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Dream of mediterranization: Range expansion of the giant water bug (*Lethocerus patruelis*) in Europe

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Short title: Expansion of giant water bug

ABSTRACT

Climate change is causing European temperate climates to shift toward mediterranean conditions, a phenomenon called ‘mediterranization’. Mediterranization is altering biological communities, facilitating expansion of species pre-adapted to mediterranean habitats. Colonization by novel species can drastically affect local biodiversity, particularly in freshwater ecosystems. *Lethocerus patruelis* is a large predatory aquatic insect whose distribution spans from the Balkans to south-eastern Asia. In the last decades, *L. patruelis* sightings outside its known range have increased, particularly in Italy. The aim of this study was to assess the drivers of this expansion and the potential for future spread.

We collected records of *L. patruelis* using published literature, citizen-science platforms, and social media. These data were used to test for directional expansion and to compare native and novel niches. Secondly, we used native observations to create a suitability model using MaxEnt, testing it using observations from Italy. Lastly, we projected the model under three future climatic scenarios to assess the potential for future expansions.

We found a significant westward and southward expansion of *L. patruelis* in Italy. Niche conservatism between native and novel ranges was observed. Nonetheless, we found limited overlap and high level of niche unfilling, suggesting an ongoing colonization process. The suitability model showed good predictive performances, indicating a preference toward mediterranean climates and a selection against agricultural areas. Suitable areas were predicted to increase under all three future climatic scenarios.

41 This study suggests an ongoing spread of *L. patruelis*, and a strong expansion potential in Europe
42 due to mediterranization. Future studies are needed to assess the means of this expansion and its
43 consequences on local biodiversity.

44 **Keywords**: niche dynamics; suitability models; climate change; Hemiptera; MaxEnt

INTRODUCTION

Climate change is already shaping European biodiversity. Many temperate regions are facing an ongoing process of *mediterranization*, with relevant consequences for freshwater systems (Bernal et al. 2013). Human transports and mediterranization are favouring the spread of Mediterranean-adapted species toward new areas of temperate Europe (Rabitsch 2008; Peltanová et al. 2012).

The giant water bug, *Lethocerus patruelis* (Stal, 1854), is an aquatic hemipteran whose distribution spans from Southern Europe to Southeast Asia (Perez Goodwyn 2006; Sareein et al. 2019). It is the largest true bug found in Europe, with a maximum body length of 6-8 cm (Perez Goodwyn 2006). *Lethocerus patruelis* and closely related species are predatory insects whose main food sources are represented by vertebrates, such as fish, amphibians, and reptiles (Ohba 2011, 2019; Christopoulos et al. 2022). Like other representatives of the family Belostomatidae, males of this species display strong parental cares, protecting the eggs until they hatch (Ohba 2019). Belostomatidae species are also known for their extremely painful bites, caused by the injection of their digestive saliva, that have led them to be informally called “toe- biters” (Haddad et al. 2010).

Despite its size and its dispersal abilities, observations of this species in Europe are scarce, with most records originating from social networks, online newspapers, and citizen science programs, and its distribution remains poorly understood (Corsini-Foka et al. 2019; Davranoglou & Karaouzas 2021; Lo Parrino & Tomasi 2021; Cianferoni & Mazza 2023). In the last decades, the range of this species has expanded both northwards and westwards (Cianferoni & Nardi 2013; Grozeva et al. 2013; Stoianova & Simov 2016; Lo Parrino 2019). *Lethocerus*

patruelis has been observed in Italy since 1997 and nowadays records have been collected all across Southern Italy (Cianferoni & Nardi 2013; Lo Parrino 2019; Castiglione et al. 2021; Lo Parrino & Tomasi 2021; Cianferoni & Mazza 2023). Records of both sexes and frequency and locations of observations suggest a stable presence in Southern Italy, although naturalization has yet to be proved (Lo Parrino & Tomasi 2021; Cianferoni & Mazza 2023). Whether its presence in Italy is the result of a human-mediated introduction or a natural range expansion is still unclear. The oldest Italian records came from areas next to major Adriatic ports and, given the positive phototropism expressed by this species, it has been hypothesized that individuals reached Italy from the Balkans following the artificial lights of boats and ships, as suggested by direct observations (Cianferoni & Nardi 2013). For this reason, Cianferoni and Nardi (2013) suggested considering *L. patruelis* as an alien species in Italy. While invasive insects represent a relevant portion of the total number of invasive species, aquatic insects rarely become invasive (Fenoglio et al. 2016; Sendek et al. 2022). Moreover, some phenomena, such as climate change or land-use modifications, can favor both the colonization by invasive species, and the natural expansions of species ranges (Hoffmann & Courchamp 2016). Thus, assessing its potential spread is relevant regardless of its origin (i.e., alien or natural range expansion). This makes the expansion of *L. patruelis* in Italy an interesting case-study, as novel predators may deeply affect trophic webs in newly colonized freshwater environments (Ficetola et al. 2012). Moreover, its spread may have consequences on human health, as Belostomatidae are suspected to be vectors of certain pathogenic bacteria, such as *Mycobacterium ulcerans* (Haddad et al. 2010; Marion et al. 2010). While there is no current evidence for pathogen transmission by *L. patruelis*, there is at least one documented report of bite on humans (Cianferoni & Nardi 2013).

The aim of this work is to assess *L. patruelis* spread in Italy, its niche dynamics, and its potential distribution under different climate change scenarios in Europe. This assessment may help monitor a fast-spreading species that can potentially affect freshwater food webs, with deep consequences on the conservation of aquatic environments.

