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GEOGRAPHICAL DISTRIBUTION PATTERNS OF *GEASTRUM MELANOCEPHALUM* (GEASTRACEAE, BASIDIOMYCOTA) IN SIBERIA IN PRESENT AND UNDER CONDITIONS OF CLIMATE CHANGE

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Determining the spatial distribution of rare fungal species is critical to understanding the environmental factors that affect them. Maximum entropy (MaxEnt) spatial distribution modeling solves this problem by allowing inferences about species distribution and ecological resistance from occurrence data. Using this method, we mapped the current and potential geographic distribution of the rare species *G. melanocephalum*. To establish the regularities in the geographical distribution of the studied species in Siberia, we created its distribution models using Wordclim bioclimatic variables and the MaxEnt software. We modelled the species' habitat suitability under current conditions (~1950–2000 AD) and in a future climate (2100 AD) based on 11 records of the species' spatial distribution. Most localities of *G. melanocephalum* in Siberia are 200–500 meters above sea level. The optimal climatic conditions for *G. melanocephalum* in Siberia are typical of the habitats represented in the Kazakh forest-steppe, South Siberian forest-steppe, and hemiboreal forests of Western Siberia, in the zone of contact between the plains and foothills.

Key words: *Species distribution modelling, Asia, rare species.*

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INTRODUCTION

Fungal, plant, and other species distribution is undergoing rapid changes in the face of habitat modification and climate change. It leads to concerns about the conservation of declining species and raises ecological questions about the processes that govern species ranges and niches. Consequently, the predictive distribution models, which match species records to patterns in abiotic environmental variables, have become an established tool in ecology and conservation (Segurado, Araújo, 2004; Guisan, Thuiller, 2005; Chapman, Purse, 2011).

Species distribution models (SDMs) constitute the most common class of ecology and biodiversity conservation models. The new software packages and the increasing availability of digital GIS have greatly facilitated the use of SDMs (Zurell et al., 2020). SDMs are empirical models connecting field observations to environmental predictor variables based on statistically or theoretically derived response surfaces (Guisan, Zimmermann, 2000).

MaxEnt is one of the most commonly used methods for inferring species distributions and environmental tolerances from occurrence data (Phillips, Dudík, 2008). MaxEnt uses the principle of maximum entropy based on presence-only data to estimate a set of functions that connect environmental variables and habitat suitability to approximate species niche and potential geographic distribution (Phillips et al., 2006). MaxEnt modeling has recently become an actively used tool for fungi. For example, it is used to identify the spatial distribution of economically significant fungal species to understand the environmental factors that affect them and as well as for a rare species, for their conservation management (Yuan et al., 2015; Guo et al., 2017; Pietras et al., 2018).

In Russia, modeling of the potential distribution of fungi by the MaxEnt method has not been previously carried out, while works on plants are widely represented (Sandanov, Naidanov, 2015; Sandanov, Pisarenko, 2018).

The gasteroid fungus of *Geastrum melanocephalum* (Czern.) V.J. Staněk is relatively rare in Russia.

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It is included in the Red Book of the Altai Territory, as well as in some regional Red Books of the European part of Russia (Voronezh, Kursk, Lipetsk, Penza, Tver and Tula Regions) and the Crimean Peninsula as a rare species or as a species with an uncertain status. The general distribution of the species is limited to Eurasia. There are about 800 records in the world, most of which are in Europe. Therefore *G. melanocephalum* is not included in the IUCN Red List. The northern border of species distribution passes through Estonia, Norway, and Sweden. In Russia, it is known mainly in the European part – in the Belgorod, Volgograd, Voronezh, Kursk, Lipetsk, Moscow, Penza, Rostov, Saratov, Tver and Tula Regions, the Stavropol Territory, as well as in the Caucasus (Sosin, 1973; Rebriev, 2007).

Siberian records of *G. melanocephalum* came from Altai Territory, Kemerovo Region, Novosibirsk Region, and Krasnoyarsk Krai (Rebriev et al., 2020). In Asia, *G. melanocephalum* has been recorded in Transcaucasia, Kazakhstan, Kyrgyzstan, Uzbekistan, and Western China. The northernmost previously known locations in Asia are the Tien Shan mountain systems, up to 2000 m above sea level (Schvartzman, Filimonova, 1970).

Rebriev et al. (2020) suggested that modern records may also indicate the expansion of the range of *G. melanocephalum* to the north, and global warming can be considered the probable cause of the phenomenon. The latter may explain the change in the ranges of other plant and fungal species (Shiryaev, Morozova, 2018; Shiryaev et al., 2019). However, new Asian records of the studied species may be associated with an increase in mycological research rather than climate change. Rebriev et al. (2020) also noted that the identified localities are located in the immediate vicinity or within the boundaries of nemoral flora refugium preserved from the Tertiary period: Northern Altai, Salair, Yenisei, Gornaya Shoria. These territories are characterized by milder climatic conditions compared to the surrounding areas: high humidity, reduced continentality, well-developed snow cover in winter, nonfreezing soils.

All assumptions about the features of the geographical distribution of the species are hypothetical, based on subjective data, and a small number of records for a rare species in Asia do not allow drawing objective conclusions and identifying patterns that affect it. However, the species is not limited in distribution by proximity to Siberia's refugium of nemoral flora. *G. melanocephalum* may have always been found in Siberia from localities with climatically close habitats to those in Europe. Perhaps, we are dealing with boundary changes in species' range and the expansion of its distribution in Siberia in an adaptation to the new habitats due to climate change.To address these issues and establish geographic patterns of the studied species distribution in Siberia based on objective data, we modeled its potential distribution using bioclimatic data (Bioclim) and the MaxEnt software to simulate the suitability of the species' habitat in the current (~1950–2000 AD) and in the future climates (2100 AD).

