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CURRENT AND PREDICTED DISTRIBUTION OF THE MOOR FROG UNDER CLIMATE CHANGE ON THE TERRITORY OF RIGHT-BANK POLISSIA OF UKRAINE

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Current and predicted future distribution of the moor frog under climate change on the territory of Right-Bank Polissia of Ukraine. Marushchak, O. Yu., Nekrasova, O. D., Dubyna, N. A., Pupins, M., Georges, J.-Y. — Amongst the 13 amphibian species inhabiting the territory of the Right-Bank Polissia — the Northern region of Ukraine — the moor frog *Rana arvalis* has been reported historically to survive at the edge of its range with recently reported decreasing populations. However, the species does not benefit from any particular conservation status in this area. Here we investigated the current distribution of this species on the territory of Right-Bank Polissia (namely Volyn, Rivne, Zhytomyr, Lviv and Kyiv regions of Ukraine) where 177 individuals were censused from our field monitoring and historical data. Based on route counts in typical

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habitats, we estimated the occurrence of the moor frog from 0.04 to 11 individuals per 100 m. Based on these field data, a GIS-modelling using an initial set of 104 bioclimatic factors (WorldClim database) identified about 1/3 ($\approx 34.7\%$, $AUC = 0.986$) of the Right-Bank Polissia territory as currently potentially favourable for this species with the largest contribution driven by two major climatic factors, temperature and precipitation, supplemented by elevation as a non-climatic driver. When constructing a probabilistic model based on predicted changes in bioclimatic factors by 2050 (MIROC-6 ssp126), it was determined that the area of climatically suitable habitat for the moor frog will significantly decrease to $\approx 15.7\%$ ($AUC = 0.891$), showing negative trends in the availability of the suitable habitats for the species on the studied territory. This can be interpreted as a result of reduction of favourable habitats and spawning places for the moor frog due to changes in the most relevant climate-related drivers, temperature and precipitation. Further, relatively low tolerance of the moor frog to anthropogenic impacts and its preference of ecotone areas may exacerbate the patterns. All these factors must be taken into account for developing operational management plans for the protection of this amphibian in the future. Since Polissia plays a key role in the conservation of many groups of native biota, its wide diversity of habitats requires urgent conservation measures in order to save this local hotspot of biodiversity in the context of global changes. This study provides further knowledge for compiling reports on the status of biodiversity to the Secretariat of the Bern Convention, officially ratified by Ukraine.

Key words: amphibians, forest zone, GIS-modelling, *Rana arvalis*, conservation status, brown frogs.

Introduction

Amphibians, due to the peculiarities of their ontogeny and ecology, occupy both water (egg and tadpole stages) and land-air habitats (for most species after metamorphosis). Yet, wetlands as habitats of major importance for amphibians are shrinking and degrading due to climate change, anthropogenic effects, pollution and impacts of alien invasive species (Davidson, 2014; Dudgeon et al., 2006; Kingsford et al., 2016; Nekrasova et al., 2021). As a result, amphibians are extremely sensitive to environmental changes (Nekrasova, 1999, 2015 a, b; Nekrasova et al., 2019, 2020; Luedtke et al., 2023), specially under direct and indirect anthropogenic influences, such as changes in hydrological regimes of spawning and wintering reservoirs, appearance of invasive species (Pupina et al., 2018), diseases (Čeirāns et al., 2023), global climate change (Tytar et al., 2018), and pollution (Marushchak & Muravynets, 2018). In addition, irreversible transformation of territories formerly suitable for the survival of populations, such as habitat fragmentation may lead to the isolation of individuals in small enclaves that are no longer suitable for populations in the long term (Alves-Ferreira et al., 2022; Čeirāns et al., 2024). Consequently, amphibians are widely considered as bioindicators of the state of the environment (Nekrasova, 2007). Since there has been a sharp decrease — sometimes up to the collapse — in the number of populations of many species of amphibians, several studies around the world have monitored changes in their habitats (e. g. reduction and fragmentation of wetlands surface areas) but also in natural populations (e. g. species diversity, morphological anomalies) (Piha et al., 2006; Machado et al., 2010; Nekrasova et al., 2019). It is urgent to conduct long term monitoring of the distribution of amphibian species by regularly collecting data on their occurrence with the aim of timely detecting trends that may potentially lead to dangerous decrease in the number and size of populations. Such science-based knowledge is of prime importance for implementing necessary measures for the preservation of these species, such as establishing the

appropriate conservation status for every species, creating operational objects of the nature reserve fund, conducting herpetoculture and strengthening versatile in-depth research and eco-educational work to preserve biodiversity.

Out of the 13 species of amphibians (Amphibia) that inhabit the territory of the Right-Bank Polissia — the Northern Range — of Ukraine, the moor frog (*Rana arvalis* Nilsson, 1842) survives at the edge of its range and the numbers of individuals of this species have been reported to decrease (Nekrasova, 2015 a). The moor frog is included in the lists of regionally rare species with the need for special protection in the Lviv, Kyiv and Ternopil regions as well as in the Annex II of the Bern Convention on the Conservation of European Wildlife and Natural Habitats (1979, officially ratified by Ukraine in 1999) and Annex IV of the Habitats Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora of the European Union (1992). As for other species of amphibians, tracking over time the locations of occurrence of the moor frog and assessing the state of its populations are relevant within the framework of nationwide monitoring of the state of biodiversity and natural resources in Ukraine and beyond.