METHODS

Species occurrences

A dataset of *L. patruelis* occurrences in Italy was curated and collated during the period January 2019 - July 2024 by Elia Lo Parrino and Filippo Tomasi. Occurrences were gathered through a regular screening of bibliography, local Italian Facebook groups, and the online forums “Natura Mediterraneo”, “Tropicamente”, and “Entomologi Italiani”. Data gathered from the internet up to 2021 have been already published elsewhere (Cianferoni & Nardi 2013, Lo Parrino & Tomasi 2021). A search on the Global Biodiversity Information Facility (https://www.gbif.org/), performed in July 2024, was then made concerning all occurrences of the species across its range, and the resulting occurrences were merged with the Italian dataset. All subsequent analyses were performed at 1 km grid resolution, and therefore to reduce spatial autocorrelation (Václavík et al. 2012) records closer than 1.5 km were removed with the *humboldt.occ.rarefy* function in the ‘humboldt’ R package (Brown and Carnaval 2019). The total dataset comprised 381 occurrences and, after thinning, the final dataset used for large-scale analyses included 253 points.

Environmental variables

We used an expert-based approach to operate an *a priori* choice of variables to include in the analyses (Santini et al. 2021). We consulted the available scientific literature on giant water bugs’ ecology to define a set of variables to explain its expansion and potential range. Variables fell into three main categories: climate, land-use/land-cover (LULC) and distance from water. We selected two bioclimatic variables considered relevant for the species: temperature of the warmest quarter (bio10), as temperature is highly relevant for the dispersal of the species

(species of the *Lethocerinae* subfamily need to warm up their muscles to be able to fly; Ohba 2019) and most observations fall in the summer period (Lo Parrino & Tomasi 2021), and precipitation seasonality (bio15), as the species shows a preference for Mediterranean climates that are best captured by this bioclimatic variable (Lo Parrino & Tomasi 2021). Climatic variables covering the period 1981-2010 were downloaded from the CHELSA repository (Karger et al. 2017). To describe future climatic conditions, the CHELSA database CMIP6 scenarios were considered (Karger et al. 2017), for the period 2041-2070. Three combinations representing different and increasingly pessimistic scenarios of socioeconomic projections (SSP) and greenhouse gas emissions (RCP) were considered: 1) SSP 1.6 - RCP 2.6, 2) SSP 3 - RCP 7, 3) SSP 5 - RCP 8.5. To ensure that the result is not dependent on the specific General Circulation Model (GCM) used to describe the climatic system (Herger et al. 2018), we selected five different GCMs: GFDL-ESM4 (Dunne et al. 2020), IPSL-CM6A-LR (Boucher et al. 2020), MPI-ESM1-2-HR (Müller et al. 2018), MRI-ESM2-0 (Yukimoto et al. 2019) and UKESM1-0-LL (Tang et al. 2019). We described LULC with two variables: percentage cover of trees, as forested areas appear to provide shelter during the winter season when giant water bugs hide in the litter (Ohba 2019), and the percentage cover of cultivated and managed vegetation, as irrigation channels can be exploited by Belostomatidae, and individuals of *L. patruelis* have been observed in artificial channels in Southern Italy (Lo Parrino & Tomasi 2021). LULC was retrieved from Tuanmu and Jetz 2014 (https://www.earthenv.org/landcover); the cover of trees was computed summing the first four layers (Evergreen/Deciduous Needleleaf Trees, Evergreen Broadleaf Trees, Deciduous Broadleaf Trees, Mixed/Other Trees), each representing the percentage cover of trees, whereas the cover of cultivated or managed vegetation was represented by the variable “Cultivated and Managed Vegetation”.

Distance from water was obtained starting from the global HydroLAKES and HydroRIVERS shapefiles (Wickel and Sindorf 2007), downloaded on July 16th, 2024 from the HydroSHEDS website (https://www.hydrosheds.org/). The two shapefiles were rasterized, merged and the distance in pixels of each cell from the nearest cell with water was then computed in the QGIS Software.

Testing for directionality of expansion

To establish whether the species is expanding in Italy and whether this expansion follows a specific direction, we developed linear models of maximum and minimum latitude and longitude in Italy as a function of the year of observation. Residual plots were visualized to check for normality; normality was met for all models except maximum longitude (Eastern side), so maximum longitude was log-transformed to increase residual normality. The effect size of the relationship between each predictor and the year of observation in each model was then used as a proxy for the directionality of expansion along a major geographical axis. This analysis can provide a first indication of the directionality of expansion, as it is unlikely that eventual patterns detected are the result of a directional expansion in the research interest and sampling effort by citizen scientists.

Niche dynamics

To assess the extent to which *L. patruelis* can extend its range in Italy, we estimated niche metrics treating Italy as the novel range and the rest of the species' range as native, using the 'ecospat' R package v. 4.1.0 (Di Cola et al. 2017). To define the environmental niche of the

160 species, we considered six environmental variables: temperature of the warmest quarter,
161 precipitation seasonality (from CHELSA; period: 1981-2010); distance from water and three
162 LULC variables (tree cover, cover of cultivated and managed vegetation). Dimensionality of
163 variables was reduced using a Principal Component Analysis (PCA). The centroids of 1 km grid
164 resolution raster cells in the 100 km buffer around occurrences were used to extract background
165 environmental conditions in the native and non-native range, excluding only cells where the
166 species was reported. Global overlap between niches was then computed via two metrics:
167 Schoener's *D* and Hellinger's *I* (Broennimann et al. 2012). These metrics range between 0 and 1
168 where increasing values are indicative of greater overlap. We then measured three metrics
169 describing the niche dynamics between the native range (here assumed to be represented by all
170 populations of Italy) and the Italian range: 1) niche unfilling (portion of environmental
171 conditions found outside the novel niche but within the native niche), 2) niche stability (portion
172 of shared environmental conditions between native and novel niche), and 3) niche expansion
173 (portion of environmental conditions found exclusively in the novel niche; Petitpierre et al. 2012,
174 Guisan et al. 2014). Calculations for these metrics were made at the 10th quantile intersection
175 both for native and novel environmental densities (Lo Parrino et al. 2023). The significance of
176 the aforementioned metrics was tested with niche equivalency and similarity tests using 100
177 replicates each. Equivalency tests pool together occurrences and divide them into two datasets;
178 then, they calculate the required niche measure and iterate the process *n* times; similarity tests
179 randomly shift the observed occurrence densities in the novel range and compare the observed
180 native niche and the simulated niche (Broennimann et al. 2012). A significant equivalency test
181 implies that metrics derived from the comparison between native and novel niches are more (or
182 less) equivalent than what expected by the comparison of two random niches. A significant

