Changes in the range of *Pterostichus melas* and *P. fornicatus* (Coleoptera, Carabidae) on the basis of climatic modeling

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Effective monitoring and preservation of biodiversity require knowledge on the distribution range of separate species. *Pterostichus melas* and *P. fornicatus* are distributed in Central and Southern Europe and the Caucasus. The study revealed to what extent the territories, included in this range, are suitable for the life of these species according to climatic parameters. According to the points of monitoring and catches obtained from the publications and data base of the global biodiversity fund GBIF and 19 climatic parameters of the WorldClim open data base using the method of maximum entropy, multi-dimensional analysis of climatic niche we distinguished the factors which have the greatest effects on the current distribution of the ground beetles. Modeling of the ranges of *P. fornicatus* and *P. melas* for 2050 and 2070 allowed us to determine that climate warming leads to decrease in the areas of ranges, making it more fragmented. The most favourable habitats shift to the north. Comparative assessment of the factors significant for the studied species revealed that in both cases, the amount of precipitations of the driest month and the driest quarter is important. By 2070, under changes in bioclimatic parameters the predicted range of *P. fornicatus* will decrease by three times, predicted range of the *P. melas* – by two times. We consider the prognosis modeling of the climate change-driven changes in ranges of model species to be promising.

Key words: Carabidae, *Pterostichus*, climatic modeling, climate changes, distribution range

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INTRODUCTION

Effective monitoring and preservation of biodiversity require knowledge on the distribution range of separate species (Thiele 1977, Kotze *et al.* 2011). Understanding the data of the patterns allows us to assess the perspectives of the further existence of species and dynamics of their ranges under the influence of various natural and anthropogenic factors (Erwin 1979, Putchkov *et al.* 2019, 2020). Modern geoinformational technologies allow us to model species ranges based on the bioclimatic parameters more accurately than in the past (Turin *et al.* 1977, Molyneux 2013, Alonso-Carné *et al.* 2017, Fick and Hijmans 2017, Poggio *et al.* 2018). Research orientated towards modeling of the changes in the ranges of species of plants and animals are becoming more often based on the method of maximum entropy implemented using the Maxent program (Avtaeva *et al.* 2019). Many large ground beetles which are unable to fly are convenient objects for modeling in this aspect.

The range of *Pterostichus* (*Feronidius*) *melas* (Creutzer 1799) is convenient for modeling its changes under the influence of global climate changes. This species is distributed in Central and Southern Europe, the Caucasus (https://fauna-eu.org/cdm_dataportal/taxon/8a5f68b2-20ed-4d49-b1c9-4672cc94c03e) and is represented by two subspecies: *P. melas italicus* (Dejean 1828) is common in France, Switzerland, Italy and Croatia and *P. m. melas* (Creutzer 1799) in the remaining part of the species' range (Giglio *et al.* 2011, 2015).

Zamotajlov & Kryzhanovskij (1992) report the similarity of populations of the nominative subspecies *P. melas melas* (Creutzer), living in Ukraine and Moldova, with earlier described populations which live in Central and Eastern Europe. The same authors in their study described the form that lives in the Northern Caucasus which is distinct by characteristic morphological peculiarities and its own range. The authors consider it a separate species, classifying it to *P. fornicatus* Kolenati (Zamotajlov & Kryzhanovskij, 1992). But later in the fundamental catalogue, Kryzhanovskij *et al.* (1995) report that in the former USSR *P. melas* is common in Moldova, Ukraine, desert-steppe and steppe zones of the Southern Russian Plain; for the territory of Ciscaucasia and the Caucasus Major *P. fornicatus* Kolenati 1845 is used as synonym for *P. melas*. For the Ukrainian Carpathians and Transcarpathia these authors, apart from *P. melas,* indicate also *P. hungaricus* Dejean 1828. Kryzhanovskij (1983) reports that this species is one of the main ones in the anthropogenically transformed territories of the European part of the USSR.

Sigida (1993) reports that in Ciscaucasia, in the plains, *P. melas* belongs to the ecological group of polytopic mesophiles, which inhabits ravine and flood plain forests, forest islands. In Adygea it is a polytopic mesophile common in different types of pre-mountain and mountain zonal landscapes, occurs in agrocenoses (Zamotajlov and Nikitsky 2010).

It is an average-sized species (the body length equals 12.8–17.0 mm; Hurka 1996, Fråudå *et al.* 2004), unable to fly. Due to reduced wings this species is absent in the islands, for example Great Britain (Luff 1992). Guéorguiev and Guéorguiev (1995) and Hieke and Wrase (1988) indicate broad distribution of *P. m. melas* in Bulgaria at altitudes of 1,500 m above the sea level, common in Albania (Guéorguiev 2007), but is known in only two of 76 regions in Macedonia (Hristovski and Guéorguiev 2015). Subspecies *P. m. melas* is common all across Moldova (Nekuliseanu and Matalin 2000).

Hurka (1996) notes that in the Czech and Slovak Republics this species lives in conditions with a broad range of moisture and light, i.e. ranging from moderately dry to moderately humid biotopes, both open and closed areas. In forest steppe they live in open forest areas, pastures, lowlands and hills. Pizzolotto *et al.* (2005) indicate *P. melas* to the group of generalist forest species – it is a "species with wide ecological tolerances might show a central value and several nuclear values (for example *P. melas*). The fewer the nuclear values, the stronger is the preference for the habitat with the central value. It is possible that species strongly linked to a given habitat show central value in that and few or no nuclear values in other habitats".

In Ukraine, *P. melas* is common practically ubiquitously, except in Northern Polesia and highland Carpathians (Kryshtal 1956, Putchkov 2011, 2018). *P. melas* is a meadow species. It lives mostly in meadow habitats, mesophile steppes, in ravines, rarer in non-dense tree-shrub communities. In mountains, it reaches the belt of beech forests. It is active mostly in twilight-night hours. It appears from late March to late October, is a mesophile, zoophage of broad specialization. The wintering phase is imago. It occurs singularly in gardens and berry fields, rarely – in ploughed lands of Southern Ukraine and Transcarpathia. Sometimes it is common in set-asides and hayfields in the steppe zone (Putchkov 2018). In the fauna of Ukraine, two subspecies are represented: *P. m. melas* in Transcarpathia and Outer Subcarpathia, and *P. melas fornicatus* (Kolenati 1845) – in the south of left-bank Polesia, Forest-Steppe and Steppe zones (Putchkov 2012). It is a mesothermophile, mesoxerophile, meadow-steppe hemipolytopic species, the larvae are soil – litter dwellers, imagoes – stratobionts of the litter, trophic specialization – zoophage, preys on various species of agricultural pest insects (Karpova and Matalin 1993, Putchkov and Brygadyrenko 2018).

In one of the most recent catalogues of coleopterans of the Palearctic, *P. fornicatus* has the status of species (Bousquet 2003) and therefore in this article it will be dealt with as a separate species.

The objective of the study was to assess the possible changes in the range of *P. melas* and *P. fornicatus* within Europe with employment of methods of bioclimatic modeling, determination of the range during the "severe" scenario of climate change.

MATERIAL AND METHODS

Material for this study was field collections made by the authors of the article (150 sites) and also the data obtained from the publications of the open data base GBIF (400 spots). Field collections were conducted in different years in the territory of Chechen Republic (Russia) and seven oblasts of Ukraine (Table 1).

