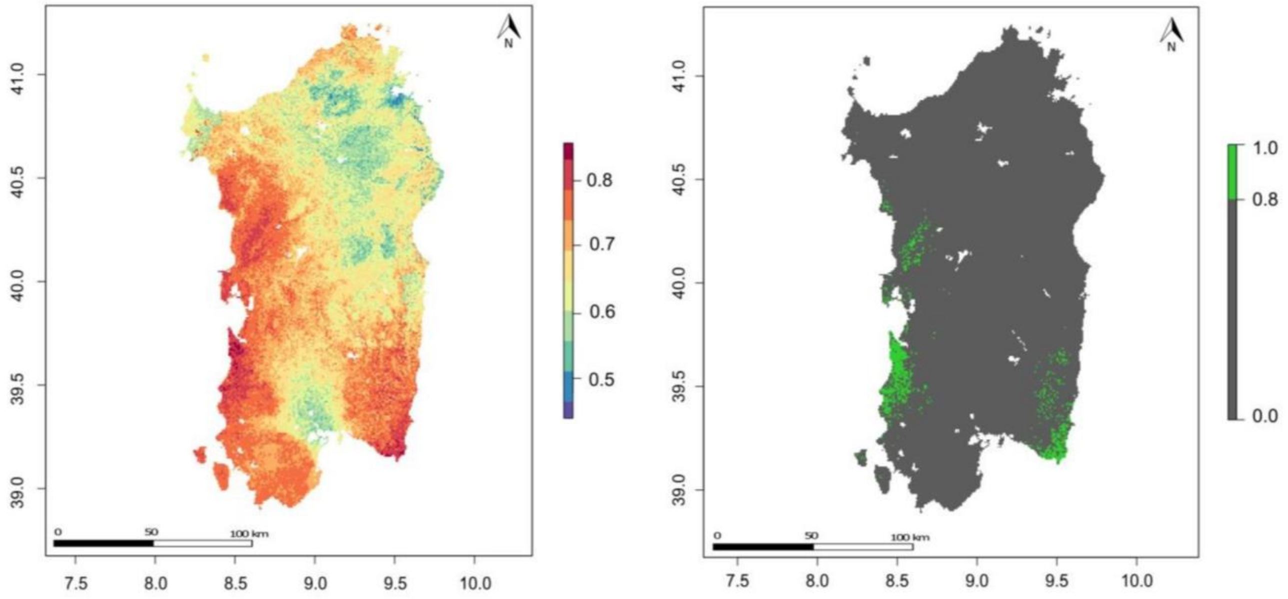
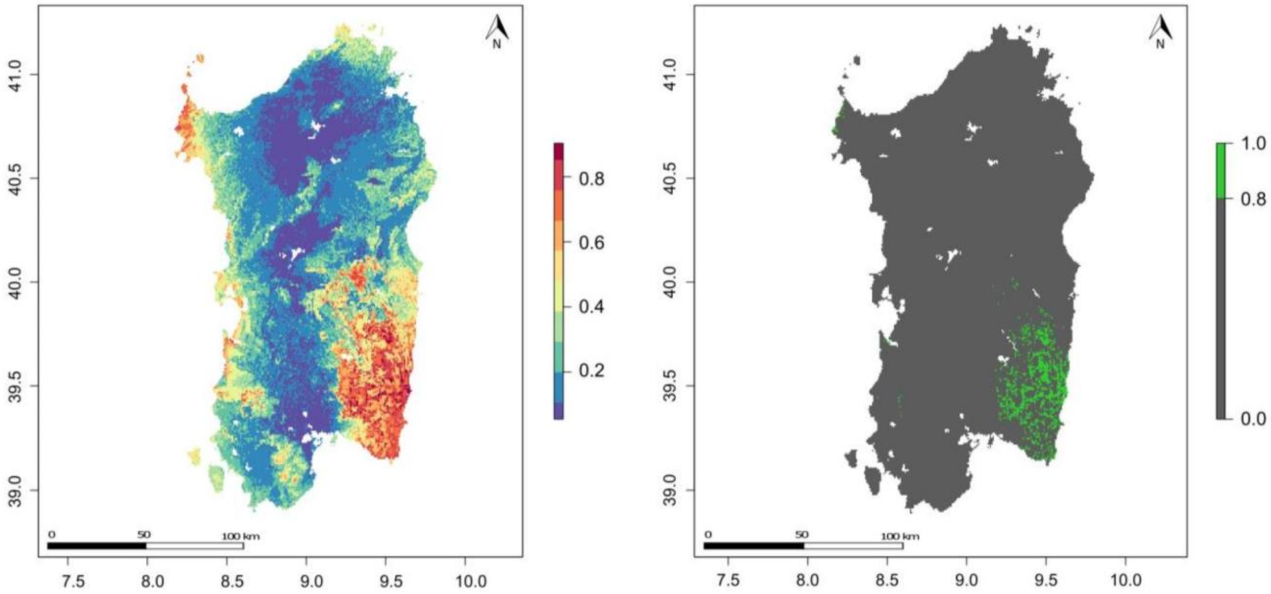


Figure 4. Suitability maps for *Anacamptis papilionacea* var. *grandiflora* (a), *A. longicornu* (b) and *Serapias lingua* (c). Left: continuous probability maps, ranging from 0- blue, minimum probability- to 1- red, maximum probability. Right: same probability maps have been catted to obtain presence-absence binary maps: probability above 0.8 is considered as potential presence (green) and under as potential absence (grey).

a)

A. papilionacea

Present



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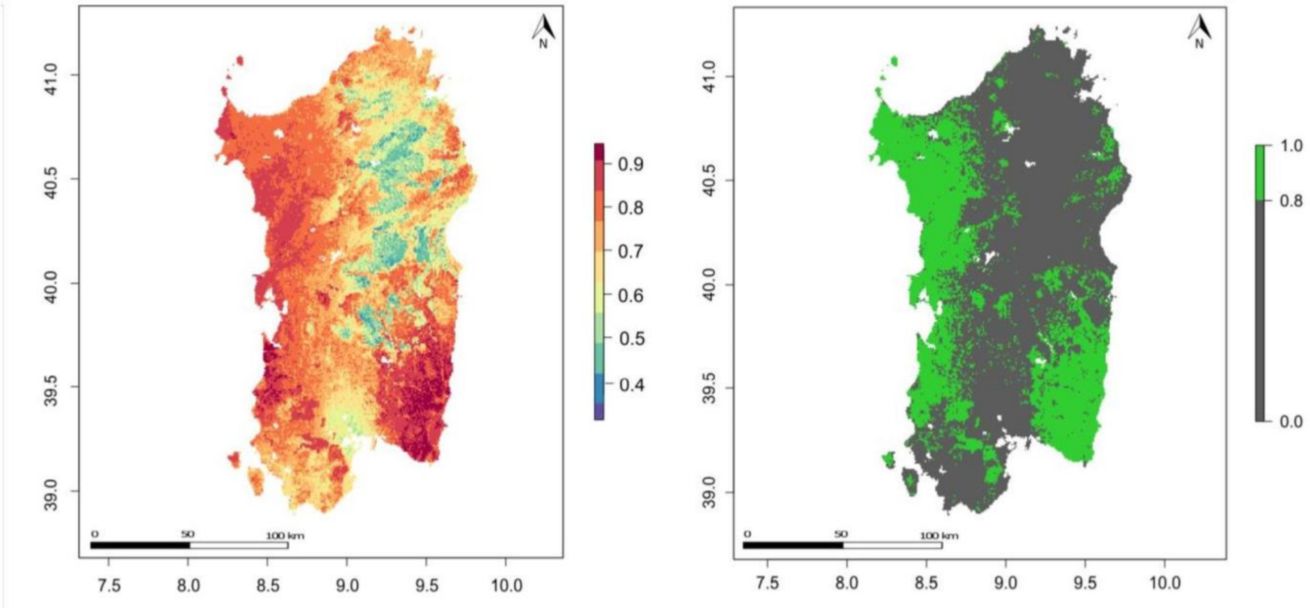
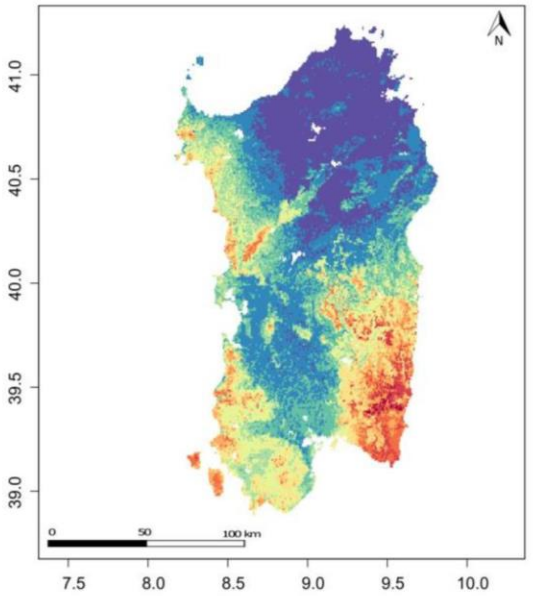
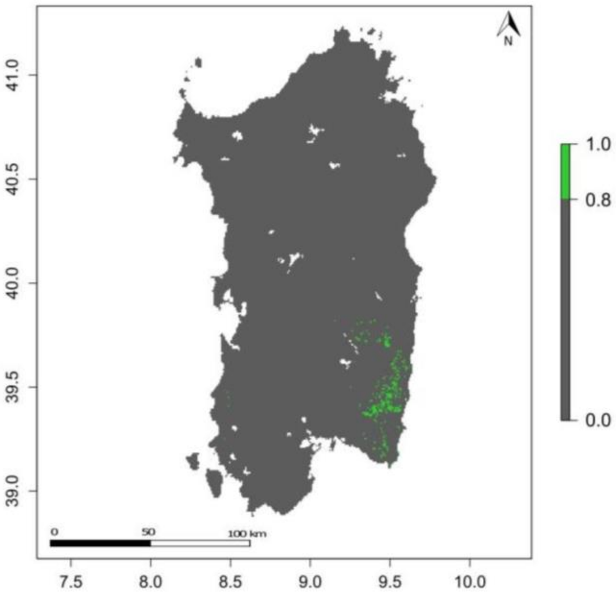


b)

S. parviflora

Present





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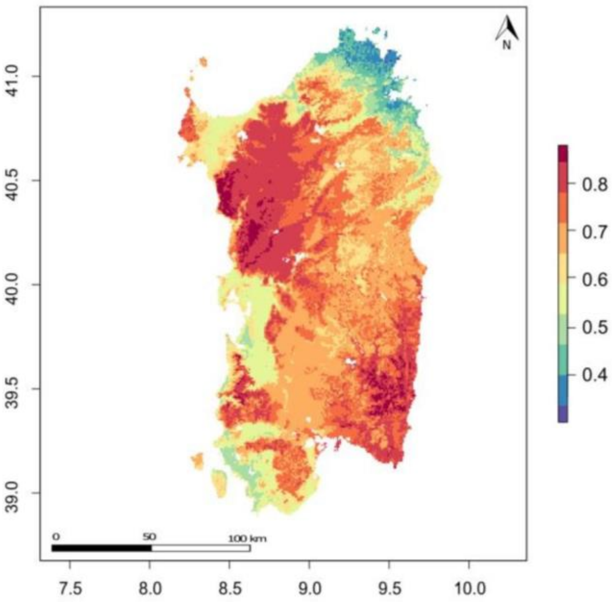
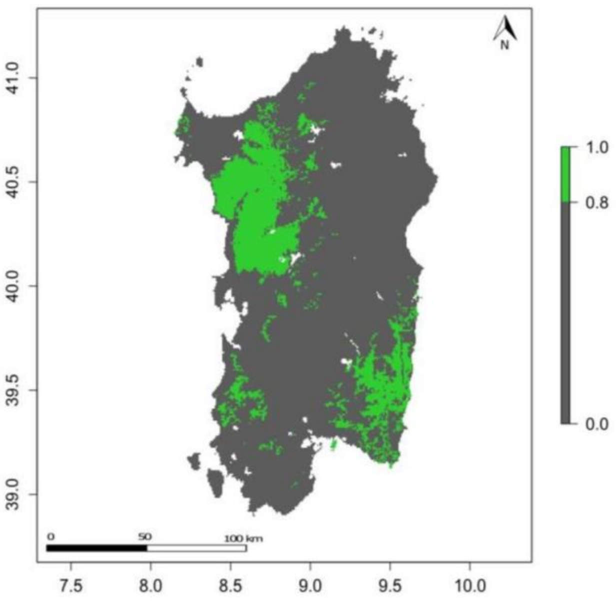
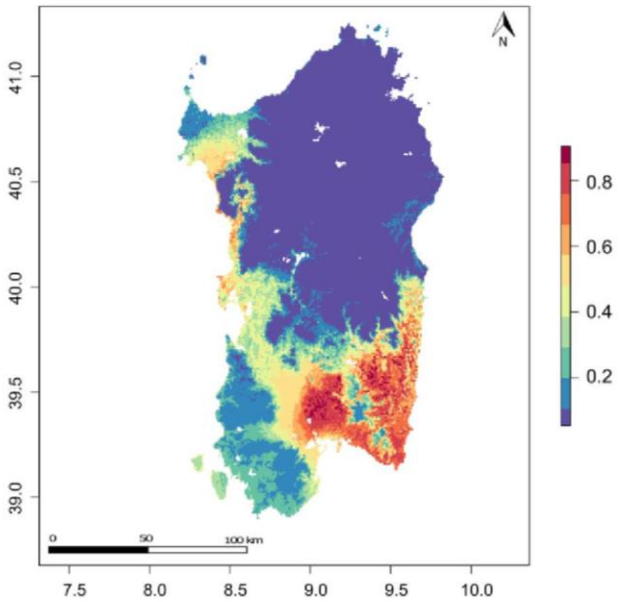


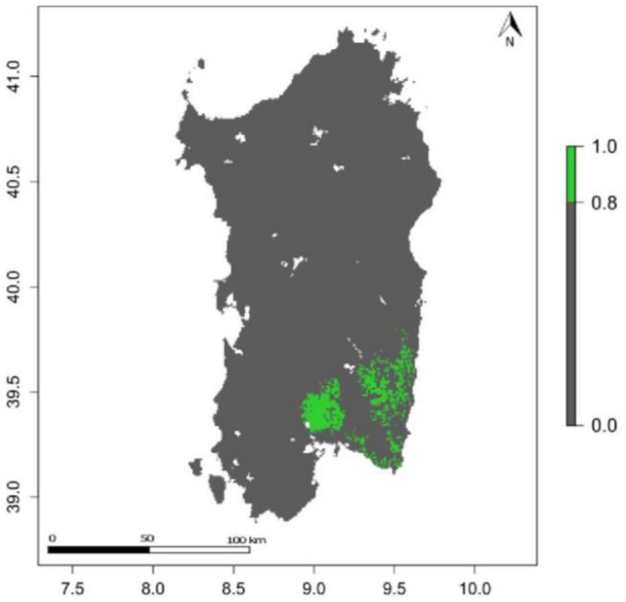


c)

O. bombyliflora

Present





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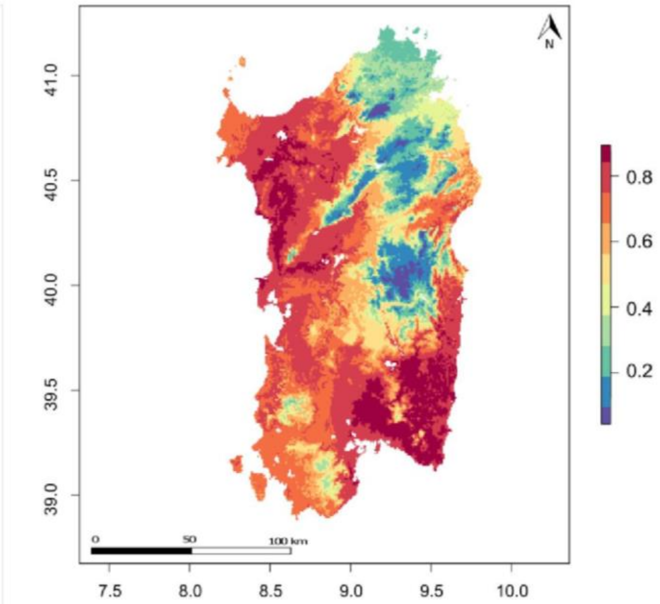
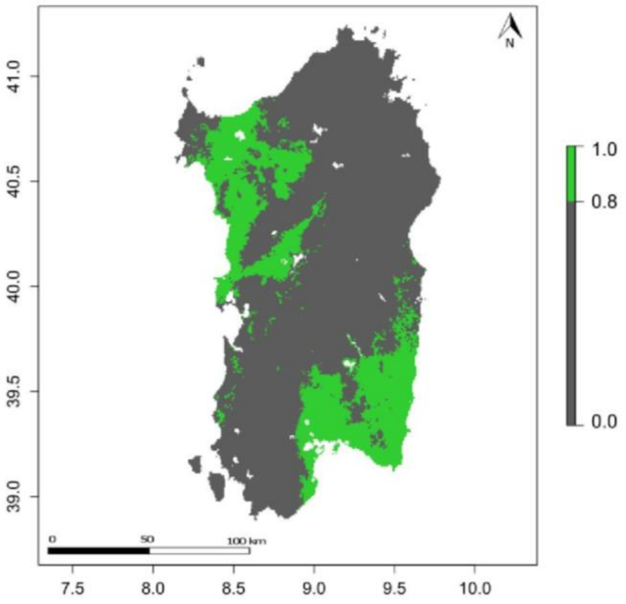
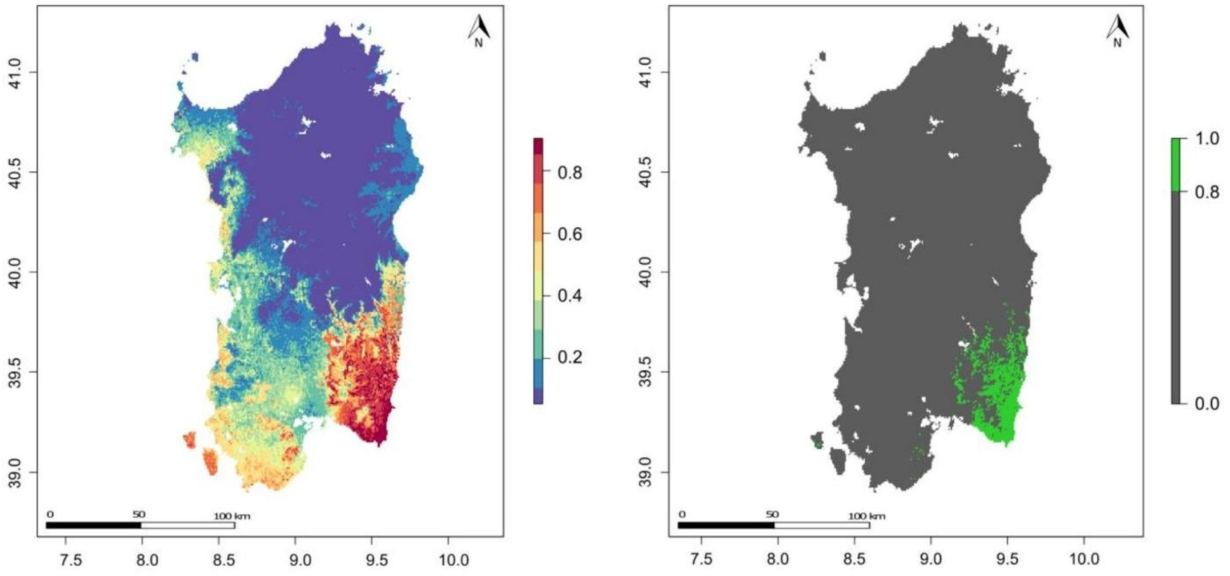




d)