similarity test means that metrics derived from the comparison between native and novel niches are more (or less) similar than what expected by the comparison of the native niche and a random niche from the novel range. We tested for niche expansion, thus we expected overlap and stability to be significantly lower than expected by chance, while expansion and unfilling to be significantly higher than under random conditions in both tests.

Species distribution modelling

Species distribution models (SDMs) relate species occurrences and pseudo-absence or background points to environmental conditions in order to estimate the distribution in environmental and geographical space (Elith and Leathwick 2009). Fitted SDMs can therefore be used to predict suitability of a species under current and future conditions, and hence assess the influence of environmental change on its distribution (Elith and Leathwick 2009). In this study, we used spatially-explicit predictions from SDMs to visualize the extent of space potentially suitable for the species under current conditions and under scenarios of future climate change. The present-day existence of a large amount of suitable and currently unoccupied areas would be a further indication of the fact that the species is not at equilibrium and is undergoing range expansion (Uden et al. 2015). We used the thinned occurrences of *L. patruelis* across both the native and novel distributions to develop Maxent SDMs (Phillips et al. 2006). This algorithm is consistently ranked among the best for SDM and it allows easy tuning of its hyperparameters in order to obtain reliable models (Elith et al. 2011, Valavi et al. 2023). Correlation among predictors was assessed with a Pearson pairwise correlation test, whereby values equal or above 0.7 indicate strong correlation among two predictors and that one of them should be dropped to avoid collinearity issues (Dormann et al. 2013). We performed this test on the variables over the

206 training area (buffer of 100 km around all thinned occurrences), using the *pairs* function in the
207 'raster' R package (Hijmans et al. 2013). No paired correlation was greater than 0.7, and the
208 highest correlation was among the two climatic variables (Figure S1). We also computed the
209 Variance Inflation Factor for each predictor, a metric that also quantifies unobserved collinearity
210 among variables, and checked that all predictors had a VIF below the recommended threshold of
211 3 (Table S1; Zuur et al. 2010). Therefore, we retained all five predictors in our Maxent models.
212 Permutation importance for each predictor of the best-performing Maxent model was computed
213 as the percentage drop in predictive performance when it was removed from the model, and
214 response curves, showcasing the effect of different predictors on the species' habitat suitability,
215 were also produced (Elith et al. 2005). As background points, we considered 20000 points
216 randomly sampled within a buffer of 100 km from presence points (to ensure that they are in
217 areas accessible to the species; VanDerWal et al. 2009). Background points were sampled with a
218 probability proportional to human density, to account for sampling bias (Stolar and Nielsen
219 2015). Geographically separated training and test data provide more robust estimates of model
220 robustness and transferability (Sutton and Martin 2022). To test the predictive performance of
221 models, we used data outside Italy as training (176 points, ~70% of occurrences) and data in
222 Italy as test (77 points, ~ 30% of occurrences). We tested eight values of beta (i.e., regularization
223 multiplier, a parameter that controls model overfitting), ranging from 1 to 8 in steps of one, and
224 two possible combinations of features (i.e., transformations of the original variables), LQ (linear
225 and quadratic features) or LQH (linear, quadratic, and hinge features). As evaluation metrics for
226 the performance of models we used the Area Under the Receiver-Operating Characteristic Curve
227 (AUC, Fielding & Bell 1997), a reliable threshold-independent measure, and the Continuous
228 Boyce Index (CBI, Hirzel et al. 2006). Both metrics range between 0 and 1 with values above 0.5

indicating better-than-random predictive ability on the Italian occurrences. The model with the best trade-off among these two metrics was used to develop spatial projections of habitat suitability for the species over the European continent. Projections under future climatic conditions were then developed for the three SSP-RCP combinations mentioned above, and keeping all non-climatic variables equal to the present due to the scarce availability of future LULC scenarios (Stanton et al. 2012). Projections developed with different GCMs were then averaged for each SSP-RCP combination, and the standard deviation among GCMs was also computed to visualize the robustness of predictions.

RESULTS

We obtained 281 total occurrences of *Lethocerus patruelis*. The occurrences ranged from 1997 to 2023, but data were mostly recent (132 observations were made in the period 2020-2024). We collected 175 *L. patruelis* occurrences from its native range and 106 from Italy. Among the occurrences reported here for the first time, we report the first known observation of this species coming from Sicily.

Linear models detected a significant shift of the southern and western boundaries of the margins of its non-native range in Italy as a function of year of observation (Western side: estimate = - 0.004, p = 0.029; Southern side: estimate = - 0.061, p = 0.002), whereas non-significant patterns were found at the Northern and Eastern boundary (Figure 1).

