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Research Article

First exhaustive distribution and habitat modelling of *Morimus asper* (Sulzer, 1776) *sensu lato* (Coleoptera, Cerambycidae) in Bulgaria

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Abstract

Although *Morimus asper*, in particular the ssp. *funereus*, is considered as widespread throughout Bulgaria, a current national mapping of the species is missing. Thus, here we present the first exhaustive study on the distribution of *M. asper* in Bulgaria. Our research combined 967 georeferenced presence records from scientific publications, from the museum collection of the National Museum of Natural History-BAS, as well as authors' and citizen scientists' field observations. An Ecological Niche Model (ENM) was generated using software MaxEnt to identify the potential distribution of the species based on niche suitability. The potentially suitable area for the species was 26% of Bulgaria (29 059 km^2). The main predictor variables in *M. asper*'s ENM assessed by a Jackknife test were the distance to mixed Fagus-Carpinus forests, the mean forest age, the mean tree height, the maximal temperature during the hottest month and the altitude. The percentage contribution to the model of the first two variables was also the largest – respectively 40% and 11%. The remaining variables contributed less than 10% each. Furthermore, we recommend some changes to the current species monitoring methodology to the National Biodiversity Monitoring System.

Key words: Cerambycidae, conservation, ecological niche model, Natura 2000, saproxylic

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Introduction

The genus *Morimus* Brullé, 1832 is represented in Bulgaria by *M. asper funereus* Mulsant, 1862, *M. orientalis* Reitter, 1894 and *M. verecundus bulgaricus* Danilevsky et al. 2016 (Danilevsky 2023). But there is uncertainty about the taxonomic status of those taxa and the correct identification of the specimens based on morphology due to the existence of "transitional" forms (Solano et al. 2013). Based on COI and ITS2 gene sequences all European and Turkish populations of *Morimus* should be referred to a single polymorphic and a polytypic species, *M. asper* (Sulzer, 1776) Solano et al. (2013). All other taxa on that territory have to be elevated to infraspecific rank and are subspecies or simple colour morphs (Solano et al. 2013). Therefore, although we provide citations and information for all the taxa as they were presented by the original authors, in this paper we consider *Morimus asper sensu lato*.

The first records of *M. asper funereus* (as *Morimus funereus*) (Fig. 1) from Bulgaria were reported by Bulgarian naturalists in the early 19th century (Yoakimoff 1899; Markovich 1904, 1909; Yoakimov 1904; Kovachev 1905; Nedelkov 1906, 1909a, b; Netolitzky 1912). Since then, occurrence data have been published in at least 33 papers (Heyrovský 1931; Roubal 1931; Chorbadzhiev 1932; Kantardjiewa-Minkova 1934; Csiki 1943; Anguélov 1960; Angelov 1964, 1967; Palm 1966; Bringmann 1996; Kodzhabashev and Penev 1998; Samuelian 1998; Hubenov et al. 2000; Guéorguiev 2001, 2018; Guéorguiev et al. 2003; Bechev and Stojanova 2004; Migliaccio et al. 2004; Georgiev et al. 2005a, b, 2006, 2015, 2018, 2019; Siering and Beier 2005; Georgiev and Hubenov 2006; Migliaccio et al. 2007; Rapuzzi and Georgiev 2007; Guéorguiev and Ljubomirov 2009; Topalov et al. 2014; Danilevsky et al. 2016; Doychev et al. 2017; Doychev et al. 2018; Kostova et al. 2019). The species was known from multiple localities, distributed throughout the country. It was recorded mainly from the foothills (Predbalkan, Kraishte) and the mountains (Stara Planina, Vitosha, Sredna Gora, Rila, Maleshevska Planina, Western and Central Rhodopes, Belasitsa and Slavyanka), as well from the Ludogorie plateau. Although there is a large amount of published and unpublished data, in general the information is occasional. *Morimus asper funereus* is a protected species included in Annex II of the EU Habitats Directive (92/43/EEC) (as *M. funereus*) and has been assessed as "Vulnerable" in the IUCN Red List (World Conservation Monitoring Centre 1996). It is also

Figure 1. *Morimus asper funereus* in its microhabitat, Sredna gora Mountains.

a protected species under the Bulgarian Biodiversity Act (09.08.2002, latest amendment, State Gazette N°102/23.12.2022). However, the species was not included in the latest editions of the European Red List of Saproxylic Beetles (Nieto and Alexander 2010; Cálix et al. 2018). The populations of the subspecies *M. asper funereus* are distributed in Slovakia, Hungary, Romania, Moldova, Ukraine and the whole Balkan Peninsula (Hardersen et al. 2017a).

The first records for *Morimus orientalis* Reitter, 1894 in Bulgaria were from Stara Zagora, Burgas and Varna by Nedelkov (1909a) not confirmed since then. Bringmann (1996) considered those findings accidental, probably transferred by transported wood from Strandzha Mts. Confirmed localities were only from Malko Tarnovo and Sinemorets (Strandzha Mts.) by Bringmann (1996). Later new localities were reported, all in Strandzha Mts. (Georgiev et al. 2015; Georgiev et al. 2018).

The first records of *Morimus verecundus bulgaricus* came from two close localities: the botanical gardens of Sofia University in Balchik and Varna (Danilevsky et al. 2016). These are the only known localities to date.

Morimus asper is a stenotopic, silvicolous, xylodetriticolous, xylophagous and saproxylic species according to its ecological requirements (Jurc et al. 2008). It inhabits predominantly deciduous and mixed forests or well-structured woodlands, often dominated by oak (*Quercus* spp.) or by beech (*Fagus* spp.), with a medium to high density of dead wood. Additionally, this beetle species is often found in coppiced stands, characterised by the presence of old stumps and decaying wood on the ground (Hardersen et al. 2017a, b; Jugovic et al. 2022). Preferred microhabitats include the leaf litter decomposition layer, moist stumps, fallen wood, the soil surface and trunks with remaining bark of trees. The species is extremely polyphagous and has emerged from the wood of *Abies*, *Picea*, *Acer*, *Alnus*, *Castanea*, *Platanus*, *Juglans*, *Populus*, *Prunus*, *Quercus*, *Salix*, *Ulmus*, *Tilia* and *Fagus* (Hardersen et al. 2017b; Leonarduzzi et al. 2017). Reported host plants for *M. asper funereus* in Bulgaria were *Populus ×canadensis* Moench, *Pseudotsuga menziesii* (Mirb.) Franco, *Fagus sylvatica* L., *Quercus pubescens* Willd., *Quercus dalechampii* Ten., another *Quercus* sp., *Salix caprea* L. (Georgiev et al. 2013; Doychev et al. 2017, 2018). In Romania favourable habitats of *M. asper funereus* were found to be *Tilia tomentosa* Moench and *Quercus petraea* (Matt.) Liebl woodlands, which are semi-shaded and semi-open habitats, characteristic of mature, old, deciduous forests (Manu et al. 2017; Manu et al. 2019). According to Bringmann (1996), *M. orientalis* develops predominantly in oak wood.