Historically confused with the grass frog (*Rana temporaria* Linnaeus, 1758), with which it still lives sympatrically nowadays (Nekrasova & Marushchak, 2021), the moor frog was historically abundant in Ukraine, especially in meadows near the edges of deciduous forest (Charlemagne, 1917). In the “August–September” period of “1978–1980”, the moor frog was reported occurring with a density of 3.1 individuals per 1000 m² in the vicinity of Boyarka town, Kyiv Region (Kuzmin, 1993). Information on the number of the moor frog in other regions of Ukraine is fragmentary (Pysanets, 2007). The only data on the abundance of the species concerns the Right-Bank Polissia, given the literature is limited to only a few works (Reshetylo, 2011; Nekrasova, 2015; Bashta et al., 2016; Marushchak et al., 2017). Nowadays, in Ukraine, and particularly on the territory of the Right-Bank Polissia, the moor frog most often occurs in ecotone areas on the border of shrub-tree biotopes and meadows, swamps, canals, and clearings (Pysanets, 2007). The species is typical for Bern Convention Resolution 4 habitats such as: *Hottonia palustris* beds in shallow water (C1.3413), rich fens, including eutrophic tall-herb fens and calcareous flushes and soaks (D4.1), beds of large sedges normally without free-standing water (D5.2), wet or humid eutrophic and mesotrophic meadows (E3.4), moist or wet tall-herb and fern fringes and meadows (E5.4), and nemoral bog conifer woodland (G3.E) (Nekrasova et al., 2018). For spawning, the moor frog mainly uses natural water bodies (e. g. seasonal after spring floods of lakes, floodplains of rivers, streams, swamps and other bodies of water) but also roadside ditches, irrigation canals, and ponds (Pysanets, 2007; Nekrasova, 2015 b). Their synanthropic habitation in fields, private estates, gardens, parks, suburban areas is well-known (Bannikov et al., 1977; Zabroda, 1983; Pysanets, 2007; Kuzmin, 2012), suggesting that the moor frog may be particularly adaptable to contrasting environmental contexts yet under the direct influence of human activities.

This study aims to report the most recent data on the records of the moor frog in the territory of Right-Bank Polissia, Ukraine, as well as to conduct geo-informational (GIS) modelling of the possible changes in its range in order to forecast trends of its abundance and distribution in the context of climate change. In addition, the publication of such data is relevant for the creation of national reports on the conser-

vation status of the species from appendices of the Bern Convention implemented by Ukraine in 1999.

Material and Methods

The study was conducted in the territory of Right-Bank Polissia — the Northern Range — of Ukraine, situated on the right bank of Dnieper (Dnipro) River (Fig. 1). The northern limit of the area runs along the border between Ukraine and Belarus, while the southern limit runs along the Irpin River basin, namely along the Nyvka River. According to its physical and geographical features, this large area (~600 x ~200 km²) belongs to the East-European district, an area of mixed, deciduous forest and forest-steppe (Marynich & Shyshchenko, 2005). It is divided into 2 major sub-areas, namely the Central Polissia (Kyiv and Zhytomyr Polissia) and the Western Polissia (Volyn Polissia), in which, in turn, the Minor Polissia is distinguished (Shcherbak, 1988). Kyiv Polissia includes the right-bank territories of Kyiv and partly Zhytomyr regions, the western limit being an imaginary line passing through the villages of Vystupovychi, Narodychi, Malyn, Radomyshl, Brusyliv. Zhytomyr Polissia occupies the entire territory of Zhytomyr Region north of the Teteriv River, as well as a small eastern part of Rivne region, with the western limit passing along the line connecting the villages of Perebrody, Klesiv, Korets, Sosnovye, and the eastern border passing along the junction with the territory of Kyiv Polissia along the villages of Vystupovychi, Narodychi, Malyn, Radomyshl, Brusyliv. Volyn Polissia is located in the interfluvium of the Western Buh and Sluch rivers, including most of the Volyn Region north of the city of Lutsk and the eastern and northeastern part of the Rivne Region, where its eastern border passes along the line of the villages of Perebrody, Klesiv, Sosnovye and Korets (Shcherbak, 1988; Marynich & Shyshchenko, 2005).

Original data (n = 102 records) were collected by the authors (OM, ON) during field monitoring in Kyiv, Zhytomyr, Rivne, and Volyn regions in “2013–2021”, between March and November, mainly during daylight hours (7:00–23:00), however occasional records in other time of the day took place as well, including road-killed individuals, calling males, post-metamorphic individuals etc.). Species identification was conducted according to standard methods (Bannikov et al., 1977; Pysanets, 2007; Kuzmin, 2012). In order to avoid mis-identification with other species (namely *R. temporaria*), the species was determined by the shape of the back-eye spot (already in post-metamorphic individuals) that stands directly towards the anterior limbs of the hollow without forming an angle in the moor frog, whereas it forms a visible obtuse angle in *R. temporaria* (Pupins & Pupina, 2011).

Statistical tests were performed using Statistica (v.10.0.228.8). During spawning, male calls were also recorded. Males were counted during route registrations per 100 m of the route with a line width of 4 m (a transect of 2 m each side of the tracking line). Individuals killed on highways were also taken into account. MAPS.ME (version 12.0.1 — Google) and Google Earth Pro (Earth version 7.3.3) programs were used for georeferencing (following Nekrasova, 2015 b).

