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LONG-TERM BIOCLIMATIC MODELLING THE DISTRIBUTION OF THE FIRE-BELLIED TOAD, *BOMBINA BOMBINA* (ANURA, BOMBINATORIDAE), UNDER THE INFLUENCE OF GLOBAL CLIMATE CHANGE

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Long-Term Bioclimatic Modelling the Distribution of the Fire-Bellied Toad, *Bombina bombina* (Anura, Bombinatoridae), under the Influence of Global Climate Change. Tytar, V., Nekrasova, O., Pupina, A., Pupins, M., Oskyrko, O. — The article describes the potential distribution area of *B. bombina* and figure out the significant climatic factors of the species at a home range scale. This species is listed on Appendix II of the Bern Convention and on Annexes II and IV of the EU Natural Habitats Directive. It is protected by national legislation in many countries, occurs in many protected areas, and is listed in many national and sub-national Red Data books and lists. We collected the occurrence records and a set of climatic variables including 19 factors from 10' resolution historical (summarizing annual trends, seasonality and extreme conditions during 1961–1990) and projected data (2050) available at the CliMond database. As a result, under climate predictions for 2050 there may be a substantial north and north-west shift of optimal habitat. Under such a scenario *B. bombina* populations may suffer mostly in the east and south of Ukraine. Under the modelled scenario the species representation in protected areas throughout the home range should be considered, but especially in Ukraine.

Key words: global climate change, *Bombina bombina*, distribution modelling, amphibians.

Introduction

Recent reports suggest that as much as a third of all known amphibians are in decline, many inhabiting areas far from obvious human disturbances (Stuart, 2008). Global warming and climate change have been implicated as forces likely to drive amphibian declines by significantly changing a habitat through time (e. g., Pounds, 2001; Carey, Alexander, 2003; Raffel et al., 2013). Meta-analysis comparing responses of a wide range of different taxonomic groups to climate change across several biogeographical regions already indicate shifts in the distribution patterns of many plants and animals (e. g., Parmesan, Yohe, 2003). The range shift parallels a 0.8 °C warming over Europe during the last century, which has shifted the climatic isotherms northwards by an average of 120 km (Beniston, 1998). The Intergovernmental Panel on Climate Change (Solomon, 2007 ;Climate Change, 2014) projections forecast changes in the global climate during the 21st century even larger than those observed during the 20th century. Further temperature warming and decreasing of water availability will produce dramatic consequences for amphibians in terms of large extinctions and/or range shifts (Araújo et al., 2006). In the context of future climate change, range shifts are a key response, and can affect species representation in protected areas. Ectotherms are more likely to track their climate space compared to endotherms (Aragon et al., 2010) and major shifts in herpetofaunal assemblages caused by climate change are predicted worldwide (Lawler et al., 2010). Northward range shift would thus be reflected in either a net extinction at the southern boundary or a net colonization at the northern boundary. Because habitat suitability is shifting with climate change, such shifts could lead to population declines and high extinction risk for species that are unable to move to new appropriate conditions because of the patchy landscape and insufficient dispersal corridors (Araújo et al., 2006).

The complex interaction between species distribution and climate change is yet insufficiently understood, but the increasing availability of information on the variation of environmental parameters in geographic space, species distribution data, and computation capacities during the last decade now allow large scale assessments of such relationships (Kozak et al., 2008). Relationships can be assessed by calculating 'environmental' or 'ecological' niches and their subsequent projection into geographic space (Guisan, Zimmerman, 2000). But testing the hypothesis that global warming has already caused amphibian declines is challenging because many factors could act synergistically with climate in complex ways (Pounds, 2001).

In this study, we aimed at projecting the availability of suitable habitat for an endangered amphibian species, the Fire-bellied toad *Bombina bombina* (Linnaeus, 1761). The species is distributed in lowlands over a wide continental area: it is widespread in Poland, Lithuania, Belarus, Western Russian Federation, Ukraine, Bulgaria, Rumania and Hungary. The western border reaches the lowlands of Austria, Czech Republic and East-Germany. The northern border of distribution follows approximately the 56° degree of latitude. The most Northern European populations are in Southern Sweden, East-Denmark, Northern Germany (Schleswig-Holstein), Belarus and Southern Latvia (Drobenkov et al., 2005; Kuzmin et al., 2008). In Sweden during the 1960s, it became extinct.