The conservation status of the Bulgarian populations of *M. asper* is favourable for all parameters (FV) in all biogeographical regions, according to the reporting under Art. 17 of the Habitats Directive 92/43/EEC in 2013 (for the period 2007–2012) and in 2019 (for the period 2013–2018) with the exception of Unfavourable-Unsatisfactory status (U1) for the perspectives and overall assessment in the Continental region in the 2013 report. The following major threats to the species were identified: use of plant protection chemicals in forestry: forest fires, felling, and the removal of dead wood. The species has been included as potentially occurring in the Standard Data Forms from 159 Natura 2000 zones in Bulgaria, according to the latest EIONET Central Data Repository (2023), but occurrence has not been registered for all of them.

Regardless of many publications providing data on the habitat preferences of *M. asper*, to date little is known about the complexity of factors determining its distribution. Environmental niche models are a useful tool for estimating the real and potential species habitats. Such models for *M. asper* were made only for Slovenia and Italy (Vrezec et al. 2014; Redolfi De Zan et al. 2023). For Slovenia, the obtained habitat suitability model using the maximum entropy approach was assessed as unreliable due to lack of sufficiently good data for the habitats of this species. Redolfi De Zan et al. (2023) used more diverse and more precise environmental data for their models as well as presence data based on citizen science using four different approaches: generalized linear model (GLM), boosted regression tree (BRT), random forest (RF) and maximum entropy (MaxEnt). RF and Max Ent models provided the best discriminant ability for the species.

In that context, our research aimed to update and for the first time to provide resolution to the current distribution of *M. asper* in Bulgaria and the main factors for its presence at a given locality in Bulgaria based on a MaxEnt's Ecological Niche Model.

Materials and methods

Study area

The territory of Bulgaria (43°N, 25°E) covers ca. 111 000 km^2 and encompasses heterogenous eco-physiographic conditions and habitats. Elevation ranges from 0 to 2 925 m asl., with highly diverse relief, stretching from extensive plains and lowlands to subalpine and alpine mountains. Five hypsometric belts consist of lowlands (0–200 m, 31.4% of the territory), hills (200–600 m, 41%), low mountains (600–1 000 m, 15.3%), mountains of average height (1 000–1 600 m, 9.8%) and high mountains (> 1 600 m, 2.5%) (Simeonov and Totzev 1997). The climate is dominated by Mediterranean, Oceanic and Continental influences, combining 12 Köppen-Geiger climate classes (Beck et al. 2018). Bulgaria is a country with a great variation in natural conditions, from the East-Mediterranean coast and steppes to the highest elevations of the Balkan mountain ranges. Broadleaved forests prevail (68.9%) above conifers (31.1%). The most widespread tree species are *Quercus* sp. (32.6%) and *Fagus* (16.1%), followed by *Pinus sylvestris* L. (16.0%) and *P. nigra* J.F. Arnold (8.5%). Nearly 80% of forests are in state ownership; the other 20% are in private or community ownership. At present, 5 780 km^2 (5.2%) of Bulgaria are under protection; of the total wooded area, 16.5% is protected in various ways. The deciduous and mixed forests dominated by *Fagus sylvatica* are the second most common forest type in Bulgaria. They form a continuous forest belt at altitudes ranging from 800 to 1 000 metres and 1 500 to 1 600 metres asl. In some places the beech forests reach lower altitudes. The forests of *Fagus orientalis* Lipsky have more limited distribution, preferring shady and humid locations, especially in places with climate inversions in Strandzha Mts. (Tzonev et al. 2006; Veen et al. 2010).

Presence data

To generate maps of the known current distribution and the predictive model of the distribution of *M. asper* subspecies in Bulgaria, we compiled into a georeferenced database the presence records from the following sources:

- published and available scientific literature encompassing 1904–2019 (110 records);

- the collection of the National Museum of Natural History – Bulgarian Academy of Sciences (89 specimens with exact location labelled, from 301);
- field data collected by the authors during 2012–2021 and by citizen science (voluntary provided data from amateurs, members of a Bulgarian Facebook group: The Insects and the Entomologists) incorporated in the SmartBirds.org database (Popgeorgiev et al. 2015) (768 records).

All available records were used to map the current distribution of *M. asper* on a 10 km × 10 km MGRS grid. Only data from the field studies and citizen science, which were with high level of accuracy (up to 20 m) were used in the Ecological Niche Modelling.

Ecological Niche Model

The Ecological Niche Model (**ENM**) was generated using software MaxEnt 3.4.1 (Phillips et al. 2017). A data matrix with biological and environmental variables for modelling was created using ArcGIS v.10.3 (ESRI, Redlands, CA, USA). We used continuous environmental variables of three types: climatic, topographic, and habitat. The climatic variables were the 19 bioclimatic parameters of the freely available WorldClim v.2, with original resolution ≈ 1 km^2 cell and averaged data from 1970–2000 (Fick and Hijmans 2017). Although slightly outdated, this is the best climatic database available for Bulgaria. Global Aridity Index and the Global Potential Evapotranspiration (CGIAR-CSI Global-Aridity and Global-PET Geospatial Database, Trabucco and Zomer (2019)) were used. We downscaled the original rasters to 40 m cells, using "cubic convulsion" resampling in ArcGIS. The topographic variables entered in the model were elevation (m above sea level), aspect (°) and slope (°), derived from a 40-m resolution Digital Elevation Model (DEM), and yearly solar radiation (kJ m-2 day-1). The habitat variables were derived from the Spatial Database of the Executive Forest Agency. These included forest types (dominated by *Fagus* sp. and *Carpinus* sp.; dominated by *Quercus* sp.; riparian forests; other deciduous forest types), forest age, average tree height, and average tree diameter. We converted the categorical data to continuous by calculating the Euclidian distance (ArcGIS tool) to each habitat type in the original vector layers and rasterizing the results to 40 m grids.

To minimize collinearity in the ENM, the correlated environmental factors and autocorrelated points were omitted from the model calculations. For that purpose, we generated 100 000 random points across the geographic scope and associated to them the corresponding values of all variables, and then tested them by Spearman Rank Order Correlations (Statistica v.10; StatSoft, Tulsa, OK, USA), setting $|r| = 0.7$ as a threshold. Then, we generated a preliminary model with 10 replicates, for which we included all environmental factors. For the set-up of the final ENM, factors were either kept or removed based on the following: the factor with the highest percent contribution (PC) from the preliminary model was retained and all its correlated factors were removed; of the remaining factors, the one with the second highest PC was retained and all the factors correlated with it were removed; and so on, until all factors were considered (Kornilev et al. 2017). After the correlation test, nine of the climatic variables remained in the analyses (Table 1). The slope and the annual solar radiation were removed from the topographic variables. The average tree diameter was removed as a

Table 1. Average Percent contribution (%) and Permutation importance (PI) of uncorrelated variables, estimated by MaxEnt's Ecological Niche Model of *Morimus asper* in Bulgaria.