O. morisii

Present



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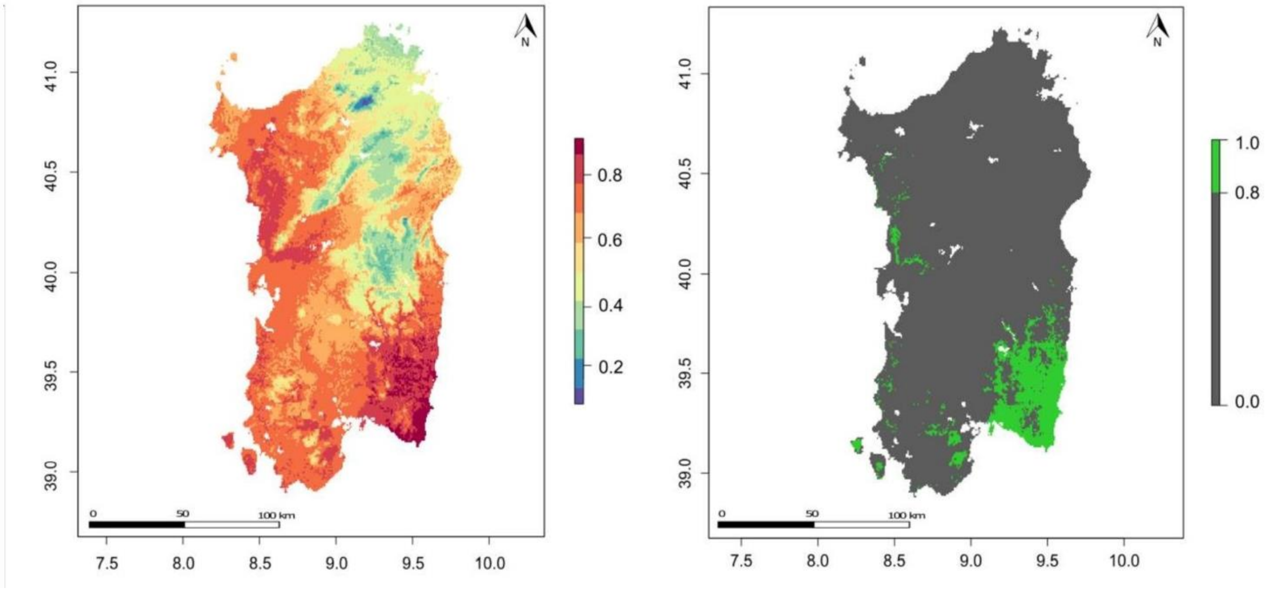
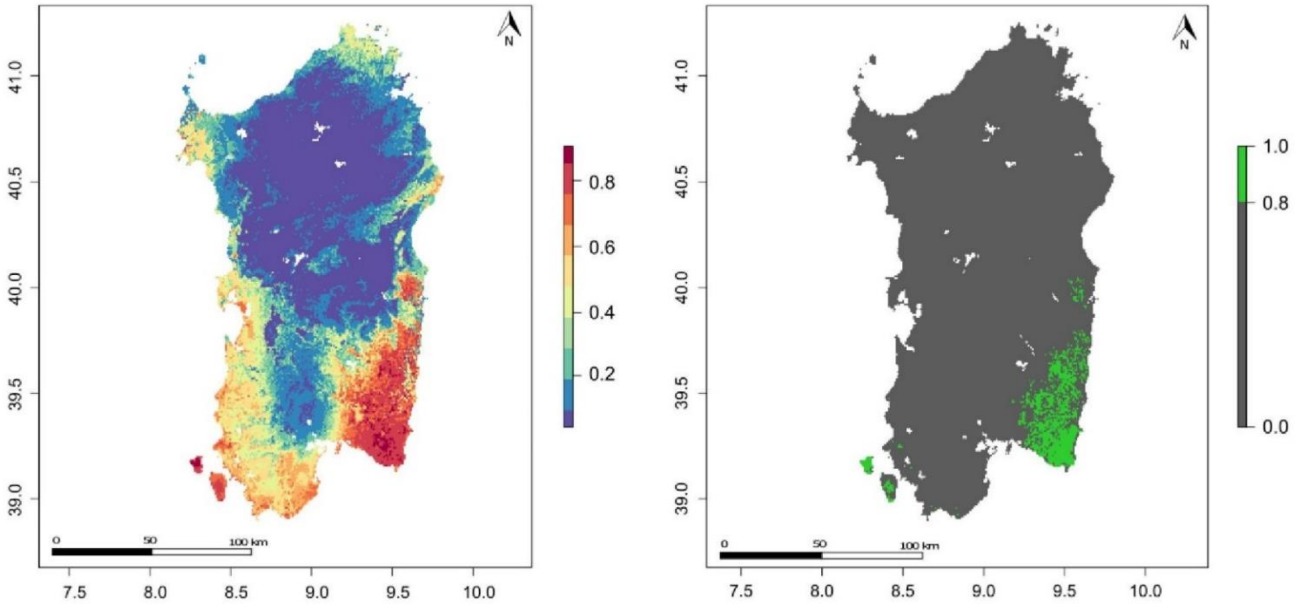


Figure 5. Suitability maps for *Anacamptis papilionacea* var. *papilionacea* (a), *Serapias parviflora* (b), *Ophrys bombyliflora* (c) and *O. morisii* (d). Left: continuous probability maps, ranging from 0- blue, minimum probability- to 1- red, maximum probability. Right: same probability maps have been catted to obtain presence- absence binary maps: probability above 0.8 is considered as potential presence (green) and under as potential absence (grey).

a)

O. tenthredinifera

Present



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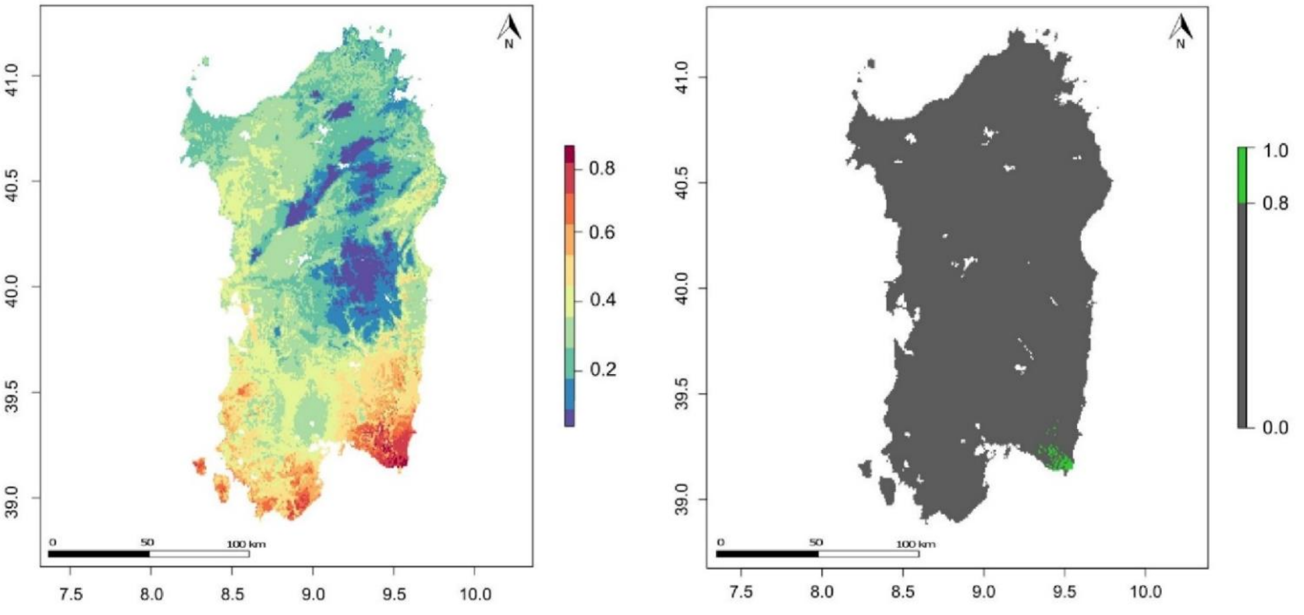
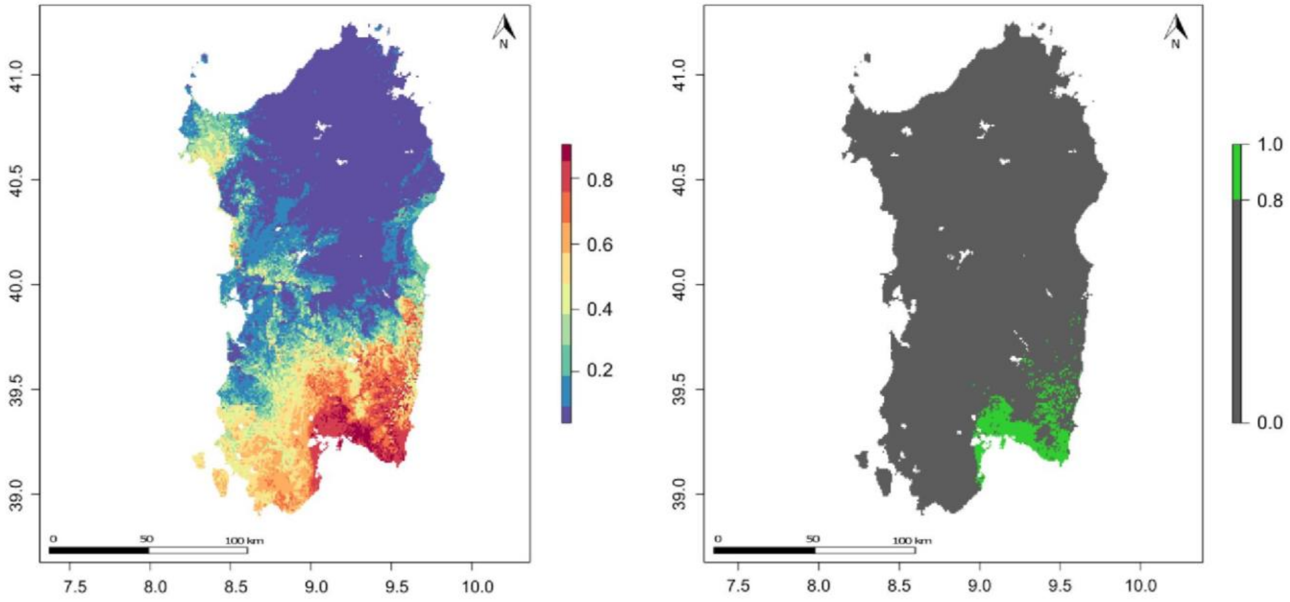


b)

O. speculum

Present



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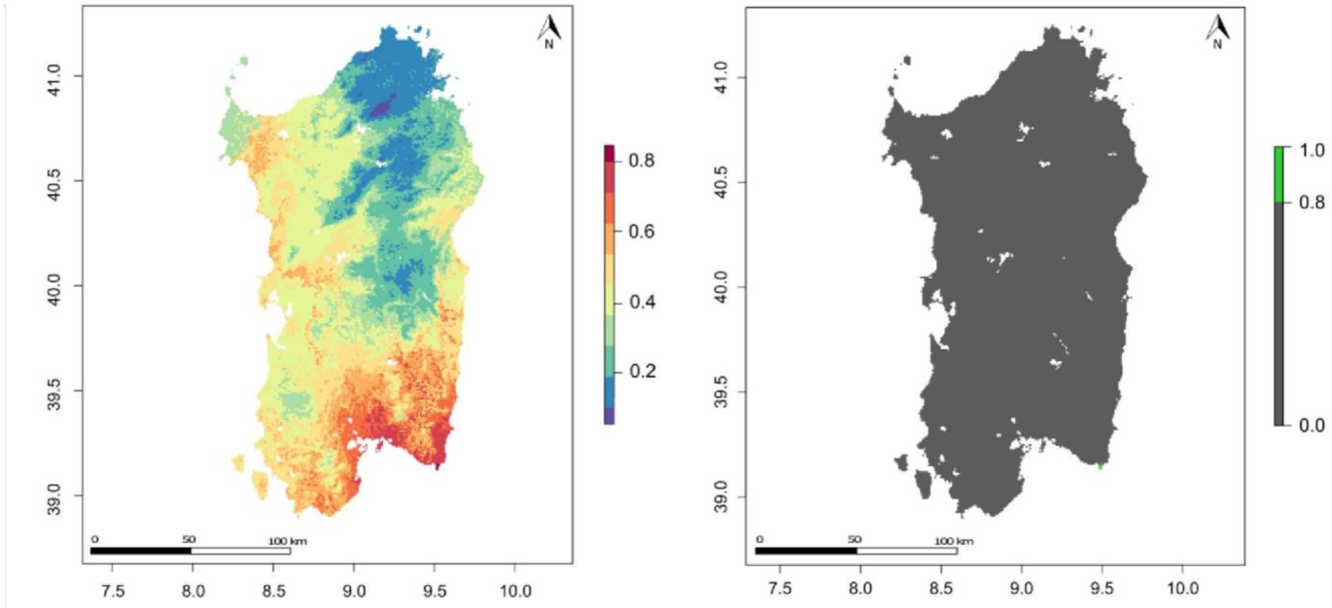

Figure 6. Suitability maps for *Ophrys tenthredinifera* (a) and *O. speculum* (b). Left: continuous probability maps, ranging from 0- blue, minimum probability- to 1- red, maximum probability. Right: same probability maps have been catted to obtain presence- absence binary maps: probability above 0.8 is considered as potential presence (green) and under as potential absence (grey).

Supplementary materials (on- line only)

Table S0. Occurrence dataset of the nine species modelled.

Species	**Lon DD**	**Lat DD**
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,37518	39,55422
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,33458	39,53078
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,60704	39,51427
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,43751	39,44389
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	8,89269	39,18865
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,33522	39,35472
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,19735	39,45729
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,42723	39,62615
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,33450	39,56115
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,55092	39,17841
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,20645	39,68135
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	8,97244	39,77478
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,18142	39,44241
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,16696	39,54161
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,30220	39,53274
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,42460	39,36023
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,29728	39,60220
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,41011	39,55045
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,54723	39,17687
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	8,58592	40,23871
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	8,44911	39,41710
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,14604	39,96021
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,19093	39,96443
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,67082	40,41013
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,17969	40,15961
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,26783	39,45713
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,15495	39,96967
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,61443	39,62534
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,53505	39,70844
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,62615	39,69071
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,55290	40,59927
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	8,73624	40,16081
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	9,00374	39,01925
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	8,49370	40,22948
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	8,69659	40,13797
Anacamptis longicornu (Poir.) R.M. Bateman, Pridgeon & M.W. Chase	8,24613	40,66205
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Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	9,08351	39,29603
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Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	9,18613	39,35423
Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	9,39418	39,60225
Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	9,43054	39,15239
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Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	9,38590	39,54631
Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	9,53406	39,18210

Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	8,46919	39,24760
Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	8,59299	39,34346
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Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	9,49080	39,59339
Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	9,42971	39,68591
Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	9,08105	39,88182
Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	8,49030	40,23313
Anacamptis papilionacea (L.) R.M. Bateman, Pridgeon & M.W. Chase var. *grandiflora*	8,24066	40,69748
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Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,60909	39,49881
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,37480	39,55394
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,32401	39,35135
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,19391	39,44406
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,42152	39,60026
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,31226	39,54111
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,52127	39,34838
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,20529	39,44619
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,19256	39,52532
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,57546	39,37525
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,40689	39,26757
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	8,59127	39,34598
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	8,44311	39,42816
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,16798	39,97689
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,30251	40,06021
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Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,64601	39,61574
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Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,45237	39,73616
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Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	8,48154	40,21614
Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,09204	41,10967
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Anacamptis papilionacea (L.) R. M. Bateman, Pridgeon & M. W. Chase var. *papilionacea*	9,51610	39,43102
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Ophrys bombyliflora Link	9,14797	39,20570
Ophrys bombyliflora Link	9,55394	39,32126
Ophrys bombyliflora Link	9,18199	39,34621
Ophrys bombyliflora Link	9,16906	39,42365
Ophrys bombyliflora Link	9,37926	39,59152
Ophrys bombyliflora Link	9,05265	39,58654
Ophrys bombyliflora Link	9,15067	39,51916
Ophrys bombyliflora Link	9,01123	39,47405
Ophrys bombyliflora Link	9,05353	39,35587

Ophrys bombyliflora Link	9,62011	39,53539
Ophrys bombyliflora Link	9,63496	39,60054
Ophrys bombyliflora Link	9,39285	39,68880
Ophrys bombyliflora Link	8,49941	40,22392
Ophrys bombyliflora Link	8,39197	40,04016
Ophrys bombyliflora Link	8,47592	40,21461
Ophrys bombyliflora Link	9,43479	39,70479
Ophrys morisii (Martelli) Soò	9,32025	39,61138
Ophrys morisii (Martelli) Soò	9,20264	39,35201
Ophrys morisii (Martelli) Soò	8,89129	38,94454
Ophrys morisii (Martelli) Soò	9,43844	39,62829
Ophrys morisii (Martelli) Soò	9,44436	39,19760
Ophrys morisii (Martelli) Soò	9,60358	39,30418
Ophrys morisii (Martelli) Soò	9,20934	39,44858
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Ophrys morisii (Martelli) Soò	9,42077	39,55300
Ophrys morisii (Martelli) Soò	9,50908	39,20643
Ophrys morisii (Martelli) Soò	8,49197	39,26944
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Ophrys morisii (Martelli) Soò	9,41927	39,70727
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Ophrys morisii (Martelli) Soò	8,50106	40,22609
Ophrys neglecta Parl.	9,35611	39,55558
Ophrys neglecta Parl.	9,52765	39,37271
Ophrys neglecta Parl.	9,60410	39,46774
Ophrys neglecta Parl.	9,54264	39,61208
Ophrys neglecta Parl.	8,83038	38,93704
Ophrys neglecta Parl.	9,32720	39,34476
Ophrys neglecta Parl.	9,21295	39,46406
Ophrys neglecta Parl.	9,28583	39,51572
Ophrys neglecta Parl.	9,17816	39,45350
Ophrys neglecta Parl.	9,17617	39,50938
Ophrys neglecta Parl.	9,38815	39,27773
Ophrys neglecta Parl.	9,39619	39,51628
Ophrys neglecta Parl.	8,48287	39,26522
Ophrys neglecta Parl.	8,25209	39,13051
Ophrys neglecta Parl.	8,59710	39,35037
Ophrys neglecta Parl.	8,59870	39,46992
Ophrys neglecta Parl.	9,62257	40,40899
Ophrys neglecta Parl.	9,63703	40,43678
Ophrys neglecta Parl.	9,62136	39,62577
Ophrys neglecta Parl.	9,43570	39,70471
Ophrys neglecta Parl.	9,63088	39,90108