In western and northern Europe the species is threatened by the loss of habitat. Recent declines in north-western Europe might also be related to climate change (Agasyan et al., 2009). Even small climatic changes could have profound effects on the abundance of the species in this area. In Latvia, for instance, the cold climate, snowless winters, cold short springs and dry hot summers are specified as negative factors based on the risks for *B. bombina* populations (Pupina, Pupins, 2016).

Material and methods

A substantial amount of species records of *B. bombina* are available through the Global Biodiversity Information Facility (GBIF, www.gbif.org) and HerpNet databases (www.herpnet.org). In addition, species records can be obtained from own field trips (Pupina, Pupins, 2015), museum collections or literature (Sillero et al., 2014). In total, 2303 georeferenced occurrence records of *B. bombina* finds were analyzed. Of these, 163 are from Latvia (Pupina, Pupins, 2015) and 866 from Ukraine (80 % personal data of O.Nekrasova: Tytar, Nekrasova, 2016; Tytar et al., 2018 a, b and from the literature: Shaitan, 1999, etc.) that cover the southern and northern boundaries of the home range of *B. bombina*.

In recent years, species distribution modeling (SDM) has been widely used to estimate ecological requirement of particular species and to characterize and map the spatial distribution of habitat occupied by species at a landscape scale (Elith, Leathwick, 2009; Franklin, 2009; Peterson et al., 2011; Phillips, Elith, 2013). The principle of SDM is related to Hutchinson super-volume theory, and emphasizes the ecological requirement of species, especially the abiotic factors controlling species distribution (Guisan, Thuiller, 2005; Li et al., 2013). In general, many climatic factors were used as predicted variables when simulating species potential distribution at large scale with coarse resolution. According to the predicted map, we can depict the climatic niche and response curves of species. Currently, there are many algorithms in SDM technique, but Elith et al. (2006) have shown that maximum entropy model (MaxEnt) is one of the best method among an array of algorithms.

The aim of this work was to simulate the potential distribution area of *B. bombina* and figure out the significant climatic factors of the species at a home range scale. Firstly, we collected the occurrence records. Secondly, we collected a set of climatic variables including 19 factors from 10' resolution historical (summarizing annual trends, seasonality and extreme conditions during 1961–1990) and projected data (2050) available at the CliMond database (Kriticos et al., 2012) (table 1). These variables represent annual trends (e. g., mean annual temperature, annual precipitation) seasonality (e. g., annual range in temperature and precipitation) and extreme or limiting environmental factors (e.g., temperature of the coldest and warmest month, and precipitation of the wet and dry quarters). Finally, we used the occurrence records and cli-

Table 1. Description of bioclimatic variables

Variable acronym	Variable
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
Bio05	Max temperature of warmest week, °C
Bio06	Min temperature of coldest week, °C
Bio07	Temperature annual range (Bio0–Bio06), °C
Bio08	Mean temperature of wettest quarter, °C
Bio09	Mean temperature of driest quarter, °C
Bio10	Mean temperature of warmest quarter, °C
Bio11	Mean temperature of coldest quarter, °C
Bio12	Annual precipitation, mm
Bio13	Precipitation of wettest week, mm
Bio14	Precipitation of driest week, mm
Bio15	Precipitation seasonality, C of V
Bio16	Precipitation of wettest quarter, mm
Bio17	Precipitation of driest quarter, mm
Bio18	Precipitation of warmest quarter, mm
Bio19	Precipitation of coldest quarter, mm

matic factors as input data of MaxEnt model to simulate the potential distribution area of the species under contemporary and future climate conditions. This study is mainly concerned with the following objects: (1) identifying climatically suitable habitats for *B. bombina* at a home range scale; (2) estimating leading climatic requirements (niche) of *B. bombina*; (3) determining suitable areas for the (re)introduction and/or conservation of the species; (4) forecast the distribution in a future climate, based on a climate change projection model for 2050.

Geographical biases in the occurrence records were dampened by thinning the distribution points with OccurrenceThinner 1.03 (Verbruggen et al., 2013).

Usually, researchers calculate correlation coefficients (e. g. Pearson coefficient) to avoid correlated variables and to reduce the effects of multi-colinearity in their models. However, from this type of analysis ecologically relevant variables could be excluded. Burnham and Anderson (1998) have made clear that applying correlation analysis in order to find a significant set of predictor variables will most probably expose false correlations. Fortunately, MaxEnt is able to incorporate complex dependencies between predictor variables, even in the presence of correlated variables, non-linearity, bimodality etc. Thus, all covariates were retained for the final model.

