Predictive distribution for *Salvia aethiopis* (Lamiaceae) in Middle Asian Region based on climatic modelling

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Abstract. Geospatial investigation of distribution *Salvia aethiopis* L. (Lamiaceae) on the eastern limits of the range is performed using climatic modeling by MAXENT approach. Climatic conditions for the 33 local populations of the species as well as territories neighbouring to them were examined in detail, using concepts of nestle-cells and a small polygone. According to obtained results, the most suitable climatic conditions are in only two small polygons (SP) around local populations with coordinates 69.96E:42.48N and 70.03E:42.47N in central part of the area. They have 7.7 average points per a cell of 9.0 maximum. Other seven SP have average points per a cell 7.1–7.3 (quite suitable climatic conditions), all in the western part of the area, with coordinates from 66.69E to 67.69E and from 38.21N to 39.26N. High values of raw prediction are in the locations with coordinates 70.97E:42.48N (0.123; Zhualyn District in Zhambyl Region, Kazakhstan), 70.03E:42.47N (0.063; Keltemashat, Tulkibas District, Turkestan Region, Kazakhstan), 67.09E:38.34 (0.063; Yuqori Machay, Surkhandarya Region, Uzbekistan), and 69.96E:42.48N (0.054; Antonovka, Tulkibas District, Turkestan Region, Kazakhstan). These local populations of *S. aethiopis* should be assessed as the most likely secondary centers for further expansion of the species in the Middle Asian Region.

1 Introduction

The detailed study of the geospatial structure of the ranges of biological species is of great importance in the development of scientific measures for the protection of rare and endangered species, assessment of the state of the gene pool of resource species, determination of factors limiting the distribution of endemic taxa, solving issues of the genesis of genera and floristic complexes, investigation of dynamics of distribution of alien invasive species, and many other scientific problems [1].

Salvia aethiopis L. (Lamiaceae family) is a European-West Asian mountain-steppe species found in Central and Atlantic Europe, the Mediterranean, in the south of Ukraine, in

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the Republic of Moldova, Asia Minor, in the Caucasus, in Iran, and Middle Asia [2]. We have studied this species in the eastern limits of its distribution. There are numerous modern finds of this species in different parts of the region, confirmed by herbarium specimens and observations in nature, presented in special data base in internet, such as GBIF and iNaturalist, and our own observations (one of them is presented in Fig. 1).

The purposes of this research are the ecological multi-parameter assessment of the summar environmental situation in locations of *S. aethiopis* and around them, with determination the set of locations and neighbouring places where combinations of climatic variables are the most suitable to existing and developing local populations which can be secondary centers for futher expansion of the species in the Middle Asian Region.

To achieve these purposes, the following tasks were set: 1) to produce the series of models for the species distribution in the Middle Asian Region, using different output formats; 2) to create the protocol for assessing the levels of suitability of environmental conditions in lacations and around them; 3) to apply original concepts of a small polygone and nestle cells to estimation of suitability of environmental conditions; 4) range the most suitable locations and nestle cells; 5) determine the most likely secondary centers for futher expansion the area of the species in Middle Asian Region.

2 Material and methods

The study was performed for 33 local populations in the Middle Asian Region. Its coordinates are presented in the Table 1.

Probablistic models for the distribution of the species in Middle Asian Region are constructed on climate layers imported from WorldClim, an international database of world climate, available at http://www.worldclim.org [3]. In the study, climatic data for 1970-2000 years were taken, including the period of *S. aethiopis* registration. According to experimental data and their expert assessment, the most informative models can be constructed with complete set of all available climatic variables [4, 5].