Niche metrics generally showed a limited overlap between the native and the novel range of the species. The niche equivalency tests were significant for both overlap measures (Schoener's D = 0.126, p <0.01***; Hellinger's I = 0.341, p <0.01***; Table 2), indicating that overlap between the native and novel niches was lower than what could be expected by chance. This was caused by a significant unfilling in the novel range, compared to the native one (unfilling = 0.431, p < 0.01**; Table 1), and not by niche expansion (niche expansion = 0; Table 1). Similarity tests did not show any significant difference between the observed niche dynamics and the ones obtained by comparing the native niche and randomly generated niches from the available conditions in the novel range, as all environmental conditions in the novel environment are a subset of the ones available in the native range of the water bug (Figure 2).

The fine-tuned Maxent model provided an excellent CBI (0.844) and a good AUC (0.746), indicating good predictive ability on the withheld dataset (Table S2). The best model included linear, quadratic and hinge features and had a regularization multiplier of two (Table S2), and

showed both CBI and AUC higher than the one of any alternative model. The most important variables according to the percentage permutation importance in this model were, respectively: precipitation seasonality (47.3 %), cultivated and managed vegetation cover (31 %), and temperature of the warmest quarter (19.3 %; Table S3). Response curves for the two climatic variables depicted preferences for values of precipitation seasonality and temperature of the warmest quarter coincident with those found in the Mediterranean region (Figure 3), a negative relationship with the cover of cultivated areas was evidenced (Figure 3). Other variables had a negligible influence on the model (Table S3): tree cover (1.8 %), and distance from water (0.8 %).

Spatial projections for the current period showcased the presence of large potentially suitable but currently unoccupied suitable areas especially in Italy and Spain, in areas with a warm and Mediterranean climate (Figure 4). Projections of suitability under future climate change scenarios (2041-2070) consistently showed an expansion of potentially suitable areas across Europe, particularly under the most severe scenarios, with a northward expansion of suitable areas (Figure 5) (Figure 5). The agreement between different GCMs was generally high (SD of habitat suitability with five different GCMs was always lower than 0.34; Figure 5), although incertitude increased for the most extreme scenario (Figure 5).

DISCUSSION

Colonization of new areas by expanding species can disrupt local communities' structure, food-webs, and functional diversity (Ficetola et al. 2012, Collins et al. 2016, Hoffmann & Courchamp 2016). Predicting the potential spread of invasive species can allow the early detection and prompt control responses during the early stages of colonization (Torres et al. 2018). In this context, citizen science can represent an important tool to assess the occurrence of a colonizing species, as it has the potential to collect high volumes of data covering large areas (Silvertown 2009, Crall et al. 2010, Larson et al. 2020). Data on the occurrence of *Lethocerus patruelis* mostly comes from citizen science, showing how this tool can complement data from traditional data sources (Lo Parrino & Tomasi 2021). Despite the lack of evidence for the establishment of viable populations in Italy, recent *L. patruelis* records in areas far from the Adriatic coasts (Supplementary Materials) suggest the unlikeliness of sporadic arrivals of dispersing individuals from the Balkans. Moreover, the directional expansion we found seems to reflect an ongoing colonization of new areas.

Analyses of niche dynamics suggest that the expansion is still ongoing, as high levels of niche unfilling are typical of range-expanding species during the colonization phase (Petitpierre et al. 2012, Strubbe et al. 2013). The significant divergence between the native and Italian niches found by the equivalency test for both Schoener's *D* and Hellinger's *I* is the result of the aforementioned high unfilling. Niche expansion is the only measure reflecting 'true' niche shifts (Petitpierre et al. 2012, Strubbe et al. 2013, Li et al. 2014, Liu et al. 2020), thus our results showed that *L. patruelis* niche is conserved in the exotic range.

Niche dynamics showed the meeting of the niche conservatism assumption, suggesting the reliability of SDM projections outside the training area (Early and Sax 2014, Pili et al. 2020,

Atwater & Barney 2021). As expected, results of SDM under the current environmental conditions confirm its preference for Mediterranean climate, with the highest levels of suitability found around the Mediterranean basin. Contrarily to our expectations, suitability for the species showed a negative relationship with cultivated surfaces. This is likely due to the variety of different agricultural systems aggregated under the "cultivated and managed vegetation" category (Tuanmu & Jetz 2014), with only a small subset of them being exploitable by *L. patruelis*. Counter-intuitively, distance from water did not affect suitability, despite *L. patruelis* biology. This may be due to the fact that HydroLAKES and HydroRIVERS, as well as the other available maps, have a spatial resolution of ~1 km, thus excluding small waterbodies potentially exploitable by aquatic insects and other organisms. *Lethocerus* nymphs, in particular, are most often found in temporary shallow waterbodies that are too small to be mapped at this scale (Nesemann & Sharma 2013). The lack of high-resolution datasets of waterbodies' features has already been indicated as one of the main obstacles to niche analyses for freshwater organisms (Loo et al. 2007, Torres et al. 2018, Lo Parrino et al. 2023). On the basis of our results, expansion of *L. patruelis* in Italy may be slowed down by the Apennine chain, particularly northwestwards, since suitability was generally low in correspondence of mountain areas. This may represent a potential reason for the observed southward expansion of this species, which seems to prefer low altitude areas.