Additional records were collected from museum collections of the National Museum of Natural History at the National Academy of Sciences of Ukraine, the State

Museum of Nature of V. N. Karazin Kharkiv National University and I. I. Schmalhausen Institute of Zoology NAS of Ukraine (48 records: $n = 36$ (before 2000), $n = 12$ (after 2000)), from scientific literature ($n = 11$, Reshetylo, 2011; Zhuravchak & Shidlovsky, 2012; Nekrasova, 2015; Bashta et al., 2016; Marushchak et al., 2017), social network (Facebook, $n = 7$), open depositories of registration points of fauna and flora finds (UkrBin <http://www.ukrbn.com>, $n = 5$) and iNaturalist (www.inaturalist.org, $n = 4$). As a first result of this study, all these sources of data provided a database of 177 geocoded points of moor frog finds. To avoid autocorrelation, records situated closer than 1 km from each other were removed in the 'ntbox' package (Osorio-Olvera et al., 2020) in R (v. 4.0.5). As a result, 50 records were discarded, and the remaining 127 records were used of the GIS-analysis.

GIS modelling of the distribution of the moor frog was performed in the program Maxent (v. 3.4.0) using 19 WorldClim bioclimatic factors (<https://www.worldclim.org/data/cmip6/cmip6climate.html>), with a resolution of 2.5 arcmin, following Nekrasova et al. (2019): bio1 (annual mean temperature), bio2 (mean diurnal range (mean of monthly (max temp–min temp))), bio3 (isothermality (bio2/bio7) ($\times 100$)), bio4 (temperature seasonality (standard deviation $\times 100$)), bio5 (max temperature of warmest month), bio6 (min temperature of coldest month), bio7 (temperature annual range (bio5–bio6)), bio8 (mean temperature of wettest quarter), bio9 (mean temperature of driest quarter), bio10 (mean temperature of warmest quarter), bio11 (mean temperature of coldest quarter), bio12 (annual precipitation), bio13 (precipitation of wettest month), bio14 (precipitation of driest month), bio15 (precipitation seasonality (coefficient of variation)), bio16 (precipitation of wettest quarter), bio17 (precipitation of driest quarter), bio18 (precipitation of warmest quarter), bio19 (precipitation of coldest quarter). Additionally, 7 bioclimatic factors (minimum temperature ($^{\circ}\text{C}$); maximum temperature ($^{\circ}\text{C}$); average temperature ($^{\circ}\text{C}$); precipitation (mm); solar radiation ($\text{kJ m}^{-2} \text{day}^{-1}$); wind speed (m s^{-1}); water vapor pressure (kPa)) for each month; elevation (elev, m) derived from the SRTM elevation data), were added to the initial set of variables (giving a total of 104 variables) (<https://worldclim.org/data/worldclim21.html>) (Fick & Hijmans, 2017).

The initial set of factors (as GeoTiff (.tif) files) was narrowed in order to avoid autocorrelation between the variables. Highly cross-correlated (>0.7) variables were removed using the 'virtualspecies' package in R (Leroy et al., 2016), resulting in a selection of only 12 variables: bio1, elev, bio10, pr4 (precipitation of April), bio11, bio4, bio3, bio17, pr6 (precipitation of June), bio15, bio12, tmin1 (minimum temperature of January). Following the algorithm of the package, instead of defining niche response functions on many correlated environmental layers, the program is instructed to define the niche strictly on Principal component (PC)1 and PCn (where n — number of received PCs, which usually explain 70–90% of the total environmental variance). This means that at this point no original correlated variables are used now directly and now the model deals with synthesized, uncorrelated dimensions. After that that contribution of each variable is quantified which gives a set of environmental variable that can be used for further modelling now free from multi-collinearity artifacts (Leroy et al., 2016).

These factors were used to model areas favourable for the existence of the moor frog both at the time of "1975–2000" and for the future forecast for the year 2050

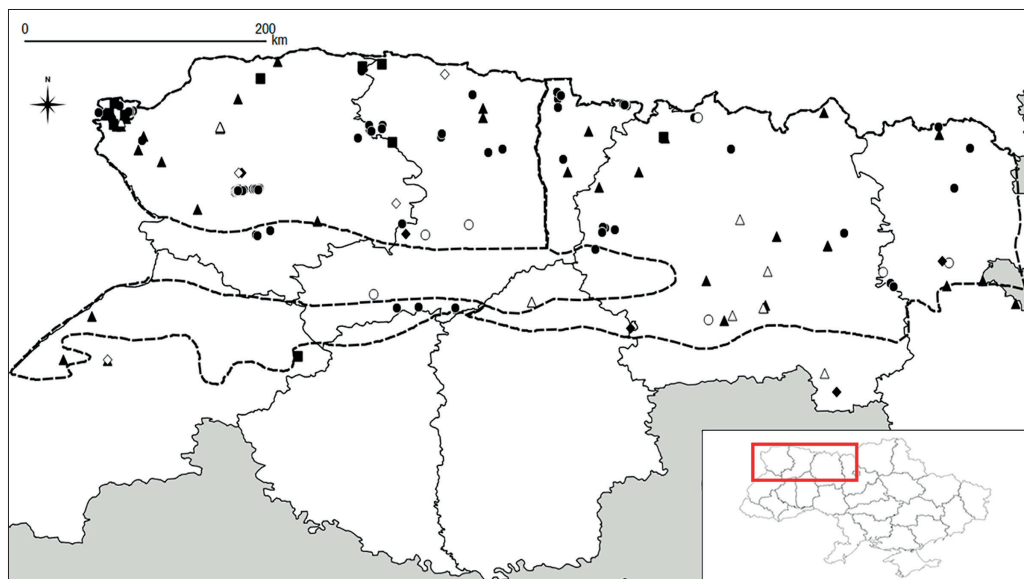


Fig. 1. Records of moor frogs (*R. arvalis*) on the study territory of Right Bank Polissia, Ukraine: ● — original records from “2013–2021” (n = 102); ○ — records from social networks (n = 7); ▲ — museum collections (before 2000, n = 36); △ — museum collections (after 2000, n = 12); ■ — literature sources (n = 11); ◆ — records from UkrBIN (n = 5); ◇ — records from iNaturalist (n = 4)

