

BIOCLIMATIC MODELING OF *CROSSIDIUM SQUAMIFERUM* (VIV.) JUR.  
(POTTIACEAE, BRYOPHYTA) DISTRIBUTION

БИОКЛИМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ РАСПРОСТРАНЕНИЯ  
*CROSSIDIUM SQUAMIFERUM* (VIV.) JUR. (POTTIACEAE, BRYOPHYTA)

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Abstract

The main purpose of the work was to test the applicability of bioclimatic modeling methods to mosses. Due to tiny size bryophyta are confined to micro-habitats, which can transmute the influence of climatic factors. *Crossidium squamiferum* was taken as test object. Potentially suitable climatic area of the species in the world was simulated using maximum entropy (MaxEnt) modeling on base of four datasets different in volume (from 24 to 267 points). All the models are characterized by valid AUC values (from AUC=0.72 to AUC=0.96). According to the calculations, the most important variables determining the distribution of *C. squamiferum* are BIO4 (Temperature seasonality) and BIO8 (mean temperature of the wettest quarter). Habitats of the species in southern Siberia mark the Northern climatic boundary of the species area in Eurasia.

Резюме

Основной целью работы являлось тестирование применимости методов биоклиматического моделирования к мохообразным. Мохообразные ввиду малых размеров приурочены к микро-местообитаниям, что может нивелировать влияние климатических факторов. Моделирование потенциального ареала выполнено для тестового объекта *Crossidium squamiferum* методом максимальной энтропии (MaxEnt) на основе четырех наборов данных, сильно различающихся по объему (от 24 до 267 точек). Все построенные модели характеризуются достоверными значениями AUC (от AUC=0.72 до AUC=0.96 соответственно). Согласно результатам моделирования, наиболее важными переменными, определяющими распределение *C. squamiferum*, являются BIO4 (Температурная сезонность) и BIO8 (Средняя температура наиболее влажного квартала). Местообитания вида на территории Южной Сибири маркируют северную климатическую границу ареала вида в Евразии.

KEYWORDS: *Crossidium*, MaxEnt, xeric regions, biogeography, mosses

INTRODUCTION

Understanding the patterns of species distribution is one of the key questions in modern botanical studies. In particular, it is necessary for making predictions of possible changes in ecosystems. It is possible to analyze relationships between species habitats and environmental factors (Elith & Leathwick, 2009) and model the patterns by different SDM (Species Distribution Models) techniques (Guisan & Zimmermann, 2000; Austin, 2007, etc.). Such kind of models usually called “climatic (bioclimatic) envelopes” and can be considered as a models of ecological niches. They analyzed the species distribution data with various environmental variables for future modeling of geographical distribution of realized ecological niches for different biodiversity levels. One of the easy ways to do this is to use MaxEnt software (Phillips, 2017). This method is widely used in modern research,

but most of the publications aimed at assessing of bioclimatic parameters affecting animal species distribution. A smaller number of works are made on botanical objects; that are mainly studies of vascular plants distribution. However there also are some detailed studies on mosses on the base of MaxEnt modelling (Désamoré *et al.*, 2012; Mateo *et al.*, 2013; Song *et al.*, 2015). At the same time, this approach is scarcely represented in publications of Russian botanists; there are only few botanical studies based on it (Sandanov & Naidanov, 2015; Sandanov *et al.*, 2016; Gudkova *et al.*, 2017; Dudov, 2017).

The reason to test bioclimatic modeling on *C. squamiferum* distribution was the recent finding of this species in Buryatia, near Mondy settlement (Tubanova *et al.*, 2017). It was the first locality for that territory. The species has narrow ecological range and is considered as a taxon of circum-Mediterranean origin (Kürschner,

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2004, 2008); it occurs in drylands of the Southern Europe, Middle East, Middle and Central Asia, Mongolia, Africa, and North America. In Russia the species is known from few localities: in the Caucasus (Republics of Dagestan and Karachaevo-Cherkessia, Stavropol Territory (<http://arctoa.ru/Flora/basa.php>); in the South of European Russia it was also reported for Saratov and Volgograd Provinces (Ignatov & Ignatova, 2003); in South Siberia it has solitary records in Altai Republic, Kurai ridge (Ignatov, 1994), Tuva (East Tannu-Ola ridge) and on the shore of Baikal Lake near Marituy Settlement (Bardunov, 1989). The question is whether Siberian localities are random or predicted.