In the Chechen Republic (Table 2) for the collection of beetles, pit-fall traps were used and manual collection was performed. As traps, plastic cups of the volume 0.5 L were used, filled with 4% solution of formalin and vinegar. In each biotope, 20 traps were installed with 10 m distance between them. The extraction of beetles was made once every ten days (Avtaeva and Kushnareva, 2017).

For the evaluation of the dependence of life cycle and seasonal dynamics on the ecological factors, we used the method of Wallin (1987). We studied the seasonal dynamics, period of reproduction and peaks of beetles' activity (Sharova and Khobrakov 2005).

Using the method of maximum entropy, the distribution of *P. melas* and *P. fornicatus* was studied, and also the factors which underlie their distribution were distinguished. For bioclimatic modeling (Molyneux *et al.* 2013), the data of the global climatic data base WorldClim (www.worldclim.org) were used: 19 bioclimatic variables with spatial resolution of the 30 seconds. For the prognosis of the range of *P. melas* and *P. fornicatus* in 2050 and 2070 we used scenario RCP8.5, i.e. scenario of "high emissions", according to which the concentration of CO_2 in 2100 would reach 936 ppm, and the mean global temperature – 16.8 °C. In other words, mean warming for the period of 2010–2100 would equal 2.4 °C.

Maxent is a program for modeling the distribution of species. Maxent assesses the distribution of conditions appropriate for a studied species according to the principles of maximum en-

Table 1. Characteristic and data source for the development of distribution map of *P. melas*

Country, region	Oblast, district	Source material
Russia, Chechen Republic	Shelkovskaya, Naursky District, Shalinsky District, Vedensky District, Paraboch Reserve, Grozny	Field collections by T. A. Avtaeva
Russia, Republic of Dagestan	Flood-plain meadow on the banks of the Awarskoje Koisu river	Field collections by T. A. Avtaeva
Russia, Krasnodar Krai	Agrocenoses	Field collections by T. A. Avtaeva
Ukraine	Donetsk, Luhansk, Zaporozhia.	Field collections by V. V. Brygadyrenko
Hungary	Oak forest 50 km away from Budapest	iNaturalist.org (2020). iNaturalist Research-grade Observations. Occurrence dataset https://doi.org/10.15468/ab3s5x accessed via GBIF.org on 2020-01-07. www.gbif.org/occurrence/1500277500
Serbia	Beli Potok, Serbia	iNaturalist.org (2020). iNaturalist Research-grade Observations. Occurrence dataset doi:10.15468/ab3s5x accessed via GBIF.org on 2020-01-07. www.gbif.org/occurrence/1500277500
Germany	Eschachtal zwischen Lackendorf und Stetten o.R., östl. Hang	naturgucker.de. naturgucker. Occurrence dataset doi:10.15468/uc1apo accessed via GBIF.org on 2020-01-07.
Bulgaria	Primorsko, BG-BR, BG	iNaturalist.org (2020). iNaturalist Research-grade Observations. Occurrence dataset doi:10.15468/ab3s5x accessed via GBIF.org on 2020-01-07. www.gbif.org/occurrence/1836690154
Austria	Obernarrach Wiese und Feuchtgebiet	naturgucker.de. naturgucker. Occurrence dataset doi:10.15468/uc1apo accessed via GBIF.org on 2020-01-07. www.gbif.org/occurrence/2329628726
Switzerland	All territory of Switzerland	Chittaro Y (2019). Swiss National Coleoptera Databank. Version 1.2. Swiss National Biodiversity Data and Information Centres – infospecies.ch. Occurrence dataset doi:10.15468/cjmjy2 accessed via GBIF.org on 2020-01-07. www.gbif.org/occurrence/2428773171
Slovenia	Osrednjeslovenska: Laibacher Becken, Ljubljana, Ljubljana	The International Barcode of Life Consortium (2016). International Barcode of Life project (iBOL). Occurrence dataset doi:10.15468/inygc6 accessed via GBIF.org on 2020-01-07. www.gbif.org/occurrence/1414957845
France	Data is not the original geo referenced one, but attached to the nearest 10x10 km grid cell	Alain Berly, N. (2019). Données naturalistes d'Alain Berly. Version 1.1. UMS PatriNat (AFB-CNRS-MNHN), Paris. Occurrence dataset doi:10.15468/dmtj3c accessed via GBIF.org on 2020-01-07. www.gbif.org/occurrence/2486365734
Turkey	Strandzha Mountain	Kostova, R. (2016). The ground beetles (Coleoptera: Carabidae) of the Strandzha Mountain and adjacent coastal territories (Bulgaria and Turkey). Biodiversity Data Journal. Checklist dataset doi:10.3897/bdj.4.e8135 accessed via GBIF.org on 2020-01-07. www.gbif.org/occurrence/1262931422

Table 2. Model Biotope and Abundance of *P. fornicatus* in the Chechen Republic

No	Biotope, coordinates	Number of collected specimens
1	Flood-plain forest near Stanitsa Kalinovskaya, 43.5649ºN 45.4990ºE	142
2	Flood-plain forest near Grebenskaya village, 43.5248ºN, 46.3954ºE	253
3	Forb meadow near flood-plain forest near Grebenskaya village, 43.3139°N, 46.2426°E	91
4	Flood-plain forests within the borders of Paraboch Reserve, 43.4687ºN, 46.3007ºE	113
5	Windbreak plantation 10 km away from Stanitsa Kalinovskaya, 43.6337ºN, 45.5591ºE	53
6	Flood-plain forests near Serzhen'-Yurt village, 43.1125ºN, 45.9929ºE	258
7	Fruit garden in Serzhen'-Yurt village, 43.1151ºN, 45.9917ºE	495
8	Pasture near Serzhen'-Yurt village, 43.1164ºN, 45.9912ºE	32
9	Flood-plain forest near Tevzana village, 42.9844ºN, 45.8978ºE	167
10	Windbreak plantation near Shali town, 43.1310ºN, 45.8717ºE	93
11	Pasture near Shali town, 43.1219ºN, 45.8618ºE	15
12	Pasture at the foot of Terek mountain range near Tolstoy-Yurt village, 43.4310ºN, 45.7422ºE	2
13	Western boundary of Grozny near the Green Zone, 43.2563ºN, 45.7336ºE	193
14	Flood-plain near Staraya Sunzha, 43.3381ºN, 45.7590ºE	641
15	Steppe area near the industrial zone of Grozny, 43.3044ºN, 45.6443ºE	267
	Total	2815

tropy. It allows one to evaluate the contribution of each climatic variable to the obtained model of species distribution, making it possible to assess the role of each biologically significant factor included in the analysis.

To develop all the models we used standard program settings with switched on evaluation of importance of contribution of each variable (jackknife method). To increase the accuracy of the models and their statistical assessment we used the tool 'random test percentage' with the parameter of 25%. This tool randomly excludes 25% of the findings out of the total number (test data) and uses them for the further check of the result of modeling. The remaining 75% of the findings were the training data the model is developed on. To characterize the quality of the model, an assessment of accuracy of descriptions of the training data is performed concerning the prognosis capabilities. Both parameters are expressed as fractions of one. The first characteristic (training data) indicates how well the developed model describes the introduced data. The second characteristic (test data) shows how well the result of modeling coincides with the test data. The model is considered of good quality when both these parameters below 0.5 (Phillips, 2015).