The jackknife variable importance feature in MaxEnt was used to assess the relative importance of the environmental predictors in the model. We determined the relative importance of variables remaining in the model with percent contribution. MaxEnt allows the construction of response curves to illustrate the effect of selected variables on probability of occurrence. Identification of the most important predictors, and the analysis of the relations between the predictors and predicted habitat suitability, allows the description of the autecology of a species.

We ran the MaxEnt models using the default setting, except for when selecting regularization values. This parameter was determined by the application of the small sample corrected variant of Akaike's Information Criterion (AICc) implemented in ENMTools 1.3 (Warren, Seifert, 2011).

Model performance was assessed using t Warren he average AUC (area under the receiver operating curve) score. AUC values >0.9 are considered to have "very good", > 0.8 "good" and > 0.7 "useful" discrimination abilities (Swets, 1988). The logistic output format was used, because it is easily interpretable with logistic suitability values ranging from 0 (lowest suitability) to 1 (highest suitability). Better interpretation is made in most cases by defining thresholds of habitat suitability.

With a reference to the classification proposed by Yang et al. (2013), five classes of potential habitats can be distinguished: unsuitable habitat (0–0.2); barely suitable habitat (0.2–0.4); suitable habitat (0.4–0.6); highly suitable habitat (0.6–0.7); very highly suitable habitat (0.7–1.0). For each model, we calculated the area of the optimal distribution, classified as highly or very highly suitable habitat (0.6–1).

Results

In total, our database on *B. bombina* consisted 2,277 georeferenced point data. After reducing the geographical sampling bias in occurrence records their number was thinned to 598. Several regularization values were tested: 1, 1.5, 2, 2.5 and 3. The better regularization value (lower value of AICc) was 2. We ran models with 10 bootstrap replicates. The resulting potential distribution of *B. bombina* within its native range under contemporary climate (fig. 1) had high AUC values (0.836 ± 0.002). In terms of the bioclimatic niche, the most suitable for the species areas are located in Poland and Ukraine (fig. 2). In Ukraine areas of high or very high suitable habitat potential (> 0.6) occupy around 46 % of the country, in Poland this figure is even higher — 65 %. Together these countries accommodate 87 % of the potential for highly or very highly suitable habitat for *B. bombina.*

At the northern border of the distribution of the toad areas of moderate suitability are found in southern Latvia. Areas of moderate suitability are found as well in Germany, Denmark and Sweden, but in these countries there are sporadic patches of even highly suitable habitat, which should favour the (re)introduction of the species. *B. bombina* has been successfully reintroduced to Sweden (Andren, Nilson, 1988), but the modelling suggests that the species has the chances to spread to a wider portion of the country.

The MaxEnt model's internal jackknife test of variable importance showed that the environmental variable with highest gain when used in isolation is *Bio2* (Mean diurnal temperature range), which therefore appears to have the most useful information by itself. The environmental variable that decreases the gain the most when it is omitted is *Bio3* (Isothermality), which therefore appears to have the most information that isn't present in the other variables. The percent contribution of *Bio2* (29.4 %) too supports the significance of this variable for contributing to the MaxEnt model. Another significant (> 10 %) contribution to the model is made by *Bio8* (Mean temperature of wettest quarter, i. e., predominantly summer, 14.9 %).

Further on, response curves gave an indication of the dependence of the predicted probability of presence (i. e., predicted suitability) on each of these variables as well as the range under which they reach an optimum of suitability. These probabilities are calculated for the range values of one variable, with all other 19 variables set to their average value over the set of presence localities.

Upward trends for variables indicate a positive relationship; downward movements represent a negative relationship; and the magnitude of these movements indicates the