Environmental variable (Unit)	Unit	Percent contribution		Permutation importance	
		Average	Min-Max	Average	Min-Max
Fagus-Carpinus forest, distance to	m	40.02	37.34–43.73	22.28	17.41–25.98
Average forest age	year	11.14	8.8–13.54	2.23	1.21–3.49
Other deciduous forest, distance to	m	8.23	7.49–9.03	8.29	1.35–2.27
Average tree height	m	6.78	3.85–9.73	5.18	3.86–6.90
Precipitation seasonality (Coefficient of Variation) (Bio15)	%	5.83	3.92–7.21	22.19	19.95–25.26
Elevation	m above sea level	5.48	4.23–6.89	4.86	3.88–6.07
Precipitation of coldest quarter (Bio19)	mm	4.20	3.16–5.25	2.34	1.66–3.29
Precipitation of wettest quarter (Bio16)	mm	3.77	1.90–5.25	11.49	9.21–13.88
Riparian forest, distance to	m	2.88	2.29–3.44	2.55	1.62–3.61
Min temperature of coldest month (Bio06)	°C	2.68	1.70–3.94	2.18	1.10–3.65
Mean temperature of driest quarter (Bio09)	°C	2.49	1.17–4.19	7.90	6.14–9.64
Quercus forest, distance to	m	1.54	1.09–2.16	1.81	6.48–9.77
Aspect	°	1.51	1.12–2.59	2.20	1.21–3.10
Precipitation of driest quarter (Bio17)	mm	1.32	0.10–2.58	0.36	0.01–0.67
Max temperature of warmest month (Bio05)	°C	1.01	0.42–3.98	1.80	0.47–4.07
Mean temperature of warmest quarter (Bio10)	°C	0.98	0.36–2.11	2.20	0.80–6.13
Mean diurnal range (Mean of monthly (max temp – min temp)) (Bio02)	°C	0.14	0.00–1.58	0.13	0.00–0.40

factor in the model as well due to its correlation with the average tree height. To avoid spatial autocorrelation, a buffer of 250 m around each point of species presence was set to remove all but one of the records. This value was chosen to reflect the maximum dispersal capacity of one *M. asper* individual.

Out of 768 points of *M. asper* presence, 546 remained for modelling. Removed points were either within 250 m of each other or within settlements. Although *M. asper* might occur naturally in settlements, especially those with old parks and old trees, we cannot be sure if the recorded beetles were not transported with cut wood, and thus we removed these records to avoid seriously distorting the model towards non-natural habitats. For all models, we used the following settings: logistic output to describe the probability of presence, calibrated using randomly 75% of the available records as training data, and the remaining 25% were used for model validation as test data; 100 000 randomly selected background points as pseudoabsence; maximum iteration was 500; replicated run type was cross-validation; 100 replicates were generated to get the average prediction. The outputs (in ASCII format) were processed and visualised using QGIS. We used the average result as a balance between a highly restricted and a highly inflated model, so that it can be optimally used for making management decisions.

The Jackknife procedure was used to indicate the most informative variables. Response curves to all variables in the model were obtained. The resultant "mean values" ENM was thresholded into unsuitable/suitable space using the "Maximum test sensitivity plus specificity logistic threshold" calculated by MaxEnt, as max SSS is one of the best threshold selection methods for presence/

absence data (Liu et al. 2005; Liu et al. 2015). The remaining data were assigned to three classes of suitability (Low, Medium, and High) for analysis, using Jenks Natural Breaks in ArcGIS. Areas were calculated from the obtained raster layer.

Descriptive statistics of the environmental factors with highest influence on the *M. asper* presence were calculated using software SigmaPlot 12 (Systat Software, San Jose, CA).

To validate the obtained ENM for *M. asper*, we collected 77 presence points available at GBIF (24 record with accuracy under 20 m) and field data collected in 2022 from the SmartBirds.org database (53 records) (Fig. 2). In cases of multiple observations within 250 m of each other, only a single one chosen randomly was removed. Thus, we used seventy points to assess the ENM. The distance between those records and the nearest pixel with suitable area according to the average ENM was calculated.

Results

We generated the first ENM for *Morimus asper s.l.* in Bulgaria as well as compiled the first mapping of its recent distribution in Bulgaria (Fig. 3), based on 546 and 967 observations, respectively. The occurrence was recorded in a total of 364 MGRS 10 km cells. The presence of *M. asper* was recorded for the first time in 291 MGRS cells, confirmed in 47 MGRS cells, and not confirmed by our study in 26 MGRS cells (Fig. 3).

