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GIS MODELLING OF THE DISTRIBUTION OF TERRESTRIAL TORTOISE SPECIES: *TESTUDO GRAECA* AND *TESTUDO HERMANNI* (TESTUDINES, TESTUDINIDAE) OF EASTERN EUROPE IN THE CONTEXT OF CLIMATE CHANGE

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GIS Modelling of the Distribution of Terrestrial Tortoise Species: *Testudo graeca* and *Testudo hermanni* (Testudines, Testudinidae) of Eastern Europe in the Context of Climate Change. Nekrasova, O., Tytar, V., Pupins, M., Čeirāns, A., Skute, A. — The study of the distribution of protected animal species in Europe is especially relevant in a changing climate. Therefore, in this work, we tried to solve the problem of the possibility of habitation of tortoises *Testudo graeca* Linnaeus, 1758 and *Testudo hermanni* Gmelin, 1789 in Eastern Europe by using species distribution models (SDMs). We used bioclimatic variables from the CliMond dataset (18 uncorrelated variables of 35) and 19 Paleoclim variables of the "early-Holocene" and "mid-Holocene". Packages Maxent and 'ntbox' were employed. In addition to our data, we used findings listed in the GBIF databases: 1,935 points for *T. graeca* and 991 points for *T. hermanni*. It has been shown that subspecies of tortoises differ in the characteristics of the ecological niche. In addition to direct anthropogenic influences, the limiting factor is the "Mean temperature of coldest quarter" (bio11) for both species. Moreover, *T. graeca* is less demanding and can tolerate both frost and higher temperatures during drier periods than *T. hermanni*. Modelling found that in the future it is possible for these species will expand in a north-eastern direction, where potentially suitable habitats will appear: by 2090 in the South of Ukraine (Odesa Region, Crimea) and East Ukraine (floodplain of the Siversky Donets River of the Don basin).
Key words: ecological niche model; distribution; tortoise; climate change; home range expansion.

Introduction

Current climate change and anthropogenic alterations of natural habitats are heavily impacting most animal species (Araújo et al., 2006; Nekrasova et al., 2019). Certain animal populations are declining and their home ranges are shrinking, whereas other are found adapting to the novel environment (Tytar et al., 2019; Kuybida et al., 2019). In recent decades home range shifting has been recorded for many species of amphibians and reptiles, particularly in Europe (Popescu et al., 2013; Tytar et al., 2018; Nekrasova and Tytar, 2012, 2014; Nekrasova et al., 2013, 2019, 2021 a). In this case some species that are native to certain parts of Europe can become invasive if they move to another part of the continent where they can pose a threat to the local herpetofauna (Kats and Ferrer, 2003; Pupina et al., 2018, Nekrasova et al., 2021 a, b). These shifts seem to be not only a consequence of climate change, but also a result of the release of individuals into the wild by pet owners, for instance of exotic reptiles (Cadi and Joly, 2004). In this respect, several alien Testudines species have been discovered in Ukraine: *Trachemys scripta* (Thunberg in Schoepff, 1792)*, Testudo horsfieldii* Gray, 1844*, Mauremys rivulata* (Valenciennes, 1833)*, M. caspica* (Gmelin, 1774) (Nekrasova, 2013; Kukushkin et al., 2017; Nekrasova et al., 2021), and in Latvia records have been made of *T. scripta, M. rivulata, M. caspica, Pelodiscus sinensis* (Wiegmann, 1835), and *T. horsfieldii* (Pupins and Pupina, 2011).

Another species to be considered is the Greek tortoise, *T. graeca* Linnaeus, 1758. Under the IUCN Red List (1996) the species is considered globally protected (evaluated as Vulnerable A1cd); regional — Europe is Vulnerable A2bcde+4bcde (2004); CITES — Appendix II, as Testudinidae spp. (Turtles of the World…, 2017); Resolution No. 6 (1998) and Annex II of the Bern Convention (Convention on the conservation of European wildlife and natural habitats; https://eunis.eea.europa.eu/species-names.jsp). Recently at a meeting of the Commission of the Berne Convention involving countries of the former Soviet Union, a discussion was held on how realistic is the habitation of this species in Ukraine (Emerald Network (Natura 2000); Ecological Networks-Meetings, 2016 (NGO representative O. Nekrasova); Marushchak et al., 2019). *T. graeca* is widespread in comparison with other representatives of the *Testudo* genus and is found in southern Europe, including areas of Romania neighbouring Ukraine (Dobrudja) (Kotenko, 1992; Sos et al., 2008). From Bulgaria the species has spread to the east and reached Turkey, the Caucasus, Iraq and the Russian Federation. To the west *T. graeca* has reached Spain and is found in Northern Africa. Human-induced introductions have occurred in Egypt, France, Italy (continental, Sardinia, Sicily), and Spain (continental, Balearic Islands) (Turtles of the World…, 2017).