(long-term trend) according to the MIROC-6 ssp126 probabilistic climate development model (Tatebe et al., 2012, 2019). The modelling was conducted on the study territory using 25 replicates, a 25% rate of randomization test (75% training, 25% testing), a “Bootstrap” replica reproduction type and simultaneous jackknife testing, which expresses the significance of a separate factor for the created model (Phillips, 2005; Nekrasova et al., 2019). We used an evaluation metric for the performance of standard distribution models (SDMs) — the area under the receiver operating characteristic (ROC) curve (AUC) for assessing the discriminatory capacity of the models (AUC > 0.7 was considered excellent). With a reference to the classification proposed by Yang et al. (2013), several grades of potential habitats were distinguished from barely suitable habitat (threshold >0.2) to highly suitable habitat (threshold >0.5).

Logistic output format was used to describe the relative probability of presence, which is a continuous habitat suitability (HS, %) range between 0 (unsuitable) and 1 (the most suitable) (Peterson et al., 2008; Mulkeen et al., 2017; Zurell et al., 2020). Using the coefficient of determination (R^2), we statistically assessed the significance of the similarity ($p < 0.05$) between the current and predicted HS maps obtained through Maxent (following Zurell et al., 2020). The closer this value is to 1, the more similar the resulting models are and, accordingly, the better the constructed predictive model (map) covers the actual species records. That is, this indicator allows us to determine how well the initial data and modelling of their actual distribution are reproduced by the model, based on the proportion of the total variation in the results explained by the model.

Visualization of records and creation of maps was carried out in the QGIS, SAGA GIS and Diva GIS. The proportion of territories favourable for the existence of the species according to the built models was calculated as the percentage of the ob-



Fig. 2. Standard (center) and rare (patternless, left and high-speckling, right) moor frog *R. arvalis* morphs found on the territory of the Right Bank Polissia, Ukraine (photos by Oleksii Marushchak)

tained map painted in a certain colour according to the obtained scale using the Adobe Photoshop CC 2018.

Results

The selected 127 records collected in the field ($n = 102$), in museum collections, literature and social networks, showed that the moor frog occurs in the entire study area — Volyn (Western) Polissia, Zhytomyr (Central) Polissia and Minor Polissia (Fig. 1).

Field observations

In the field, 102 moor frogs were observed from spring to autumn, from early March (2019, Dubensky fort, Dubno, Rivne Region) to late October (2020, Orzhiv village, Rivne Region). Data on the number and frequency of occurrence of the moor frog on route records are shown in Table 1. Additionally, during the field inspections of the hydrotechnical structures on the territory of the abandoned hospital complex near the homestead of the Rivne Nature Reserve, moor frogs were found every time in 2013, 2014, 2018, 2020, with two, four, three, and two individuals encountered, respectively (included in a total of 102 observations from the investigated area).

In the most active phase of the spawning season (April), a cluster of 47 moor frogs was registered on 100 m of the shoreline of a spawning pond (Zhytomyr Region, Malynskyi District, Staritsa, Irsha River near Malyn, April 2014). At the end of the spawning season, 11 individuals were registered on 100 m of the shoreline of a spawning reservoir (Volyn Region, Manevytskyi District, south of the village of Galuziya, channel by the road, April 2021).

Visual inspection of individuals found in the field permitted us to distinguish several colour morphs, which differed from the general description found in the literature (Kuzmin, 2012). These morphs included animals that were completely devoid of “lambda”-like or any other pattern elements while other individuals had large numbers of black dots with increased speckling (Fig. 2). Individuals without any colour pattern were found near the Bile lake, Volodymyrsky District, Rivne Region, and contributed to 1.8% (1 individual) of the whole sample ($n = 56$). Individuals with high speckling were found near Pisochne lake, Shatsky District, Volyn Region, and accounted for 6.7% (a single individual) of the sample ($n = 15$).

Table 1. Number (individuals/100 m of the route) of moor frogs *R. arvalis* during route surveys on the territory of the Rightcoastal Polissia, Ukraine between 2013 and 2022 (published data are indicated with associated references); length of the transect when counting the individuals is indicated in the Locality section