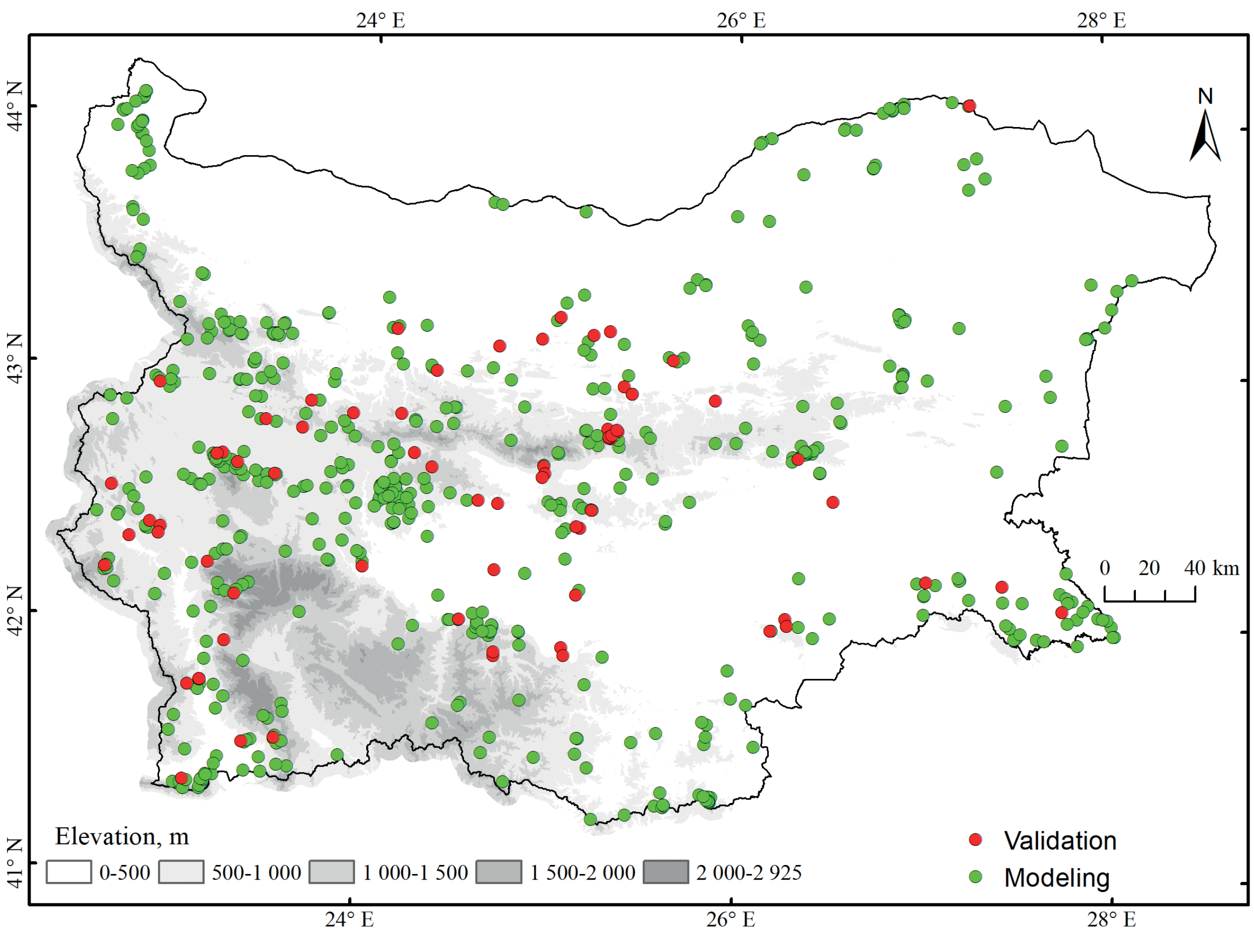

Figure 2. Map of the records used in generating and validating the environmental niche model of *Morimus asper* in Bulgaria.

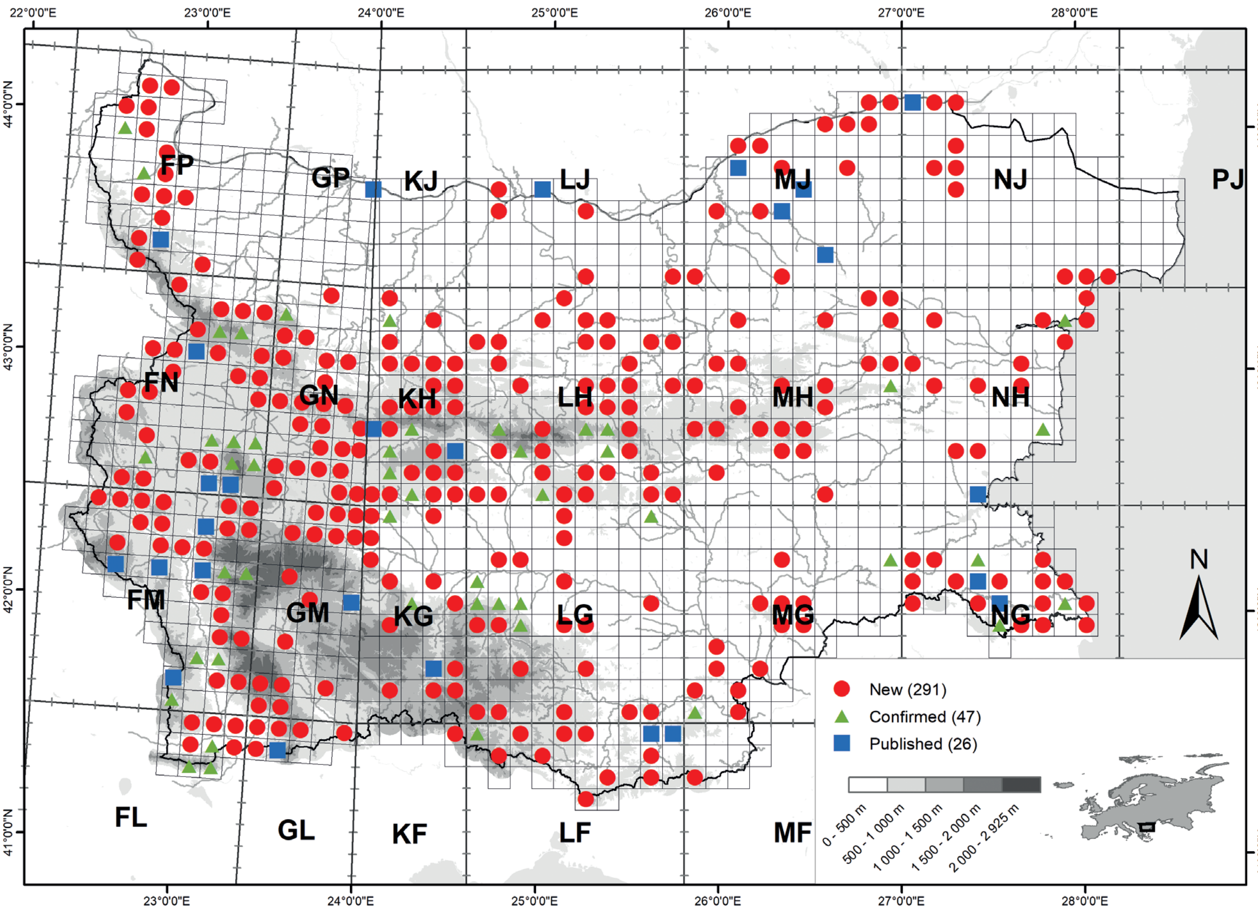

Figure 3. Distribution of the *Morimus asper* in Bulgaria based on a 10 km × 10 km MGRS grid.

Ecological Niche Model

The ENM predictive power was relatively high with AUC value (Area Under the Curve): 0.83 (SD = 0.06). The threshold for unsuitable/suitable area was 0.34.

Potentially suitable habitats for *M. asper* occupy 26% of Bulgaria (Fig. 4). The overall suitable area (29 059 km^2) was distributed into 5 573 km^2 of high suitability, 10 652 km^2 of medium suitability, and 12 834 km^2 of low suitability habitats. The most suitable areas were old mountain beech forests and low-land riparian forests. The predicted largest suitable habitats patches are the beech forest belt of Belasitsa Mts., the beech forest belt of Osogovo Mts., the deciduous forest belt of Pirin Mts., Rila Mts. and West Rhodopes Mts., high parts of Eastern Rhodopes, Vitosha Mts., Lozenska Mts., Sredna Gora Mts., the beech forest belt of Stara Planina Mts., Strandzha Mts., and the coastal floodplain forests. In northern Bulgaria the suitable areas are small and fragmented along the riparian forests. The suitable habitats along the Black Sea Coast are also highly fragmented; those are generally floodplain deciduous forests (longoz).