The obtained model contains 4 sections: statistical analysis of the accuracy of the model, map of potential distribution of species, analysis of contributions of climatic variables used in the analysis to the obtained model and control parameters and models. Moreover, the Output folder will contain the Plots folder which contains illustrative material in *.png format. It can be opened in any graphical editor. One of the important parameters used to assess the obtained model is Area Under Curve, which is the area under the Receiver Operating Curve. AUC measures the capability of model to identify places where a species is present and those where it is absent, and ranges from 0 to 1.

For the study of the layers, QGIS 3.4.3 (Quantum GIS, USA 2019) was used. Prediction the potential ranges of *P. melas* and *P. fornicatus* was performed using the program Maxent 3.4.1 (Phillips *et al.* 2017; Maxent software for modeling species niches and distributions; Version 3.4.1, USA, http://biodiversityinformatics.amnh.org/open_source/maxent). During the statistical analysis the accuracy of the obtained models was checked using random selection. The program was set to select 25% of the findings and set them aside for testing. Random test percentage was 132 point locations of the species for the entire range. Maxent program has three initial formats: initial, cumulative, and logistic. Logistic format is the most convenient for assessing the probability of findings in the interval from 0 to 1. During the development of the model for the training selection the threshold of 10 percentiles was set. This means that the assumption that 90% of "presence points" describe typical environment of the species, whereas the remaining 10% live in not entirely typical conditions for the species. Using the method of maximum entropy, multi-dimensional analysis of the climatic niche was performed, factors which influence the current distribution of the studied species were distinguished.

While processing the initial data in Maxent, a map of the most probable regions of the distribution of *P. melas* and *P. fornicatus* was developed. Moreover, the modeling resulted in the tables which contain the data on the contribution of each of the analyzed factors (percent contribution) and their permutation importance. The first parameter is determined heuristically and depends on particular route the Maxent code moved in order to reach optimum solution. The second parameter depends not on the route travelled, but on the final model.

In the QGIS program, for the each species the layers of the current range and the prognosis range for 2050 and 2070 were developed. In the same program, we calculated the area of each range. The area was calculated in the table of attributes to each layer through the calculator of fields. Then, the obtained area in square meters was converted into square kilometers.

Results

Analysis of the field material showed that in the conditions of Chechen Republic, *P. fornicatus* inhabits both more humid shaded forest biotopes and open steppe areas. At the same time, its abundance in forest was 3-5 times higher than in the steppe biotopes. During the study of an urban ecosystem (on the example of Grozny), *P. fornicatus* was determined to be the dominant species by the number in transformed biotopes with heavy anthropogenic load. In the industrial zone of Grozny, in the sward areas earlier polluted by oil, *P. fornicatus* was recorded as superdominant. Table 3 presents the main bioclimatic factors on which the distribution of this species depends.

Average value of AUC in the obtained model equals 0.998 ± 0.001, meaning 90-percent probability that in the places in which the species is predicted to be present it actually is present, therefore confirming the reliability of the obtained model (Fig. 1). The main contribution which affects the distribution of this species is made by the precipitations in the driest month, average and lowest temperature of the coldest month of the year, and seasonal changes in the temperature (variation coefficient). During the modeling

Table 3. The main factors affecting the distribution of *P. fornicatus*

Environment factors	Contribution percentage	Permutation importance
Precipitations of the driest month	29.4	5.6
Mean temperature of the coldest quarter	30.9	64.9
Seasonality of the temperature (variation coefficient)	10.2	1.2
Minimum temperature of the coldest month	0.2	22.9

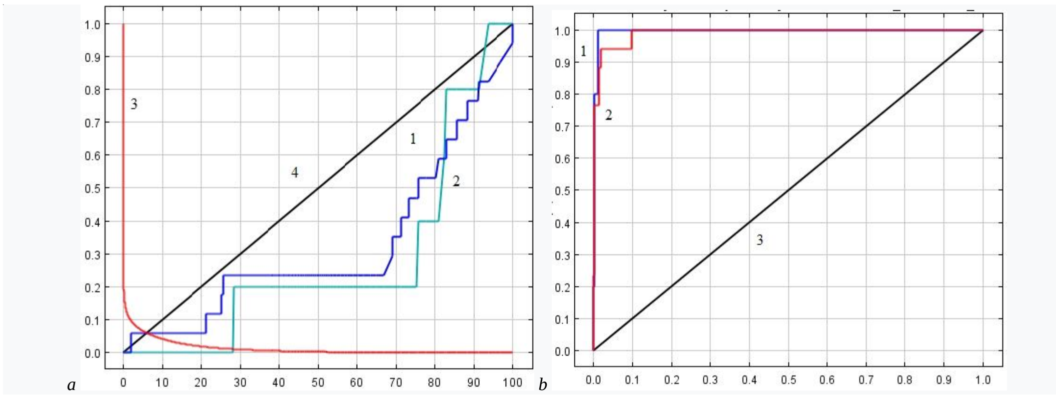

Fig. 1. Analysis of the accuracy of the model of probable distribution: *a* – omission and Predicted Area for *P. fornicatus*: *1* – test data, *2* – training data, *3* – fraction of the initial data presented, *4* – predicted emission; *b* – trend of the operating curve AUC: *1* – test data, *2* – training data, *3* – random prediction

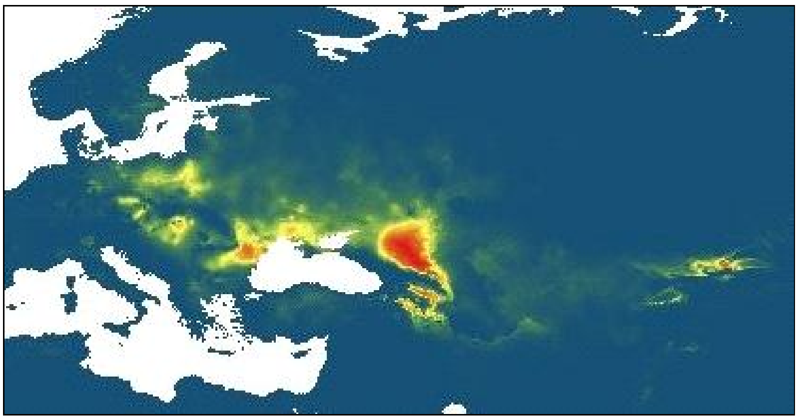

Fig. 2. Model of potential (probable) range of *P. fornicatus* assessed in Maxent software basing on the data of WorldClim: in red the most suitable areas for living are indicated (70–100%), orange – 50–70%, yellow – 20–50%, blue – 0%.

in the Maxent environment, it was found that the greatest influence on the distribution of the imago was exerted taken by a complex of factors associated with temperatures of the coldest period. According to the obtained model, the most significant values were the minimum temperatures of November, January and February.

Statistical analysis of the results showed high accuracy of the model. Parameter of AUC for the training data equals 0.991, confirming the accuracy of the model of the probable range. For the test data, AUC was also high (0.997). Test locations well coincide with the predicted dynamics for the data obtained from the distribution by Maxent. The figure demonstrates that curves of the test and training parameters are located far from the straight central line, which shows the reliability of the prognosis of the model at the random level, indicating the high expected capacity of the obtained model. This is related to the fact that during the analysis, we used a quite large amount of geographical location points of species.

Fig. 2 visualizes the model of current range of *P. fornicates*, more or less favourable places for its existence are distinguished. In the process of the interpolation, the program did not cut the marine area, although the contour of the Caspian Sea coastline is clearly seen. According to the obtained model, the most favourable territories for this species are the Caucasus, South Ukraine, Moldova, Outer Subcarpathia. The eastern margin of the range of the species is limited by the coast of the Caspian Sea. This corresponds to the current range of this species.

