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Sensitivity of wild plants to climate change

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Abstract. – Measuring and modelling the response (sensitivity) of wild plants to current and future climate is crucial to predict future biodiversity and ecological assets. Our research group is using a range of experimental approaches to address this goal. To predict range shifts in plant species under climate change scenarios, we use species distribution models (SDMs). This approach is applied to native species of conservation interest and to alien taxa, in order to check the predictive power of SDM for future invasiveness, when used on early detected alien taxa. Another line of investigation deals with changes in breeding system and seed ecology promoted by climate change. We also evaluate the impact of past natural climatic changes in plant evolution and, finally, our research deals with the study of plant functional traits in relation to climate change.

Application of SDMs to native species of conservation interest. – Species distribution models (SDMs) relate environmental variables to species occurrence records, to gain insights into ecological or evolutionary drivers or to help in predicting habitat suitability across large scales (Elith & Leathwick 2009). We modelled the present and future predicted distribution of the soft-water pools specialist *Hypericum elodes* L. (Carta 2015), in order to facilitate appropriate decision making for its conservation and monitoring. *Hypericum elodes* is confirmed as a climate-sensitive species, with a W-European distribution. The model shows a marked negative influence of climate change, with *ca.* 58% reduction in the number of pre-existing bioclimatically suitable localities by 2050.

In the chasmophytic hypsophilous *Primula apennina* Widmer, an Italian endemic plant of conservation interest occurring on Tuscan-Emilian Apennines, we modelled (Astuti *et al.* 2019) the potential current distribution and projected it in year 2070, under different CO_2 emis-

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sions scenario projections. We found that the distribution model built under the climate conditions returned a severe decline of cell occurrence coupled with an extremely low occurrence probability of *P. apennina* for all cells, hence predicting a "next-to-the-extinction scenario". This prediction may be due to an upward range shift in elevation, which has been documented in many mountain plants combined to a "no place left to go" effect, as northern Apennines reach the maximum elevation at little more than 2100 m. Other Italian endemics studied by our research group, which are experiencing a reduction at lower elevations, possibly linked to climate change, are *Athamanta cortiana* Ferrarini (Ansaldi *et al.* 2011) and *Salix crataegifolia* Bertol. (Roma-Marzio *et al.* 2015).

Despite climate change can have significant impacts on the survival of plant species, it is seldom included in the assessment of the extinction risk according to IUCN Red List criteria. In a recent paper (Attorre *et al.* 2018) we addressed the effect of climate change on plant species spatial distribution. 37 Italian policy species (listed in the Habitat Directive and Bern Convention) were used as case study. A stochastic SDM incorporating data on plant dispersal, generation length, and habitat fragmentation was used to predict a range shift due to climate change according to two climatic scenarios. All taxa were potentially affected by climate change through a reduction of their range, albeit only two were characterized by critical decline probabilities. Species with the highest predicted reduction of range were those from lowlands, where fragmentation of natural habitats has occurred since the last decades.

Altogether, SDM can inform conservation spatial planning strategies minimizing the conservation costs, especially if the phylogenetic relationship among species is considered, with consequent reduction of redundant species (Carta *et al.* 2019).

Evaluation of SDMs temporal projection. – SDMs are widely used to forecast climate change impacts. Such temporal extrapolations are a common practice in plant ecology, but their effectiveness is hardly assessed, due to the absence of distribution data at the time when model is projected (*i.e.*, future data). The uncertainty associated with SDMs projections is poorly characterized, despite its potential value to decision makers. To test the reliability of SDM future projections, we performed SDMs on nine Italian endemic species (D'Antraccoli *et al.* 2019), using historical biological data (1910-1930) and historical climatic maps ('past models'). Then, these models were projected to current climate ('projected models'), and compared with SDMs realized with current biological data (1980-present) and current climatic maps ('present models'). Accordingly, it was possible to test theoretical "future" distributions, with current potential distributions (in this case, corresponding to the "future"). In four out of the nine case studies we observed an overestimation of the projection function, and in five an underestimation. These differences seem correlated to the ecological features of the species: stenoecious species, showing a limited habitat tolerance range, seem prone to overestimation. On the contrary, euryecious species, showing wider habitat tolerance range, seem prone to underestimation. Further research is required to assess the reliability of SDM-based conservation programmes for species with different levels of ecological tolerance.