Overall, 50% of suitable territories, and 11% of the highest suitability habitat areas, fall within the terrestrial protected areas of the NATURA 2000 network in Bulgaria. An essential part of the territory of all National and Natural Parks in Bulgaria is suitable for *M. asper* presence according to the ENM (57% of their territory) which represents 9% of the total suitable area.

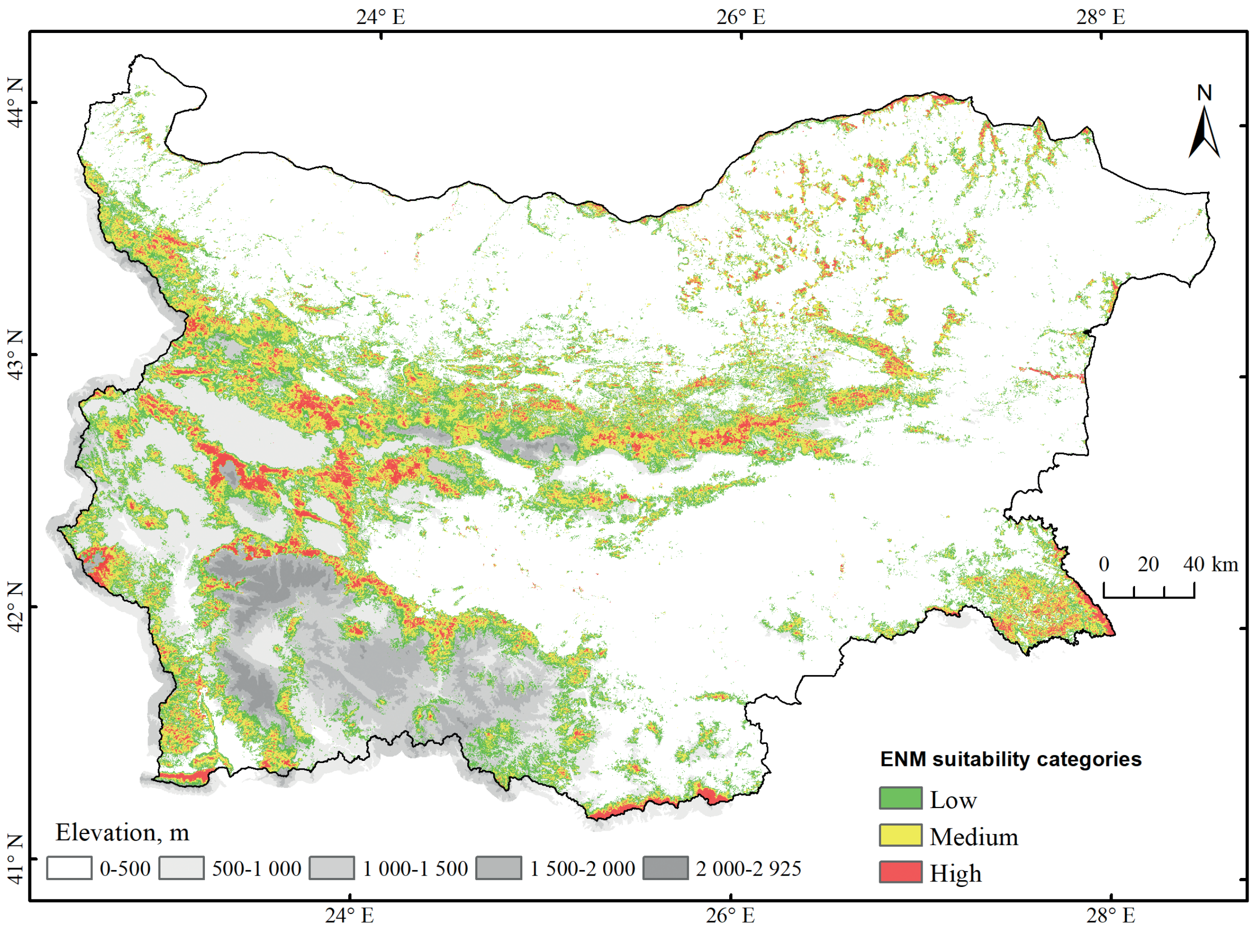

Figure 4. Map of the average Ecological Niche Model for *Morimus asper* in Bulgaria.

Estimates of the environmental variables' importance for the ENM

Both the percent contribution to the model and the Jackknife procedure were used in determining the importance of individual variables to the model. Both analyses showed as the most important predictors contributing to the model the distance to Fagus-Carpinus forest (40% contribution) and the average forest age (11% contribution). The remaining environmental factors contributed less than 10% each (Table 1). Although with much smaller contribution, according to the Jackknife test the next most important variables are the maximum temperature at the warmest month and elevation, and mean temperature at the warmest quarter (Table 1 and Fig. 5).

Main factors statistics

The mean values and variation in the main ecological factors contributing to the ENM of *M. asper* are shown in Table 2 and Fig. 6. The distances of precise observations to Fagus-Carpinus forests vary from 0 m to nearly 15 km, but the values' distribution is highly asymmetrical and most of the species' locations are indeed very close to the nearest pixel of the polygons – 50% of the species records are up to 57 m of the Fagus-Carpinus forest polygon and 90% of the records are up to 1.3 km. The average age of the forests (at which 90% of the *M. asper* records were located), was between 0–120 years, forming two peaks