According to some sources, it is believed that Ukraine also covers the native area of *T. graeca* (IUCN Red List; Tatarinov, 1973). The first mentions of *T. graeca* appeared around the 1950s and came from Western Ukraine. In 1948 one individual of the Greek tortoise was found in the vicinity of Chernivtsi (Tatarinov, 1973). The tortoise was kept in a terrarium; unfortunately, in 1958 it died due to a sharp drop in temperature. In 1956, in the valley of the Prut River 9 Greek tortoises of various age and sex were found in a hilly sand habitat. Earlier the Romanian zoologist K. Kiritsescu (1930) noted that this tortoise is sporadically found in the south of Romania in the valleys of the Danube and Prut rivers (according to Tatarinov, 1973).

No less interesting is the distribution of a closely related protected species *Testudo hermanni* Gmelin 1789, which also is found in the south of Eastern Europe, in countries neighbouring Ukraine, namely Romania (Dobrudja; Sos et al., 2008). Towards the east the species reaches Turkey, and to the west it is found far as Spain. Introductions seem to have occurred in a number of countries: Malta (?), Spain (Balearic Islands), Cyprus. IUCN Red List: Near Threatened (2004); CITES: Appendix II, as Testudinidae spp. (Turtles of the World ..., 2017); Resolution No. 6 (1998) and Annex II of the Bern Convention (Convention on the conservation of European wildlife and natural habitats; https://eunis.eea.europa.eu/species-names.jsp).

In this paper we intend to focus on these two protected species, *T. graeca* and *T. hermanni*, that in the coming future may expand into Eastern Europe. Using an ecological niche modelling approach, we aim to question to what extent are environmental conditions suitable for the naturalization of these terrestrial species in Eastern Europe (for instance, in Ukraine). Also, we considered important to analyse the possibilities of the expansion of *T. graeca* and *T. hermanni* in Ukraine according to future changes of the climate.

Material and methods

Occurrence data collection

Occurrence data was collected from the original datasets, collection materials (Schmalhausen Institute of Zoology National Academy of Sciences of Ukraine, Kyiv; field data collection in Turkey, 2021, fig. 1), GBIF databases (GBIF.org, 2021 a, b); all records are non-duplicate. To account for sampling bias, we used the nearest neighbour distance ('ntbox' package in R; Osorio-Olvera et al., 2020) method for thinning the data. Occurrence points that were ≤ 0.1 units away from each other were removed to avoid errors due to spatial autocorrelation. As a result, the number of points significantly decreased: from a total 4630 points to 1935 for *T. graeca* and to 991 points from a total of 16,490 points for *T. hermanni.*

Environmental data

For building the species distribution models (SDMs) we used bioclimatic variables from the CliMond dataset (Kriticos et al., 2014; https://www.climond.org/ (accessed 27 December 2020), A1B). Of 35 bioclimatic variables, highly correlated (> 0.7) predictors were removed using the 'virtualspecies' package in R, resulting in a selection of 18 centered around 1975 (1970–2000) and 2090 (2081–2100). For performing the analysis the following bioclimatic variables (CliMond) were used: bio01 “Annual mean temperature”, °C, bio02 “Mean diurnal temperature range” (mean (period max-min)), °C, bio03 “Isothermality” (bio02÷bio07), bio04 “Temperature seasonality” (C of V), bio14 “Precipitation of driest week”, mm, bio06 “Min temperature of coldest week”, °C, bio07 “Temperature annual range” (bio05-bio06), °C, bio08 “Mean temperature of wettest quarter”, °C, bio10 “Mean temperature of warmest quarter”, °C, bio11 “Mean temperature of coldest quarter”,°C, bio12 “Annual precipitation”,mm, bio14 “Precipitation of driest week”, mm, bio15 “Precipitation seasonality” (C of V), bio18 “Precipitation of warmest quarter”, mm, bio25 “Radiation of driest quarter” (W m^{-2}), bio28 “Annual mean moisture index”, bio31 “Moisture index seasonality” (C of V), bio34 “Mean moisture index of warmest quarter”. We also used 19 bioclimatic variables from the Paleoclim database (http://www.paleoclim.org/) for paleoclimate simulations. We reconstructed the species’ paleogeography by projecting species distribution models (SDMs) onto palaeoclimatic conditions of the Pleistocene: “early-Holocene” (11.7–8.326 ka), “mid-Holocene” dating back to 6000 years BP (resolutions 2.5 arc-minutes (~5 km), v1.0, Brown et al., 2018; Fordham et al., 2017).