Region	Locality	Biotope	Date	Density (ind./100 m)
Rivne	Between the villages of Bilska Volia and Rudka of Biloozerskyj massif of Rivnenskyj nature reserve (100 m)	Blueberry thickets with a significant predominance of moss in the litter, approximately 50 m from the shore of the Bile lake	07.2013	2.0 (Marushchak et al., 2017)
			07.2013	12.0 (juv.)
Rivne	Forested area to the southeast from village of Dubivka (1000 m)	An abandoned field overgrown with bushes	05.2013	5.0 (Marushchak et al., 2017)
Rivne	oak forest around the office of Rivnenskyj nature reserve (500 m)	Woodland with tall grass, ecotone	07.2013	0.2 (Marushchak et al., 2017)
Rivne	Village of Dubivka (1500 m)	Roadside channel with water, near the meadow	05.2014	3.2
Rivne	Ornithological *zakaznyk "Vovchi Gory" (700 m)	Meadows with abandoned sand quarries	05.2018	0.14
Rivne	To the southeast from village of Bushcha (300 m)	Mixed forest, with undergrowth	05.2020	1.0
Rivne	Botanical *zakaznyk of local importance "Plavskyj" (800 m)	Abandoned field in the floodplain of the river	07.2020	6.5
Rivne	Between villages of Bilska Volia and Berezhna (100 m)	Channel by the road, the end of spawning; number of vocalizing males	04.2021	3.0
Volyn	To the south from village of Hrushivka and Berezhne lake (500 m)	An old abandoned ground road	08.2018	2.2
Volyn	To the southwest from village of Hrushivka (500 m)	An abandoned forest road, overgrown with grass, and blackberries on the side	08.2018	1.6
Volyn	From village of Peresika to Hniablyshche lake (100 m)	The forest road was overgrown with blackberries	08.2018	1.0
Volyn	To the southeast from the village of Gonchyj Brid (1000 m)	The forest road was overgrown with blackberries	08.2018	0.3
Volyn	Pisochne lake (400 m)	Dirt road along the lake with blackberry grown on the side of the sandbank	09.2018	2.0

Continued Table 1

Region	Locality	Biotope	Date	Density (ind./100 m)
Volyn	Village of Svalovychi (300 m)	Abandoned garden to the south from the village	08.2019	0.67
Volyn	Village of Buchyn (100 m)	An oxbow coast	08.2019	2.0
Zhytomyr	Between villages of Kurchytska Huta and Hodurky (1500 m)	Mixed forest with minor undergrowth	07.2019	0.4
Zhytomyr	Poliskyj nature reserve, Didove lake	Forest, Selezivske forestry, sq. 12, 13, 19, 20, 27, 33, 36, 39–40	06.2014	2.0 (Nekrasova, 2015)
Zhytomyr	Poliskyj nature reserve	Bolotnytsia river coast	06.2014	0.04–0.17 (Nekrasova, 2015)
Zhytomyr	Poliskyj nature reserve	Forest, Selezivske forestry, wet biotopes of sq. 33	06.2014	1.7 (Nekrasova, 2015)
Kyiv	The confluence of the Tal and Myrchanka rivers (100 m)	The dry marshy area of the interfluvium with a thick hornbeam and aspen undergrowth	08.2021	24.0

* In Ukraine (and some other post-Soviet countries) zakaznyk is a type of protected area (yet not strict nature reserve) created for the conservation of certain natural complexes or specific species, yet with some human activities.

Current distribution

By analysing the present local distribution of the moor frog in the Right-Bank Polissia and creating a distribution model for “1975–2000”, we found that a third (34.7%) of the Right-Bank Polissia was qualified as suitable for the existence of the moor frog (Fig. 4): this included 24.3% of the territory as suitable ($0.5 < HS < 0.7$) and another 10.4% of the territory as highly suitable ($HS > 0.7$).

As far as current distribution of the moor frog is concerned, the most important bioclimatic indicators with the greatest contribution to the model were related to precipitation and temperature (bio1 (annual mean temperature, accounting for 38.1% of the model), elevation (for 17.8%), bio10 (mean temperature of warmest quarter for 17.4%) and pr4 (precipitation in April for 10.1%)). According to the results of the jackknife test, the AUC for each bioclimatic factor bio01 (annual mean temperature), bio11 (mean temperature of coldest quarter), bio04 (temperature seasonality (standard deviation $\times 100$)) and tmin1 (minimum temperature in January) had the largest values (over 90%), showing that such a variable as elevation does not seem to be a reliably contributing factor in the whole model and should not be treated as such based on 25 model replicas (AUC = 0.986) (Fig. 5).

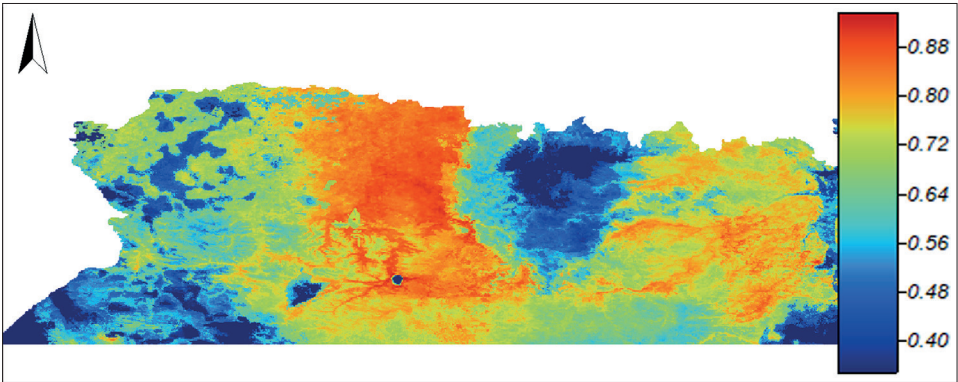


Fig. 3. Model (AUC = 0.986; St.dev = 0.003) distribution of suitable (HS > 0.5) and highly suitable (HS > 0.7) habitats for the moor frog *R. arvalis* according to climatic factors for the period “1975–2000” in the territory of the Right Bank Polissia, Ukraine