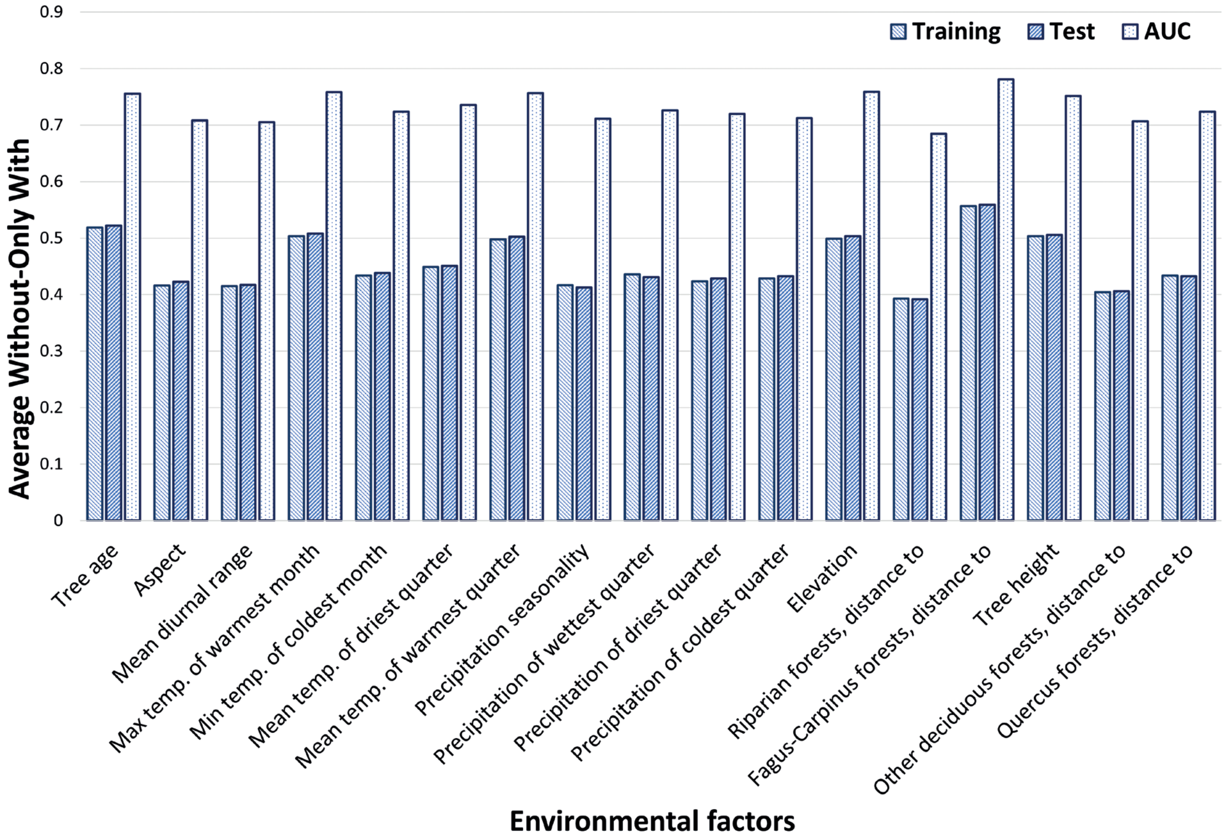

Figure 5. Jackknife results of MaxEnt ENM for *Morimus asper* in Bulgaria – average gain and area under the curve (AUC) on training and test data between models built without and only with a given variable. Variables that are more closely related to the distribution of the species are indicated by smaller differences in both gain and AUC.

Table 2. Descriptive statistics of the environmental variables with highest influence on the suitability of the habitats according to the ENM at the points of *Morimus asper* registrations.

Environmental variable (Unit)	Mean	Std Dev	Std. Error	Min	Max	Median
Fagus-Carpinus forests, distance to (m)	504.85	1286.66	66.71	0.00	14802.00	56.57
Average forest age (year)	54.42	46.11	2.39	0.00	170.00	55.00
Average tree height (m)	12.00	8.83	0.46	0.00	32.00	14.00
Maximum temperature at the warmest month (°C)	23.88	2.43	0.13	11.35	29.42	24.15
Elevation (m asl)	668.65	391.22	20.28	1.00	1663.0	645.00

– at 0 (records out of the forest stands) and at 40–70 years forests. The values of tree height were also asymmetrical, with a bimodal distribution forming one peak at 0 m and then between 15–20 m; most records (90%) are in forests with tree height up to 24 m. The frequencies' accumulation at zero values are due to many findings near the forests but not in them, normal for the beetle's dispersion during the mating season. The most frequent records (60%) of *Morimus* are at locations with maximum temperature in the warmest month between 22–26 °C, and 90% of them are at locations with maximum temperature in the warmest month up to 26.7 °C. The frequency distribution of the records related to the elevation is quite platykurtic, 70% were between 180 m and 1 000 m asl, and 90% were up to 1 200 m, which coincides with the deciduous forest belt. Still, the species reaches elevations of up to 1663 m.

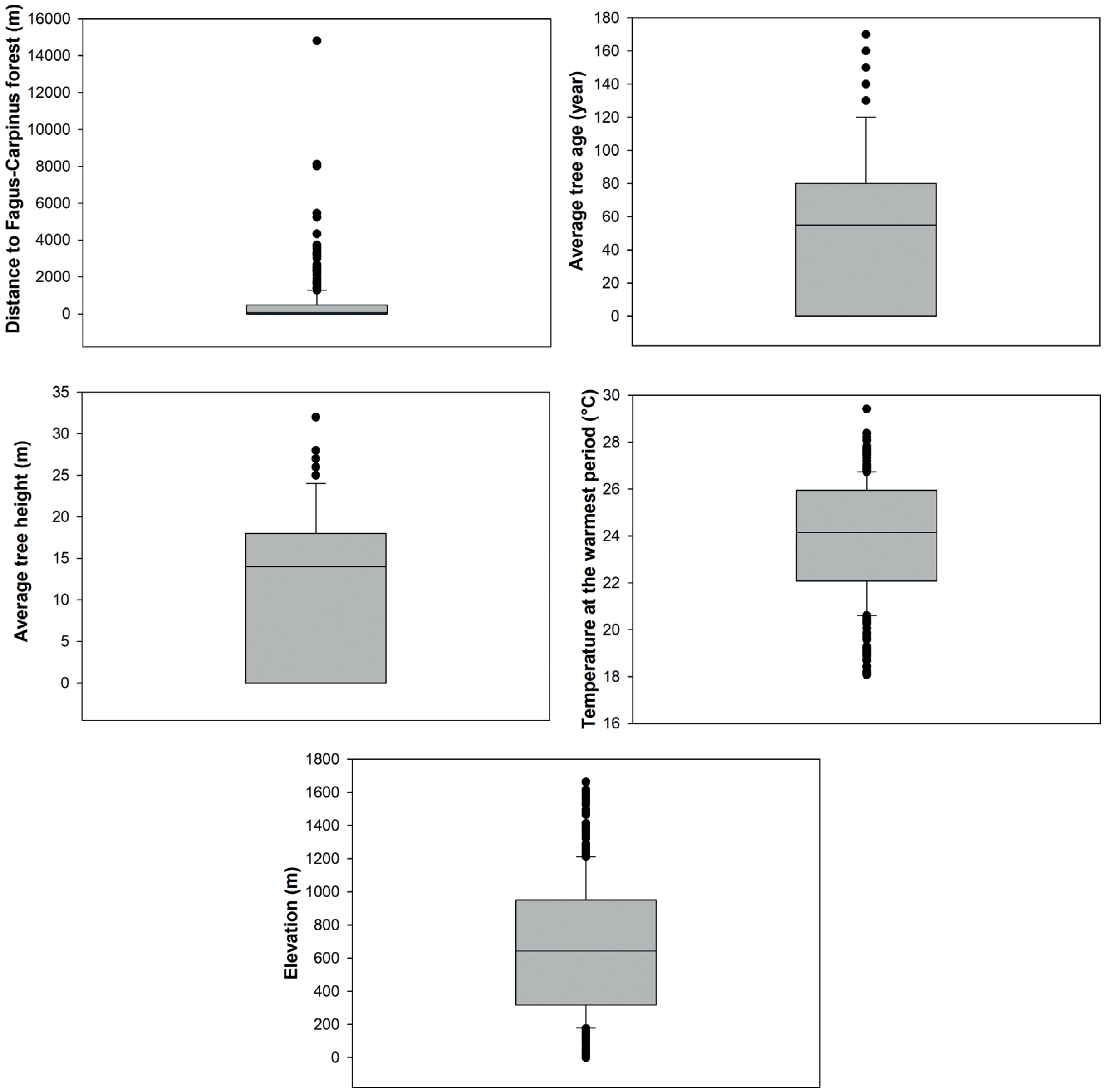

Figure 6. Variation of the main environmental factors contributing to the ENM of *Morimus asper* in Bulgaria.