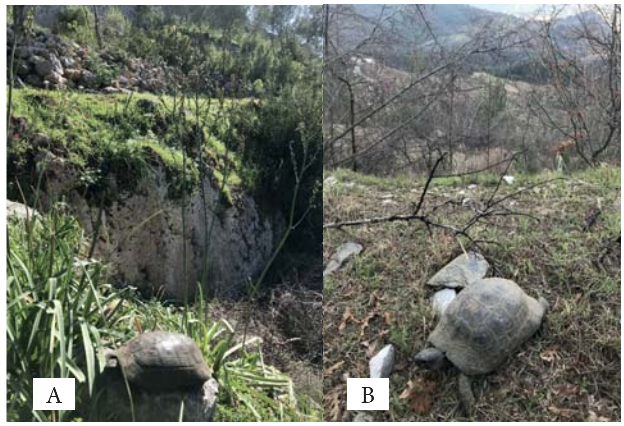


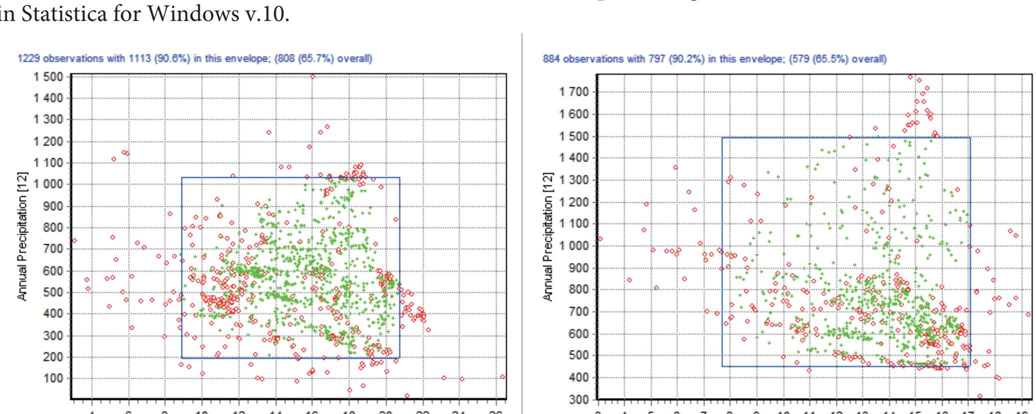
Fig. 1. Habitats occupied by *T. graeca*: A — ruins of an ancient city near Demre (Andriake Ancient City, Antalya, Turkey, vertical walls, Turkey); B — terraces of a garden of a village in the mountains (in Gazipasa area, Antalya, Turkey).

Model building

Niche clustering using the ‘ntbox’ package in R (Osorio-Olvera et al., 2020) provides methods for performing k-means clustering and allows to project the obtained results in geographic and environmental spaces (known as Hutchison’s duality; Colwell, Rangel, 2009).

Ecological niche and species distribution modelling (SDM) methods have been employed to explore the potential home range of invasive species in new environments: the Maxent algorithm (running 35 replicates) and DivaGis (the Bioclim module). The Maxent v.3.4.4 software (Phillips, 2005; Peterson et al., 2008) was utilized using the default settings. Maxent, unlike other distributional modelling techniques, uses only presence and background data instead of presence and absence data.

Evaluation metrics for SDMs (performance): Methods to measure the performance of the SDMs include Partial ROC (Peterson et al., 2008), binomial tests (Anderson et al., 2003) and the confusion matrix (Fielding and Bell, 1997). The area under the receiver operating characteristic (ROC) and the area under the receiver-operator curve (AUC) were used for assessing the discriminatory capacity of the models: AUC > 0.9 is considered excellent. The true skills statistic (TSS) was also considered. GIS-modelling was accomplished using SAGA GIS, DivaGis, QGIS (Nekrasova et al., 2019). Statistical processing of the obtained data was carried out in Statistica for Windows v.10.