Ophrys neglecta Parl.	9,41625	39,71241
Ophrys neglecta Parl.	8,50654	40,25281
Ophrys neglecta Parl.	9,00446	39,02836
Ophrys neglecta Parl.	8,55797	39,89705
Ophrys neglecta Parl.	8,50761	40,25902
Ophrys neglecta Parl.	9,09378	41,10136
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Ophrys speculum Link	9,30351	39,46922
Ophrys speculum Link	9,29112	39,63168
Ophrys speculum Link	9,14721	39,21546
Ophrys speculum Link	9,20027	39,34311
Ophrys speculum Link	8,83391	38,93682
Ophrys speculum Link	9,40772	39,60851
Ophrys speculum Link	9,52688	39,20380
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Ophrys speculum Link	9,00358	39,47676
Ophrys speculum Link	9,07256	39,34608
Ophrys speculum Link	8,59486	39,34796
Ophrys speculum Link	9,63511	39,55771
Ophrys speculum Link	9,65309	39,63604
Ophrys speculum Link	9,43589	39,71189
Ophrys speculum Link	8,49942	40,23619
Ophrys speculum Link	8,49942	40,23619
Ophrys speculum Link	8,51019	40,07908
Ophrys speculum Link	9,43589	39,71189
Ophrys speculum Link	8,95782	39,72048
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Serapias lingua L.	9,18028	39,44948
Serapias lingua L.	8,93992	39,80906
Serapias lingua L.	9,42741	39,63900
Serapias lingua L.	9,30030	39,53996
Serapias lingua L.	9,57646	39,57561
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Serapias lingua L.	8,72672	40,23914
Serapias lingua L.	9,21085	40,17693
Serapias lingua L.	9,76714	40,51709
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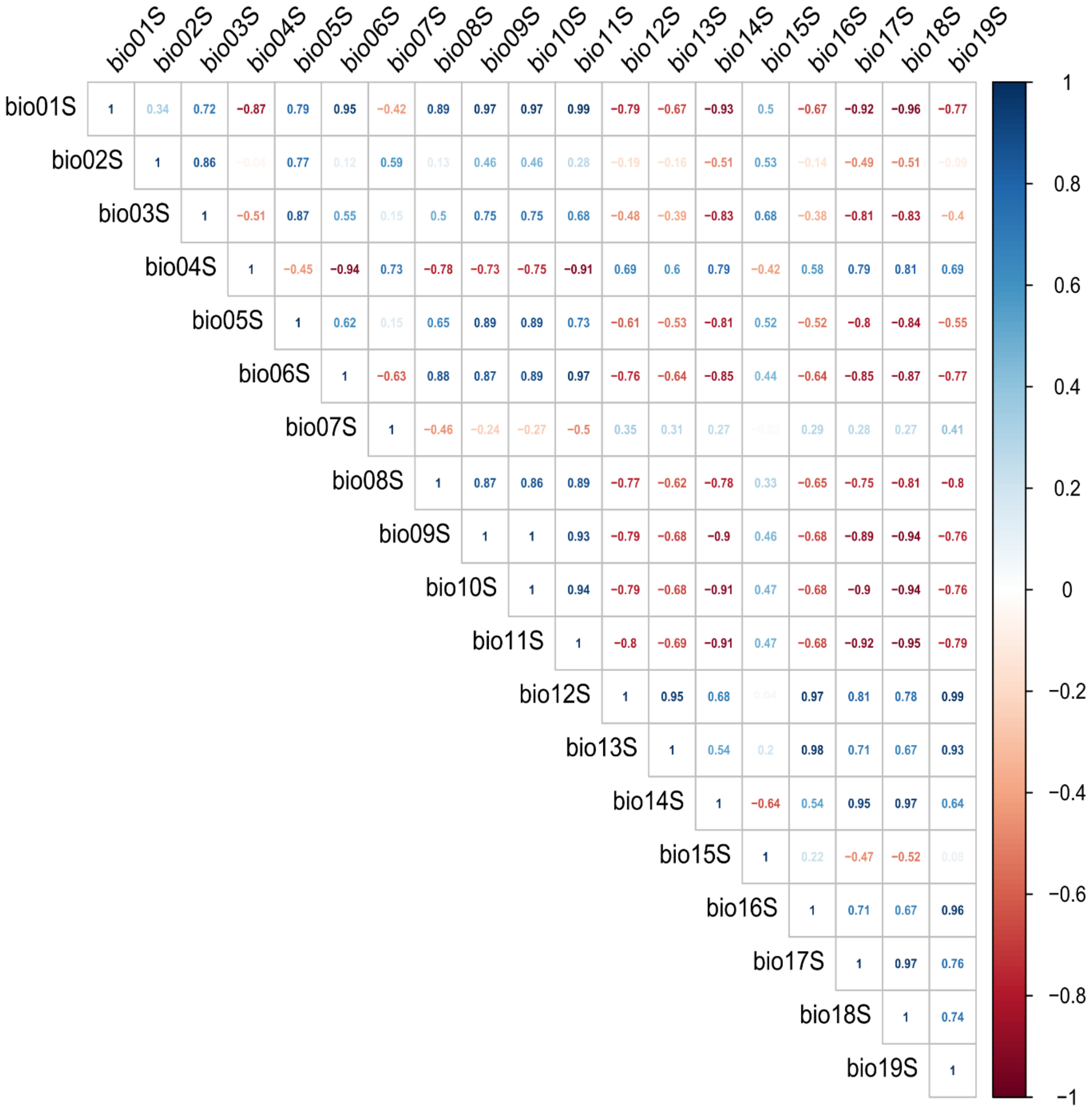
Serapias lingua L.	9,44321	39,71739
Serapias lingua L.	9,57016	39,62844
Serapias lingua L.	8,50289	40,23058
Serapias lingua L.	9,12481	39,85871
Serapias lingua L.	8,51197	40,07931
Serapias lingua L.	8,73608	40,16576
Serapias lingua L.	8,50872	40,22785
Serapias lingua L.	9,09155	41,10762
Serapias parviflora Parl.	9,37489	39,55377

Serapias parviflora Parl.	8,46725	39,27553
Serapias parviflora Parl.	9,15352	39,20449
Serapias parviflora Parl.	8,83161	38,93901
Serapias parviflora Parl.	8,49396	39,45386
Serapias parviflora Parl.	9,29400	39,62846
Serapias parviflora Parl.	9,57150	39,63613
Serapias parviflora Parl.	8,69955	40,23948
Serapias parviflora Parl.	9,14499	39,99041
Serapias parviflora Parl.	9,61573	39,63027
Serapias parviflora Parl.	9,42106	39,81184
Serapias parviflora Parl.	9,43699	39,72611
Serapias parviflora Parl.	9,54900	39,63938
Serapias parviflora Parl.	9,12481	39,85871
Serapias parviflora Parl.	8,50778	40,07525
Serapias parviflora Parl.	8,49751	40,26398



	bio01S	bio02S	bio03S	bio04S	bio05S	bio06S	bio07S	bio08S	bio09S	bio10S	bio11S	bio12S	bio13S	bio14S	bio15S	bio16S	bio17S	bio18S	bio19S
bio01S	1	0.34	0.72	−0.87	0.79	0.95	−0.42	0.89	0.97	0.97	0.99	−0.79	−0.67	−0.93	0.5	−0.67	−0.92	−0.96	−0.77
bio02S		1	0.86	−0.04	0.77	0.12	0.59	0.13	0.46	0.46	0.28	−0.19	−0.16	−0.51	0.53	−0.14	−0.49	−0.51	−0.09
bio03S			1	−0.51	0.87	0.55	0.15	0.5	0.75	0.75	0.68	−0.48	−0.39	−0.83	0.68	−0.38	−0.81	−0.83	−0.4
bio04S				1	−0.45	−0.94	0.73	−0.78	−0.73	−0.75	−0.91	0.69	0.6	0.79	−0.42	0.58	0.79	0.81	0.69
bio05S					1	0.62	0.15	0.65	0.89	0.89	0.73	−0.61	−0.53	−0.81	0.52	−0.52	−0.8	−0.84	−0.55
bio06S						1	−0.63	0.88	0.87	0.89	0.97	−0.76	−0.64	−0.85	0.44	−0.64	−0.85	−0.87	−0.77
bio07S							1	−0.46	−0.24	−0.27	−0.5	0.35	0.31	0.27	−0.03	0.29	0.28	0.27	0.41
bio08S								1	0.87	0.86	0.89	−0.77	−0.62	−0.78	0.33	−0.65	−0.75	−0.81	−0.8
bio09S									1	1	0.93	−0.79	−0.68	−0.9	0.46	−0.68	−0.89	−0.94	−0.76
bio10S										1	0.94	−0.79	−0.68	−0.91	0.47	−0.68	−0.9	−0.94	−0.76
bio11S											1	−0.8	−0.69	−0.91	0.47	−0.68	−0.92	−0.95	−0.79
bio12S												1	0.95	0.68	0.04	0.97	0.81	0.78	0.99
bio13S													1	0.54	0.2	0.98	0.71	0.67	0.93
bio14S														1	−0.64	0.54	0.95	0.97	0.64
bio15S															1	0.22	−0.47	−0.52	0.08
bio16S																1	0.71	0.67	0.96
bio17S																	1	0.97	0.76
bio18S																		1	0.74
bio19S																			1

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

<u>**Section 3**</u>

Morphological plasticity and reproductive strategies: the strange case of Dr. *Pterygiopsis affinis* and Mr. *Pterygiopsis "sorediata"*.

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(<u>In Preparation</u>)

Introduction

While the stratified organization of lichen thallus is known to occur since the lower Devonian (Honegger et al., 2013), the most primitive lichens had a crustose, unorganized thallus, not well differentiated, without an actual stratification, with blue algae as photosynthetic partners (Dal Forno et al., 2013). These primitive lichens, still occurring in many environments, are normally crustose cyanolichens, and usually require liquid water to allow blue algae to efficiently photosynthesize and fix nitrogen. They normally adopt a pioneer strategy, tolerate strong environmental stresses, and grow on mineral soil and rocks, which are poor in nutrients. Furthermore, they can stand inconstant water availability, and dominate the landscapes in mountain and desert environments, which are normally characterized by high solar irradiation, and random water dripping.

These cyanolichens have an extreme phenotypic plasticity. Since their growth dynamics are strongly influenced by environmental conditions, the infraspecific phenotypic variability can range from “typical” to very uncommon forms, such as chimeras (Henskens et al., 2012). They can also be associated to other photosynthetic partners than cyanobacteria, such as green algae, and/or use different reproductive strategies, in order to widen their ecological range. Because of their high variability, some groups are difficult to collocate taxonomically, and the delimitation of infrageneric taxa is often debatable.

One of most arguing taxa is the family Lichinaceae, which includes crustose cyanolichens, with varying morphology and different photobionts. One of the most complex genera among the Lichinaceae is *Pterygiopsis*, which counts 20 infrageneric, mainly epilithic, from crustose to sub-squamulose or umbilicate taxa (Mycobank database, URL: http://www.mycobank.org/, Robert et al., 2013). Some of these taxa are known from the type material only, and thus their interpretation is often problematic. *P. affinis* (Massal.) Henssen. is the sole species of the genus known to occur in Italy. It is quite rare, and grows on calcareous and dolomitic outcrops throughout the country.

During a field survey in the 80’s, specimens of a lichen very similar to *P. affinis* were collected. However, they had a sorediate surface, and a clearly thicker thallus. Some of them only had rare fruiting bodies.

Taxonomic classification of lichens is traditionally based on anatomy and morphology, and in particular on characteristics of the fruiting bodies. However, there are several taxa which reproduce by vegetative propagules only. This issue is faced normally by treating sexual and asexual specimens as separate taxa. However, according to the hypothesis of species pairs (Poelt, 1970; 1972), it is possible that the same species could have different reproductive strategies. According to this hypothesis, fertile taxa are treated as primary, and sterile taxa (reproducing by vegetative propagules) as secondary species. It has been demonstrated that often lichens adopt asexual reproductive strategies when driven by of the limited availability of free-living photobionts. Since the mycobiont is often strongly selective as far as the photobionts are concerned (Rikkinen, 2013), the occurrence of cyanolichens in many environments can be strongly limited by the circumstantial availability of appropriate cyanobionts (Belinchón et al., 2014). Hence, several cyanolichens do facilitate the dispersal of the whole consortium by producing vegetative propagules (soredia, in the most primitive organizations). In lichens, normally sorediate taxa have a different (usually wider) ecological and distributional pattern than their sexual counterparts (Mattsson and Lumbsch, 1989). On the other hand, most of sexually reproducing taxa are distributed in regions corresponding to their speciation center (e.g. Cetrelia, Randlane and Saag, 2004).

As a support to taxonomic or evolutionary investigations, species distribution models (SDMs) may be helpful in exploring and understanding possible differences between taxa, when combined with morphological, chemical or molecular data (Martellos et al., 2014; Graham et al., 2004). Climatic niche modelling techniques are often used to outline biogeographical patterns, describing groups of organisms in terms of ecological response (e. g. Ellis et al., 2007; Wiersma and Skinner, 2011; Bendiksby et al., 2014). However, a need to extend ecological biogeographical studies to a wider spectrum of lichen diversity has been raised (Leavitt and Lumbsch, 2016).

This study aims at defining the taxonomic position of the sorediate specimens of *Pterygiopsis affinis* s.l. collected in Italy, clarifying whether the reproductive strategy, which normally provides a solid set of characters for taxonomical purposes, can be used in the case of this cyanolichen for delimiting two different taxa. Furthermore, it aims at depicting the climatic niche of the sorediate and non sorediate specimens of *P. affinis* s.l. by mean of ecological niche models, in order to support evidences obtained by the classic morpho-anatomical approach.

Material and methods

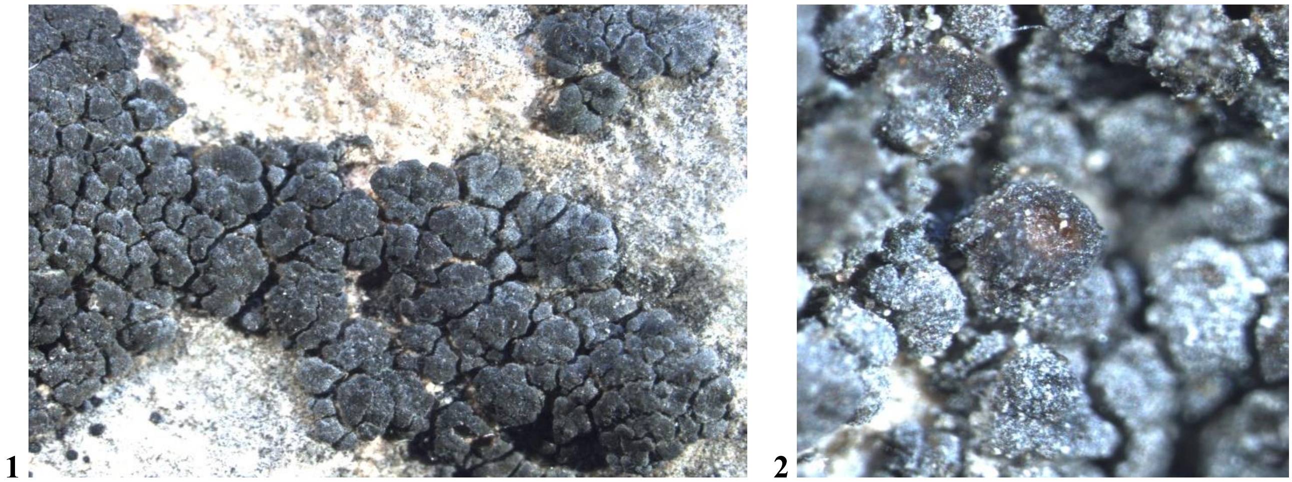
Pterygiopsis affinis

P. affinis is a rare epilithic lichen, which tolerates high solar radiation and prolonged drought. It grows on south-exposed rocks, often along seepage tracks. It has a crustose thallus, blackish to dark grey, placodioid, with effigurate margin (photos 1-2), fixed to substrate through a gelatinous matrix (Massalongo, 1853; Henssen, 1963; 1979). Thallus organization is pseudoparenchimatic, with fan-disposed hyphae. The photobiont is a chorococcoid, unicellular cyanobacterium of the genus *Gloeocapsa*, with cells folded into a yellowish-dark mucilaginous envelope. According to Massalongo (1853), apothecia are lecanorine, arising from pycnidia (Henssen, 1963). They are round, concave, with proper margin and a dark-reddish disk, sinked into the thallus. Asci are thickened at the top, multi-spored, with hyaline, sub-globose to broadly ellipsoid ascospores, ca. 6-12 × 3-6 µm. Hymenium is hyaline, with paraphyses in the marginal zone.

Massalongo (1855) divided the species *Enchylium affine* in the two varieties:

- *E. affine* var. *pulvinatum*, with thallus surface characterized by outward, pruinose, dark granules more densely aggregated and by the absence of apothecia, found on oolitic rocks, very abundant on pre-alps near Verona;
- *E. affine* var. *melanophaeum*, with thallus made of incoherent granulations, vaguely similar to little furfuraceous warts, strongly dark both when wet or dry, and apothecia, with ascii and spores as described in the typical form, found on dolomite rocks in all the surroundings of Verona.

However, Massalongo later revise his idea of two infraspecific taxa (1856), since, he explained, the material he had was sterile.



Photos 1-2: thallus and apothecia (respectively) of *Pterygiopsis affinis* (samples: 312 A- B, *Enchylium affine*, Herb Massal., HbTO).

Study area

Italian peninsula is situated in the Mediterranean basin, with an area of 324 000 km²: the north western border is signed by the Alps, while the peninsular portion face Mediterranean Sea, with a coastal line developing in 7 456 km (Ligurian sea, Tirrenian sea, Ionian sea e Adriatic sea).

Italian territory is constituted for the 41,6% of hills, mainly center- south or prealpine pedemountain, with different origins (sedimentary, morainic, volcanic); 35,2% of mountains, Alps, of Mesozoic and Cenozoic origin, and Apennines, originated in Oligocene; and 23,2% of plain, main is the Po alluvial plain.

Given the latitude extension and mountains orientation, and their interaction, as barriers, with the humid air masses, the area has peculiar ecological characteristics.

Thank to its heterogeneity, Italy has been classified on climatic and biogeographic basis (Blasi et al., 2014) in 2 Divisions (Temperate and Mediterranean climate), and 7 Provinces (biogeography: alpine, Po plain, Apenninic, Tirrenian, Adriatic, Illiric, Ligurian): these divisions, with their climate, are detailed in Supplementary material S0.

Field surveys

Several field surveys were carried on since 2016, in order to collect fresh material of both sorediate and typical morphotypes of *P. affinis*.

A first field survey was carried out in June 2016 in the Puglia Region area of Alta Murgia. It was aimed at finding further population of the sorediate morphotype. During the survey several specimens were collected in the site were the first population was discovered years ago (Gravina in Puglia, beside the homonymous river). Therefore, the survey area was extended towards south-east, up to Murgia Materana, leading to the collection of other specimens from different populations.

In summer 2017 several other field surveys were carried out, starting from the localities in which the type material was collected (Veneto, N Italy, near Verona). Further surveys were carried out in other locations, selected among those which have environmental conditions potentially suitable for the taxon (see table 1).

Stazione	**Regione**	**Provincia**	**Località**	**DD lon**	**DD lat**	**TSB code**
S1	Puglia	Bari	Gravina In Puglia, Parco di Botromagno	16,4125028	40,820975	41031 41032
S3	Puglia	Bari	Gravina in Puglia, along river Gravina, left orogr. bank	16,4085472	40,827756	41033
S5	Basilicata	Matera	Matera, along river Gravina, in the canyon on the left orogr. bank	16,6563583	40,600933	41034
S6	Basilicata	Matera	Matera, Parco dei Monaci, along river Gravina, right orogr. bank	16,6487444	40,610114	41035 41036
S8	Basilicata	Matera	Matera, Contrada Murgia Timone	16,6203194	40,663214	41037 41038
T1	FVG	Trieste	Val Rosandra, rockwall “Falchi”, under “Vecchia Ferrovia” trail	13,873981	45,6228	41039
T2	FVG	Trieste	Prosecco, Napoleonica, rockwall “G”	13,745886	45,694816	41040
T6	Umbria	Perugia	Monte di Pale, near the Eremo di Santa Maria Giacobbe on calcareous rock.	12,770594	42,985839	41041
T9	Veneto	Verona	Marciaga	10,709546	45,599514	41042

Table 1: sampled localities 2016-2017, from which fresh material was collected.

The specimens collected during the field surveys, and used in this paper, have been stored in the TSB Lichen Herbarium (codes: 41031, 41032, 41033, 41034, 41035, 41036, 41037, 41038, 41039, 41040, 41041, 41042).

Herbarium specimens

Several specimens were obtained on loan from different herbaria, and they were preliminary checked:

those without fruiting bodies were excluded from microscopy processing, the ones lacking collection data removed from georeferencing. Hence, a total of 12 specimens were selected for further analysis: 8 from the University of Trieste Herbarium (TSB), 2 from the University of Turin Historical Herbarium (TO), 1 from the University of Graz (GZU), 1 specimen from the Finnish Museum of Natural History-Botanical Museum (H), (table 2).