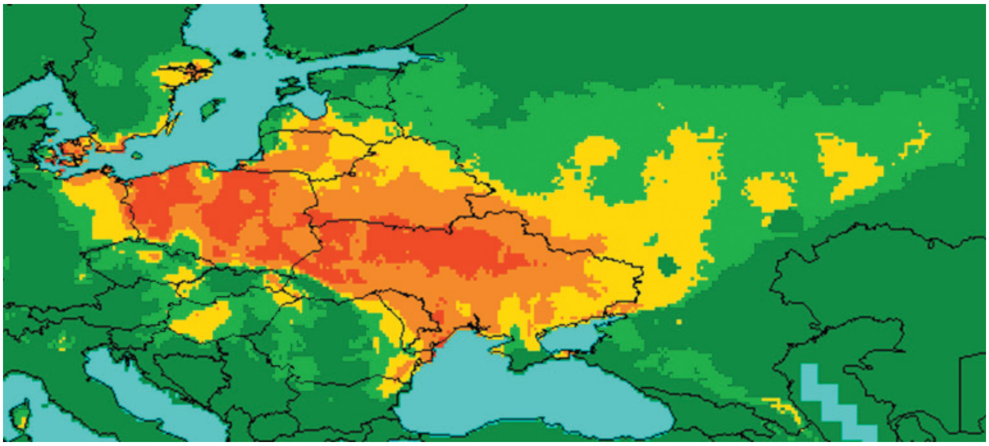
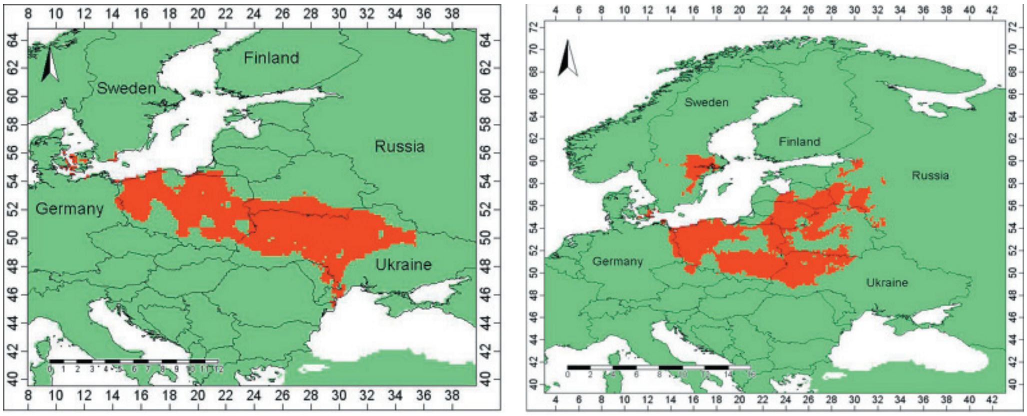


Fig. 1. The potential distribution map for *B. bombina* under contemporary climatic conditions. The colour gradient represents high (red) to low (green) habitat suitability for the species.



A B

Fig. 2. The predicted areas of high or very high suitable habitat potential (> 0.6) for *B. bombina* (A — for contemporary climate conditions; B — for projected climate in 2050).

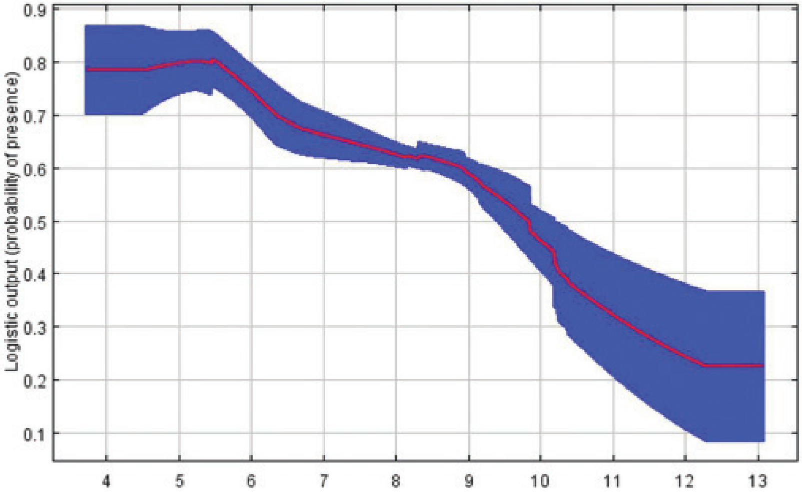


Fig 3. Response curve showing how the logistic prediction changes as the environmental variable *Bio2* (Mean diurnal temperature range, °C, X-axis) is varied, keeping all other environmental variables at their average sample value. The curve shows the mean response of the 10 replicate Maxent runs (red) and and the mean +/– one standard deviation (blue).

strength of the relationship (Baldwin, 2009), essentially they demonstrate biological tolerances. The corresponding response curve for *Bio2* shows a clear downward trend (fig. 3), representing a negative relationship between increasing values of the Mean diurnal temperature range and predicted probability of presence (i. e., habitat suitability) for *B. bombina* in the locality.