During the modeling, the graphs of the curves of dependence of the distribution of *P. fornicatus* on the parameters of bioclimatic parameters were obtained (Fig.3).

Visualization of the model of range of *P. fornicatus* for 2050 showed that the range undergoes no significant changes. The most suit-

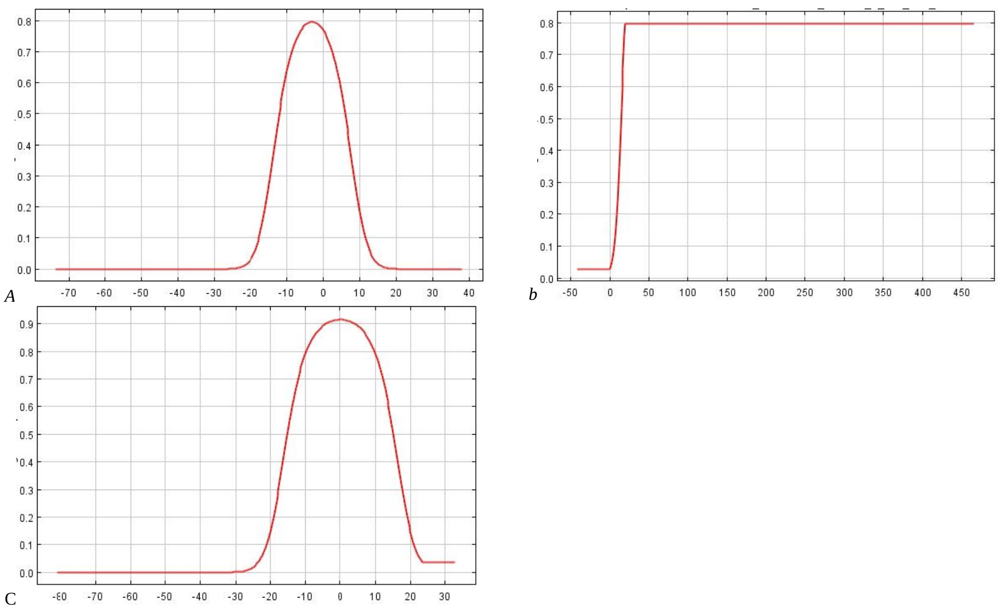

Fig. 3. Curves of dependence of the model of probable distribution of *P. fornicatus* on bioclimatic parameters: *a* – Bio11; along the abscissa axis – mean temperature of the coldest quarter of year; on the ordinate axis – index of suitability for the species, *b* – Bio14; on the abscissa axis – amount of precipitations in the driest month of the year; on the ordinate axis – index of suitability for the species, *c* – Bio 6; on the abscissa axis – minimum temperature

able places for the species remain the Caucasus and South-East Ukraine (Fig. 4).

Prediction of distribution of *P. fornicatus* in 2070 showed that the species' range decreases, becomes disjunct (Fig. 5). The most suitable conditions remain in the Caucasus, the remaining territories are in the range of 40–60% according to the suitability scale and form a number of local territories located approximately on the same latitude, including Astrakhan and Volgograd Oblasts and regions in North Kazakhstan.

The area of the current range of *P. fornicatus* is 879 305 km^2, in 2050 it will be 857 526 km^2, and in 2070 – 300 655 km^2. Thus, by 2070, under changes in bioclimatic parameters the area will decrease by three times.

During modeling of the spatial distribution of *P. melas* in the Maxent program, mean value of AUC for *P. melas* was 0.995 ± 0.001, which is a quite high value, which allows us to state the model is reliable (Fig. 6). The greatest effects on the current distribution of *P. melas* (Table 4) are the result of precipitations (precipitations of the driest month and quarter) and temperature (seasonal temperature, average temperature of the driest and warmest quarter). It should be taken into consideration that these factors can take effect both directly and indirectly through the food base. In accordance with the existing prognoses,

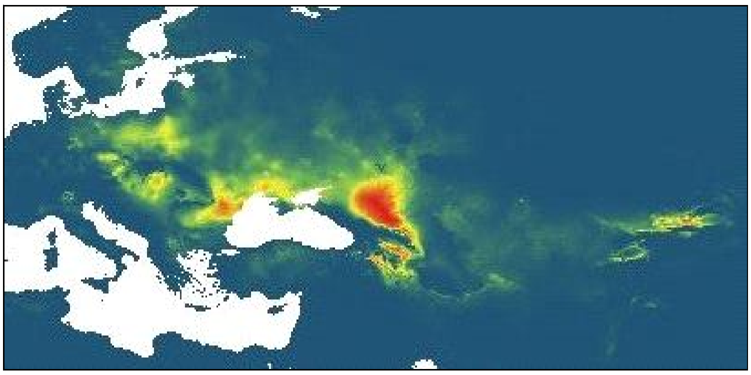

Fig. 4. Presumed range of *P. fornicatus* in 2050 at mean increase in average temperature to 2100 equaling 2.4 ºC: for keys see Fig. 2

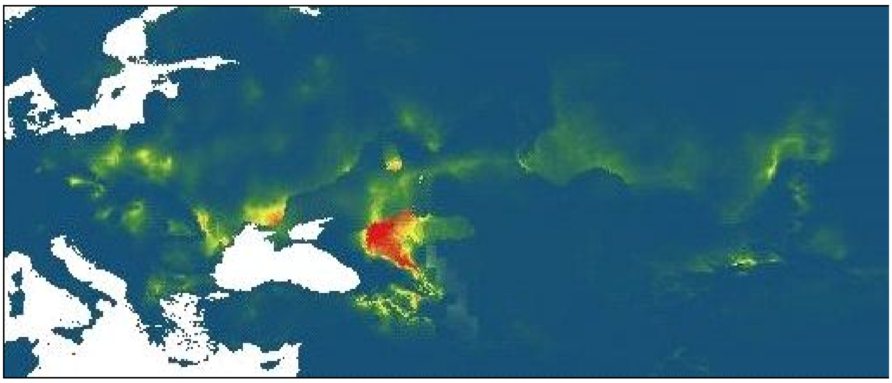

Fig. 5. Predicted range of *P. fornicatus* in 2070 at mean increment of 2.4 ºC to 2100: for keys see Fig. 2 ASK BRIG

Table 4. The main factors which affect the distribution of *P. melas*

Factors of the environment	Percentage contribution	Permutation importance
Precipitations of the driest quarter	32.7	8.1
Average temperature of the driest quarter	16.9	3.7
Precipitations of the driest month	14.6	0.1
Seasonality of the temperature (variation coefficient)	12.3	5.7
Mean temperature of the warmest quarter	2.1	16.6
Lowest temperature of the coldest month	0.6	38.0