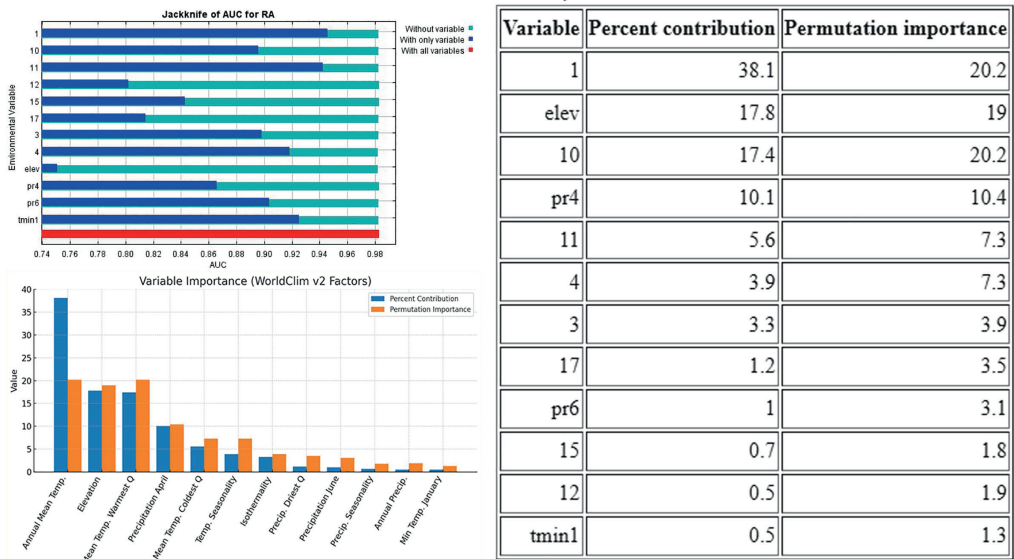


Fig. 4. Results of the jackknife test and calculation of the contribution of each individual bio-climatic factor (from 0 to 1 marked with blue line) to the Maxent model implemented for the present distribution model of the moor frog *R. arvalis* for “1975–2000” period in the territory of Right Bank Polissia, Ukraine

Predicted distribution

With regard to the distribution of suitable habitats for the moor frog by 2050, the built probabilistic model of the distribution in accordance with the predicted values of the forecasted 12 bioclimatic factors indicated that the proportion of the surface of the Right-Bank Polissia’s territory predicted to be suitable ($0.5 < HS < 0.7$) and most suitable ($HS > 0.7$) will decrease to 14.6% and 1.1%, respectively (Fig. 6). In total, these indicators make up 15.7% of the territory suitable for the species in the future, which corresponds to a decrease observed on the whole-European scale (Fig. 5). The value of the coefficient of determination when comparing models of present and predicted HS distribution is $R^2 = 0.83$.