Herbarium	**Sample**	**Name**	**Collection**	**Region/Province**	**Site**	**Date**
TSB	30599	*Pterygiopsis “sorediata”*		Puglia, Bari	Gravina in Puglia, river's right orogr. bank	agosto 1996
	30589	*Pterygiopsis “sorediata”*		Abruzzo, L'Aquila	Pagliare, Loc.Colonia Franca	1997
	30588	*Pterygiopsis affinis*		Abruzzo, L'Aquila	Pagliare, Loc.Colonia Franca	1997
	30596	*Pterygiopsis affinis*		Puglia, Bari	Gravina in Puglia, river's right orogr. bank	agosto 1996
	227777	*Pterygiopsis affinis*		Puglia, Foggia	Vieste, Torre di Porticello	1996
	5759	*Forssellia affinis*		FVG, Trieste	Monte Grisa	1985?
	31981	*Pterygiopsis affinis*		Campania, Salerno	Capo Palinuro light house	2000
	34674	*Pterygiopsis affinis*		Liguria, Imperia	Col Garezzo, near Triora	2000
HbTO	312C	*Enchylium affine*	Lichenes Exsiccati Italiae (Massalongo)			
	312A	*Enchylium affine*	Lichenes Exsiccati Italiae (Massalongo)			
GZU	355	*Pterygiopsis affinis*	Lichenes Rariores Exsiccati (A. Vězda)	Sardegna, Cagliari	Rocca Concali Petuntu, “Casa Perdu Melis” visit center	29/08/1989
H	2	*Forssellia affinis*	Herbarium Lichenum (V. Rasanen)	Liguria, Genova	Bogliasco	aprile 1937

Table 2: herbarium specimens selected for anatomical analysis.

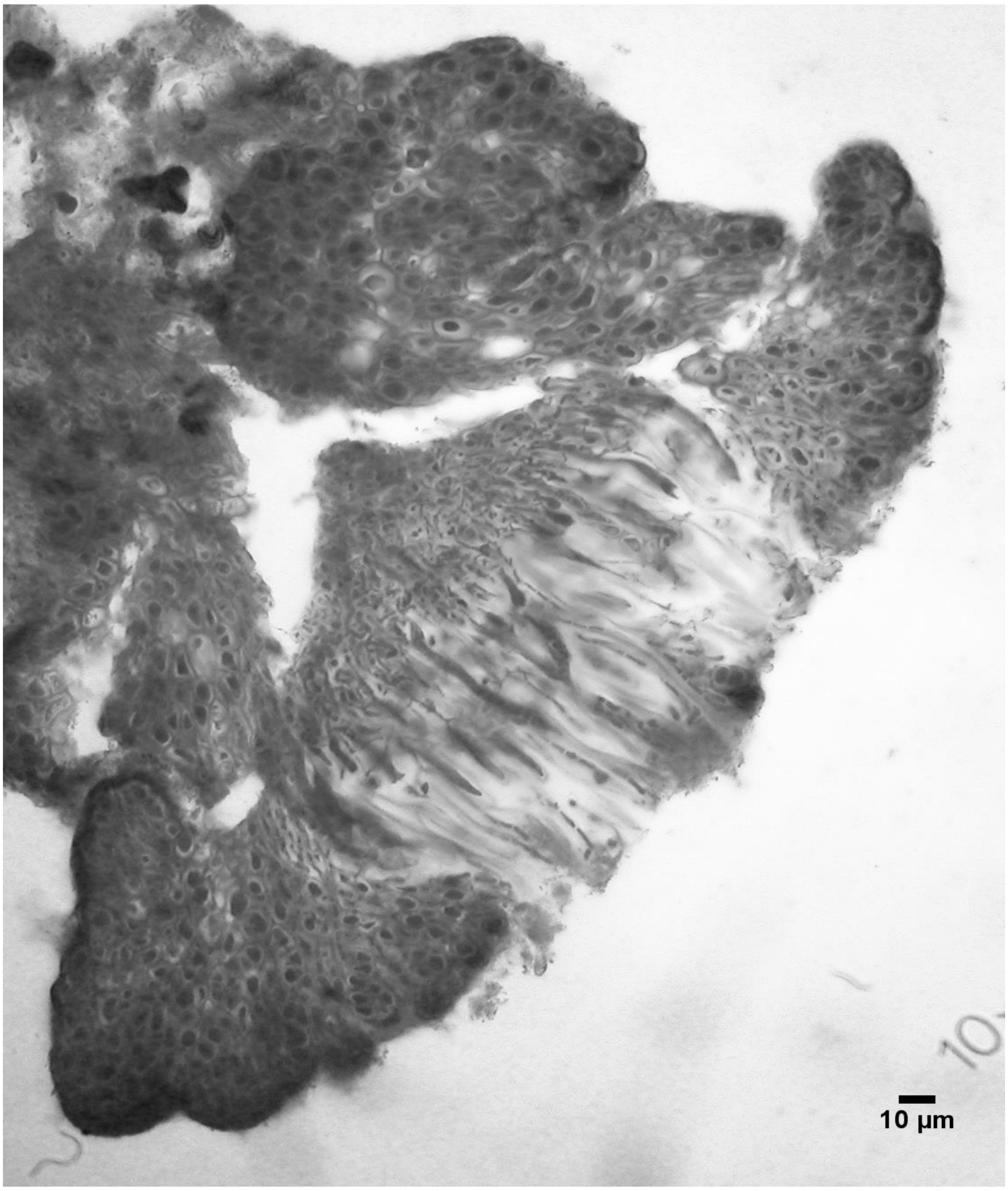
All examined specimens, including both the specimen analyzed for morpho- anatomic analysis and the ones georeferenced, and used for niche analysis, are listed in Supplementary materials (S1).

Morpho-anatomic investigation

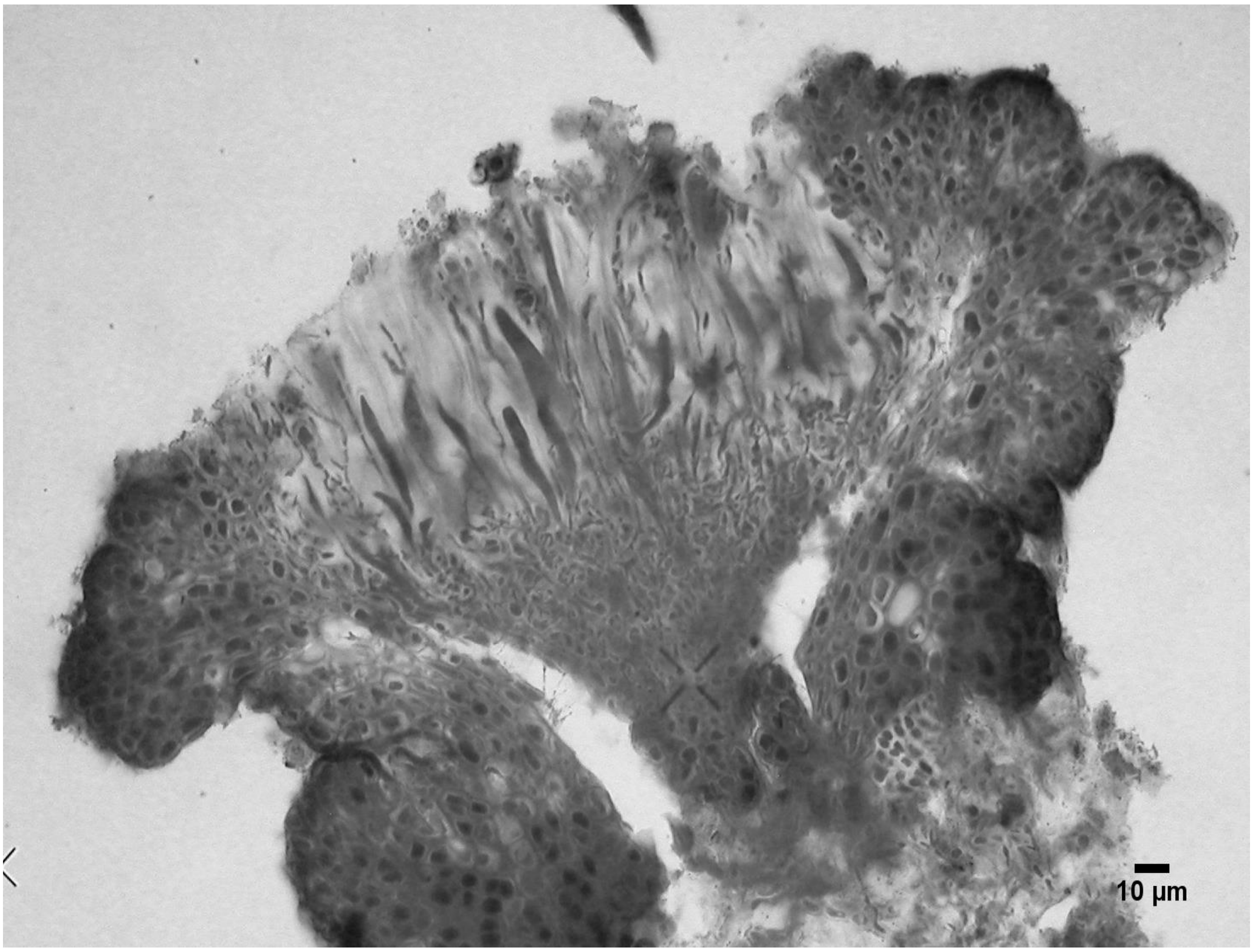
Microscopy processing

Specimens were processed using a dissecting microscope (Leica MZ16). Anatomy was studied using cryostat thin sections (10 micrometers) (Leica CM3050 S Research Cryostat) observed at light microscope (Zeiss Axioplan I). Sections were cut in ice support, dyed with Lactophenol-CottonBlue, fixed in glycerin and processed as permanent slides (photos 3-4).

3



4



Photos 3-4: *Pterygiopsis affinis* fruiting bodies, sectioned at 10 µm (sorediate sample St.5 (TSB41034), in light microscopy (40x).

Data analysis

Thirteen micro anatomical parameters have been recorded for every sample: hymenium- subhymenium- epihymenium height, spores- ascii- algae- picnidiospores- pseudoparenchimatic cells lenght and width, algae mucilage layer thickness. Samples sections have been photographed and measured by mean of ImageJ free software (Rueden et al., 2017).

Measures obtained from samples of the two morphotypes have been compared, by mean of ordination, to assess whether characters are recurring, and are correlated with the presence of soredia. Samples selected for this analysis are listed in table 3.

ID	Name	Specimen	Reproduction
1	S1_1	Survey 2016 (TSB 41031)	sorediate
2	S1_2	Survey 2016 (TSB 41032)	sorediate
3	S3	Survey 2016 (TSB 41033)	sorediate

4	S5	Survey 2016 (TSB 41034)	sorediate
5	S6_1	Survey 2016 (TSB 41035)	sorediate
6	S6_2	Survey 2016 (TSB 41036)	sorediate
7	S8_1	Survey 2016 (TSB 41037)	sorediate
8	S8_2	Survey 2016 (TSB 41038)	sorediate
9	T1	Survey 2017 (TSB 41039)	typical
10	T2	Survey 2017 (TSB 41040)	typical
11	T6	Survey 2017 (TSB 41041)	typical
12	T9	Survey 2017 (TSB 41042)	typical
13	30598	Herbarium (TSB)	sorediate
14	30589	Herbarium (TSB)	sorediate
15	30596	Herbarium (TSB)	typical
16	5759	Herbarium (TSB)	typical
17	312 C	Herbarium (HbTO)	typical
18	312 A	Herbarium (HbTO)	typical
19	355	Herbarium (GZU)	typical
20	2	Herbarium (H)	typical

Table 3: list of specimens selected microscopy processing, and reproductive strategy.

Principal Component Analysis (Pearson, 1901) was used to evidence clustering tendency between morphotypes.

Micro anatomical parameters have been tested for correlation by mean of Spearman test, in order to check the possibility of using synthesized measures. The correlation plot is shown in figure 1. The results allowed to synthesize coupled dimensions (spores- ascii- algae- picnidiospores- pseudoparenchimatic cells lenght and width) in a ratio (D/d), reducing the total set to 9 parameters.

Principal Component Analysis (PCA) has been applied for building the bi-dimensional PC-space onto which the 2 groups of samples have been collocated, in order to check grouping tendency. The Mann–Whitney U test (Mann and Whitney, 1947) was applied for every parameter to evidence possible significant differences between sorediate and typical samples. This test uses the sum of ranks to calculate data distribution (U) between the two groups (S/T), with a confidence interval for significance set at 95%.

Ecological niche investigation

Response variables

Occurrence data have been obtained from herbarium collections and field surveys. They were georeferenced *a posteriori* by using Q-Gis software (2.18.6 “Las Palmas” version, 2016). For avoiding spatial auto-correlation, we excluded occurrences which are in the same 1x1 kilometer cell in the grid used for climatic modelling (see below). The final dataset contains 11 occurrences for the typical, and 8 for the soredіate morphotype (supplementary material S2).

Predictor variables

Nineteen bioclimatic variables were obtained from Chelsa Climate portal (URL http://chelsa-climate.org/, Karger et al., 2017). The variables have a spatial resolution of 30 arcsec (0,83×0,83= 0,5×0,7 km ca. at our latitude), and are available in the form of raster layers. They are derived from monthly measures of temperatures and precipitations, incorporating the topoclimate (corrected with orographic precipitation and wind fields). Furthermore, the variable “altitude”, from the WorldClim portal (URL http://www.worldclim.org/, Hijmans et al., 2005; O’Donnel and Ignizio, 2012), was used. In order to verify whether predictor variables were correlated, a Spearman test was performed (R “corrplot” package; Wie and Simko, 2017). A Principal component analysis by mean of “FactoMineR” (Le et. al., 2008) and “Factoextra” (Kassambara and Mundt, 2017) packages developed for R software (R Core Team 2016) was performed to depict the environmental space, and how the occurrences are related to it.

Geology, on the contrary, was used as an environmental filter. At the end of the modelling processing, the suitability maps were filtered for suitable geological substrate units. Out of the list of 29 categories of main lithology acquired from Geological Map of Italy (1:1,000,000, Servizio Geologico d’Italia, OneGeology Portal, ISPRA), only those suitable for the occurrence of *P. affinis* were selected, and converted into a raster, containing three groups of substrates: metamorphic, sedimentary carbonatic and sedimentary siliciclastic.

The rasters of all predictor variables were cropped to the study area ("raster" R package, Hijmans and van Etten, 2012), which extent ranges from 6,47486 to 19,68319 Decimal Degrees (DD) longitude, and 35,15819 to 47,19986 DD latitude (SR WGS84).

As last step, two finer-scale models were trained, focusing only on areas with the highest suitability for the sorediate and typical morphotypes, in order to enhance possible further environmental differences, which could arise comparing smaller areas. The modelling procedure is the same used for the broad scale, while other than the 19 bioclimatic variables, and Altitude, Albedo (Liang, 2000) and Bare Soil Index (BSI, Rikimaru et al., 2002) raster data were used. They were produced from satellite imagery (Sentinel 2- remote sensing data September 2018. European Space Agency- ESA), and added as further predictors. All the predictor variables were resampled to a finer resolution of 15 arcsec (at our latitude ca. 460×340 m). The focus area (A1) for the sorediate morphotype is located between Alta Murgia and Murgia materana (Puglia and Basilicata regions). It measures ca. 2050 km^2, with an extent ranging from 13,46230 to 13,88850 DD longitude, and 45,59340 to 45,87710 DD latitude (SR WGS84). The focus area (A2) for the typical morphotype is located in the surroundings of Trieste city (Venezia Giulia region). It measures ca. 1055 km^2, and ranges from 16,27180 to 16,77180 DD longitude, and 40,52380 to 40,96020 DD latitude (SR WGS84).

Environmental niche models

The spatial distribution of the two morphotypes was analyzed by using 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 MaxEnt, a machine learning method based on the principle of maximum entropy, (Phillips et al., 2006). Since different algorithms can provide similar predictions, with slight differences, the resulting models were combined in a final ensemble model, which averages their results on the basis of individual model performance scores, for obtaining more reliable predictions (Araújo and New, 2007; Merow et al., 2013).

Since the use of presence-only data can bias the analysis, and often lead to unrealistic predictions, mostly overestimating suitability areas, pseudo-absences (i.e. inferred absence data obtained starting from actual occurrence distribution; Chefaoui and Lobo, 2008; Phillips et al., 2009) were generated with a simple random sampling approach. Pseudo-absences were generated 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 a TSS score higher than 0,6.

Models were generated using 70% of presence data for training, and 30% for testing in 10 replication runs for each algorithm. Beta multiplier was adjusted to 2 (Moreno- Amat et al., 2015; Shcheglovitova and Anderson, 2013).

Ensemble models

Models obtained by the three algorithms 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), TSS threshold was used as selection method. All the models with a TSS value lower than 0,7 (used as a precautionary threshold, since the suggested threshold is 0,6 - Araújo et al., 2005; Engler et al., 2011) were excluded from further computations. Both the broad an fine scale models were produced by following the same procedure.

Niche overlap between sorediate and typical morphotypes was calculated with ‘I similarity statistic’ (Warren et al., 2008; Rödder and Engler 2011), which was chosen for its simplicity, comparability and good performance. The ‘I similarity statistic’ is derived from the traditional D overlap index (Schoener, 1968) integrated with the Hellinger distance measure (I). It measures the overall match between two probability distributions across all cells in a gridded space, and ranges from 0 (no overlap) to 1 (complete overlap, Warren et al., 2008).

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

Results

Morpho-anatomic investigation

In PCA, the 2 first principal components retain 43,07 % of the information (fig. 2).

A correlation circle (fig. 3) displays variables on the principal component (PC) space. Variables that are correlated with PC1 and PC2 are the most important in explaining the variability in the data set (table 4).

	PC1	**PC2**
algD_r	0,3727	37,128
h_Mucil	2,0513	8,3127
parD_r	0,8878	0,9698
spD_r	6,6364	15,637
Im	28,012	1,9428
sub	27,354	0,0082
epi	24,766	5,3051
ascD_r	1,4653	15,584
picD_r	8,4553	15,112

Table 4: variable importance in explaining the principal components.

Samples of the two morphotypes do not cluster (fig. 4), but rather they partially overlap in a continuum range of variability, also when compared with the individual sample graph (fig. 5).

The Mann–Whitney U test shows that the 2 morphotypes do not differ significantly with regard to morphological parameters, but only slightly for the pseudoparenchimatic cells dimension ratio (fig. 6, table 5).

	U	**Z**	**p-value**
algD_r	55496,0	5,7765	$< 10^{-4}$
h_Mucil	49734,0	-7,6592	$< 10^{-4}$

parD_r	72006,5*	0,3843	*0,70077983*
spD_r	55910,5	5,6404	$< 10^{-4}$
Im	58623,0	4,7557	$< 10^{-4}$
sub	66767,5	2,0956	*0,03611653*
epi	66416,0	-2,2106	*0,02706488*
ascD_r	56143,5	-5,5681	$< 10^{-4}$
picD_r	48890,0	7,9321	$< 10^{-4}$

Table 5: resume of U Mann Whitney test results. U- value: difference between S/T rank distribution for every parameter. Z- value is the normal distribution variate value. * indicate significance.