Simulations were run in MAXENT computer program based on maximum entropy method [6, 7], with different settings of options. In Basic Settings of Maximum Entropy Parameters: Random test percentage – 50, or 40, or 30; Regularization multiplier – 1; Max number of background points – 10000, 100000, or 1000000; Replicates – 1; Replicates run type – Crossvalidate, Bootstrap, and Subsample. In Advanced Settings of Maximum Entropy Parameters: Add samples to background – Yes, Do clamping – Yes, Write output grids – Yes, Write plots – Yes, Maximum iterations – 1500, Convergence thresholg – 0.00001; Adjust sample radius – minus 8 and minus 9 for 5.0 arcminutes models, minus 6 and minus 7 for 0.5 arcminute models; Default prevalence – 0.5. Regularization values: linear/quadratic/product: 0.720, categorical: 0.250, threshold: 1.830, hinge: 0.500.

The study has significant methodical significance. The procedure for multi-level assessment of the statement of the environment from least suitable to highly suitable is proposed and implemented in detail. If we use the default setting for adjust sample radius (zero value) in Advanced settings of Maximum Entropy Parameters, we will not be able to see and analyze the ecological differentiation in the cells around the locations. Reducing size of dots using negative values allow to analyze ecological situation in cells which are in contact with a location (so named the nestle cells).

In contrast to our previously proposed gradation of climatic suitability, which includes three levels [8], 9-level gradation was used in this study, which made it possible to more accurately differentiate the ecological situation between the cells of small polygons. Also, we offered to compose numerograms for small polygons [8]. Such numerograms show the levels of climate suitability in neighboring cells and find the best of them for plant reproduction.

Fig. 1. *S. aethiopis* in the Middle Asian Region. Uzbekistan. Surkhandarya region. Boysun mountains. Near the village Sina; 67.66E: 38.39N. Photo O. Turdiboev. June 07, 2021.

3 Results

In accordance with the presence of hiatus, where local populations of this species have not been found, we propose to divide its range in the Middle Asian Region into three separate parts: western, central and eastern. In the global model obtained at 1/12 arc-degree resolution (near 50 sq. km in a cell), there are several zones highly suitable (red colored) and suitable (orange colored) for the species as well as territories with quite suitable climatic conditions (they having yellow and near yellow colors on plot files). Most of them are in the western and central parts of the regional distribution of the species, and only one small fragment of yellow color is in the eastern part of the area.

The western group of populations (Pamir-Alai) is the most numerous. It includes almost half of the counted localities – 16 out of 33, and occupies the territory within the following limits: from 66.69E to 67.89E, and from 38.11N to 39.26N. The distance between neighboring populations in the western group usually does not exceed 20 km (Fig. 2).

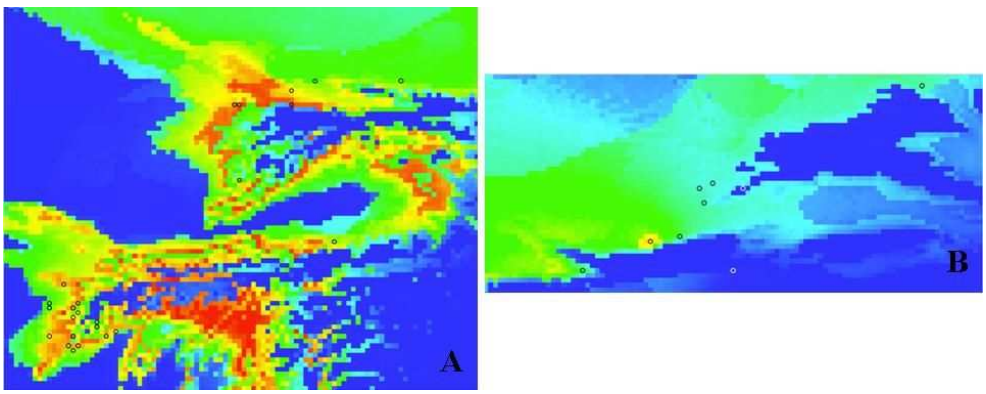

Fig. 2. A. Western and central parts of the range of *S. aethiopis* in the Middle Asian Region. Black circles show the position of populations. Borders are: left – 65.97E, right – 74.09E, up – 44.24N, and

bottom – 37.43N; **B.** Eastern part of the range of *S. aethiopis* in the Middle Asian Region. Black circles show the position of populations, white circles are two outliers. Borders are: left – 74.09E, right – 82.45E, up – 46.14N, and bottom – 42.42N.