#### MATERIALS AND METHODS

Georeferenced occurrence data for *Crossidium squamiferum* were accessed from our own samples and from online databases: Moss Flora of Russia (<http://arctoa.ru/Flora/basa.php>, accessed 16th May 2018), Tropicos (<http://www.tropicos.org>, accessed 16th May 2018), and GBIF.org (GBIF Occurrence Download <https://doi.org/10.15468/dl.ja3fon> 16th May 2018).

In total, we gathered 267 non-duplicate geocoordinates from Russia (see above), Europe (Austria, Germany, Czech Republic, France, Greece, Spain, Portugal), Canary Islands and Africa (Algeria, Morocco, Tunisia), Near East (Israel, Lebanon, Palestine), and also Cyprus, Transcaucasia, Kazakhstan, Pakistan, China, Mongolia, and Americas (Argentina, Arizona, California, Colorado, Nevada).

From this massif, four datasets of different volume were selected:

1. Brief dataset from Eurasia – 24 coordinates (Arctoa-DB, Tropicos.org, our own data for Buryatia and Kazakhstan).
2. Brief dataset of worldwide species distribution – 29 coordinates from the same sources.
3. Full dataset – 267 coordinates (the same sources & GBIF data).
4. Revised big dataset – 68 coordinates (in the full dataset closely situated points were removed and some additional points were added from Mongolia manuscript (Tsegmed, 2010)).

We used these datasets to test the predictive power of the MaxEnt approach and to analyze how potential distribution of the species and other modeling parameters changed. The distribution of suitable habitats of the species was evaluated by MaxEnt according to the principles of maximum entropy (Phillips *et al.*, 2006; Phillips & Dudik, 2008). A detailed description of the principles and procedures is available online (<http://web2.uconn.edu/cyberinfra/index.html>; and also in Russian <http://gis-lab.info/qa/maxent.html>).

Nineteen bioclimatic variables with 5 arc-min resolution from Worldclim (Hijmans *et al.*, 2005) were employed as environmental predictors in Maxent 3.3.3k (Phillips & Dudik, 2008). MaxEnt approach is a good

choice for studies on species distribution when you have presence-only species records and the model can be simulated when you have a limited number of points of species distribution. After the whole analysis the best model was identified by means of the Area under ROC Curve (AUC) statistic value. The parameters selected were: 'Auto features', percentage of test sample = 25%, maximum number of iterations = 1500, cross-validation procedure, background at random in the entire study area. We then used all models to project the potential distribution of *Crossidium squamiferum*.

The results of the MaxEnt calculations were visualized in the form of maps which show the probability of the presence of the object in different areas. The colors display the calculated probabilities according to the scale: warmer colors show areas with better predicted conditions; from 0.69 (yellow) to 0.92 and more (orange and red); green – is conditions similar to those in which the species was collected (~0.5-0.6); blue shades indicate unlikely conditions.

#### RESULTS AND DISCUSSION

The analysis revealed that an increase of records used in modeling leads to the decrease of potential distribution of species in prediction maps (Fig. 1, A-D). These results connected with test AUC values for each data set: 1 – 0.72, 2 – 0.86, 3 – 0.96, 4 – 0.91. So, the prediction was more accurate when we used more available coordinates. This is consistent with previous studies, which present the importance of using more species distribution localities in the analysis (Feely & Silman, 2011). By the way, results of modeling of dataset-1 have good predictive power. Without data for American continent the map of potential distribution included the western parts of North and South America where the studied species is present (Fig. 1, A). The same situation observed for Mediterranean countries and Canary Islands (Fig. 1, B, C). Suitable conditions for the species are shown in Middle Asian territory (Fig. 1, A-D); and it was indeed reported for Turkmenistan, Uzbekistan, Tadjikistan, Kyrgyzstan (Ignatov & al., 2006). Similarly, the models show a high probability of the species finding in Anatolia, Balkans and Apennine Peninsula. And really, in Turkey *C. squamiferum* is rather common (Uyar & Çetin, 2004), many labels are available on-line from Swedish Museum of Natural History (<http://herbarium.nrm.se/search/specimens>); it also occurs in Albania, Bulgaria, Bosnia-Herzegovina, Montenegro, Greece, Croatia, Macedonia, Romania, Serbia and Italy (Sabovljević *et al.*, 2008; Hodgetts, 2015). Contrariwise, for some known records the models predict a low probability of presence of the species in the territories, about 0.3 only. These are reports for Great Britain (Hodgetts, 2015), Crimea (Ignatov *et al.*, 2006), Chad and Cape Verde (O'Shea, 2006). The localities are on periphery of the area and anyway, they are marked as more probable than adjacent territories (Fig.1, D).