Climate change is expected to play a relevant role in affecting distribution shifts, physiology, phenology, abundance, and community structure of Heteroptera (Musolin 2007). Climate change has already been proposed as a possible reason behind *L. patruelis* spread in Italy (Cianferoni & Mazza 2023), but this work represents the first attempt to investigate the relationship between climatic factors and this species' potential distribution. All projections of SDM on future climatic scenarios showed an increase of suitable areas for *L. patruelis*, particularly in Central

Europe and on Mediterranean mountain chains, such as the Apennines and the Pyrenees, potentially loosening the barrier effect played by mountains. The process of mediterranization of invertebrate fauna in Central Europe is an already observed phenomenon, and is particularly evident in certain groups, such as Heteroptera and Gastropoda (Rabitsch 2008, Peltanová 2012). Watercourses in temperate regions may be particularly sensitive to mediterranization (Bernal et al. 2013), with potential consequences on their community compositions. Concerning Mediterranean mountains, climate change is causing an increase in average annual temperature and a decrease in spring precipitation (Bravo et al. 2008). This is expected to cause composition shifts in biological communities, with Mediterranean species substituting cold- and temperate-adapted species (Ruiz-Labourdette et al. 2012, 2013, Hernández et al. 2017). The projected suitability for *L. patruelis* under all climatic scenarios is thus coherent to the ongoing mediterranization of European fauna.

CONCLUSIONS

Our results showed that *Lethocerus patruelis* range expansion trend in Europe represents another example of the mediterranization of European fauna. While it is still not possible to assess whether human introductions may have played a role in its spread, our results show that *L. patruelis* expansion is likely driven by environmental factors. Given the potential harmful impacts that the spread of this predator may have on local communities, particularly on freshwater vertebrates, we recommend further investigations into its poorly-known biology and the drivers of its spread. Assessing whether *L. patruelis* is naturally expanding its range or if it was introduced in novel areas by human activities may represent an important step for planning any potential eradication or containment action.

Data availability

The datasets and R code used in this study are available from: https://zenodo.org/records/14046410.

TABLES

Table 1. Niche metrics estimated with the 'ecospat' R package (Di Cola et al. 2019) and obtained comparing the native and non-native niche of the giant water bug *Lethocerus patruelis*, where the non-native range is found in Italy and the native range stretches from the Balkans to South-eastern Asia. Equivalency *p* = p value from a niche equivalency test, Similarity *p* = p value from a niche similarity test.

Measure	Estimate	Equivalency *p*	Similarity *p*
Schoener's *D*	0.126	<0.01***	0.950
Hellinger's *I*	0.341	<0.01***	0.980
Expansion	0	1	1
Stability	1	1	1
Unfilling	0.431	<0.01**	1

FIGURE CAPTIONS

Figure 1. Observations of the giant water bug *Lethocerus patruelis* in Italy are shown, together with results from four tests of minimum/maximum longitude/latitude as a function of the year. Separate linear models were developed for each range margin (north, east, south, east) and significant results are reported.

Figure 2. A. Map of giant water bug *Lethocerus patruelis* occurrences in the native range (in green) and in the non-native range (in red); freshwater ecoregions of the world according to Abell *et al.* 2008 are shown and the ones containing occurrence points of the species are highlighted in blue. **B.** Circular plot of environmental variables used to develop a Principal Component Analysis. **C.** Niche dynamics between areas of giant water bug range outside Italy and Italy, treated as the non-native range.

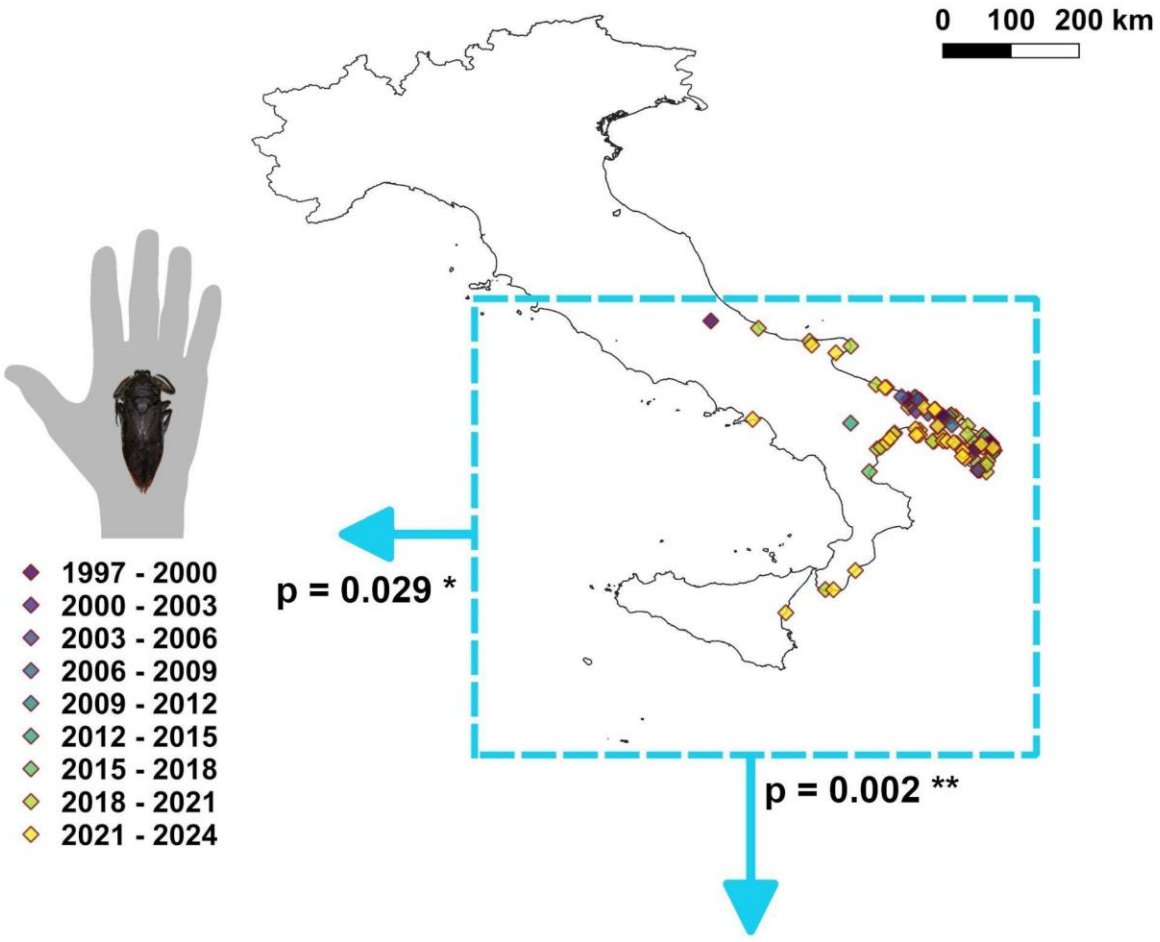
Figure 3. Response curves for predictor variables employed for modelling the ecological niche and the expansion of the giant water bug *Lethocerus patruelis*. Habitat suitability for the species is represented on the y-axis and ranges from 0 to 1. These curves were fitted with a fine-tuned Maxent species distribution model.