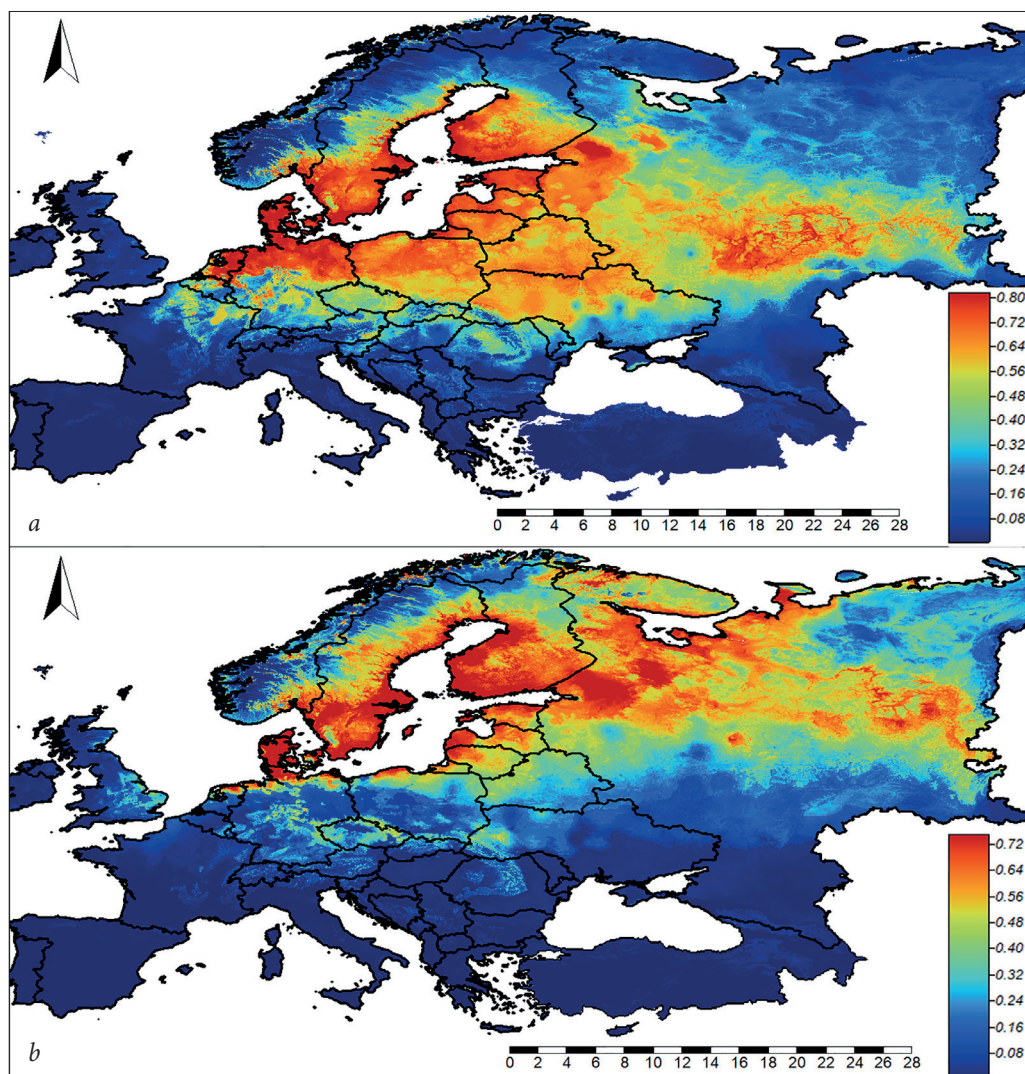


Fig. 5. Potential (probabilistic) habitat suitability model for the moor frog *R. arvalis* distribution (AUC = 0,762; St.dev = 0.001) in Eastern Europe: *a* — current “1975–2000”, *b* — forecasted by 2050

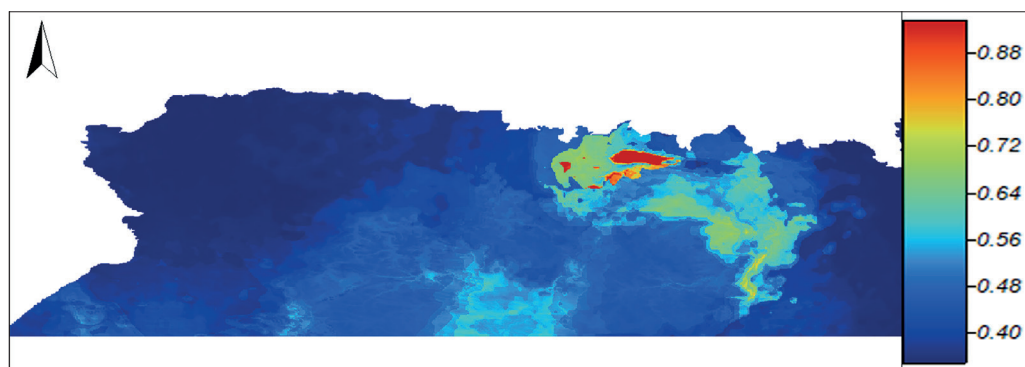


Fig. 6. Model (area under the receiver-operator curve, AUC = 0.891; St.dev = 0.019) distribution of favorable areas ($0.5 < HS$) for the moor frog *R. arvalis* in the Right Bank Polissia, Ukraine, according the model of development of climatic factors MIROC-6 with climatic factors for year 2050

This GIS modelling using combinations of 12 climate factors shows that by 2050, the distribution of the moor frog will shift northward in Eastern Europe, while the moor frog will disappear from most of the territory of Ukraine, especially from the southern part of its range (Fig. 3).

Discussion

Over the last decades, the Right-Bank Polissia — the Northern Range — of Ukraine was considered as the edge of distribution of the moor frog *Rana arvalis* with reported declining populations (Nekrasova, 2015 a) raising conservation issues. For example, in the Pripyat River basin north of Kyiv, Reshetylo (2011) reported the relative abundance of the moor frog as low as 6% compared to the more numerous fire-bellied toad *Bombina bombina* (Linnaeus, 1761) — 25%, edible frog *Pelophylax esculentus* (Linnaeus, 1758) — 23%, grass frog *R. temporaria* — 13%, and marsh frog *Pelophylax ridibundus* (Pallas, 1771) — 11%.

Despite the fact that *R. arvalis* demonstrates a decrease in both numbers and in the extent of biotopes able to support the long-lasting survival of the species, it still seems to be the most numerous and widespread species of brown frogs (*Rana* spp.) on the northern part of Ukraine. In the course of the work, new points of occurrence of this species were reported on the territory of the Right-Bank Polissia. There, the species was encountered during route counts, with highest densities, clusters of individuals (up to 47 individuals per 100 m) recorded in spawning reservoirs during the most active spawning phase, yet with still significant numbers at the end of the season (24 individuals per 100 m), as well as later—when juveniles emerged from the water after completing metamorphosis (>12 individuals per 100 m). At other times of the year, the population size drops to values of 0.3–0.04 individuals per 100 m in typical biotopes.

The current widespread distribution of the moor frog in particular in the Polissia can be explained by the fact that our model for current distribution highlighted that about one third of the region's area hosts suitable habitats for the species (Fig. 3). Our models identified the major drivers of the moor frog distribution, namely annual mean temperature (bio1), mean temperature of warmest quarter (bio10) and precipitation in April (pr4) that accounted for >50% of the present distribution model. This is consistent with the moor frog ecology that has been reported to preferentially occur in meadows near the edges of deciduous forest (Charlemagne, 1917), and more recently in ecotone areas at the border of shrub-tree biotopes and meadows, swamps, canals, but also clearings (Marushchak, 2022) that are increasingly represented due to commercial logging exploitation and subsequent successional processes. Furthermore, the current distribution of the moor frog in northern Ukraine can be explained by its low level of synanthropisation but ability to inhabit moderately transformed landscapes, e. g. meadows, parks, pastures (Marushchak, 2022). The results of this study are consistent with our former field observations since 2000, which highlighted the importance of the area of Rivne, Volyn, Zhytomyr, Lviv and Kyiv regions for the moor frog (Nekrasova et al. 2015 a; Bashta et al., 2016; Marushchak et al., 2017).