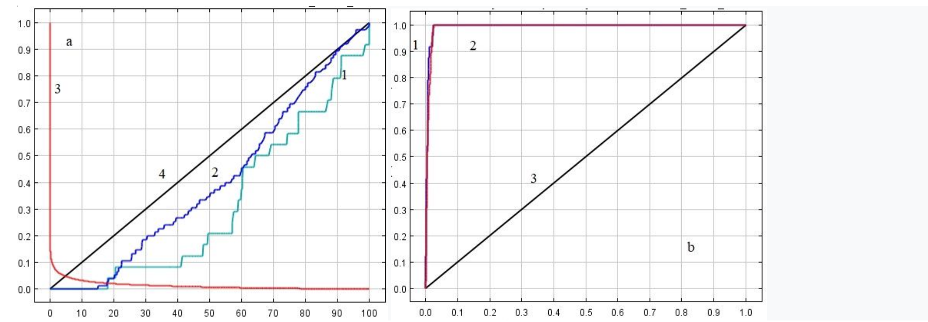

Fig. 6. Statistical analysis of the obtained model of the probable distribution of *P. melas*: *a* – omission and Predicted Area for *P. melas*: *1* – test data, *2* – training data, *3* – fraction of the initial data which were predicted, *4* – predicted emission; *b* – trend of the operative curve AUC: *1* – test data, *2* – training data, *3* – random prediction

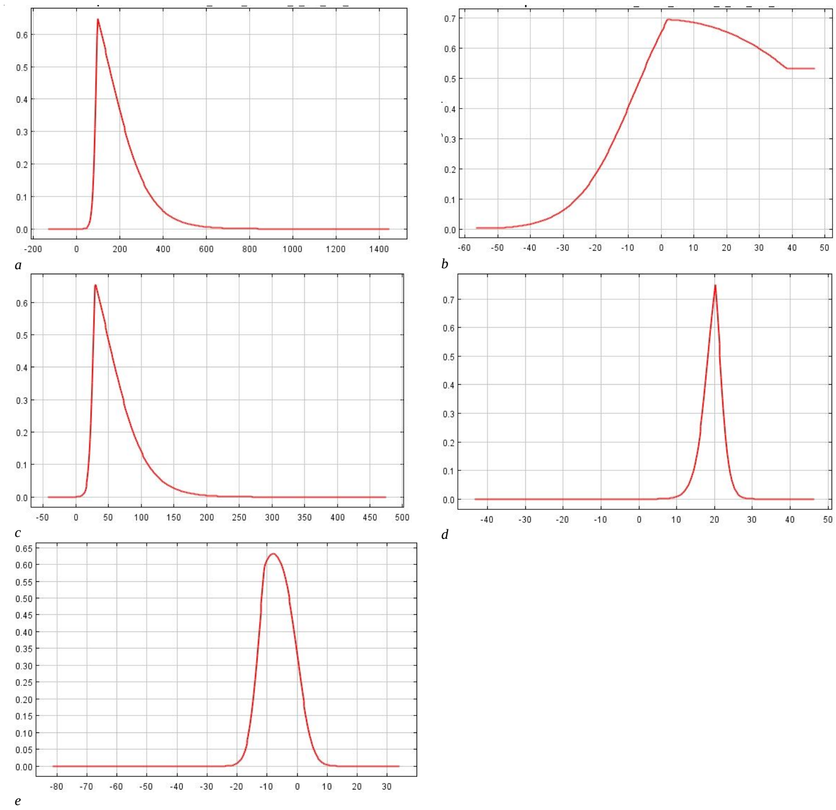

Fig. 7. Curves of dependence of the model of probable distribution of *P. melas* on bioclimatic parameters (on the ordinate axis – index of suitability for the existence of the species): *a* – Bio17, on the abscissa axis – amount of precipitations in the dry quarter of the year; b – Bio 9, on the abscissa axis – temperature of the driest quarter of the year; *c* – Bio 14, on the abscissa axis – amount of precipitations in the driest month of the year; *d* – Bio 10, on the abscissa axis – temperature of the warmest quarter of the year; *e* – Bio 06; on the abscissa axis – temperature of the coldest month of the year

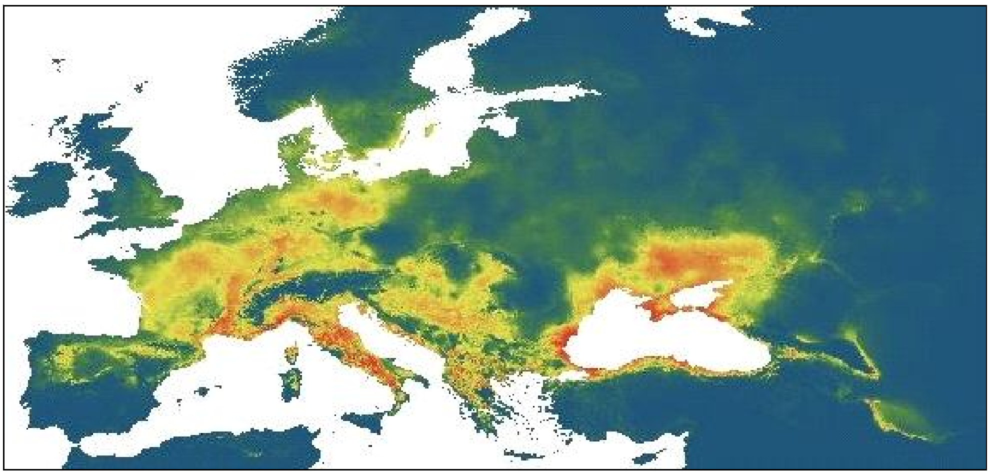

Fig. 8. Area of distribution of *Pterostichus melas:*in red the most suitable zones for living are indicated (80–100%), orange – 50–80%, yellow – 20–50%, green – less than 10%, dark blue – 0%

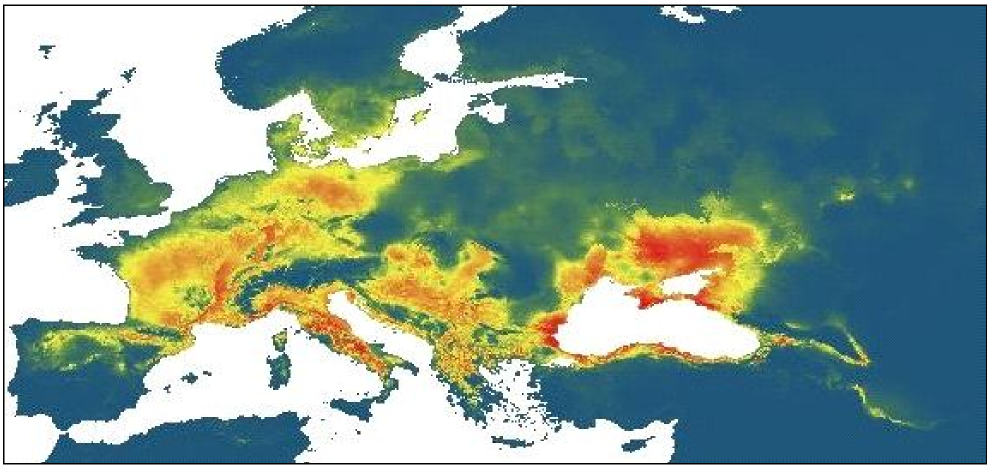

Fig. 9. The area of distribution of *P. melas* for 2050 at annual increment of the temperature measuring 0.03–0.05 ºC: for keys see Fig. 8

in Europe, except for the Mediterranean region, increase in the amount of precipitation over winter is expected, for example by 15–30% in Central and Northern Europe (Giorgi *et al.* 2004). In general, the models predict the decrease in the amount of summer precipitations (June-August) in the greater part of Europe.