A B

Fig. 2. The “Ecological envelope” — relationship bio01 “Annual mean temperature”, °C & bio12 “Annual precipitation”, mm (DivaGis): A — *T. graeca*; B — *T. hermanni*.

Results

Limiting factors for distribution

T. graeca is more widespread than *T. hermanni*. In Turkey, it is quite common and occupies a variety of habitats: from roadsides to mountain terraces, gardens, historic ruins up to the steep forest slopes of the Antalya coast. The GIS modelling revealed that the limiting and important factors (percent contribution, Maxent) for the distribution of *T. graeca* are: bio01 "Annual mean temperature" — 25.4 %, bio34 "Mean moisture index of warmest quarter" — 19.1 %, bio11 "Mean temperature of coldest quarter" — 14.9 % (33.3 % permutation importance). Within this "ecological envelope" 66 % of *T. graeca* are found in areas where the "Annual mean temperature" (bio1) ranges an optimum of +10 to +21 °C (limits vary from +3 to +26 °C), the mean consisting +15 °C (DivaGis).

T. hermanni is less common, but is found together with *T. graeca* in the Danube basin, as well as in countries such as Romania, Bulgaria, and in various places of the Balkan Peninsula, etc. GIS modelling revealed that the limiting and important factors (percent contribution) shaping the distribution of *T. hermanni* are: bio25 "Radiation of driest quarter" — 32.4 %, bio03 "Isothermality" — 14.8 %, bio11 "Mean temperature of coldest quarter" — 13.1 %. Within this «ecological envelope» 66 % of *T. hermanni* are found in places where the "Annual mean temperature" (bio1) ranges an optimum of +9 to +17 °C (limits are between +5 and +19 °C), the mean being +13 °C (DivaGis).

Niche clustering

Using the clustering algorithm (a statistical tool which explains the difference in conditions) for visualizing the Hutchison's duality (K-means clustering, Colwell and Rangel 2009), we concluded that the distinguished clusters of niches roughly coincide with the distribution of subspecies in Eastern Europe (fig. 3). This clustering result explains the widespread distribution of *T. g. ibera* and habitat features that it prefers. The obtained results also show the uncertainty and prospects for the description of a new taxa (for example, *T. graeca* in Turkey — "?", fig. 3, A). It is also noticeable that in the south of the Balkan Peninsula (Albania, Greece) environmental conditions for tortoises are very different, and it is here that another species is found — *T. marginata* (fig. 3, B). This species was also introduced: Cyprus, Italy (continental, Sardinia [prehistoric]), where conditions are also favorable for it.

Ecological niche modelling

To study the distribution of the considered protected species under present and future conditions, we created two models (Maxent, CliMond 1975 and 2090) for each of the species (fig. 4 and fig. 5). From the modelling it can be concluded that the *T. graeca* tortoises have twice larger potentially suitable for habitation areas than *T. hermanni*, and

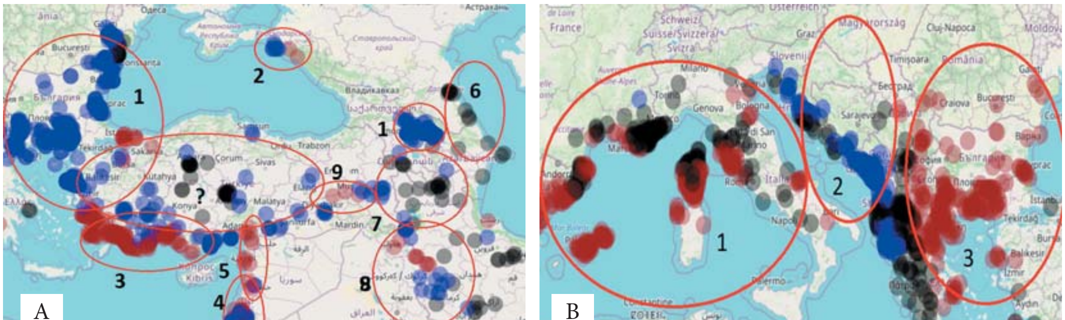


Fig. 3. Niche clustering (Geographic space, CliMond 1975 (1970–2000)) from: A — *T. graeca* (*1. T. g. ibera, 2. T. nikolskii, 3. T. g. anamurensis, 4. T. g. floweri, 5. T. g. antakyensis, 6. T. g. pallasi, 7. T. g. armenica, 8. T. g. perses,* buxtoni, *9. T. g. terrestris*); B — *T. hermanni (1. T. h. hermanni, 2. T. h. hervegovinensis, 3. T. h. boettgeri),* red circles showing the approximate ranges of subspecies according to "Turtles…, 2017" World" (2017).