Under future climate change warmer temperatures are expected to lead to the convergence of daytime and nighttime temperatures, meaning a reduction of the diurnal temperature range (Rohr, Raffe, 2010). These effects of temporal variation in temperature will be more pronounced in temperate regions and theoretically may turn out to enhance habitat suitability for *B. bombina*.

Compared with the area of the most optimal habitat under current climate prediction, the predictions for 2050 show a clear north and north-west shift of such habitat. It is questionable, of course, can the toads track their climate space. This may greatly depend on their migratory abilities and how fragmented is the landscape. Once again, in terms of

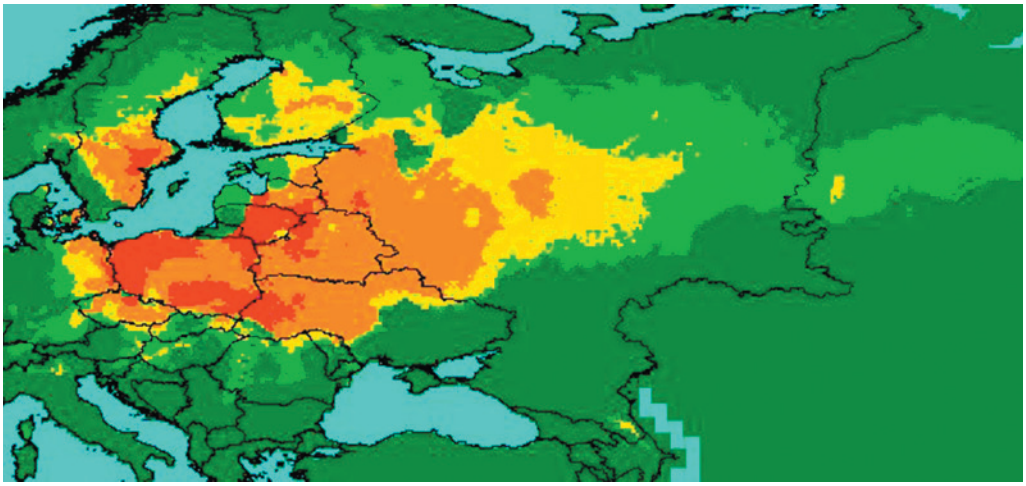


Fig. 4. The potential distribution map for *B. bombina* under projected 2050 climatic conditions. The colour gradient represents high (red) to low (green) habitat suitability for the species.

the bioclimatic niche, large suitable (> 0.6) for the species areas will continue to persist in Poland. Conditions are predicted to considerably improve for the species in Lithuania, neighbouring areas of Belarus, as well as in Latvia, where patches of highly suitable habitat conditions will appear. Moderate habitat suitability may promote the species to expand as far as Estonia and up to the latitude of Saint Petersburg in Russia (fig. 4).

Optimal habitat is predicted to expand in Sweden, but is likely to shift to the north-east from its current location. If so, this may have an impact on measures for reintroducing the species.

In Ukraine, however, areas of potential high or very high habitat suitability are predicted to drastically drop from 46 % of the country to 18 %, meaning there could be a net extinction of *B. bombina* at the southern boundary of the home range of the species. In the context of these shifts the species' representation in protected areas can seriously be affected, particularly in the south and east of the country. Preemptive measures should be undertaken to preserve the toad and its associated habitats in the west and north-west of Ukraine, where favourable conditions are predicted to persist.

Conclusions

Species distribution modelling has confirmed that vast areas in Poland and Ukraine, in terms of the bioclimatic niche, are highly suitable for the Fire-bellied toad, *B. bombina*. Further to the north areas of moderate suitability are found in a number of countries ranging from Denmark to Latvia. The modelling suggests that prospects for the species in Sweden could be better than thought.

Modelling has shown that the Mean diurnal temperature range is an important dimension of the bioclimatic niche of the toad and the expected convergence of daytime and nighttime temperatures under global climate change may favour the species.

Under climate predictions for 2050 there may be a substantial north and north-west shift of optimal habitat. Under such a scenario *B. bombina* populations may suffer mostly in the east and south of Ukraine. Optimal habitat is predicted to expand in Sweden, but is likely to shift from its current location. This may affect ongoing efforts to reintroduce the species to the country.

Under the modelled scenario the species representation in protected areas throughout the home range should be considered, but especially in Ukraine.

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