The analysis of the curves of dependence of the distribution of *P. melas* on bioclimatic parameters revealed the ranges of this species' tolerance (Fig.7). During the study, the map of suitability for the distribution of *P. melas* was developed (Fig. 8). Analysis of the range revealed that optimum (60–100%) conditions for *P. melas* are those of Central and Southern France, Italy, coast of Bulgaria, North-East Coast of Turkey, South Coast of Romania, Central and South Germany, South Ukraine up to Kirovohrad and Poltava Oblasts, the Crimean Peninsula, South-West Coast of the Black Sea. On the map, these territories are coloured red, orange and yellow. The Alps zone falls out of the range of *P. melas*. The territories with suitability of 20–40% include Spain, the Netherlands, Belgium, Northern France and Germany, Central and South England, South-

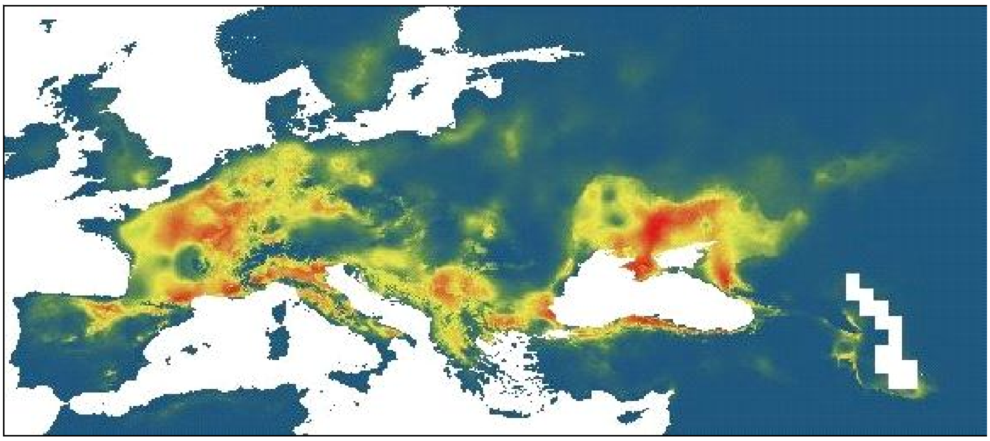

Fig. 10. Area of the distribution of *P. melas* in 2070 at annual increment of the temperature equaling 0.03–0.05 ºC: for keys see Fig. 8

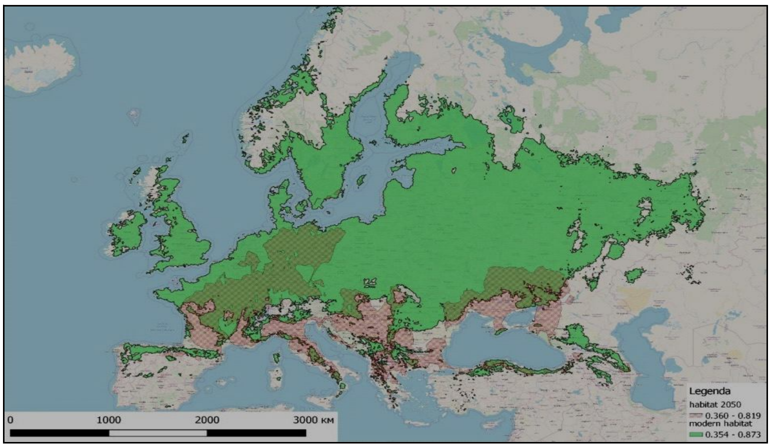

Fig. 11. Comparison of *P.melas* current range and range for 2050

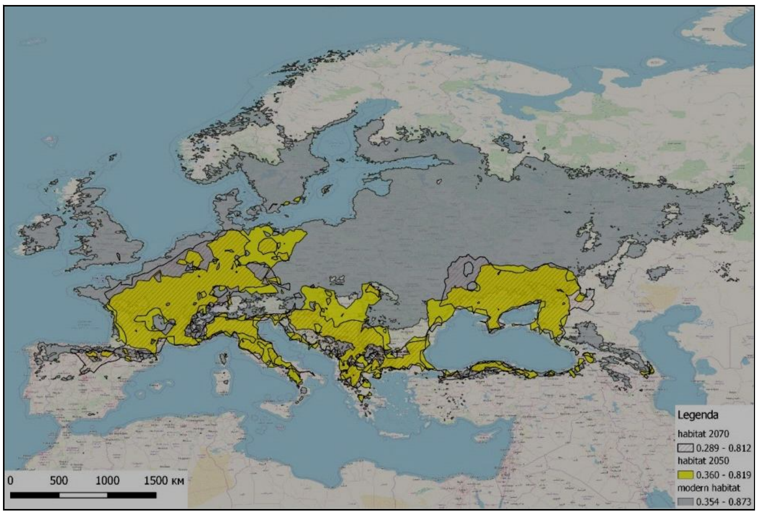

Fig. 12. Map of comparison of *P. melas* current range and ranges for 2050 and 2070

West Sweden, Poland, the Baltic countries, South-West Finland, Belarus, Azerbaijan, Georgia (Fig. 8).

In the model for 2050 the most suitable territories are coloured red, they are reduced in area and shift to the north (Fig. 9).

Predicted area of the range in 2070 decreases by two times, and the most suitable areas for living shift to the North of Italy, France, Spain. The range becomes fragmented and large territories become excluded, including the South part of Poland, Germany, Estonia, North Latvia, Romania and Slovakia (Fig. 10).

In the conditions of climate change, the estimation of its future changes becomes one of the most important tasks. As poikilothermic organisms, beetles significantly depend on the temperature of the environment, therefore the change in climate parameters inevitably leads to the shift of the borders of their ranges. By 2070 the range decreases, becomes more fragmented and shifts to the North, which corresponds to the literature data (Fig. 11, 12).

DISCUSSION AND CONCLUSION

The obtained models of the ranges of both species correspond to the existing data. This is confirmed also by high parameters of AUC. At the same time, the program visualizes the potential territories the species would live in, but where it is not found currently, which are fully suitable for its existence according to a complex of bioclimatic parameters. Presumably the distribution of this species is not determined using any limited set of factors and the absence of species is due to historical reasons. The indicated territories the species could inhabit are the territories suitable for it. Therefore, the potential range of the studied species is broader than the actual one. The MaxEnt program takes into account only abiotic factors, whereas the distribution of species may be affected by biotic and anthropogenic factors. The maps of the distribution ranges which we obtained could be considered as the range suitable for inhabitation.

At the average temperature of the cold quarter equaling –10 ºC to +7 ºC the probability of presence of *P. fornicatus* is 60–80% (Fig. 3a). Probability of presence of this species is high in the territories with the range of precipitations of the driest month from 30 to 450 mm and higher (Fig. 3b). The most comfortable temperature of the coldest month for the existence of *P. fornicatus* is in the range of –12 ºC to +14 ºC, which explains the presence of the species in the territories with a mild marine climate (Crimea, South Ukraine). Perhaps, the dependence of the distribution on winter temperatures is related to the life cycle and seasonal dynamics of *P. fornicatus*. It is a summer-autumn species which breeds from the midsummer to early or mid autumn. The wintering is performed by larvae of older ages, individuals of the maternal generation and some of the immature individuals of the daughter generation.

The range of most suitable temperature of the coldest *P.melas* month is –10…0 ºC (Fig. 7e). Perhaps, the dependence on the temperature of the coldest month is related to the realization of the life cycle of this species (Fig. 7d) which belongs to late-summer species, imagoes of which hibernate and breed again in the following year and whose larvae and individuals of the mother generation winter (Matalin 2006).