Ecological investigation

Climatic drivers

Correlation test and PCA analysis outputs are reported in Supplementary materials (fig. S3a-b). The first two PCs explain 71,4 % of the variation in the data. Variance along PC 1 is mainly correlated with mean temperature of coldest quarter, minimum temperature of coldest month, annual mean temperature and precipitation of warmest quarter. PC 2 is mainly correlated with temperature annual range, mean diurnal range, temperature seasonality and precipitation of coldest quarter. The most influent variables on distribution of the sorediate morphotype are Bio13 (Precipitation of Wettest Month), Bio15 (Precipitation Seasonality), Bio8 (Mean Temperature of Wettest Quarter) (supplementary fig. S4a). This morphotype seem to reach the maximum probability of presence in sites with less than 80 mm precipitation in the wettest month, with a variability in monthly precipitation lower than 33% over the whole year, and with a mean temperature of the wettest quarter of the year below 10 °C (supplementary fig. S4b). The typical morphotype distribution is most influenced by Bio3 (Isotermality), Bio2 (Mean Diurnal Range), Bio11 (Mean Temperature of Coldest Quarter) (supplementary fig. S5a). This morphotype has the maximum probability occurrence in areas where temperature day-to-night variation is 2 times the summer-to-winter variation, the mean of the monthly temperature ranges over a year less than 3,5 °C, and a temperature above 8 °C in the coldest quarter of the year (supplementary fig. S5b).

Refining the scale, we can observe that the most influencing variables for the distribution of the sorediate morphotype are Bio13 (Precipitation of Wettest Month), Bio12 (Annual Precipitation), Bio16 (Precipitation of Wettest Quarter) (S6a). The sorediate morphotype seems to reach the maximum probability of occurrence in site with less than 68 mm of precipitation in the wettest month, but with more than 650 mm precipitation yearly, and more than 200 mm in the wet season (S6b). The typical morphotype distribution is more influenced by Bio15 (Precipitation Seasonality), Bio14 (Precipitation of Driest Month), BSI (Bare Soil Index) (S7a). This morphotype has the maximum probability of occurrences in sites characterized by a variability in monthly precipitation lower than 18% over the whole year, less than 80 mm precipitation in the driest month, and bare soil index not exceeding -0,3 (in a range from -1 to 0.6, -0.3 means “outcrops with rare vegetation shading”) (S7b).

Distributional maps

Suitability maps are reported in figures 7 and 8. The distribution depicted for the sorediate morphotype is centred in the south-eastern part of the country (Adriatic area), mainly from Alta Murgia, in the southern Puglia Region, till the coastal plain in Molise and Abruzzo Regions. The probability of presence decreases moving northwards, but is still high in some dry valleys, and on the coast, till 43° DD latitude (Ancona area, Marche Region), while it dramatically decreases to 0,2 northward. The typical morphotype is predicted to have its core distribution in north-eastern Italy, with the highest probability in the carsic area of the Friuli Venezia Giulia Region. Other predicted hotspots are: the areas surrounding the Maggiore (Piemonte and Lombardia regions) and Garda (Lombardia and Veneto regions) lakes, the piedmont area of Maritime Alps and Maritime Apennine, the outback of Circeo promontory (Lazio Region), the outback of the Gaeta gulf (Lazio and Campania Regions), the north-western Sicily, and the south-western and north-western Sardinia. On the Adriatic side of the peninsula the typical morphotype shares with the sorediate morphotype the coastal plains of central Italy, from Ancona (Marche Region) until the Gargano promontory (Puglia Region).

The results of the climatic niches overlap tests highlights a high I similarity value (I > 0,80), which indicate a high degree of overlap between the predicted distribution of the two morphotypes. This can suggest that the niches are different at a very fine, microhabitat scale only.

Discussion

Reconstructing the taxonomical history of a poorly known taxon could be a tricky and intense effort, since often data are fragmentary, or incomplete. On one side, it is very complicated to obtain historical material for microscopy processing. On the other hand, occurrences which could be georeferenced with enough detail to be used in niche modelling are scarce: GPSs are commonly used only recently, and historical records often lack enough information for properly georeference localities *a posteriori*. Hence, the adoption of two different, complementary approaches, morphological and ecological investigations, was necessary for better understanding the relationships between the two morphotypes of *P. affinis*.

Normally, in an infrageneric taxon, specimens with both fruiting bodies and vegetative propagules rarely occur. In the case of *P. affinis*, it was observed that the massively sorediate specimens were also the ones with the lower number of mature apothecia. The abundance of sexual and asexual reproductive strategies seem to be inversely proportional, hence reflecting a continuous morphological variation ranging from a "typical", reproducing only sexually morphotype, to an exclusively asexual, sorediate one.

This is clearly visible in figure 4, where a clustering is not detectable; the features of samples obtained from specimens of the two morphotypes mostly overlap. The slight differences are mostly due to the variable hymenium dimensions of sorediate morphotype, and the variable algal dimensions in the typical morphotype. However, these slight differences are still not enough for producing a clear clustering. These slight differences in anatomy are comparable with inter-site differences (fig. 5). As an example, two specimens collected before 1940 (H2, HbTO_312A) isolate from others in PCA analysis. As far as the results of U test are concerned, pseudoparenchimatic cells dimensions seems to significantly differ between the two morphotypes. This slight difference could however be due to the position of the measured cells in the thallus: in fact, since they were measured in the surroundings of apothecia, the arising of fruiting bodies could have stretched the fungal cells. Also, one of the key characters for taxonomic delimitation in lichens, i.e. the dimensions of spores, does not show significant differences between the two morphotypes.

Pterygiopsis affinis is rare, little and very difficult to distinguish in the field from other cyanolichens of the same family. Hence, field collection always need a confirmation in the lab, as a good practice. The georeferencing *a posteriori* of herbarium specimens was a complex task, which required a careful and critical interpretation of specimen labels, often impossible given the poor information available. Since *P. affinis* is rare, few occurrences only were available for each morphotype. Hence, an ensemble approach for developing ecological niche models was adopted. This approach is especially recommended with cryptic or poorly known taxa, or with few occurrences (Araújo and New, 2007). It also generate more cautious predictions, since it produces a weighted average of only the models, produced by different algorithms, which perform above a specific performance threshold. This approach has been used for understanding and forecasting distributional and ecological patterns for conservation strategies on several organisms (Sletvold et al., 2013; Martellos et al., 2014; Ongaro et al., 2018), but also as first assessment for exploring ecological and climatic niche of uninvestigated groups of organisms (Gaston et al., 2008; Sagarin et al., 2006).

In producing the ecological niche models, geology was used as a filter, instead of as a categorical predictor. Geology could be a robust predictor for species distribution. However, since geological map has a resolution of 30 arcsec (0,5×0,7 km ca. at our latitude), in our opinion it is not fine enough to evidence outcrops suitable for colonization. Using it among other predictors resulted, in several tests, in a poor performance of the models, which often marked as unsuitable or poorly suitable sites in which the species was actually sampled. This happens since the geological map assign to each cell in the raster the value of the main lithology of the cell, while *P. affinis*, as well as many other species, do require only a limited outcrop to colonise (which could be a small calcareous, sun exposed wall, among siliceous rocks). Hence, it was decided to use the geological map *a posteriori*, once the models have been built, as a geographical mask for filtering the potential distributions. Even if this colud lead to the loss of some sites potentially suitable for colonization, at least a major potential bias in the models has been removed.

The models depict the sorediate morphotype as occurring in sites with a Mediterranean-temperate, dry climate, typical of the hilly and plain zones in the south of the Italian peninsula. Predictor variables which explain the most its distribution are all related to precipitation, hence depicting an environmental limit for this morphotype, which is negatively affected by higher precipitations.

The typical morphotype is predicted to occur mostly in sites characterized by fresh-Mediterranean climate, typically coastal (with a degree of day to night variation in temperature, but low seasonal thermal excursion and high temperatures also in winter). Its distribution is most influenced by temperature, indicating that precipitations, do not constitute an environmental limit for this morphotype.

Since the typical morphotype is adapted to Mediterranean climate, and is hence distributed mostly in the Mediterranean basin, the temperature is a limiting factor for its distribution. While sharing a huge portion of the niche with the typical (overlap > 80%), the sorediate morphotype seems to be, on the contrary, most affected by precipitation. This pattern can be explained by the influence of precipitation on the availability of free living algae (Rikkinen et al., 2002). The sorediate morphotype occurs in very dry sites, in which is more difficult to find the appropriate free-living photobiont. Thus, the lichen adopts a vegetative reproductive strategy, in order to ensure the propagation of the whole symbiosis.

The development of niche models at finer scale for the most suitable areas for the two morphotypes reinforces the trends described above, and further underlines the dependence of the sorediate morphotype from availability of free-living photobiont.

Conclusions

Pterygiopsis affinis seem to be a typical example of “species pair” (Poelt, 1970; 1972). The primary species develops fruiting bodies (apothecia), and reproduces sexually, while the secondary species reproduces mostly vegetatively by soredia, even if rarely developing fruiting bodies. The two morphotypes do not differ for other morpho-anatomical features.

This study takes in account two complementary approaches (ecology and morpho-anatomy) to understand whether the two morphotypes could be treated as different taxa. Our evidences are against this hypothesis. However, this work is a first step, which should be followed by a molecular phylogenetic investigation, which will be done on specimens collected in an extensive sampling conducted with a random systematic design, and integrated with fine scale data on environmental conditions.

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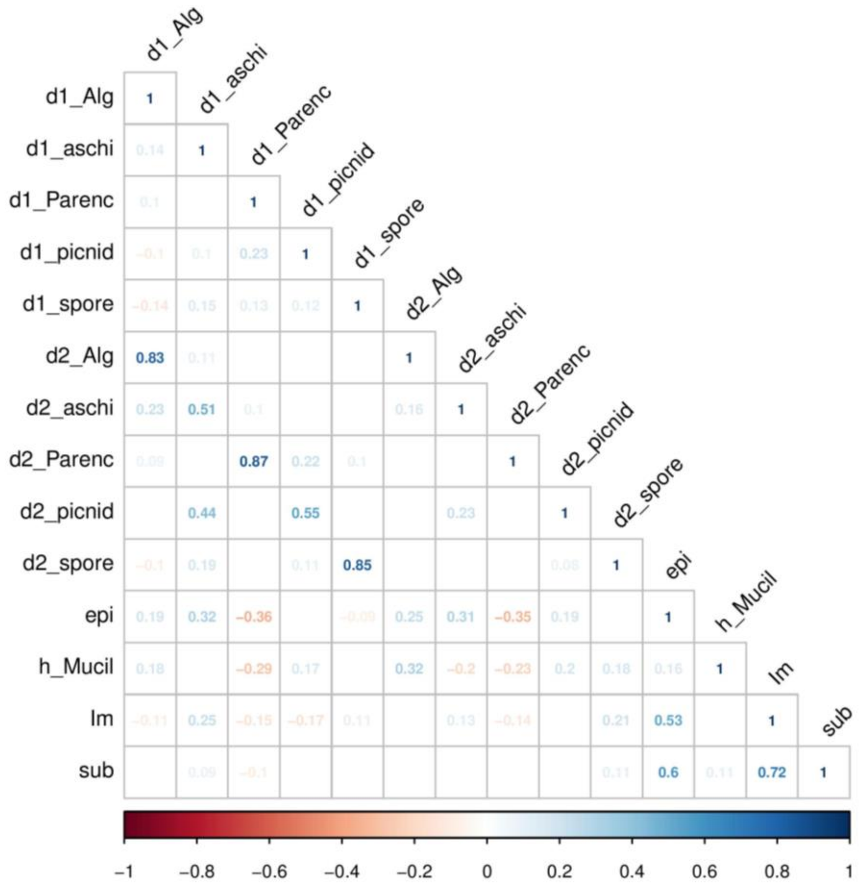
Figures



	d1_Alg	d1_aschi	d1_Parenc	d1_picnid	d1_spore	d2_Alg	d2_aschi	d2_Parenc	d2_picnid	d2_spore	epi	h_Mucil	lm	sub
d1_Alg	1													
d1_aschi	0.14	1												
d1_Parenc	0.1		1											
d1_picnid	−0.1	0.1	0.23	1										
d1_spore	−0.14	0.15	0.13	0.12	1									
d2_Alg	0.83	0.11				1								
d2_aschi	0.23	0.51	0.1			0.16	1							
d2_Parenc	0.09		0.87	0.22	0.1			1						
d2_picnid		0.44		0.55			0.23		1					
d2_spore	−0.1	0.19		0.11	0.85				0.08	1				
epi	0.19	0.32	−0.36		−0.09	0.25	0.31	−0.35	0.19		1			
h_Mucil	0.18		−0.29	0.17		0.32	−0.2	−0.23	0.2	0.18	0.16	1		
lm	−0.11	0.25	−0.15	−0.17	0.11		0.13	−0.14		0.21	0.53		1	
sub		0.09	−0.1							0.11	0.6	0.11	0.72	1

Figure 1: Correlation plot of micro anatomical paramenters, colour intensity indicates high rho values.

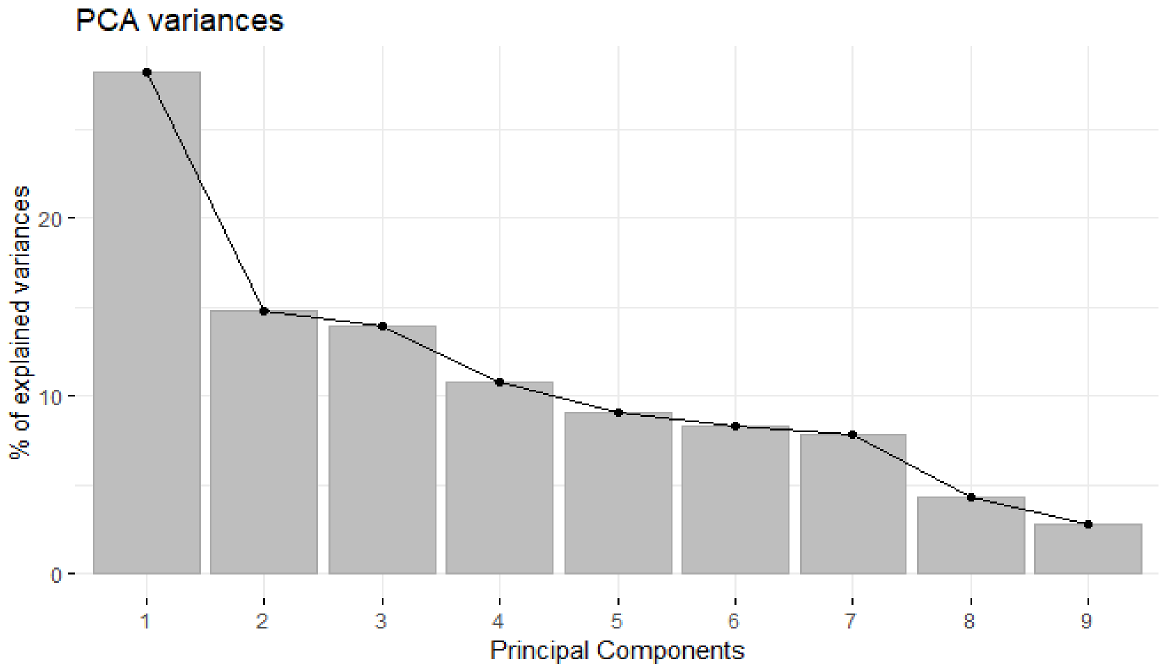


Figure 2: % of variance explained by each dimension (PC1=28,24%; PC2=14,83%).

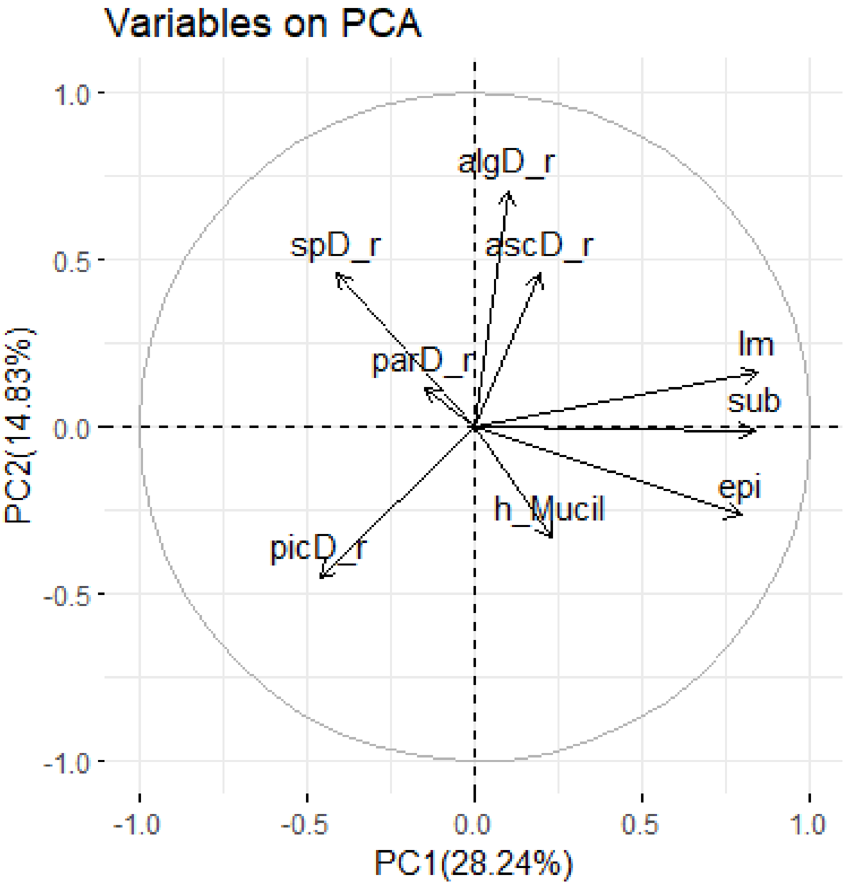


Figure 3: Correlation circle and variables in PC space.

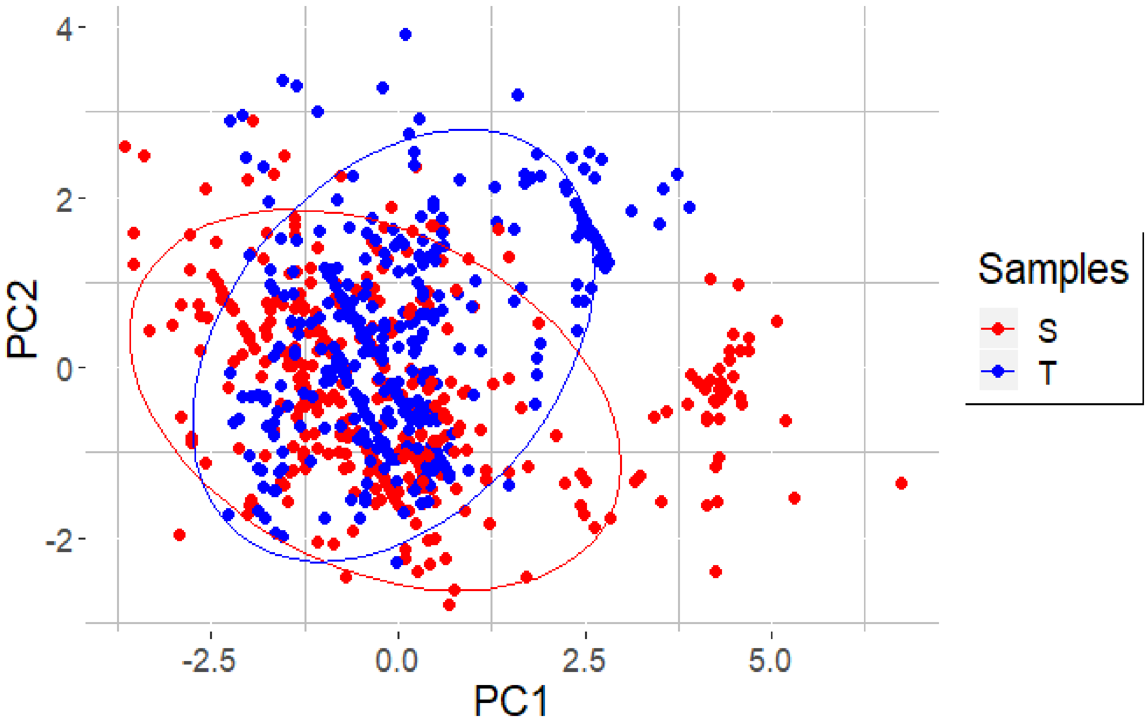


Figure 4: PCA plot, red is the sorediate group, and blue is the typical one.