Application of SDMs to predict invasiveness of alien species. – SDMs have also been extensively applied to invasive species to assess the risks of biological invasions (Jiménez-Valverde *et al.* 2011). Despite this, two core assumptions of SDMs are violated when modelling invasive species. These species are not in equilibrium with their environment and niche quantification in space and time are limited (Gallien *et al.* 2012). To improve our understanding of SDMs applied to biological invasions, we aim to compare the current distribution of selected alien species (either casual, naturalized, or invasive) introduced in Italy near the end of 19th century, to their potential distribution, modelled using past distribution and past climate data. This should allow to get insights into SDMs performance in predicting the "future" degree of invasiveness in alien plants.

Reproductive and regeneration strategies under climate change. – Plant persistence and migration in face of climate change depends on successful reproduction by seed. To assess plant population persistence and survival we primarily observe the disruptive association between reproductive (breeding system) - regenerative (seed ecology) stages and the climatic conditions experienced by wild plant populations. Self-pollinated plants or even mixed breeding systems may be favoured under unpredictable environments (Carta *et al.* 2016a), which may be the case under a climate change scenario. The promotion of a shift toward self-fertilization under climate change, even maladaptive, may favour self-pollination (Casazza *et al.* 2018). Changes in the breeding systems may also result in the development of seeds showing different degrees of seed dormancy (Carta *et al.* 2015). Whilst these strategies may allow acclimatisation of populations, their effects on plant reproduction cannot be reduced to a qualitative interpretation of absolute positives and negatives (Fernández-Pascual *et al.* 2019). In this context, we conducted laboratory experiments to describe the shape of the seed germination niche, discovering associations with the current climate. These studies highlighted species-specific (Carta *et al.* 2014, 2016b) or even population-specific (Carta *et al.* 2016c) climatic cues, triggering seed germination that may negatively impact population survival.

Climate change and plant evolution. – Natural climatic changes that occurred through geological times are one of the drivers of evolution in plants. For instance, we recently evaluated the role played by Plio-Pleistocenic climatic changes in shaping the current genetic structure of black pine (*Pinus nigra* J.F.Arnold) in the Mediterranean (Naydenov *et al.* 2016, 2017). Applying molecular (AFLP and sequences of nuclear ribosomal ITS), karyological (relative genome size estimations and chromosome counts) and morphometric methods to the *Euphorbia verrucosa* alliance (Cresti *et al.* 2019), we underlined the importance of southern European peninsulas as refugial and diversification areas during the Pleistocene, providing additional evidence that Mediterranean high mountain plants are suffering severe range contractions due to climate warming.

Finally, by estimating divergence times under a random molecular clock based on nrITS phylogeny of the genus *Gagea* (Liliaceae), we revealed that this genus most likely originated in southwestern Asia, starting its diversification in the Early Miocene (Peterson *et al.* 2019). In the Middle Miocene, *Gagea* migrated to the Mediterranean and to East Asia, while migration into Euro-Siberia took place in the Late Miocene. During the Pleistocene, the Arctic was colonized and *Gagea serotina,* the most widespread species, reached North America. The Mediterranean basin was colonized multiple times from southwestern Asia or Euro-Siberia. Most of the currently existing species originated during the last 3 Ma. All these migration and diversification rounds paralleled the main climatic changes which shaped the current climate of northern Hemisphere.

Vegetative functional response of plants to climate. – The Mediterranean basin is characterised by increasingly dry summers and the study of the adaptive traits developed by plants living in this stressful environment is of great interest, also in relation to climate projections for this area. Summer drought in which the combined action of water deficit, high air temperatures and excess of light could be very stressful, is generally considered the primary constraint to plant growth in Mediterranean Basin. Considering that climate change is expected to increase temperatures and the intensity and/or frequency of drought in the Mediterranean basin (IPCC 2013), the characterization of plants living in this stressful environment and of their response to constraints related to climate is of great interest.

Mediterranean plants have developed different mechanisms to cope with summer drought involving morphological, biochemical, and physiological changes. Plant functional traits are useful features to study ecological strategies and to determine how plants respond to environmental factors (Perez-Harguindeguy *et al.* 2013). Leaf area, specific leaf area, leaf dry matter content and succulence index were studied in different plants living in different habitats such as coastal sand dunes, sea rocky cliffs, and Mediterranean maquis (Ciccarelli 2015; Ciccarelli *et al.* 2016; D'Antraccoli *et al.* 2018). These studies highlighted how co-occurring species can evolve different responses to the climatic stress factors in the Mediterranean area.

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