According to a series of predictive models obtained, the most promising territories for the formation of new populations of the species are the foothills and low mountains of the Terikliktau and Khazratishokh ridges, where the climatic conditions for the habitation of this species are assessed as suitable (estimated level 8) and highly suitable (estimated level 9). These territories are located 150–200 km to the east from the easternmost local populations of the western group of populations and have a total area of more than 3500 sq. km.

Seven of 16 populations live in the western group of populations in the most suitable climatic conditions. Five of them are concentrated between 66.93E and 67.22E, and two other populations are located separately: to the west (66.69E: 38.38N) and to the east (Table 1). The expertly calculated sum of points in the corresponding small polygons varies from 64 to 66, and the average points are from 7.1 to 7.3, which corresponds to quite suitable environmental situation. According to the values of the probability of finding a species in raster cells, the most suitable climatic conditions in the western group of populations are in two local populations of the species with coordinates 67.09E: 38.34N and 67.09E: 38.84N. At the same time, the more southern population has a lower expert assessment of the environment states in a small polygon, which is due to the assessment of the southern cell in the nestle (level 4 is ambivalent, close to low suitable).

The central group consists of eight local populations, which place between 69.96E and 72.88E, 40.04N and 42.89N. The distance between neighboring local populations in the central group can exceed 50 km. The expertly calculated sum of points in the corresponding small polygons varies from 46 to 69, and the average points are from 5.1 to 7.7, which corresponds to four levels – from ambivalent to suitable environmental situation. There are two small polygons with the most suitable habitat conditions for *S. aethiopis* in the Middle Asian Region (the expertly calculated sum of points is 69, and the average points is 7.7 for both polygons): around locations with coordinates 69.96E: 42.48N (Antonovka, Tulkibas District, Turkestan Region, Kazakhstan) and 70.03E: 42.47N (Keltemashat, Tulkibas District, Turkestan Region, Kazakhstan). Also, there are high values of raw prediction are in the locations with coordinates 70.97E:42.48N (0.123; Zhualyn District in Zhambyl Region, Kazakhstan), and 70.03E:42.47N (0.063; see above).

The eastern group consists of nine local populations, which are between 75.69E and 81.53E, 42.76N and 45.97N. The distance between neighboring local populations in the eastern group can exceed more than 60 km (Fig. 2B). The expertly calculated sum of points in small polygones varies from 13 to 61, and the average points are from 1.4 to 6.8, which corresponds to seven levels – from very low suitable to quite suitable environmental situation. Two local populations with coordinates 78.25E:42.81N and 78.47E:44.22N can be estimated as outliers.

Table 1. Calculated prediction values for environments suitability estimation near 33 local populations of *Salvia aethiopis* in Middle Asia Region

1	2	3	4	5	6	7	8	9
66.69	38.38	0.027434	66.00	0.7648	688678688	65	7.2	**
66.70	38.94	0.011100	40.61	0.5682	155555556	42	4.7	

66.73	38.88	0.012013	41.81	0.5875	555556568	50	5.6	
66.93	39.26	0.041056	87.25	0.8295	888888666	66	7.3	**
67.02	38.21	0.036405	81.82	0.8119	884888866	64	7.1	**
67.09	38.34	0.062610	100.0	0.8813	788886767	65	7.2	**
67.09	38.84	0.044736	94.60	0.8413	866887846	61	6.8	*
67.10	38.11	0.016045	52.25	0.6554	888666565	58	6.4	*
67.15	38.69	0.023924	59.87	0.7393	767777887	64	7.1	**
67.19	38.20	0.040107	85.83	0.8262	468888666	60	6.7	
67.22	38.92	0.042982	90.13	0.8359	788885857	64	7.1	**
67.24	38.75	0.026805	62.55	0.7606	857577775	58	6.4	*
67.53	38.55	0.010002	39.93	0.5425	555757757	53	5.9	
67.58	38.59	0.009575	39.66	0.5316	118555757	44	4.9	
67.69	38.36	0.035952	78.18	0.8099	787687876	64	7.1	**
67.89	38.42	0.021237	57.48	0.7157	888774711	51	5.7	
69.96	42.48	0.053983	100.0	0.8648	777788889	69	7.7	***
70.03	42.47	0.062761	100.0	0.8815	778889895	69	7.7	***
70.07	41.09	0.009823	39.81	0.5380	363655577	47	5.2	
70.94	42.74	0.027337	65.87	0.7642	776777877	63	7.0	**
70.97	42.48	0.122662	100.0	0.9356	998399113	52	5.8	
71.36	42.90	0.009549	39.64	0.5309	555555655	46	5.1	