However, our GIS based forecasting modelling indicates a significant decrease by almost 55% in the proportion of potentially suitable habitats for the moor frog by 2050. These forecasting probabilistic models are characterized by a high degree of reliability (the value of the coefficient of determination when comparing models: $R^2 = 0.83$). In this study, the performance of our models was evaluated using the area under the curve (AUC). Despite the fact that some authors have criticized this index for assessing the discriminatory capacity of the models (Lobo et al., 2008; Jiménez-Valverde, 2012), this approach proved to be effective in modelling amphibians' and reptiles' (and even associated fungal diseases) habitat suitability with great results (Nekrasova et al., 2017; Tytar et al., 2023; Jakóbič et al., 2024). Our models were associated with $AUC > 0.85$ that are considered excellent (Elith et al., 2011), strengthening the reliability of our findings. Despite the fact that the moor frog, as a species with quite a considerable ecological plasticity, inhabits a large number of diverse habitats (especially in open grassland ecosystems), the modelling results only provide an understanding of the change in favourable climatic conditions and require ground verification of the obtained models. However, we can already see how important the Polissia biotopes are for the conservation of amphibian populations (Nekrasova et al., 2015 a, Marushchak et al., 2017).

The forecasted trends in the moor frog distribution reported at the scale of Eastern Europe are consistent with the fact that the major drivers of its distribution are directly influenced by climate change. Our results show that when considering the global range of the moor frog, the major drivers of its distribution are mainly temperature related: annual mean temperature, extreme values of warm and cold quarters and precipitation in the month when spawning season for the species starts (April). Moreover, Polissia area is characterized by high number of water bodies, that are too acidic for the amphibians to spawn and survive (Marynich & Shyshchenko, 2005; Nekrasova et al., 2015 b). Therefore, accumulation of fresh water and time it remains before drying up are of extreme importance to the amphibians of this region, including moor frog, as are the temperature conditions that enable them to overwinter successfully. Elevation seems to be a variable that, following the jackknife test results, has the worst result (Fig. 4) in terms of reliability of its contribution level (at least in the studied area, due to the limited range of elevation change in the area). The variables representing the humidity levels and temperature regime define the fundamental physiological boundaries of the species and explain its wide distribution in Northern and Eastern Europe (Roček & Šandera, 2008). Whereas for marginal populations at the southern edge of the species range, the key determinant is humidity, especially the precipitation value of the wettest month, as a main source of the moisture for the rest of the season of the frogs' activity, while northern populations are not as limited in moisture due to higher level of precipitation throughout a year (according to the data from the Ukrainian Meteorological Center of The State Emergency Service of Ukraine, average precipitation level in Polissia region within the 2020–2025 period was 520–680 mm/year compared to only 280–390 in steppe and forest-steppe zone (<https://www.meteo.gov.ua/en/>)). Both the mentioned values are lower than

those considered normal for the mentioned regions taking into account a general increase in the average annual temperature in Ukraine (1.2–1.5 °C above the climate norm). Given the expected significant reduction of southern populations in Ukraine by 2050, they should be considered a conservation priority. The obtained results confirm the importance of preserving the ecotone landscapes of Polissia and maintaining the hydrological regime as key conditions for the long-term survival of the moor frog, as well as the important role of Polissia wetlands as refugia for the species' conservation in the context of climate change. Our GIS-based models predict that by 2050, these climate-driven changes in environmental conditions will lead to a shift in the range of the species to the north, whereas the southern populations will disappear except within valleys of large rivers (e. g. Prypiat, Horyn, Sluch, Teteriv, Irpin). Such climate-driven shifts in the geographic distribution have also been reported in other amphibians and water-living reptiles, including the fire-bellied toad *Bombina orientalis*, and the European pond turtle *Emys orbicularis* (Tytar et al., 2018; Nekrasova et al., 2021) that also occur presently in the Right-Bank Polissia of Ukraine.

This study highlights the major role played by the Right-Bank Polissia of Ukraine for the present and future conservation of amphibians in Ukraine and beyond. Importantly, studies like ours, taking into account the modelling of a particular species on a given territory, play a significant role in assessing the status and trends of biodiversity at both small and large scales. Modeling allows us to identify the most relevant, and the most vulnerable environmental components as drivers of the species distribution in current and future contexts. Such studies may also update the actual status of the concerned species, with major implications for making decisions aimed at species conservation (e. g., adding to/removing from protected species lists, creation of objects of the nature reserve fund, initiation and creation of national programs for species breeding, etc.). Such state-of-the-art knowledge of present and future species status and distribution is of prime importance for international institutions, such as the Secretariat of the Bern Convention. In the case of the moor frog in Ukraine, our results indicate that the northwestern part of the country may become the last place where the species will survive by 2050, though favourable and excellent territories (in terms of microclimatic conditions) represent only about 1% of the surface area of the Right-Bank Polissia territory. Therefore, considering the capability of this species to occur in an extremely diverse range of habitats, both natural and those altered by human activity, while showing a preference for ecotones, we recommend that land management maintains such diverse landscapes, particularly in the northern area of Zhytomyr region, in order to increase the moor frog's chances of survival in the coming century.

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