Results of bioclimatic modeling based on data from

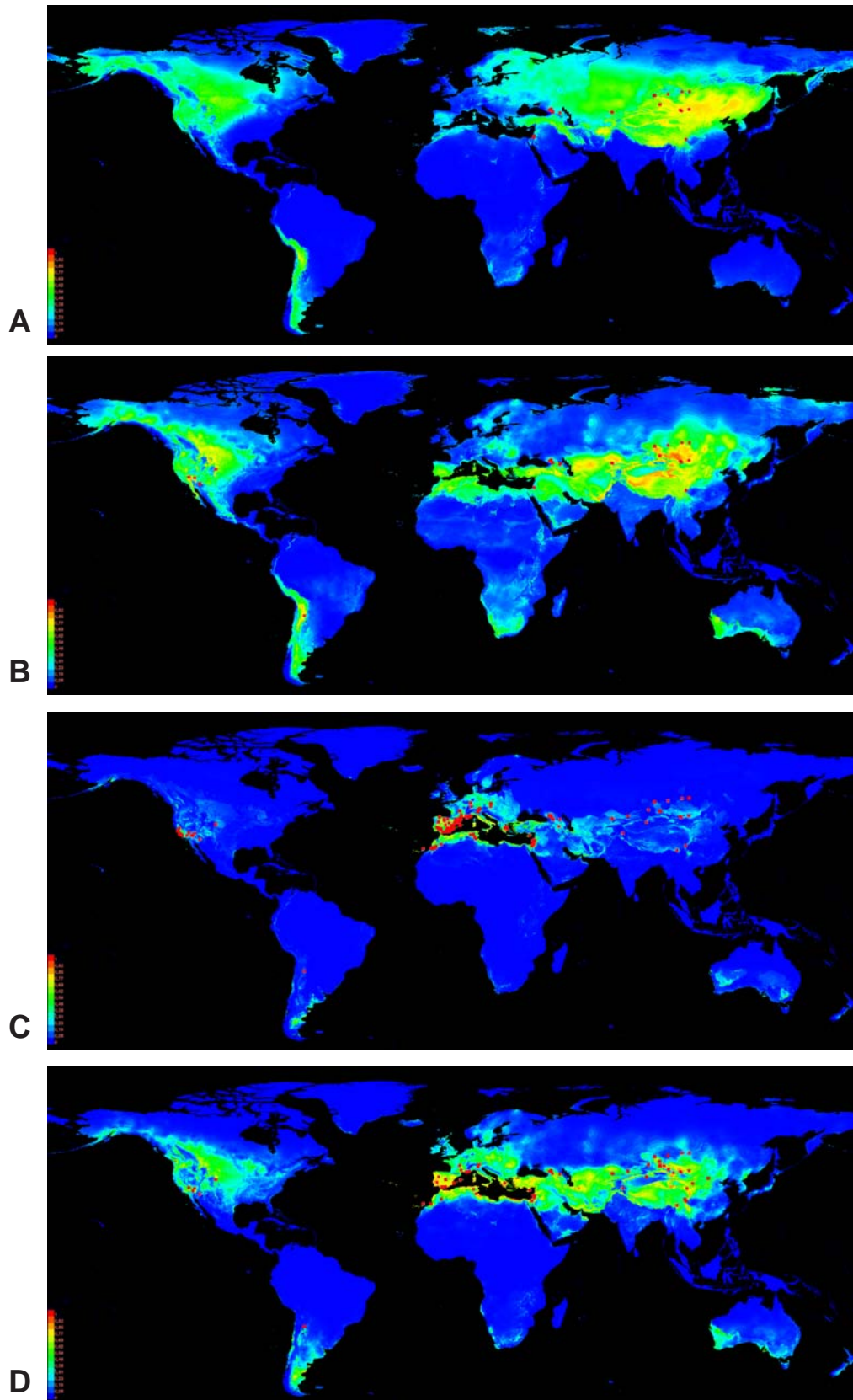


Fig 1. MaxEnt modeling of *Crossidium squamiferum* for different volume datasets. **A:** Eurasian brief dataset (dataset-1, 24 coordinates); **B:** brief dataset of worldwide distribution (dataset-2, 29 coordinates); **C:** big dataset from all easy-available localities (dataset-3, 267 coordinates); **D:** revised big dataset (dataset-4, 68 coordinates). Red dots show the presence locations. The probability of the species presence is reflected by logarithmic color scale, see lower left corner: blue is unlikely conditions, probability less than 0.38; green – 0.38-0.69; yellow to orange for area with suitable conditions and probability of species occurrence 0.69-0.9.



Table 1. Analysis of variable contributions for *Crossidium squamiferum* models, showing: Percent contribution (PC) and Permutation importance (PI) for four datasets, discussed in the text.

Variable	Dataset 1		Dataset 2		Dataset 3		Dataset 4	
	PC	PI	PC	PI	PC	PI	PC	PI
Bio1	66.95	69.98	1.02	19.77	5.77	14.41	7.85	6.71
Bio3	0.74	0.00	25.43	41.98	34.13	40.37	44.48	68.32
Bio4	0.00	0.00	0.68	0.79	<b>14.7</b>	1.39	6.73	0.56
Bio8	0.06	0.01	8.81	25.53	<b>17.58</b>	3.13	11.17	5.63
Bio11	<b>2.99</b>	<b>0.00</b>	<b>28.25</b>	0.00	2.4	10.68	<b>6.38</b>	0.00

all known localities revealed that new findings could be found only within currently known distribution area of the species (Fig. 1, C). Analysis from dataset-4 predicted more possible new findings for *C. squamiferum* in Eurasia (Fig. 1, D).

So, the analysis showed good predictive power with using bioclimatic variables for *C. squamiferum*. Higher number of records provides higher accuracy of elaborated models. However, strong bias in representation of data on species occurrence in particular area (in our case it was better studied European part of the area of *C. squamiferum*) distorts bioclimatic model and reduces its predicting power. More evenly represented records are better for evaluation of species distribution and for estimation of bioclimatic parameters suitable for its growth.