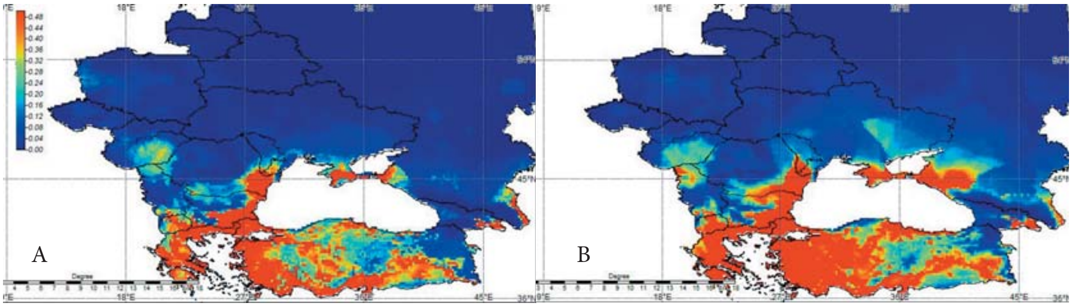


Fig. 4. Potential (probabilistic) model of *T. graeca* expansion built in the Maxent program based on the CliMond: A — 1975 (1970–2000); B — 2090 (2081–2100)) climatic data and GBIF data (2021 a). Areas of the highest habitat suitability (> 0.3–0.5) are colored in red and areas of the lowest (< 0.2) — in blue (SAGA GIS).

the range of temperatures and precipitation under which the former species can occur is much wider compared to the latter. At the same time, the range of two species of tortoises in the future may increase in Eastern Europe by around a third by 2090 (fig. 2, 3). A constructed regression model revealed that these tortoises can occupy similar territories (for example, in Romania, Bulgaria, etc.), the coefficient of determination was $R^2 = 0.4$. It is noticeable that even under the modern climate; such portions of Ukraine as the South-West of Odesa Region are suitable for *T. graeca* (namely, the Danube basin) and Crimea (fig. 4). By 2090 it will expand to the Dniester, other places in the Odesa Region, along the border with Moldova (reproduction cases are known, Kukushkin et al., 2017), and in the Crimea (reproduction cases are known, Kukushkin et al., 2017) almost reaching the Sivash. The range of *T. hermanni* will also expand to the Danube basin, Odesa Region, and Eastern

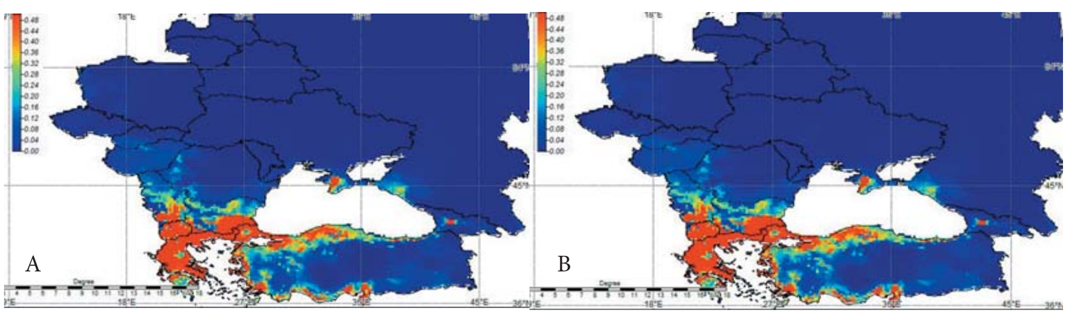


Fig. 5. Potential (probabilistic) model of *T. hermanni* world expansion built in the Maxent program based on the CliMond: A — 1975 (1970–2000); B — 2090 (2081–2100)) climatic data and GBIF data (2021). Areas of the highest habitat suitability (> 0.3–0.5) are colored in red and areas of the lowest (< 0.2) — in blue (SAGA GIS).