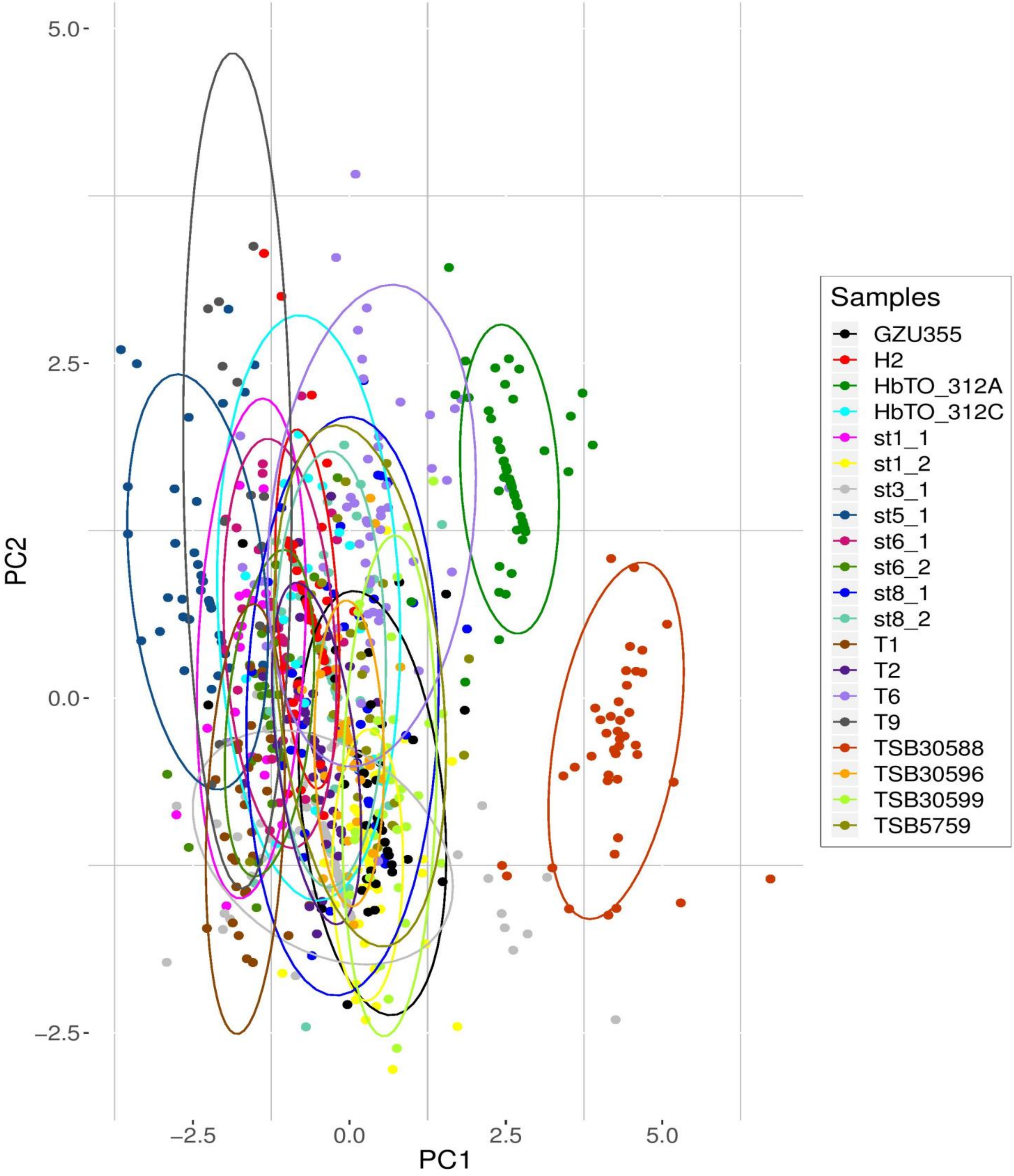


Figure 5: PCA plot, colours are referred to the different samples.

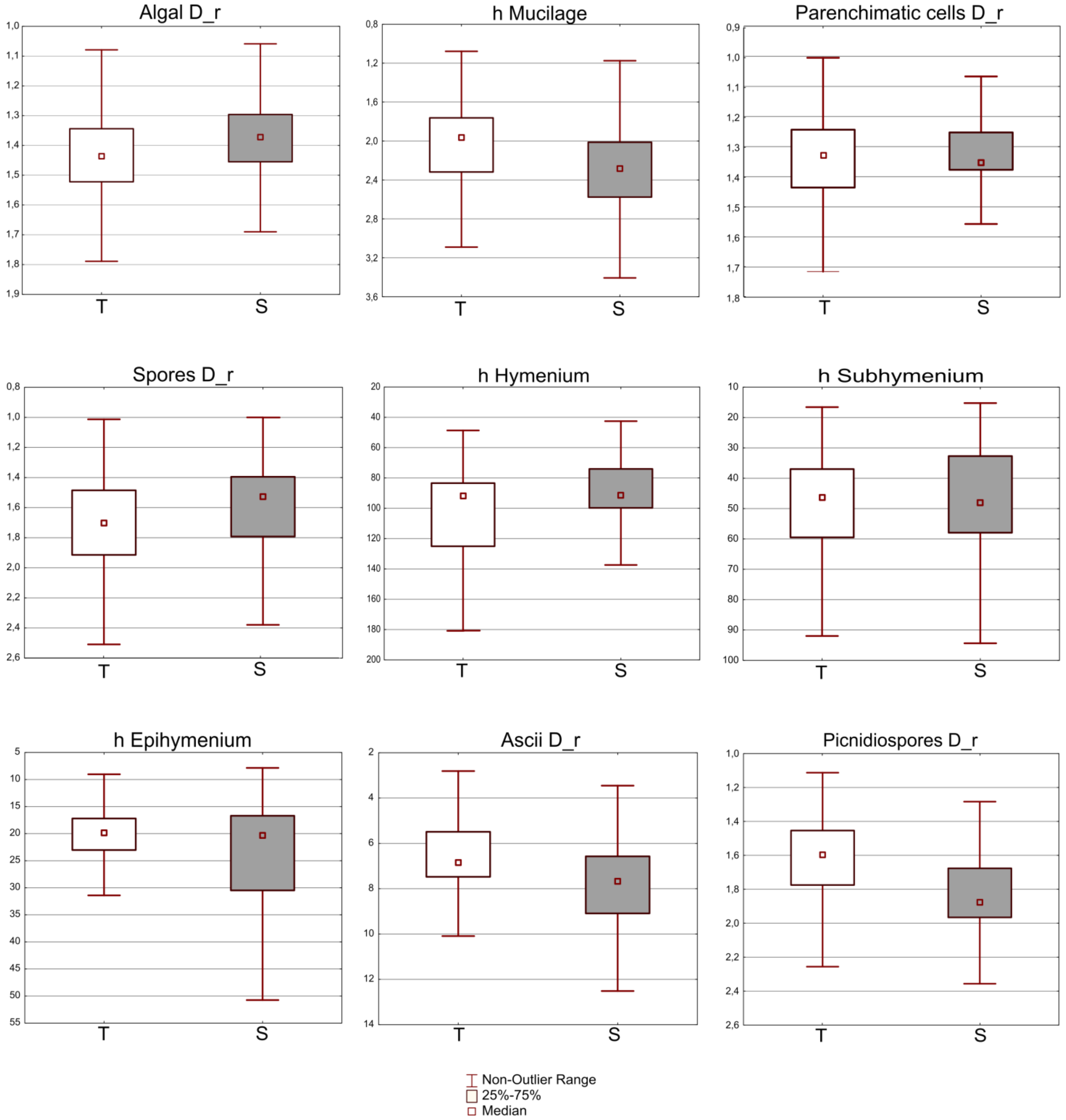


Figure 6: Mann–Whitney U test boxplots one for every parameter considered (from top- left to bottom-right: algal dimensions ratio, mucilage layer height, parenchymatic cells dimensions ratio, spores dimensions ratio, hymenium, subhymenium, epihymenium heights, ascii dimensions ratio, picnidiospores dimensions ratio).

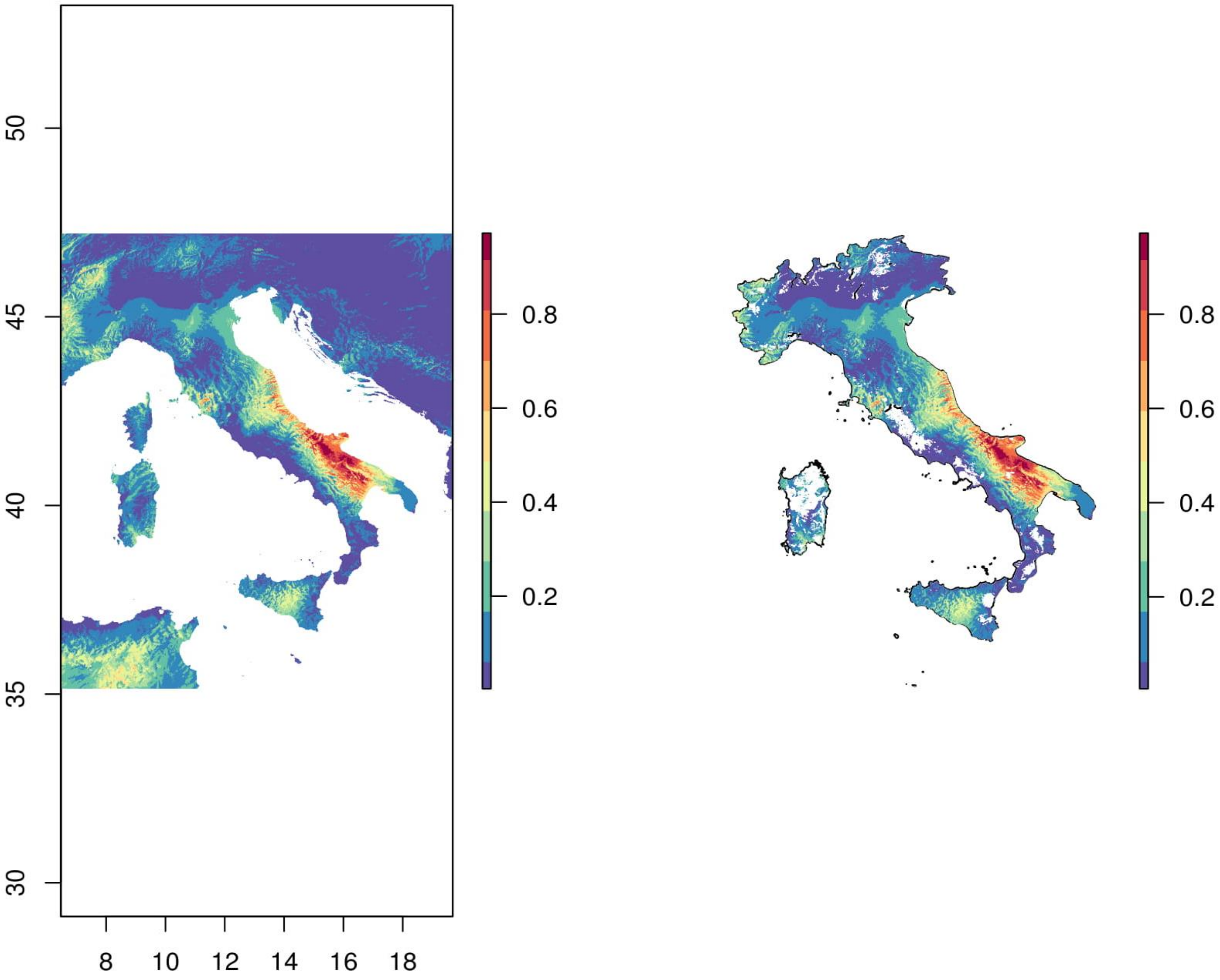


Figure 7: Distributional map for the sorediate morphotype (right: climate suitability only, left: filtered with geology).

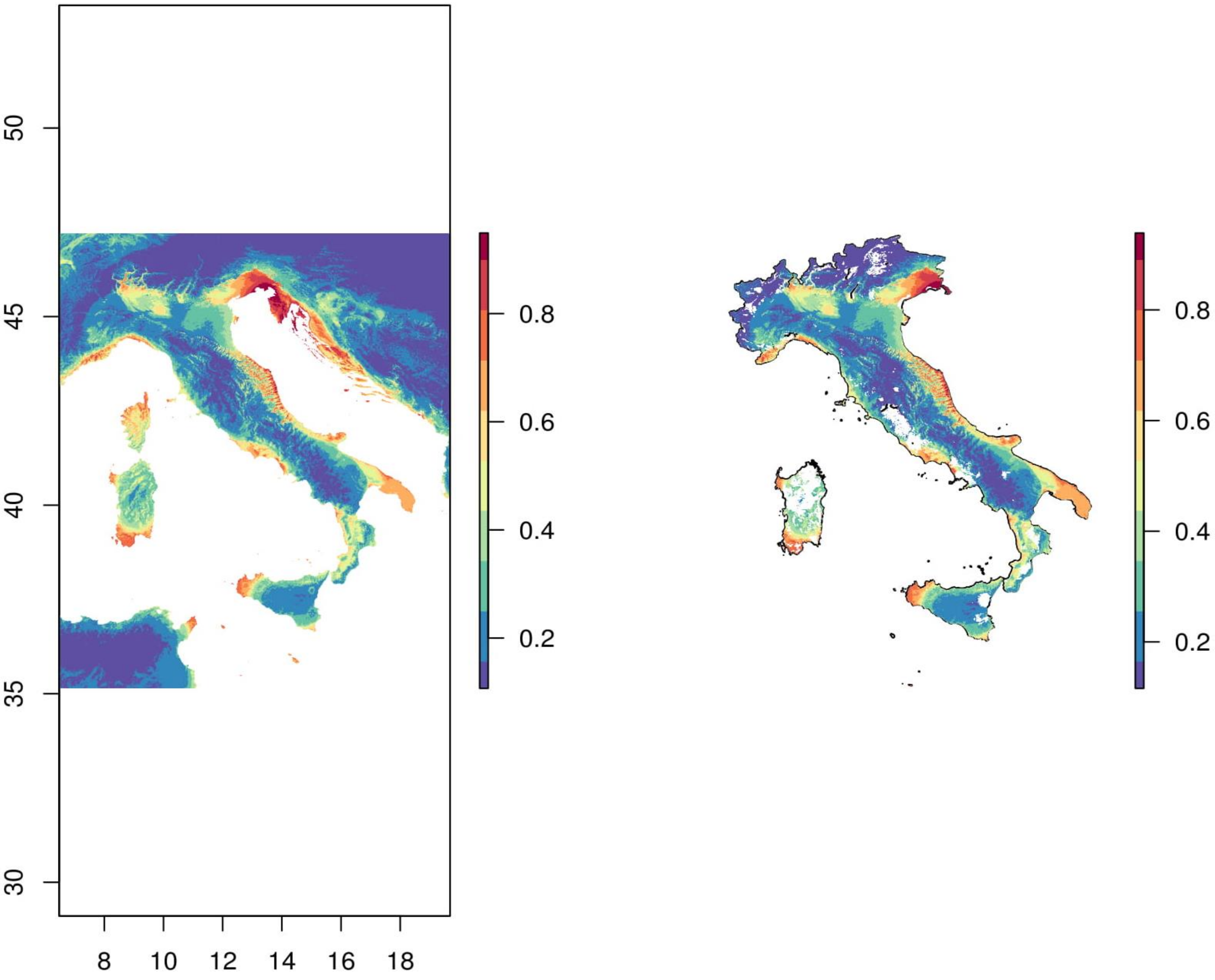


Figure 8: Distributional map for the typical morphotype (right: climate suitability only, left: filtered with geology).

Supplementary materials

S0: Summary of climatic and biogeographic classification of Italy (Blasi et al., 2014).

Divisions (2)

Temperate: AnnMeanT > 5°C

High annual thermal excursion: MinTColdestMonth < 3°C
MaxTWarmestMonth > 30°C
MonthMeanT < 10°C for 4- 8 month/y
MinPrec: 800 mm/y
MaxPrec: 2000 mm/y
Pluviometric regime: continental (min in winter)
apenninic (min in summer)
Summer aridity: absent/ < 2 months

Mediterranean: AnnMeanT>13°C

Low annual thermal excursion
MinPrec: 500 mm/y
MaxPrec: 1400 mm/y
Summer aridity: present > 2- 3 months/y

Provinces (7)

Alpine: 0°C > AnnMeanT > 10°C

Preciptations: abundant, snow
Preciptation regime: continental (min in winter)
Summer aridity: absent
Climate: oceanic (northern areas), semi- continental, sub- continental (pre- alpine valleys).

Po plain: AnnMeanT > 10°C

High annual thermal excursion: MinTColdestMonth < 0°C
MaxTWarmestMonth > 25°C
Prec < 1400 mm/y
Climate: continental (N), apenninic (S).

Apenninic: AnnMeanT > 0°C, often >10°C

Pluviometric regime: continental (min in winter)
apenninic (min in summer)
Climate: oceanic, semi- continental, depending on latitude, exposition and altitude.

Tirrenian: AnnMeanT > 10°C

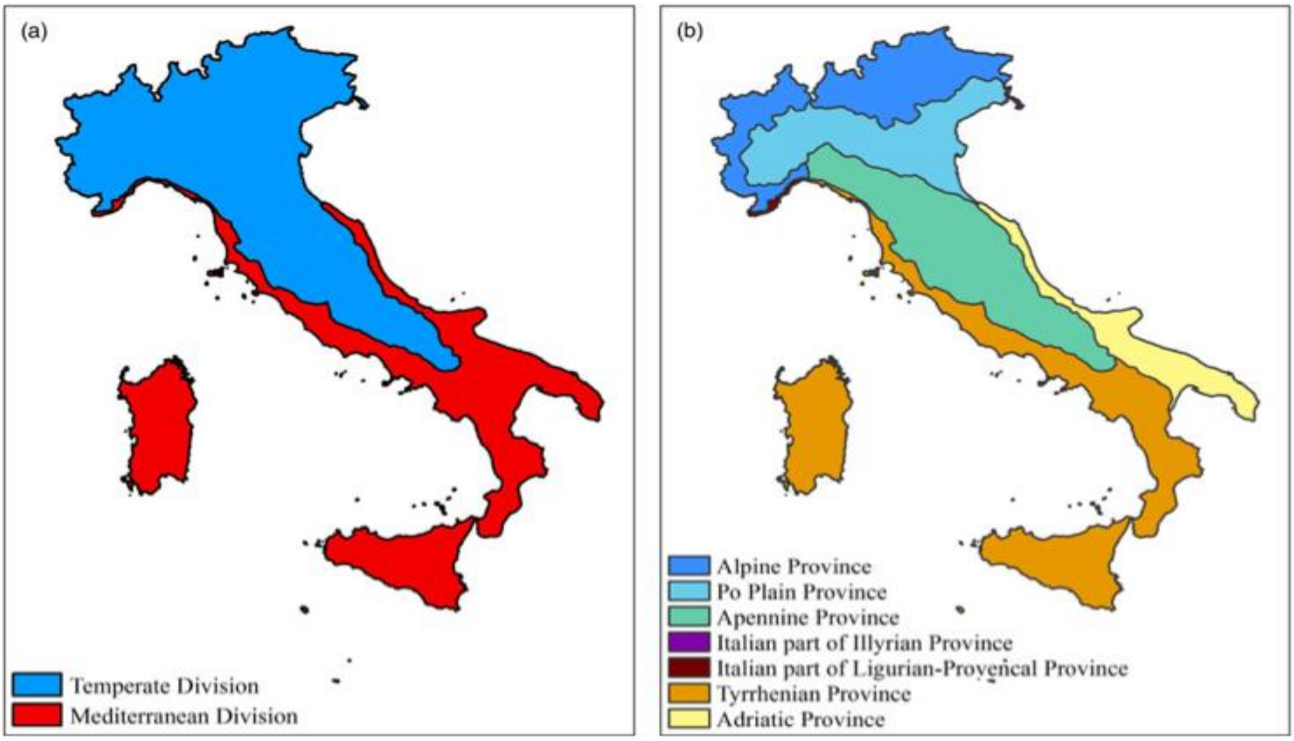
MinTColdestMonth > 2,5°C
Low annual thermal excursion (< 18°C)

MinPrec: 600 mm/y
MaxPrec: 1000 mm/y
Climate: Mediterranean

Adriatic: AnnMeanT > 10°C
Annual thermal excursion >18°C
MinTColdestMonth > 3°C
MaxTWarmestMonth > 27°C
MinPrec: 600 mm/y (S)
MaxPrec: 800 mm/y (N)
Summer aridity: present > 2- 3 months/y (N)
= 4- 5 months/y (S)

Illiric: fresh Mediterranean climate, alpine influence sometimes.