Figure 4. Habitat suitability for the giant water bug *Lethocerus patruelis* in Europe, predicted with a fine-tuned Maxent species distribution model. The value 0.0073 represents the minimum training presence and 0.1811 the 10th percentile training presence. In light blue are reported observation points for the species in Europe, used to develop the model together with data from the rest of the species range.

Figure 5. Habitat suitability maps for the giant water bug *Lethocerus patruelis* in Europe for the period 2041-2070 under three combinations of Shared Socioeconomic Pathway (SSP) and Representative Concentration Pathway (RCP): SSP1-RCP2.6, SSP3-RCP7.0, and SSP5-RCP8.5. On the right, standard deviation among five General Circulation Models used to describe the climate system. 0.0073 represents the minimum training presence and 0.1811 the 10th percentile training presence.

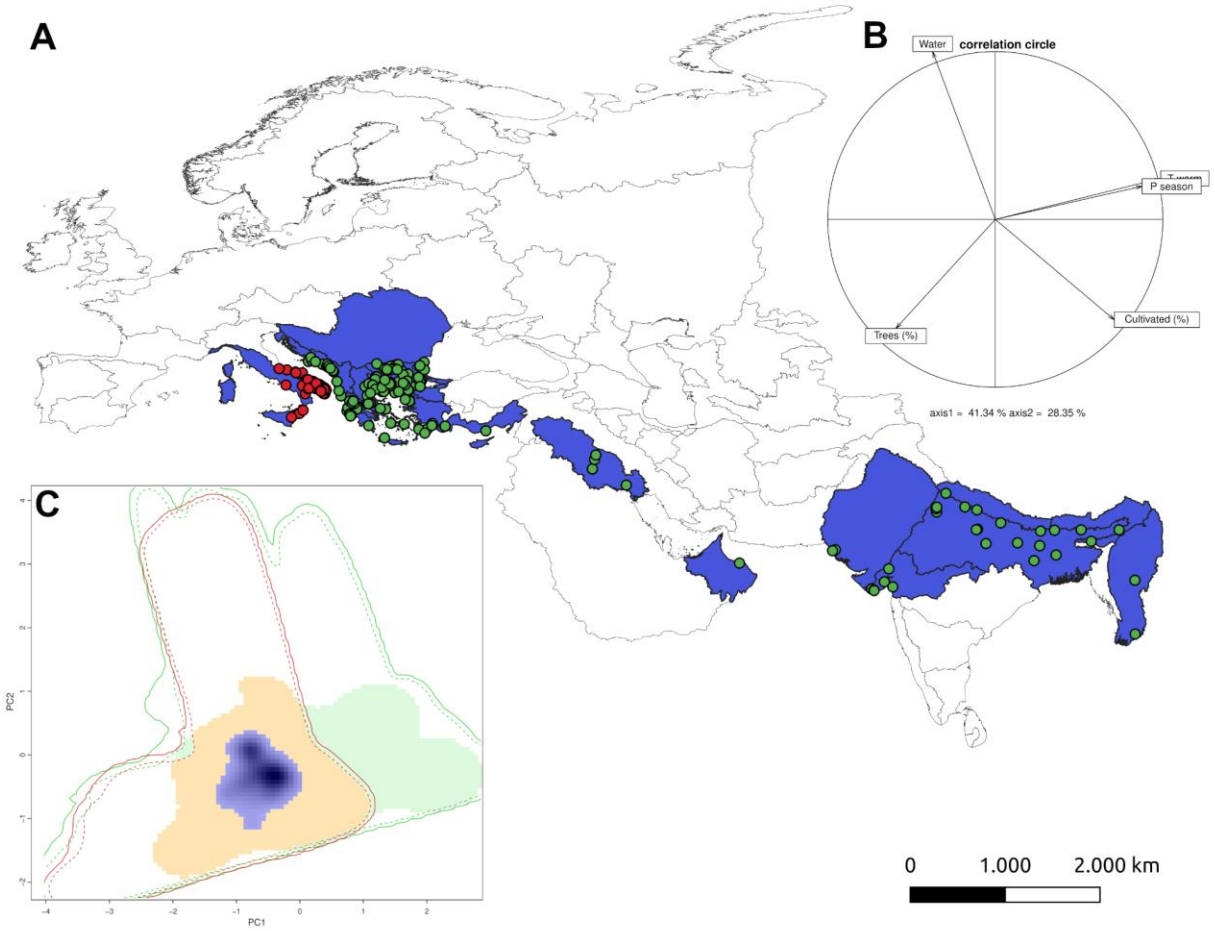
380 **FIGURES**

381 **Figure 1.**



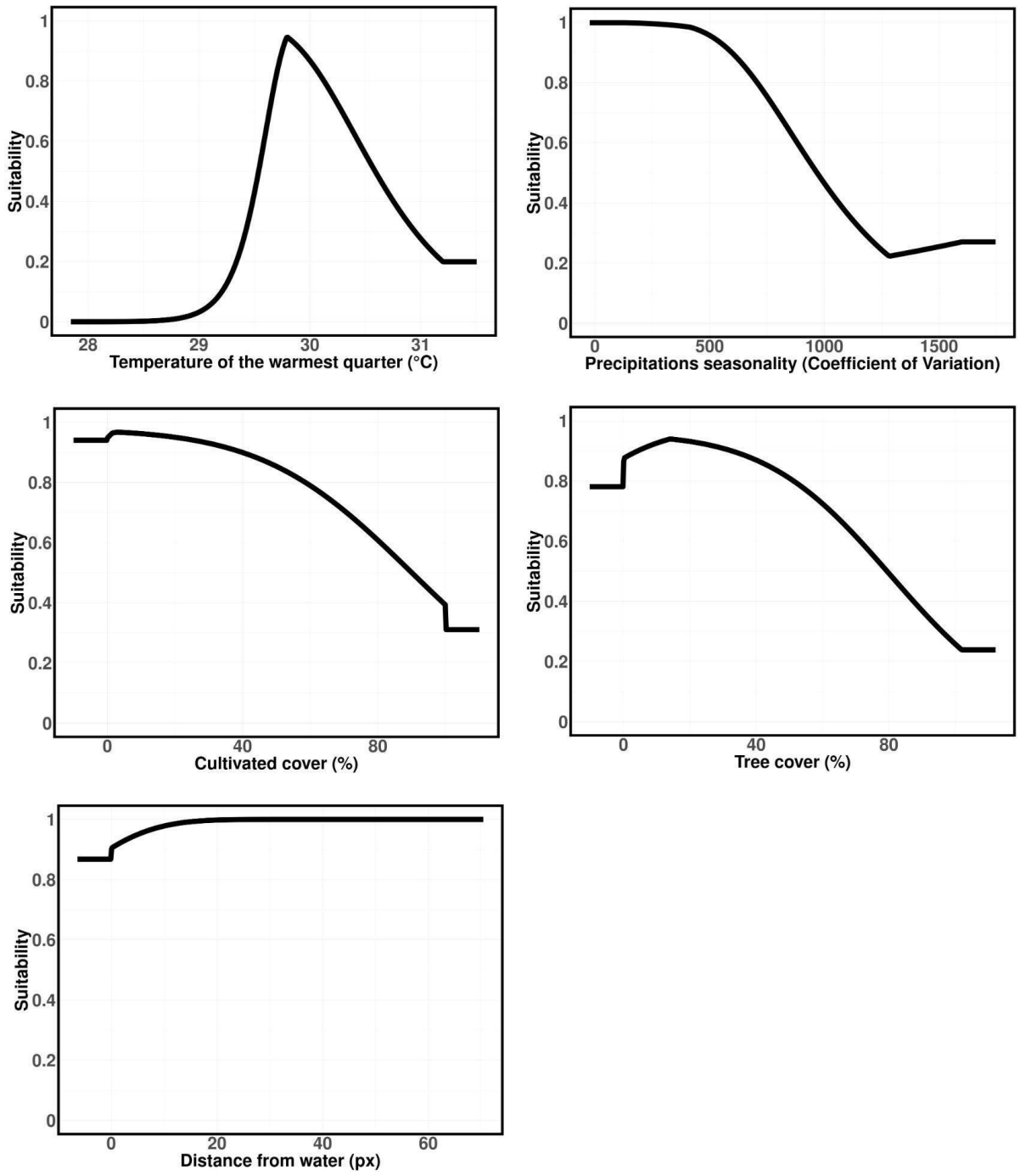
382

383 **Figure 2.**



384

385 **Figure 3.**