The next important moment is that MaxEnt is useful for distinguishing climatic and historical factors in species area formation. Thus, in our analysis models predict the occurrence *C. squamiferum* in south-west Australia, as this territory is suitable for it due to climatic parameters (Fig.1, D), but the species is absent in Australian bryoflora (Australian..., 2015), likely because its diaspores did not reach this continent.

Variables with high contribution were bio 1 – annual mean temperature, bio3 – isothermality, bio4 – temperature seasonality, bio8 – mean temperature of wettest quarter, bio 11 – mean temperature of coldest quarter (table 1). Annual mean temperature made high or medium percent contribution to the models, but usually has big permutation importance. So, the influence of this variable is not valuable for *C. squamiferum* distribution. The key variables determining the species distribution are temperature seasonality and mean temperature of wettest quarter (see dataset3). For dataset 1 precipitation seasonality (bio 15) has the highest contribution (19.42%) with small permutation importance (0.67). This was the reason of wide projected distribution for studied species (Fig. 1), but this analysis was helpful to understand predictive power of MaxEnt approach. Recently found locality (Tubanov *et al.*, 2017) is on the northern climatic boundary of the species area in Eurasia.

Predictive maps showed high probability of new findings of the species on the territory of Russia (south-western part of Republic of Khakassia and the southern part

of Zabaikalskii region). Future survey studies on these territories can help to understand the validity of such prognosis. Future findings of this species (mostly on the northern limit of distribution in Eurasia) will be helpful in understanding its ecological features and preferences.

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