The marginal response curves of the environmental factors showed that the probability of the species occurrence is maximal when the distance to Fagus-Carpinus forest is minimal, and sharply decreases with an increase in the distance. A positive relation between probability of occurrence and forest age and tree height was observed, as the probability sharply increases after 50–60 years forest age, after which the probability remains constant. The same tendency was observed for the average tree height factor – the probability increases abruptly up to 15 m, and more smoothly to 40 m, after which it remains constant. The probability of occurrence was maximal when maximum temperature of the warmest month ranges between 18–25 °C, most probable at 22 °C corresponding to the mountains, another probability maximum is at 30 °C corresponding to the lowland habitats. The response curve of the elevation showed that the probability of the species occurrence increases to 1 000 m, subsequently it gradually decreases, and after 2 000 m asl it is practically zero (Fig. 7).

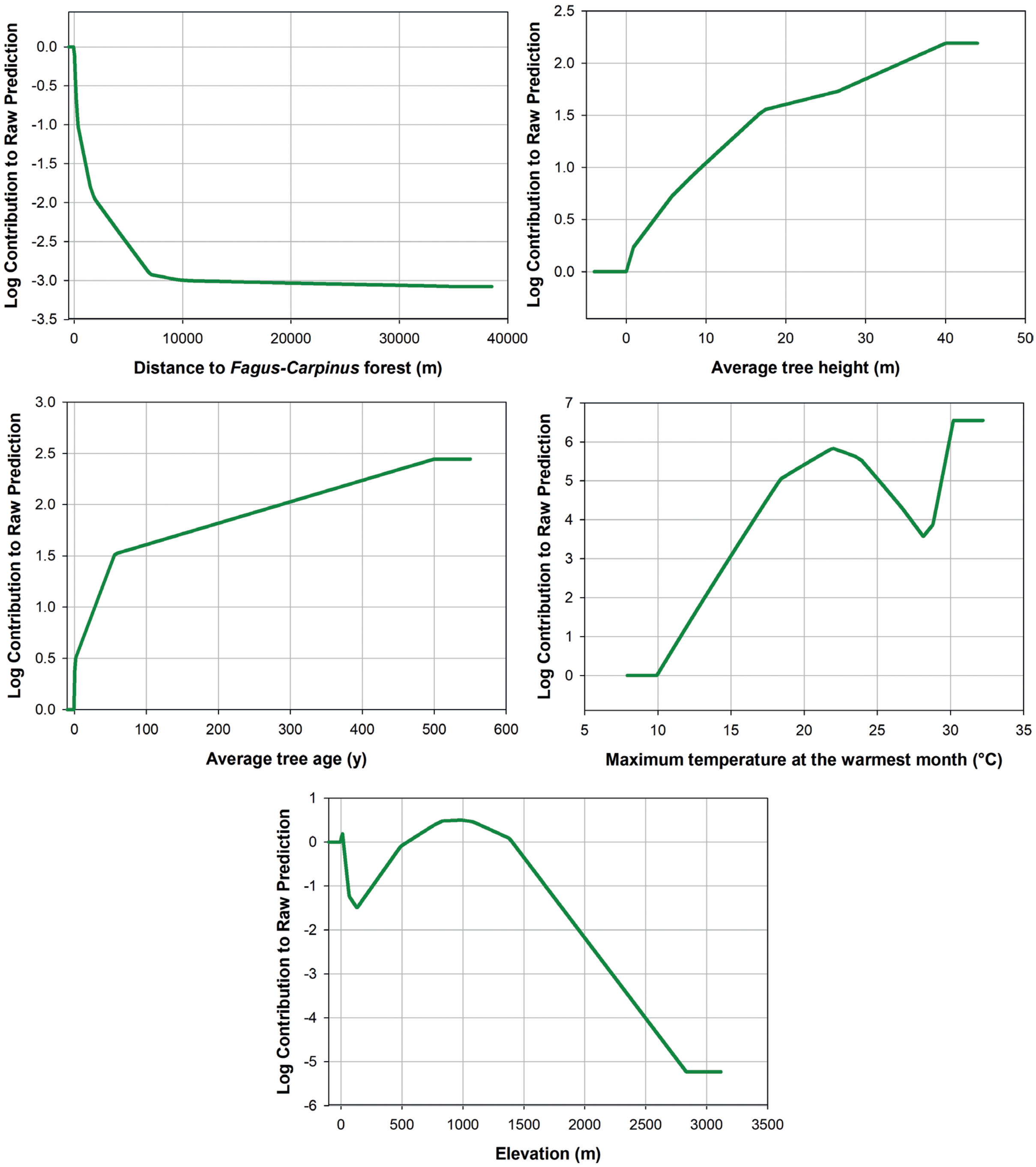

Figure 7. Marginal response curves of major variables contributing to the ENM of *Morimus asper* in Bulgaria.

Validation of the ENM

Overall, 84% of the records used for validating the ENM fall within predicted suitable habitats (57% of all) or were less than 250 m to the nearest (27% of all).

Discussion

The ENM of *M. asper* showed old growth forests dominated by *Fagus* sp. and *Carpinus* sp. with tall trees as the most suitable habitats for the species in Bulgaria, followed by other deciduous forests with much lower probability and riparian forests, in a broad altitudinal range (0–2 000 m asl). The highest probability of species occurrence was connected also with moderate air temperatures – maximum at 22 °C in the mountains, and 30 °C in the plains. The main predictors in the obtained ENM for *M. asper* in Bulgaria were different but in accordance with those obtained by Redolfi De Zan et al. (2023) in Italy, where the high autumn normalised difference vegetation index (correlated to biomass and canopy biophysical parameters such as photosynthetic activity), low autumn solar radiation and annual mean temperature between 7–13 °C were the main factors determining the species distribution. In our preliminary model, prior to the exclusion of this variable, contribution of the annual mean temperature in Bulgaria was 0.3%. However, comparing the response of the species to 'annual mean temperature (Bio01)' in Bulgaria and Italy, a common peak in the probability of occurrence (between 6–10 °C in Bulgaria) was observed, but the main difference is that in Bulgaria there is a second peak connected to much warmer territories, where the mean annual temperature is over 14 °C.