Ligurian: Mediterranean dry climate.



S1: list of examined specimens

Exsiccata on loan

Enchylium affine var. *pulvinatum*. **Italy:** *Veneto*: Verona (?), *A. Massal*. 312 B (HbTO);

Enchylium affine A. Massal. **Italy:** *Piemonte*: Valsesia, Borgosesia, Monte Fenera, 1869, *Carestia* 910 (HbTO); *ibid. Veneto*: Verona (?), *A. Massal*. 312 A (HbTO).

Enchylium affine var. *melanophaeum*. **Italy:** *Veneto*: Verona (?), *A. Massal*. 312 C (HbTO);

Forssellia affinis (Massal.) Zahlbr. **Italy:** *Liguria*: Prov. Genova, Bogliasco, 0-50m, 1937, *C. Sbarbaro* 2 (H).

Pterygiopsis affinis (Massal.) Henssen. **Italy**: *Sardegna*: Prov. Cagliari, Monte Arcosu, Rocca Concali Petuntu, Casa “Perdu Melis”, 39,156696° N / 8,864191° E, 520 m, 1989, *P. L. Nimis* and M. Tretiach 355 (GZU); *ibid.* Prov. Cagliari, Monte Arcosu, Rocca Concali Petuntu, Casa “Perdu Melis”, 39,156696° N / 8,864191° E, 520m, 1989, *P. L. Nimis* 355 and M. Tretiach (H);

Pterygiopsis australiensis Henssen. **Australia:** *Northampton*: Kalbarri National Park, 1987, *A. Henssen* Iso 31357 (H).

Pterygiopsis canariensis Henssen. **Spain:** *Canary Islands*: Fuerteventura, Parco Rural de Betancuria, 1988, *A. Henssen* Para 32050 (H).

Pterygiopsis convoluta Henssen. **Australia:** *Northampton*: Kalbarri National Park, 1987, *A. Henssen* Iso 31373a (H).

Pterygiopsis concordatula (Nyl.) P. M. Jorg. Finland: *Tavastia*: Korpilahti, Janissaari, 1875, *J. Norrlin* (H) [cf.]; 1875, [det. *Pyrenopsis concordatula*], (H); *ibid.*, *Tavastia*: Korpilahti, Janissaari, 1875,det. Nylander [*Pyrenopsis concordatula*] *J. Norrlin* (H); *ibid.*, *Tavastia*: Korpilahti, Janissaari, 1875,[det. *Pyrenopsis concordatula*] *J. Norrlin* (H); *ibid.*, *Salla*: Oulanka National Park, Pikkukongas, 178m, 2009, *J. Pikala*? 36044 (H); *ibid.*, *Padasjoki*: Pajanne lake, Kelvenne island, 80m, 2007, *J. Pikala*? 31848 (H).

Pterygiopsis coracodiza (Nyl.) (Forss.) Henssen. **Finland:** *Lohja*: Paksalo, 32m, 2004, *J. Pikala* 24344 (H); ibid., 1870, det. Nylander [Psorotichia spp.], H. Kullhem (H); *ibid.*, Tavastia: Korpilahti, Janissaari, 1875, J. Norrlin (H).

Pterygiopsis foliacea Henssen. **Chile:** *Aconcagua*: Zapallar, Cerro de la Cruz, -32,551158° N / -71,471519° E, 10m, 1965, *A. Henssen* 50 (H).

Pterygiopsis spp. (Massal.) Henssen. **Finland:** *Lohja*: Kiviniemen, 35m, 2003, *J. Pikala*? 23165 (H); *ibid.*, Paksalo, 32m, 2004, *J. Pikala* 24343 (H).

<u>Specimen analysed</u>

Enchylium affine A. Massal. **Italy:** *Veneto*: Verona (?), *A. Massal*. 312 A (HbTO).

Enchylium affine var. *melanophaeum*. **Italy:** *Veneto*: Verona (?), *A. Massal*. 312 C (HbTO);

Forssellia affinis (Massal.) Zahlbr. **Italy:** *Liguria*: Prov. Genova, Bogliasco, 0-50m, 1937, *C. Sbarbaro* 2 (H). *Friuli- Venezia Giulia*: Prov. Trieste, Monte Grisa, 180 m, 1985, *P. L. Nimis* 5759 (TSB).

Pterygiopsis affinis form *affinis* (Massal.) Henssen. **Italy**: *Sardegna*: Prov. Cagliari, Monte Arcosu, Rocca

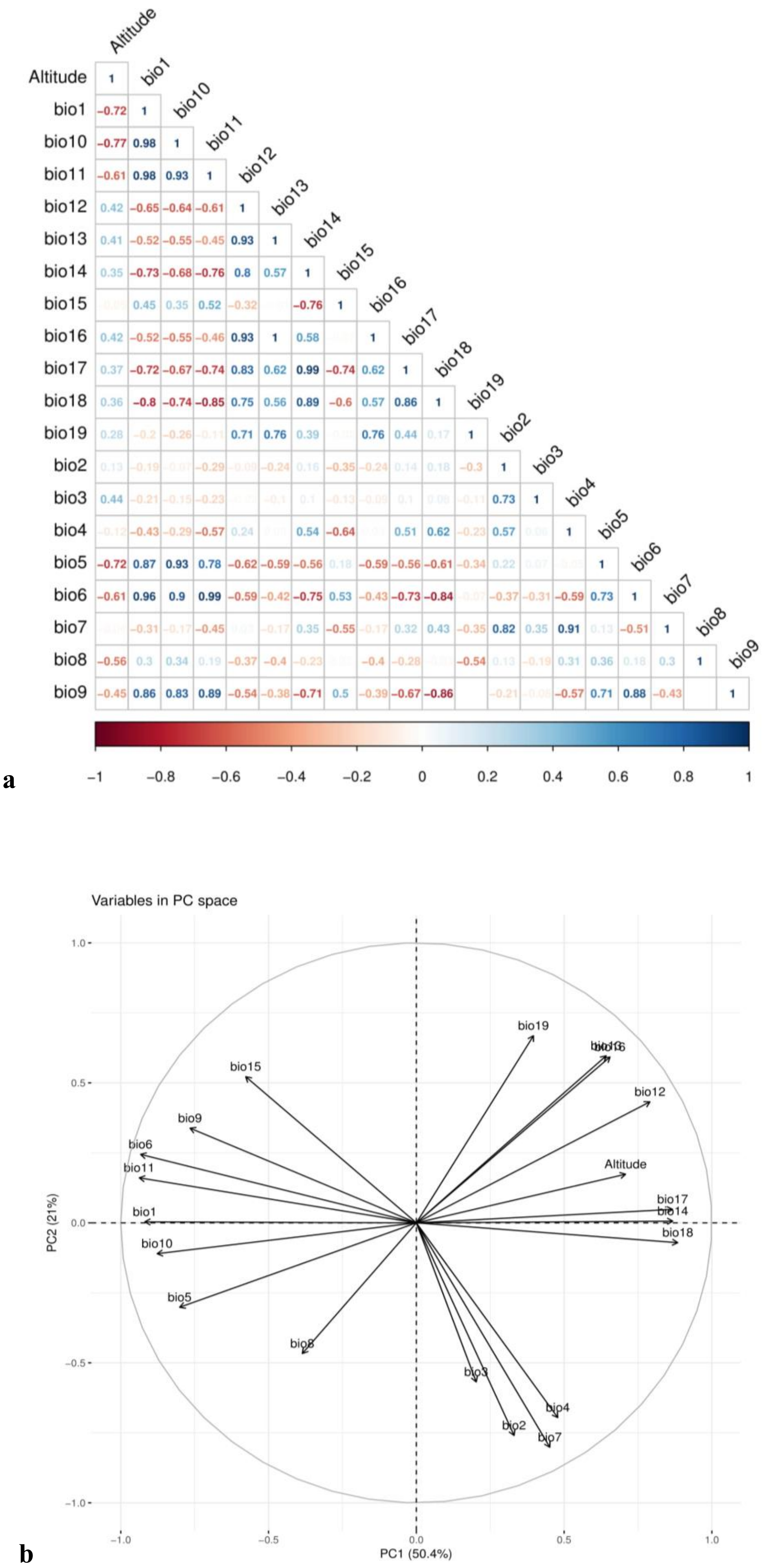
Concali Petuntu, Casa "Perdu Melis", 39,156696° N / 8,864191° E, 520 m, 1989, *P. L. Nimis* and M. Tretiach 355 (GZU). *Puglia*: Prov. Bari, Gravina in Puglia, 330 m, 1996, *M. Tretiach* 30596 P. L. Nimis (TSB); *ibid*., Prov. Foggia, Torre di Porticello, near Vieste, 10-30 m, 1996, *M. Tretiach* 22777 P. L. Nimis (TSB). *Campania:* Prov. Salerno, Capo Palinuro light house, 150 m, 2000 *M. Tretiach* 31981 P. L. Nimis (TSB). *Liguria*: Prov. Imperia, Triora, Col Garezzo, 1400 m, 2000, *M. Tretiach (with J. Hafellner)* 34674 P. L. Nimis (TSB). *Friuli-Venezia Giulia*: Prov. Trieste, Val Rosandra, 13,873981° E / 45,622800° N, 250 m, 2017, *L. Morosini* 41039 S. Ongaro (TSB); *ibid.*, Prov. Trieste, Prosecco, Napoleonica, 13, 745886° E / 45,694816° N, 180 m, 2017, *L. Morosini* 41040 S. Ongaro (TSB). *Umbria*: Prov. Perugia, Monte di Pale, near "Eremo Santa Maria di Giacobbe", 12,770594° E / 42,985839° N, 530 m, 2017, *L. Morosini* 41041 S. Ongaro (TSB).
Veneto: Prov. Verona, Marciaga, 10,709546° E / 45,599514° N, 390 m, *L. Morosini* 41042 S. Ongaro (TSB);

Pterygiopsis affinis form *sorediata* (Massal.) Henssen. **Italy**: *Abruzzo*: Prov. Aquila, Pagliare, Loc. Colonia Franca, 415 m, 1997, *M. Tretiach* 30588 P. L. Nimis (TSB); *ibid.* Prov. Aquila, Pagliare, Loc. Colonia Franca, 415 m, 1997, *M. Tretiach* 30589 P. L. Nimis (TSB). *Puglia*: Prov. Bari, Gravina in Puglia, 330 m, 1996, *M. Tretiach* 30599 P. L. Nimis (TSB). *Puglia*: Prov. Bari, Gravina in Puglia, 16,412503° E / 40,820975° N, 350 m, 2016, *M. Tretiach* 41031 S. Ongaro (TSB); *ibid.*, Prov. Bari, Gravina in Puglia, 16,412503° E / 40,820975° N, 350 m, 2016, *M. Tretiach* 41032 S. Ongaro (TSB); *ibid.*, Prov. Bari, Gravina in Puglia, 16,408547° E / 40,827756° N, 360 m, 2016, *M. Tretiach* 41033 S. Ongaro (TSB). *Basilicata*: Prov. Matera, near Tenuta Parco dei Monaci, 16,656358° E / 40,600933° N, 125 m, 2016, *M. Tretiach* 41034 S. Ongaro (TSB); *ibid.*, Prov. Matera, near Tenuta Parco dei Monaci, 16,648744° E / 40,610114° N, 125 m, 2016, *M. Tretiach* 41035 S. Ongaro (TSB); *ibid.*, Prov. Matera, near Tenuta Parco dei Monaci, 16,648744° E / 40,610114° N, 125 m, 2016, *M. Tretiach* 41036 S. Ongaro (TSB); *ibid.*, Prov. Matera, Contrada Murgia Timone, 16,620319° E / 40,633214° N, 380 m, 2016, *M. Tretiach* 41037 S. Ongaro (TSB); *ibid.*, Prov. Matera, Contrada Murgia Timone, 16,620319° E / 40,633214° N, 380 m, 2016, *M. Tretiach* 41038 S. Ongaro (TSB).

S2: Occurrence dataset for modelling procedure

Species	**DD lon**	**Ddlat**	**Data source**
Pterygiopsis "sorediata"	16,412503	40,820975	S1- field Survey (Puglia 2016)
Pterygiopsis "sorediata"	13,308169	42,339375	TSB30589- L'Aquila (AQ)
Pterygiopsis "sorediata"	16,407951	40,824645	S2- field Survey (Puglia 2016)

Pterygiopsis "sorediata"	16,408547	40,827756	S3- field Survey (Puglia 2016)
Pterygiopsis "sorediata"	16,656358	40,600933	S5- field Survey (Puglia 2016)
Pterygiopsis "sorediata"	16,648744	40,610114	S6- field Survey (Puglia 2016)
Pterygiopsis "sorediata"	16,657297	40,611725	S7- field Survey (Puglia 2016)
Pterygiopsis "sorediata"	16,620319	40,663214	S8- field Survey (Puglia 2016)
Pterygiopsis affinis	7,759731	44,041442	TSB22777- Vieste (FG)
Pterygiopsis affinis	15,284032	40,033962	TSB31981- Palinuro (SA)
Pterygiopsis affinis	16,140041	41,906923	TSB34674- Triora (IM)
Pterygiopsis affinis	8,866592	39,177183	GZU355- Cagliari (CA)
Pterygiopsis affinis	13,750153	45,692415	TSB5759- Monte Grisa (TS)
Pterygiopsis affinis	13,873981	45,6228	T1- field Survey (Friuli Venezia Giulia 2017)
Pterygiopsis affinis	13,745886	45,694816	T2- field Survey (Friuli Venezia Giulia 2017)
Pterygiopsis affinis	9,065786	44,383845	H2- Bogliasco (GE)
Pterygiopsis affinis	12,770594	42,985839	T6- field Survey (Umbria 2017)
Pterygiopsis affinis	13,002918	43,428502	T8- field survey (Marche 2017)
Pterygiopsis affinis	10,709546	45,599514	T9- field Survey (Veneto 2017)



	Altitude	bio1	bio10	bio11	bio12	bio13	bio14	bio15	bio16	bio17	bio18	bio19	bio2	bio3	bio4	bio5	bio6	bio7	bio8	bio9
Altitude	1																			
bio1	−0.72	1																		
bio10	−0.77	0.98	1																	
bio11	−0.61	0.98	0.93	1																
bio12	0.42	−0.65	−0.64	−0.61	1															
bio13	0.41	−0.52	−0.55	−0.45	0.93	1														
bio14	0.35	−0.73	−0.68	−0.76	0.8	0.57	1													
bio15	[illegible]	0.45	0.35	0.52	−0.32	[illegible]	−0.76	1												
bio16	0.42	−0.52	−0.55	−0.46	0.93	1	0.58	[illegible]	1											
bio17	0.37	−0.72	−0.67	−0.74	0.83	0.62	0.99	−0.74	0.62	1										
bio18	0.36	−0.8	−0.74	−0.85	0.75	0.56	0.89	−0.6	0.57	0.86	1									
bio19	0.28	−0.2	−0.26	−0.11	0.71	0.76	0.39	[illegible]	0.76	0.44	0.17	1								
bio2	0.13	−0.19	−0.07	−0.29	−0.09	−0.24	0.16	−0.35	−0.24	0.14	0.18	−0.3	1							
bio3	0.44	−0.21	−0.15	−0.23	[illegible]	−0.1	0.1	−0.13	−0.09	0.1	0.08	−0.11	0.73	1						
bio4	−0.12	−0.43	−0.29	−0.57	0.24	[illegible]	0.54	−0.64	[illegible]	0.51	0.62	−0.23	0.57	0.06	1					
bio5	−0.72	0.87	0.93	0.78	−0.62	−0.59	−0.56	0.18	−0.59	−0.56	−0.61	−0.34	0.22	0.07	−0.05	1				
bio6	−0.61	0.96	0.9	0.99	−0.59	−0.42	−0.75	0.53	−0.43	−0.73	−0.84	−0.07	−0.37	−0.31	−0.59	0.73	1			
bio7	[illegible]	−0.31	−0.17	−0.45	0.03	−0.17	0.35	−0.55	−0.17	0.32	0.43	−0.35	0.82	0.35	0.91	0.13	−0.51	1		
bio8	−0.56	0.3	0.34	0.19	−0.37	−0.4	−0.23	[illegible]	−0.4	−0.28	[illegible]	−0.54	0.13	−0.19	0.31	0.36	0.18	0.3	1	
bio9	−0.45	0.86	0.83	0.89	−0.54	−0.38	−0.71	0.5	−0.39	−0.67	−0.86		−0.21	[illegible]	−0.57	0.71	0.88	−0.43		1

Figure S3: Correlation Plot (a) and Variables in PC space (b)

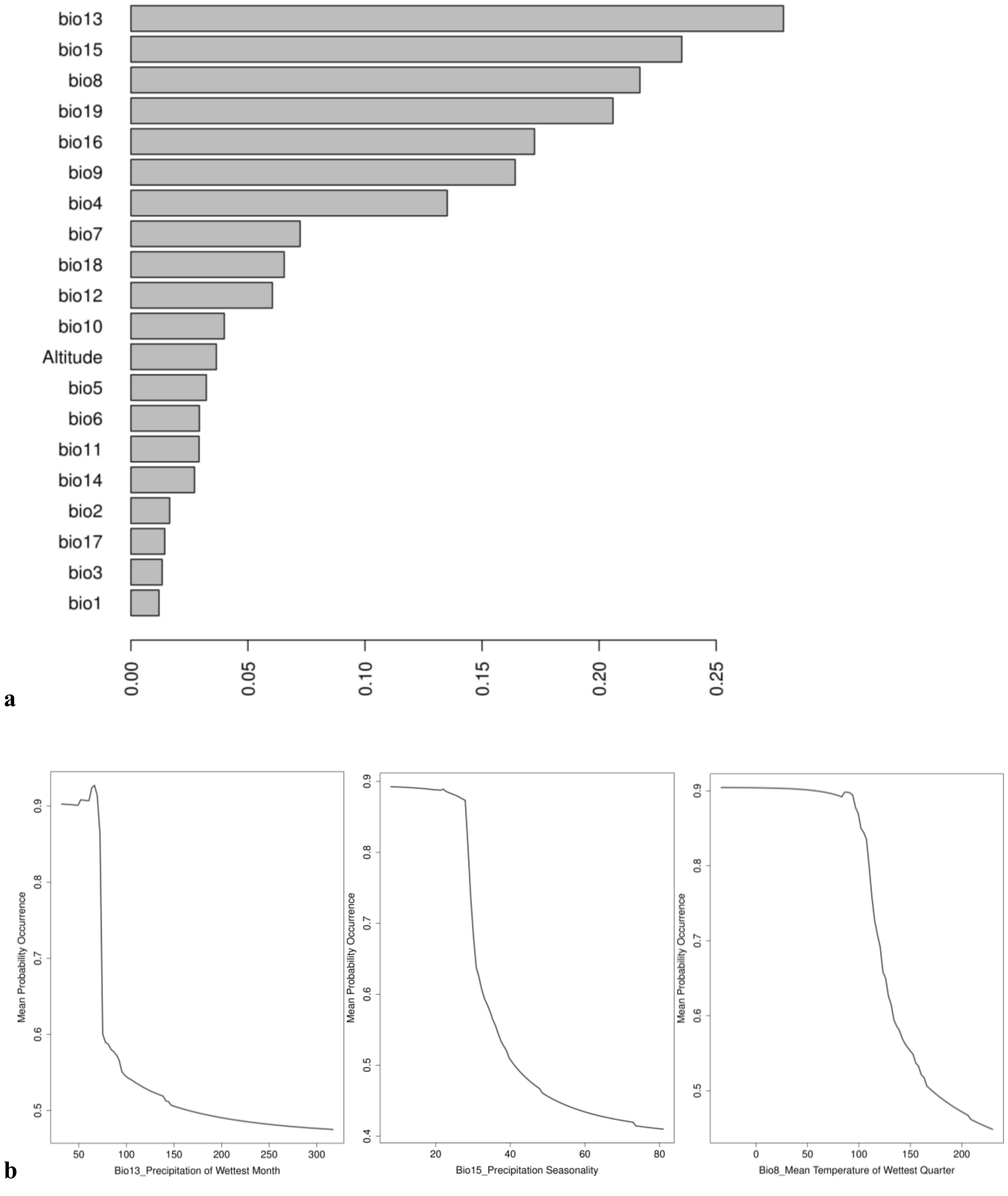


Figure S4: Variable permutation importance (a) and response curves[1] (b) for sorediate morphotype. [1]Variables in x-axis: Bio13 (mm), Bio15 (%), Bio8 (°C*10).