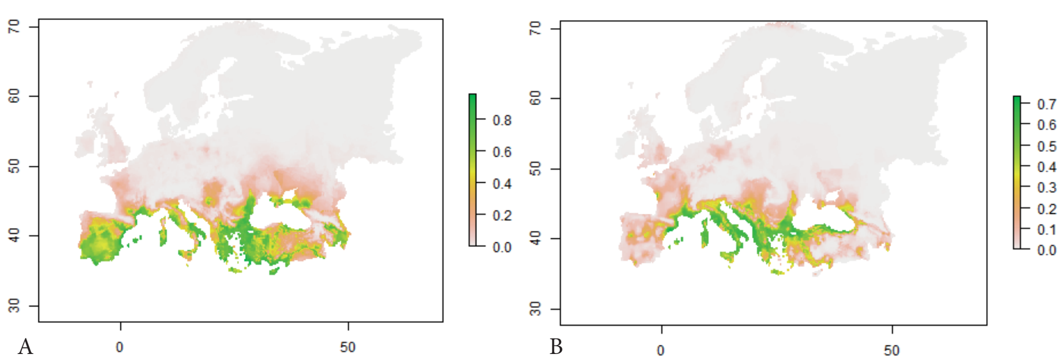


Fig. 6. Result of the analysis of Binomial tests (CliMond 2090 (2081–2100)): A — *T. graeca*; B — *T. hermanni*.

Crimea (fig. 5).

The performance of the SDMs was quite high (AUC > 0.97, TSS > 0.63). Thus, we can conclude that *T. graeca* has significant prospects for distribution in the south of Eastern Europe. In general, the species is less demanding on temperature factors and can inhabit anthropogenic territories, giving it certain advantages (fig. 1, 2).

Discussion

GIS modelling revealed that bio11 "Mean temperature of coldest quarter" is the limiting factor for both species. This explains the difficulties in the expansion of these species in a northward direction. Moreover, most tortoises *T. graeca* (90 %, DivaGis) tolerate low temperatures during the cold period (bio11) — from –2 to +14 °C (limits are in the range of –6 to +17 °C), the mean being +7 °C, and *T. hermanni*: 90 % of individuals are met between averages of –1 to +11 ° C (limits: –3 to +12 °C), with the mean of +6 °C (DivaGis). There are also differences between the two species concerning survival characteristics: *T. graeca* better tolerates higher temperatures and rather low humidity, whereas *T. hermanni* occupies more humid biotopes (fig. 2). In the future quite promising areas for expansion, besides the South of Ukraine (Odesa, Kherson Regions) and Crimea may be areas on the left bank of the Dnipro (including the Siversky Donets, fig. 6). Naturally, in the coastal regions and in the floodplains of rivers, these species of tortoises can be met together. An interesting fact is that land tortoises have virtually no competitors among the local herpetofauna and they are not predators, therefore they cannot harm other animals, unlike aquatic species of Testudines. An increase in the area in the Black Sea region and in the South of Ukraine can contribute to the protection of these species, where in the past (namely, the "mid-Holocene" dating back to 6000 years BP) it was already found according to the results (in the Crimea) of paleontological excavations (Szczerbak, 1966) and supported by of our modelling (Nekrasova et al., 2019).

Conclusions

GIS analysis revealed that even under modern conditions in Eastern Europe there are promising areas for the habitation of two species of tortoises, especially in the South of Ukraine (Odesa Region, Crimea). With the climate warming in the future, by 2090 it is likely that the home range of the considered species could expand towards the area of Eastern Ukraine (floodplains of the Siversky Donets River belonging to the Don basin). Moreover, the limiting factor for both species is bio11"Mean temperature of coldest quarter", which is a very important factor determining the successful wintering of juveniles. *Testudo graeca* is more common and tolerant to higher temperatures and fairly low humidity. Nevertheless, both protected species may well coexist in coastal areas and upper terraces of river valleys, where particularly light soils are found. These species do not pose a predation threat to any native animal species and do not compete for food with other species of the herpetofauna. Also, they are protected globally and have a high nature conservation status. Besides climatic factors, the distribution of land tortoises in Eastern Europe can also be limited by direct anthropogenic impact (extraction from the wild for pet reasons, plowing, pesticide use in fields and gardens, death on roads, etc.).

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