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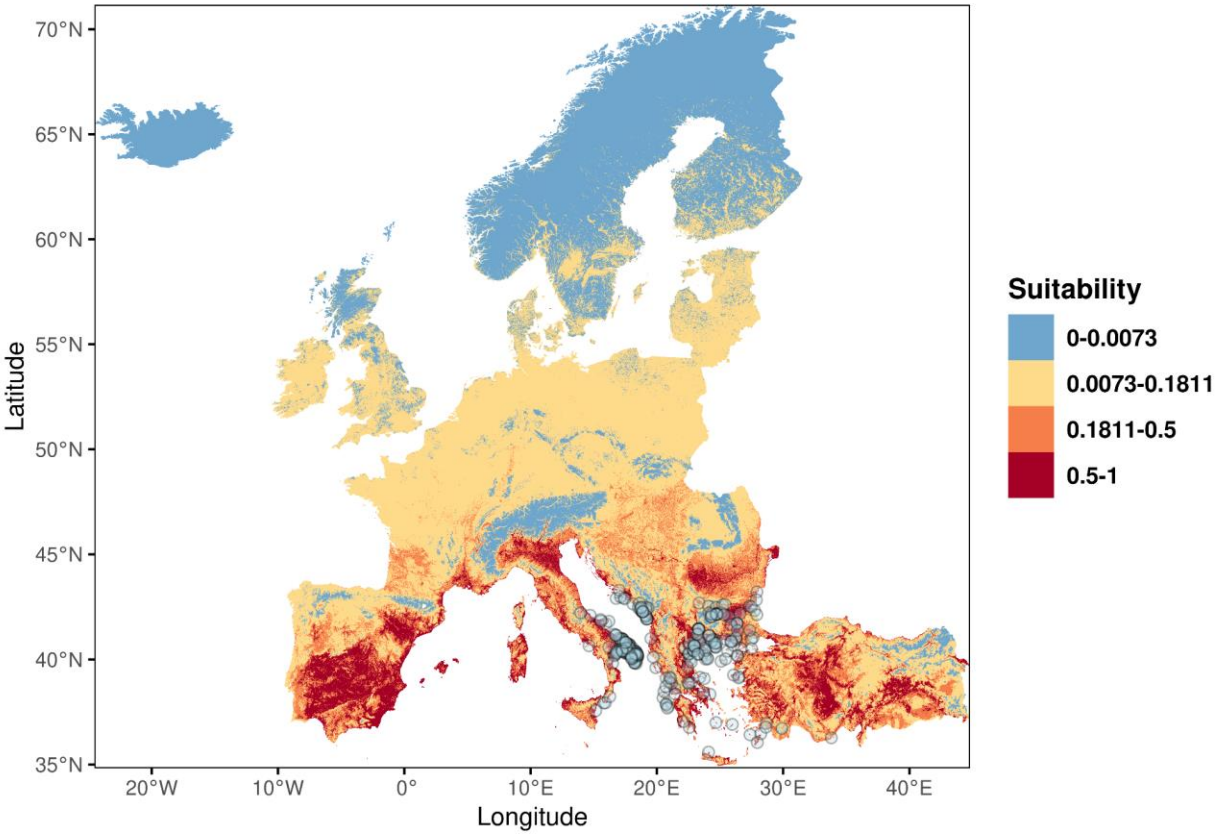
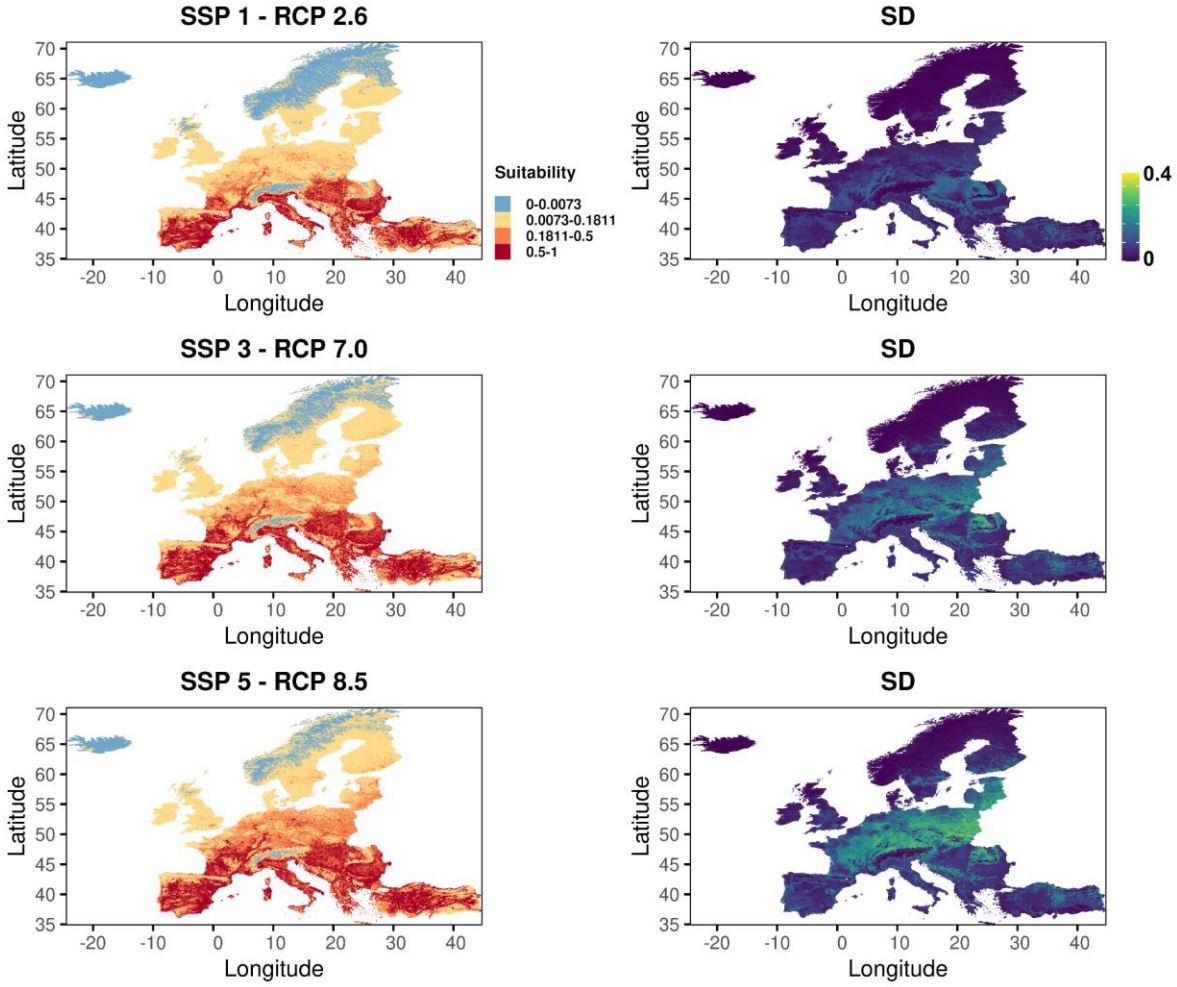
387 **Figure 4.**



388

389 **Figure 5.**



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DATA AVAILABILITY

Data can be downloaded at the link:

CODE AVAILABILITY

The full code used to generate results in this paper is available at the link:

COMPETING INTERESTS

The authors declare that they have no conflict of interest.

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