The generated ENM presented prominent ecological continuity of the suitable habitats in Central and Southwestern Bulgaria, and almost no continuity in northern and eastern Bulgaria with significant fragmentation of the suitable habitats. Special attention must be paid to the Black Sea Coast, where large patches of lowland and riparian forests still exist but are fragmented and under high threat because of anthropogenic pressures. The *M. asper* populations in those areas are quite isolated due to the low dispersal ability of the beetle (Rossi de Gasperis et al. 2016; Cateau et al. 2018).

The isolation of the suitable habitats in Strandzha Mts. according to the ENM gives a reasonable explanation for the distribution of the *M. asper orientalis* in Bulgaria, limited to that area. In addition, most of the records were from oriental beech woods in contrast to the statement of Bringmann (1996) that the species predominantly develops in oak wood.

The suitable habitats in the vicinity of the only known locality of *M. asper verecundus bulgaricus* are also highly isolated, possibly greatly limiting the subspecies' ability to disperse.

A large area of the potential optimal habitats falls within existing protected areas: National and Natural parks, as well as terrestrial NATURA 2000 sites, which theoretically provides sufficient capacity to protect *M. asper*. To ensure high genetic diversity and effective population size, however, their connectivity must be maintained through functioning, undisturbed biocorridors. Ensuring the continuity of optimal habitats for *M. asper* would allow the species to migrate and occupy new suitable habitats where it is not currently found. A measure in that direction was the proposed creation of "stepping stone" habitats for saproxylic beetles between larger conservation territories (parks, reserves, etc.), for example by retaining dead wood in managed forests along the designed dispersal routes (Bełcik et al. 2019). The protection of populations and habitats in the small suitable areas in northern Bulgaria and along rivers is of great importance for the preservation of the genetic diversity of *M. asper*. As many of these areas are poplar plantations that are cleared and then replanted, it is necessary to leave a certain percentage of dead wood in the felling, without disturbing the surrounding natural tree vegetation, before planting the new saplings. This measure would ensure a smoother and safer transition of the population from one habitat to another, given their relative low displacement capacity.

The favourable conservation status of *M. asper* populations in Bulgaria, assessed during the preparation of the specific reports under Art. 17 of the Habitat Directive in 2013 and 2019, should be maintained with the necessary measures to reduce the threats to the species, mainly concerning forest management practices. The availability of suitable dead wood is crucial for all saproxylic species and even a temporary lack could bring rapid population collapse (Seibold et al. 2015; Bełcik et al. 2019). The fragmentation of suitable habitats for *M. asper* has to be reduced to a minimum, maintaining well-connected natural and semi-natural forests with a diverse age structure, autochthonic deciduous tree species and sufficient number of mature and decaying old trees in various stages of aging. The recommended amount of dead wood has to be above 20–35 m^3/ha (or 3–8% of the total volume of available wood) and all dead trees larger than 22–50 cm in breast-height diameter not to be removed after felling, allowing more dead wood in advanced stages of decomposition to develop, as well as designating strict forest reserves with exceptionally high amounts of dead wood, that would serve as a refuge for and sources of saproxylic specialists such as *M. asper* (Gossner et al. 2013; Della Rocca et al. 2014).

An important step for the protection of suitable habitats for *Morimus* and the sustainable use of the forest resources in Bulgaria that has been taken is to FSC certify all state forestries. Unfortunately, the actual implementation of the measures related to this certificate are still not fully implemented, a fact that we have observed often during our field work. Another problem observed so far is the carrying out of the necessary monitoring activities of the insect species included as criteria in this certification, as well as the activities of carrying out the mandatory regular monitoring and reporting under Art.17 of the Habitat Directive to the EC. The monitoring activities conducted to date have not been regular and comprehensive. One of the main reasons for that is mainly the lack of capacity and human resources, and the resulting excessive engagements of scientists and forest workers, another is the still poorly developed citizen science in Bulgaria. Citizen science is a useful approach to solving this problem, accelerating the process of gathering occurrence data (Zapponi et al. 2017; Redolfi De Zan et al. 2023). It is especially suitable for relatively easy observation and identification of species such as *Morimus asper*.

In addition, we recommend changes in the monitoring scheme for *M. asper* of the National Biodiversity Monitoring System in Bulgaria. They include a shift from quantitative to qualitative monitoring with bigger sample size. The current methodology consists of walking along a transect (1 km long, 5 m wide) and counting the number of live individuals of the species for the given transect (Chehlarov 2014). The effectiveness of such monitoring would benefit from increased field effort, which has so far proven impossible as mentioned above, due to lack of sufficient time for sampling, finances, and human capacity. A good knowledge of the ecological requirements of the species is necessary also in order to plan field work at the optimal time and weather conditions, otherwise the reported number may not reflect the actual abundance of the species due to low detection probability. On the other hand, the qualitative monitoring requires less efforts at a single sampling site (transect) of observation and could allow covering a bigger area of monitoring with increased sample size. At the same time, the change in frequency of occurrence is a good early indicator for changes in population trends. If a negative trend in frequency is registered, it is necessary to carry out a quantitative study. In order for the results of the national monitoring to be compatible with those of the reports under the Habitat Directive of EEC, we propose the following changes in the monitoring scheme for standardization and easier data management: 1. Field observations should be carried out at least 8 of the 10 × 10 km squares of the ETRS grid that contain medium and highly suitable habitats according to the presented ENM. In each of the 10 km squares, between 10–30 sample sites with a size of 1 km × 1 km should be selected, in which 1 sampling unit – a transect with a length of 1 km should be sampled randomly. 2. Parameters to count: presence of the species (walking along the transect until its registration or the transect ends); reporting the presence of threats to the species for the entire sample site. 3. Assessment parameters: the proportion of the 1 km^2 squares with registered presence of the *M. asper* from the total number of sampled 1 km^2 squares; the proportion of 1 km^2 squares with registrations of the species-specific threats (listed in the standard protocol) from the total number of sampled squares. In such manner the monitoring scheme could easily incorporate citizen science data to become much more effective, although these data alone are not sufficient for the status of the species to be assessed.

To fill the gap in the scientific capacity and to develop citizen science in Bulgaria, it is necessary for a broad educational campaign to be carried out in partnership between the Bulgarian Ministry of Environment and Waters, the Executive Environment Agency, and scientific and educational institutions. Only this can ensure reliable forest certification and the implementation of measures for the protection of forest habitats and forest specialist species, including *Morimus asper*.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

Conceptualization: RK, RB. Data curation: RB. Formal analysis: GP, RK. Investigation: RB. Methodology: GP, YVK, RK. Resources: RB. Software: RK, GP. Validation: YVK, GP. Visualization: GP, RK. Writing – original draft: YVK, RK, RB. Writing – review and editing: GP, RB, YVK, RK.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Morimus asper occurrence in Bulgaria data set

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Data type: occurences

Explanation note: Data set with locations of *Morimus asper* in Bulgaria. Includes occurrence data from literature, field studies and citizen science incorporated into the SmartBirds database, as well as occurrence data from GBIF used to create a distribution map of the species, *M. asper* Ecological Niche Model and its verification.

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