Comparative assessment of the factors significant for the studied species revealed that in both cases, the amount of precipitations in the driest month and the driest quarter is important. Most species of *Pterostichus* genera prefer humid biotopes compared with low temperatures (Korolev and Brygadyrenko 2014, Brygadyrenko 2016). Average temperature of the warmest quarter and month is associated with the period of reproduction. For *P. melas* and *P. fornicatus* it corresponds to August–September. Study of the seasonal dynamics of *P. fornicatus* in the conditions of the Chechen Republic revealed that the first females with eggs in the abdominal section of the body occur in the traps in the second decade of August. High temperatures are dangerous for both reproducing beetles and the eggs they lay. Temperature of the cold period is important to the wintering larvae and imagoes which have already undergone reproduction. According to our data, for *P. fornicatus* the temperature of the coldest month is within –10…+14 ºC, and the mean temperature of the coldest quarter –10…+7 ºC. For *P. melas* the average temperature of the warmest month is +20 ºC, while the coldest – within –10…0 ºC. The range of this species is significantly broader and occupies practically the whole of Europe. Distribution of this species is determined by climatic and edaphic conditions, and also historical changes of the vegetation cover in the territory of Europe. At the same time, their distribution is weakly dependent on the food base.

Ranges developed using the Maxent program include territories in which the species has not been recorded. It has to be noted that the program determines the territories of possible presence of species. Perhaps, when the species spreads to such a territory, there is probability of its rapid adaptation to new conditions. For example, recently in a flood plain forest near city Penza a Caucasian endemic *Carabus cumanus* Fischer, 1823 was found.

Modeling of the ranges of *P. fornicatus* and *P. melas* for 2050 and 2070 allowed us to determine that climate warming leads to decrease in the areas of ranges, making it more fragmented. The most favourable habitats shift to the north. This is confirmed by the recent data for other groups of insects (Komlyk and Brygadyrenko 2019a, 2019b). For example, two thirds of the studied species of butterflies of Europe are currently found 35 to 250 km north from the locations where they were recorded several decades ago (Primak 2002). RCP 8.5 is a scenario of anthropogenic greenhouse gas emissions, according to which mankind will not reduce the rate of emissions, and the concentration of carbon dioxide in the air by 2100 will be 930 ppm (parts per million). Thus, we made an attempt to visualize the changes in the ranges of the studied species according to the most severe scenario, assuming that this is the most probable way of further development of the climate situation. The events of spring 2020 showed that the pandemic has led to an improvement in the environmental situation in different regions, however, this does not mean that this will seriously affect the global climate at all.

By the evaluation of the perspectives of using approaches of bioclimatic modeling of the ranges of ground beetles with the Maxent software pack, we can indicate the perspectives of these studies. Employment of these approaches allowed us to extrapolate the fragmented data about particular locations in large territories, unstudied with regard to this aspect. It allowed us to determine the territories which are similar according to bioclimatic parameters. Also we consider the prognosis modeling of the climate change-driven changes in ranges of model species to be promising.

Such studies can be undertaken also for local territories. The obtained model of potential distribution range of the species would help in planning the search in any particular territory. Field surveys based on the obtained maps can contribute to finding new places inhabited by the species. Modeling the ranges of species is especially important due to climate change. Such models allow one to evaluate the range in future.

REFERENCES

Alonso-Carné J., Estrada-Peña A. & García-Martín A. 2017. Análisis comparativo de la información de temperatura de las bases de datos WorldClim, ECA&D y MODIS en el Paleártico Occidental. *Geographicalia* 69: 1. doi:10.26754/ojs_geoph/geoph.2017692317

Avtaeva T.A. & Kushnareva S.A. 2017. K faune zhuzhelic (Coleoptera, Carabidae) gornukh rajonov Chechenskoj Respubliki [The fauna of ground beetles (Coleoptera, Carabidae) in the mountainous regions of the Chechen Republic]. *Vestnik Moskovskogo Gosudarstvennogo Oblastnogo Universiteta* 4: 6–14. [in Russian]

Avtaeva T.A., Sukhodolskaya R.A., Skripchinsky A.V. & Brygadyrenko V.V. 2019. Range of *Pterostichus oblongopunctatus* (Coleoptera, Carabidae) in conditions of global climate change. *Biosyst. Divers.* 27(1): 76–84. doi:10.15421/011912

Bousquet Y. 2003. Tribe Pterostichini. In: Löbl J. & Smetana A. (Eds.). Catalogue of Palearctic Coleoptera. Vol. 1. Archostemata – Myxophaga – Adephaga. Apollo Books, Stenstrup. Pp. 462–521.

Brygadyrenko V.V. 2015. Parameters of ecological niches of Badister, Licinus and Panagaeus (Coleoptera, Carabidae) species measured against eight ecological factors. *Balt. J. Coleopterol.* 15(2): 137–154.

Brygadyrenko V.V. 2016a. Evaluation of ecological niches of abundant species of *Poecilus* and *Pterostichus* (Coleoptera: Carabidae) in forests of steppe zone of Ukraine. *Entomol. Fenn.* 27(2): 81–100.

Erwin T.L. 1979. Carabid beetles: Their evolution, natural history, and classification. Junk, Hague – Boston – London.

Fick S.E. & Hijmans R.J. 2017. WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.* 37(12): 4302–4315. doi:10.1002/joc.5086

Fråudå H., Hardå K.W. & Lohså G.A. 2004. Diå Käfår Ìittålåuropas. Band 2. Adåphaga. 1. Ñarabidaå (Laufkäfår). Elsåviår, Spåktrum Akadåmisñhår Vårlag, Íåidålbårg, Germany.

Giglio A., Brandmayr P., Pasqua T., Angelone T., Battistella S. & Giulianini P.G. 2015. Immune challenges trigger cellular and humoral responses in adults of *Pterostichus melas italicus* (Coleoptera, Carabidae). *Arthropod Struct. Dev.* 44(3): 209–217.

Giglio A., Giulianini P.G., Zetto T. & Talarico F. 2011. Effects of the pesticide dimethoate on a non-target generalist carabid, Pterostichus melas italicus (Dejean, 1828) (Coleoptera: Carabidae). *Ital. J. Zool.* 78(4): 471–477.

Guéorguiev B. 2007. Annotated catalogue of the carabid beetles of Albania (Coleoptera: Carabidae). Pensoft Publishers, Sofia-Moscow, Bulgaria.

Guéorguiev V.B. & Guéorguiev B.V. 1995. Catalogue of the ground-beetles of Bulgaria (Coleoptera: Carabidae). Pensoft Publishers, Sofia-Moscow, Bulgaria.

Hieke F. & Wrase D.W. 1988. Faunistik der Laufkafer Bulgariens (Coleoptera, Carabidae). *Deut. Entomol. Z.* 35(1–3): 1–171.

Hristovski S. & Guéorguiev B. 2015. Annotated catalogue of the carabid beetles of the Republic of Macedonia (Coleoptera: Carabidae). *Zootaxa* 4002(1): 1–190. doi:10.11646/zootaxa.4002.1.1

Hurka K. 1996. Carabidae of the Czech and Slovak Republics. Print Centrum, a. s., Zlin, Czech Republic.