71.67	40.04	0.015428	51.61	0.6465	666666777	57	6.3	*
72.88	42.89	0.012852	44.36	0.6037	555555666	48	5.3	
75.69	42.76	0.006852	33.11	0.4482	443555432	35	3.9	
76.91	43.32	0.029023	68.14	0.7748	777777775	61	6.8	*
77.40	43.39	0.005622	32.48	0.3999	555544432	37	4.1	
77.70	44.21	0.003679	27.49	0.3037	444444444	36	4.0	
77.75	43.92	0.003905	28.84	0.3164	444444444	36	4.0	
77.97	44.33	0.003395	24.67	0.2870	444444444	36	4.0	
78.25	42.81	0.000454	09.16	0.0511	111211222	13	1.4	o
78.47	44.22	0.000337	07.75	0.0384	333111113	17	1.9	o
81.53	45.97	0.004283	29.81	0.3367	444444444	36	4.0	

Columns are: 1 – X (longitude), 2 – Y (latitude), 3 – Raw prediction values, 4 – Cumulative prediction values, 5 – Logistic prediction values, 6 – numerograms for small polygons based on expert estimation of suitable levels by colors of cells, 7 – sum of points for nine cells of a small polygon, 8 – average score per a cell of a small polygon, 9 – expert estimation for better small polygones (***– fine, ** – very good, * – good, o – Outliers).

The expertly calculated sum of points in small polygones varies from 13 to 61, and the average points are from 1.4 to 6.8, which corresponds to seven levels – from very low suitable to quite suitable environmental situation. Two local populations with coordinates 78.25E:42.81N and 78.47E:44.22N can be estimated as outliers.

4 Discussion

Generated models show that *S. aethiopis* has a high potential to expand its presence in the western and central parts of the species range in the Middle Asian Region. Eastern part is less suitable to distribute the species to other territories, with exception of the local population with coordinates 76.91E: 43.32N, which is in quite suitable conditions.

According to obtained results, the most suitable climatic conditions are in only two small polygons (SP) around local populations with coordinates 69.96E:42.48N and 70.03E:42.47N in central part of the area. They have 7.7 average points per a cell of 9.0 maximum. Other seven SP have average points per a cell 7.1–7.3 (quite suitable climatic conditions), all in the western part of the area, with coordinates from 66.69E to 67.69E and from 38.21N to 39.26N. High values of raw prediction are in the locations with coordinates 70.97E:42.48N (0.123; Zhualyn District in Zhambyl Region, Kazakhstan), 70.03E:42.47N

(0.063; Keltemashat, Tulkibas District, Turkestan Region, Kazakhstan), 67.09E:38.34N (0.063; Yuqori Machay, Surkhandarya Region, Uzbekistan), and 69.96E:42.48N (0.054; Antonovka, Tulkibas District, Turkestan Region, Kazakhstan). These local populations of *S. aethiopis* should be assessed as the most likely secondary centers for further distribution of the species in the Middle Asia Region.

New registration of the species in 2021 (see Fig. 1) is in the northern cell of small polygon around the location 67.69E:38.36N, having suitable environmental conditions – 8th level (second position in the numerogram; see Table 1), and that fact supports the model obtained.

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