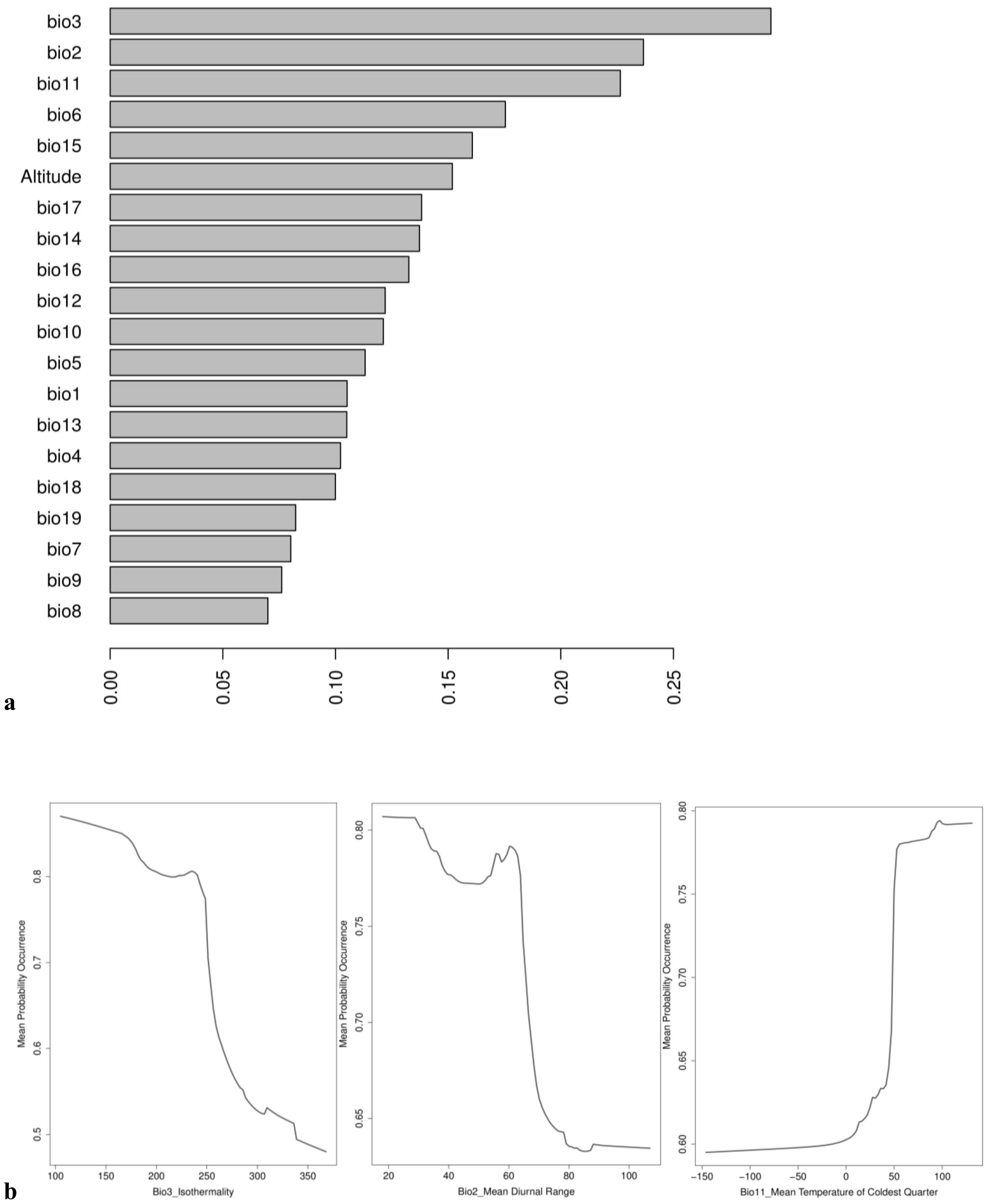


Figure S5: Variable permutation importance (a) and response curves[1] (b) for typical morphotype. [1]Variables in x-axis: Bio3 (%), Bio2 (°C*10), Bio11 (°C*10).

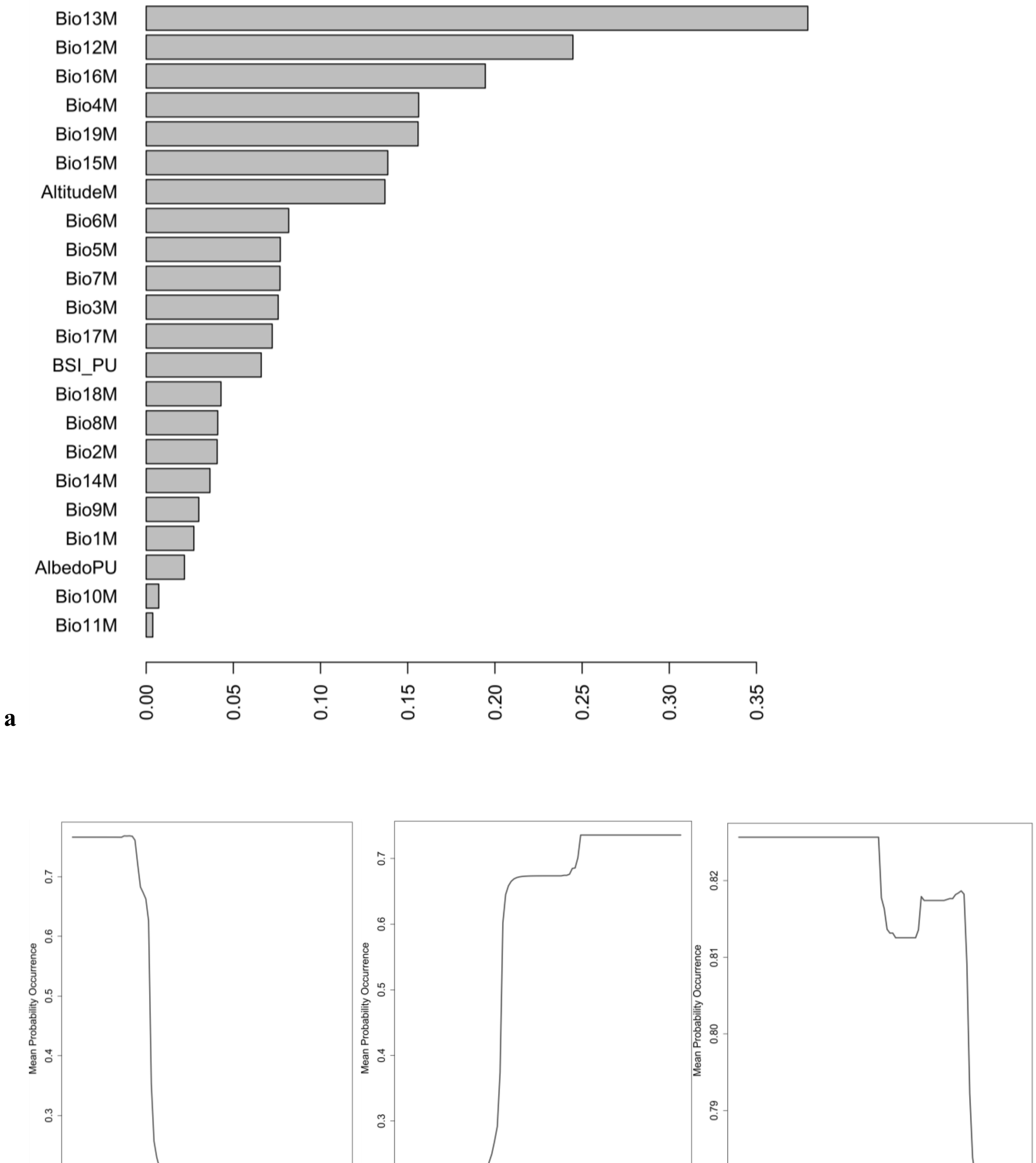


Figure S6 Variable permutation importance (a) and response curves[1] (b) for sorediate type in A1 focus area.

[1] Variables in x-axis: Bio13 (mm), Bio12 (mm), Bio16 (mm).

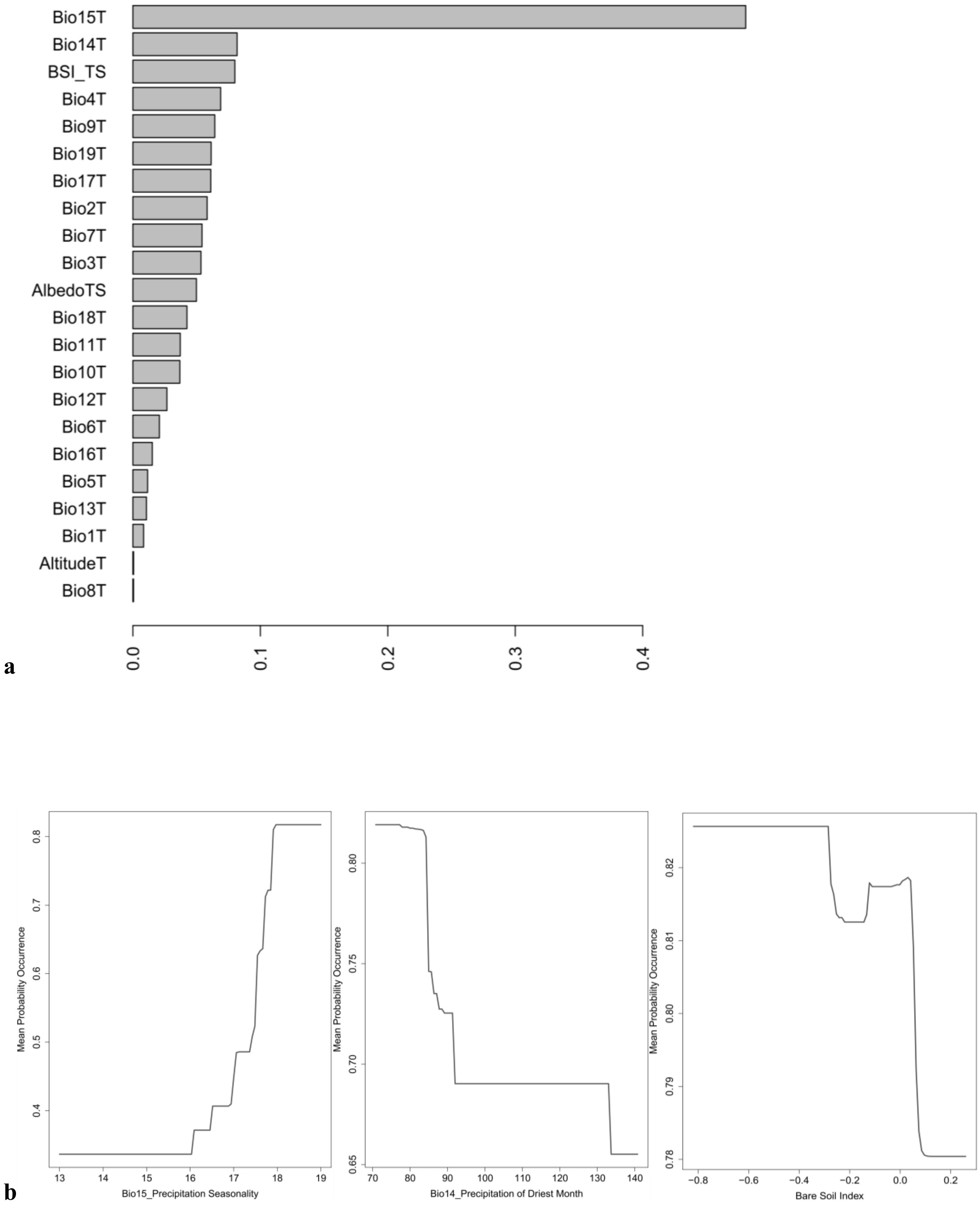


Figure S7 Variable permutation importance (a) and response curves (b) for typical type in A2 focus area. [1]Variables in x-axis: Bio15 (%), Bio14 (mm), BSI (RGB gradient for A2).

Conclusions

These studies provide further evidence of the usefulness of the climatic modelling in addressing ecological questions, since they highlight links between species characteristics and environmental conditions.

Differences in morpho-anatomy of *Solenopsora* infrageneric taxa are reflected in their ecology: they all occur in sites with Mediterranean climate, but with fine differences highlighted, mostly regarding micro-environmental conditions.

The investigation of the different reproductive strategies adopted by different morphotypes of *Pterygiopsis affinis* started from a more taxonomic point of view, then switched to an ecological one. Difference between the two morphotypes has been reasonably explained as response to different ecological conditions, which prompted an adaptive strategy by the species. One of the major issues in modelling the ecological niche of lichens, is the scale: lichens are small in size, and often occur in very small spots. Hence, modelling techniques should use high resolution climatic data, which could be very difficult to find for large portions of Earth’s surface. Further investigations will be addressed to refine spatial scale analysis, coupled with a molecular analisys of the two morphotypes.

Questions about systematics and functional traits can be strongly supported by species distribution modelling tool. However, most studies are mainly focused on the effects of global change on species distribution, and their management. The overall potential distribution of Sardinian orchids is predicted to widen in 2070 scenario (HadGEM 2 - Earth System, RCP 4.5). This could lead to several outcomes: competition among taxa, and loss of less adapted ones; hybridization among sympatric taxa in new taxonomical entities, increasing local biodiversity, or to its decrease if parental taxa will disappear. In any case, these outcomes would lead to a disruption of ecosystem services and dynamics. The results of this study could be of interest when planning climate change adaptation strategies, especially as far as biodiversity conservation is concerned.

Climate and niche modelling tools are powerful instruments from which systematics and ecology could greatly benefit, and lot of potential applications and methodologies are still to explore. The continuation of these studied will hopefully provide novel approaches for applying species distribution modelling techniques, especially to lichens, and other interesting groups.

Publications

Marcantonio, M., Martellos, S., Altobelli, A., Attorre, F., Tordoni, E., **Ongaro**, S., Rocchini, D., Da Re, D., Chiarucci, A., Bacaro, G. (2017) How does spatial scale affect species richness modelling? A test using remote sensing data and geostatistics, Annali di Botanica, 7: 1-14. [*Research article*]

Abstract. Spatially-explicit dataset of plant species occurrences collected in the Province of Siena (Central Italy) is analysed, with the aim of investigating a) the relative role of environmental factors in shaping spatial patterns of plant species richness, and b) how the spatial scale at which predictors have been sampled determines the explicative power of species richness models. The optimal spatial resolution of analysis was evaluated with respect to the total deviance explained by models, using a set of environmental and remotely sensed derived predictors calculated at different spatial scales. Results confirm the hypothesis that the predictive power of landscape structure is influenced by the spatial scale at which predictor variables have been sampled. Furthermore, the relevance of identifying a proper geographical scale of investigation, hence minimizing the redundancy in the predictor variables and maximising the explanatory power of the single groups of predictor variables, is highlighted as well.

Keywords. community structure, kriging, generalised linear models, spatial autocorrelation

Ravera, S., Vizzini, A., Cogoni, A., Aleffi, M., Benesperi, R., Bianchi, E., von Brackel, W., Cataldo, D., D'Antonio, C., Di Nuzzo, L., Favero-Longo, S. E., Gheza, G., Isocrono, D., Matteucci, E., Martellos, S., Morosini, L., Nimis, P. L., **Ongaro**, S., Poponessi, S., Puntillo, D., Sguazzin, F., Tretiach, M. (2018) Notulae to the Italian flora of algae, bryophytes, fungi and lichens: 5, Italian Botanist 5: 31-43. [*Floristic contribution*]

Abstract. In this contribution, new data concerning bryophytes, fungi, and lichens of the Italian flora are presented. It includes new records and confirmations for the bryophyte genera *Diplophyllum* and *Ptychostomum*, the fungal genera *Arrhenia*, *Gymnosporangium*, and *Sporidesmium* and the lichen genera

Arthonia, *Coenogonium*, *Flavoplaca*, *Gyalolechia*, *Parmotrema*, *Peltigera*, *Pterygiopsis*, *Squamarina*, *Tornabea*, and *Waynea*.

Keywords. Ascomycota, Basidiomycota, Bryidae, Jungermanniidae, floristic data

Isocrono, D., Benesperi, R., Catalano, I., Gheza, G., Matteucci, E., **Ongaro**, S., Potenza, G., Puntillo, D., Ravera, S., Pittao, E. (2018) Lichenes Italici Exsiccati ex Società Lichenologica Italiana. Fascicle II (Nos. 13-24), Notiziario della Società Lichenologica Italiana 31. [*Floristic project*]

Abstract. The second issue of Lichenes *Italici exsiccati ex Società Lichenologica Italiana*, the series of *exsiccata* distributed by the Italian Lichen Society (Società Lichenologica Italiana, SLI), is presented.
The labels of 13-24 numbers are listed.

Key words. Lichens, *exsiccate*

<u>*Other contributes*</u>

Ongaro, S., Guttova, A., Pittao, E., Girardello, M., Martellos, S. (2016) Lichen symbiosis and environmental niche modelling: a protocol for optimization, *I Congresso Unificato SiTE SIB UZI*, Book of Abstract, p.19. [*oral presentation*]

Ongaro S., Morosini L., Martellos, S., Tretiach, M. (2018) Preliminary climatic distribution model fro Pterygiopsis affinis as a mean for field surveys planning, *113° Congresso SBI*, Book of Abstract, p. 56. [*oral presentation*]

Fačkovcová, Z., Zozomová-Lihová, J., Slovák, M., Kučera, J., Piknová, K., Timdal, E., Martellos, S., **Ongaro**, S., Guttová, A. (2016) Towards taxonomy, phylogeography and ecology of *Solenopsora* species (Leprocaulaceae) – elements with a strong link to Mediterranean-type ecosystems, IAL8 Abstracts, p. 56. [*poster*]

Ongaro, S., Martellos, S., Tretiach, M. (2016) Considerazioni preliminari su una possibile nuova *Pterygiopsis* trovata in Puglia, *29° Convegno SLI*, Notiziario della Società Lichenologica Italiana 29: 45. [*poster*]

Ongaro, S., Martellos, S., Tretiach, M. (2017) *Pterygiopsis affinis* vs *Pterygiopsis "sorediata"*: advances on anatomy, *30° Convegno SLI,* Notiziario della Società Lichenologica Italiana 30: 48. [*poster*]

Ongaro, S., caredda, A., Martellos, S., Cortis, P. (2017) Modelling Present and future climatich niche of most common Sardinian orchids, *112° Congresso SBI*, Book of Abstract, p. 82. [*poster*]