Karpova E.V. & Matalin A.V. 1993. Annotirovannyj spisok zhuzhelic (Coleoptera, Carabidae) juga Moldovy [An annotated check list of carabids (Coleoptera, Carabidae) of Southern Moldova]. *Entomol. Rev.* 72: 570–585. [in Russian]

Komlyk V.O. & Brygadyrenko V.V. 2019a. Morphological variability of Bembidion aspericolle (Coleoptera, Carabidae) populations in conditions of anthropogenic impact. *Biosyst. Divers.* 27(1): 21–25. doi:10.15421/011903

Komlyk V.O. & Brygadyrenko V.V. 2019b. Morphological variability of *Bembidion minimum* (Coleoptera, Carabidae) populations under the influence of natural and anthropogenic factors. *Biosyst. Divers.* 27(3): 250–269. doi:10.15421/011935

Korolev Î.V. & Brygadyrenko V.V. 2014. Influence of individual variation in the trophic spectra of *Pterostichus melanarius* (Coleoptera, Carabidae) on the adaptation possibilities of its population. *Folia Oecologica* 41(1): 34–43.

Kotze D.J., Brandmayr P., Casale A., Dauffy-Richard E., Dekoninck W., Koivula M.J., Lövei G.L., Mossakowski D., Noordijk J., Paarmann W., Pizzolotto R., Saska P., Schwerk A., Serrano J., Szyszko J., Taboada A., Turin H., Venn S., Vermeulen R. & Zetto T. 2011. Forty years of carabid beetle research in Europe – from taxonomy, biology, ecology and population studies to bioindication, habitat assessment and conservation. *ZooKeys* 100: 55–148. doi:10.3897/zookeys.100.1523

Kryshtal O.P. 1956. Entomofauna gruntu ta pidstylky v dolyni serednioji techiji riky Dnipro [Entomofauna of soil and litter in the valley of Dnipro river midstream]. Kyiv State University, Kyiv. [in Ukrainian]

Kryzhanovskij O.L. 1983. Zhuki podotrjada Adephaga: Semejstva Rhysodidae, Trachypachidae; semejstvo Carabidae (Vvodnaja chast' i obzor fauny SSSR) [The beetles of the suborder Adephaga: Families Rhysodidae, Trachypachidae, Carabidae (Introduction and a review of the USSR fauna)]. Nauka, Leningrad. [in Russian]

Kryzhanovskij O.L., Belousov I.A., Kabak I.I., Kataev B.M., Makarov K.V. & Shilenkov V.G. 1995. A checklist of the ground-beetles of Russia and adjacent lands (Insecta, Coleoptera, Carabidae). Pensoft Publishers, Sofia, Bulgaria.

Luff M.L. 1992. Provisional atlas of the ground beetles (Coleoptera, Carabidae) of Britain. Biological Records Centre, Huntingdon, England.

Matalin A.V. 2006. Geographic variability of the life cycle in *Pterostichus melanarius* (Coleoptera, Carabidae). *Entomol. Rev.* 86(4): 409–422. doi:10.1134/s0013873806040051

Molyneux N., Soares I. & Neto F. 2013. WorldClim and DIVA software for modeling current and future climates at a 5 km resolution. *Combating Climate Change* 2013: 325–342. doi:10.1201/b14056-18

Nekuliseanu Z.Z. & Matalin A.V. 2000. A ñatalogue of the ground-beetles of the Republic of Moldova (Insecta, Coleoptera: Carabidae). Pensoft, Sofia – Moscow.

Pizzolotto R., Brandmayr P. & Mazzei A. 2005. Carabid beetles in a Mediterranean region: Biogeographical and ecological features. In: European Carabidology 2003. Proceedings of the 11th European Carabidologist Meeting. DIAS Report, No. 114, 243–254.

Poggio L., Simonetti E. & Gimona A. 2018. Enhancing the WorldClim data set for national and regional applications. *Sci. Total Environ.* 625: 1628–1643. doi:10.1016/j.scitotenv.2017.12.258

Primak R. 2002. Osnovy sohraneniya bioraznoobraziya [Biodiversity conservation framework]. Izdatelstvo Nauchnogo i Uchebno-Metodicheskogo Tsentra, Moscow. [in Russian]

Putchkov A. 2011. Ground beetles of the Ukraine (Coleoptera, Carabidae). *ZooKeys* 100: 503–515. doi:10.3897/zookeys.100.1545

Putchkov A.V. 2012. Faunisticheskij obzor karaboidnyh zhukov (Coleoptera, Caraboidea) Ukrainy [A review of the caraboids-beetles (Coleoptera, Ñaraboidea) of Ukraine]. *Ukrainskyj Entomologichnyj Zhurnal* 5: 3–44. [in Russian]

Putchkov A.V. 2018. Zhuky-turuny (Ñoleoptera, Carabidae) transformovanykh tsenoziv Ukrajiny [Ground-beetles (Ñoleoptera, Carabidae) of transformed cenoses of Ukraine]. I. I. Schmalhausen Institute of Zoology, Kyiv. [in Ukrainian] doi:10.15421/511802

Putchkov A.V. & Brygadyrenko V.V. 2018. Ridkisni tverdokryli nadrodyny Caraboidea (Coleoptera, Adephaga) Dnipropetrovs'koji oblasti [Rare beetles of the Caraboidea superfamily (Coleoptera, Adephaga) in Dnipropetrovsk oblast]. Zhurfond, Dnipro. [in Ukrainian] doi:10.15421/511801

Putchkov A.V., Brygadyrenko V.V. & Markina T.Y. 2019. Ground beetles of the tribe Carabini (Coleoptra, Carabidae) in the main megapolises of Ukraine. *Vestn. Zool*. 53(1): 3–12. doi:10.2478/vzoo-2019-0001

Putchkov A.V., Brygadyrenko V.V., & Nikolenko N.Y. 2020. Ecological-faunistic analysis of ground beetles and tiger beetles (Coleoptera: Carabidae, Cicindelidae) of metropolises of Ukraine. *Biosyst. Divers*. 28(2): 163–174. doi:10.15421/012022

Sigida S.I. 1993. Landshaftno-biotopicheskoe raspredelenie i jekologicheskaja harakteristika zhuzhelic (Coleoptera, Carabidae) Predkavkaz'ja i severnyh sklonov Central'nogo Kavkaza [Landscape and biotopic distribution and ecological characteristic of carabids (Coleoptera, Carabidae) of Ciscaucasia and northern slopes of the Central Caucasus]. *Entomol. Rev.* 72(1): 11–38. [in Russian]

Thiele H.U. 1977. Carabid beetles in their environments. Springer-Verlag, Berlin. doi:10.1007/978-3-642-81154-8

Turin H., Haeck J. & Hengeveld R. 1977. Atlas of the carabid beetles of the Netherlands. North-Holland Publishing Company, Amsterdam.

Zamotajlov A.S. & Kryzhanovskij O.L. 1992. Matrialy k izucheniju kavkazskikh zhuzhelic triby Pterostichini (Coleoptera, Carabidae) [Materials for the study of Caucasian species of ground beetles of Pterostichini tribe (Coleoptera, Carabidae)]. *Entomol. Rev.* 71(2): 351–358. [in Russian]

Zamotajlov A.S. & Nikitsky N.B. 2010. Zhestkokrylye nasekomye (Insecta, Coleoptera) Respubliki Adygeja (annotirovannyj katalog vidov) [Coleopterous insects (Insecta, Coleoptera) of Republic of Adygheya (annotated catalogue of species)]. Adyghei State University Publishers, Maykop. [in Russian]

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