MATERIAL AND METHODS

Object of study (Taxa)

Geastrum melanocephalum is a fungus from the Geastraceae family, growing on soil (Fig. 1).

Biodiversity data overview and study area

This research includes materials collected during our expeditions in the Altai Territory in 2007. E.A. Davydov provided one sample from a 2018 collection from the buffer zone of the Tigireksky Reserve. Voucher specimens of the studied species are stored in the

a *b*

Fig. 1. *a* – fruiting bodies of *Geastrum melanocephalum* on soil, *b* – a typical habitat of species in the Altai Territory.

Рис. 1. *а* – плодовые тела *Geastrum melanocephalum* на почве, *b* – типичное местообитание вида в Алтайском крае.

MG Popov Herbarium (NSK), Novosibirsk, Russia. We obtained the species locations from our previous paper (Rebriev et al., 2020).

We used records supported by specific geographic coordinates only. In total, we included 11 locations of *Geastrum melanocephalum* in Siberia (Fig. 2): Novosibirsk Region: Loc. 1 (N54.8667°, E83.05°), Loc. 2 (N54.8605°, E83.0515°); Altai Territory Loc. 3 (N53.2833°, E83.7167°); Loc. 4 (N51.15°, E83.0167°); Kemerovo Region: Loc. 5 (N53.6355°, E86.8272°), Loc. 6 (N53.65°, E86.8167°), Loc. 7 (N54.419°, E85.6886°), Loc. 8 (N54.4651°, E86.9141°), Loc. 9 (N55.3167°, E86.0667°), Loc. 10 (N55.3551°, E86.0868°); Krasnoyarsk Territory Loc. 11 (N53.1333°, E92.8833°).

SDM algorithms, predictor type, software and data used

We used the computer program DIVA-GIS (Hijmans et al., 2012) for mapping and geographic data analysis (internet source 1). We downloaded data on the relief and the heights of the studied locations, as well as global data on current (~1950–2000 years) and future (2×CO_2 climate conditions, CCM_3 model, 2100 AD) climates (internet source 2 and 3), source Worldclim, version 1.3. We obtained the global country boundaries WGS84 (internet source 4). All the 19 environmental layers of Bioclim (BIO1-BIO19) constructed using the DIVA-GIS with 2.5-minute resolution (30 arc seconds square) encompassed most of the Asian subcontinent (Hijmans et al., 2005). We downloaded data on the Biomes, terrestrial ecoregions of the World (Olson et al., 2001), from internet source 5 and 6. Biome boundaries are clarified by internet source 7.

We used MaxEnt (Phillips, Dudík, 2008) to conduct species habitat suitability modeling. Spatial distribution pattern for *G. melanocephalum* using the maximum entropy method (MaxEnt) based on a 11-distribution records dataset. We used DIVA-GIS and MaxEnt programs in accordance with the recommendations from the manual on spatial analysis of plant diversity and distribution (Scheldeman, Zonneveld, 2010). The methodology of work is most fully described in our recent publication (Vlasenko et al., 2021).

The MaxEnt model for current climate we obtained have high Area Under Receiver Operating Characteristic Curve (AUC) value: 0.965. To evaluate the model, we used a test sample that included 25 % of all distribution records. The AUC value for the test data was 0.989. Both AUC values fall within the range of 0.9–1, thus corresponding to the excellent discrimination (Scheldeman, Zonneveld, 2010). In analysis, we used the 10-percentile training threshold for the presence, found in the table of thresholds generated by MaxEnt. The threshold value for species is 0.091.

The MaxEnt model for future climate we obtained have high Area Under Receiver Operating Characteristic Curve (AUC) value: 0.964. To evaluate the model, we used a test sample that included 25 % of all points of presence. The AUC value for the test data was 0.985. Both AUC values fall within the range of 0.9–1, thus corresponding to the excellent discrimination (Scheldeman, Zonneveld, 2010).

In analysis, we used the 10-percentile training threshold for the presence, found in the table of thresholds generated by MaxEnt. The threshold value for species is 0.071.

RESULTS AND DISCUSSION

Distribution modeling for Geastrum melanocephalum in relation to the relief elevation

In Siberia, *G. melanocephalum* is distributed between the 51st parallel in the South and the 56th parallel in the North. Locations of *G. melanocephalum* in Siberia are spread from west to east from the extreme point in the Altai Territory up to Krasnoyarsk Territory. Figure 2 shows areas of *G. melanocephalum* based on a relief.

Locations of *G. melanocephalum* in Siberia are in the lowlands (two localities in Novosibirsk Region and two localities in Kemerovo Region), uplands (one locality in Altai Territory and four localities in Kemerovo Region), and low mountains (one locality in Altai Territory, near the Tigirek).

The analysis shows that the species is absent in the most flatland areas of Siberia at altitudes up to 200 meters. At the same time, the identified distribution records of species at heights up to 200 meters, are located in the immediate border with relief elements, which we characterized as uplands.

The transitional border is somewhat conditional. Suppose we rely on the geomorphology and types of plant communities represented here. In that case, the distribution records of species identified here are located in the zone of contact with the plain of previously existing hills, which are the extension of offshoots of the South Siberian mountain ranges – Altai, Salair, Kuznetsk Alatau, and Western Sayan.

In the middle altitude mountains, the species was recorded at one extreme point of the Siberian range in the foothills at the foot of the Tigirek Range on the lower border of the mountain forest-steppe. Literature data indicate that the species can be found at altitudes up to 2000 meters. Nevertheless, it is not found in the mountains in Siberia.

a *b*

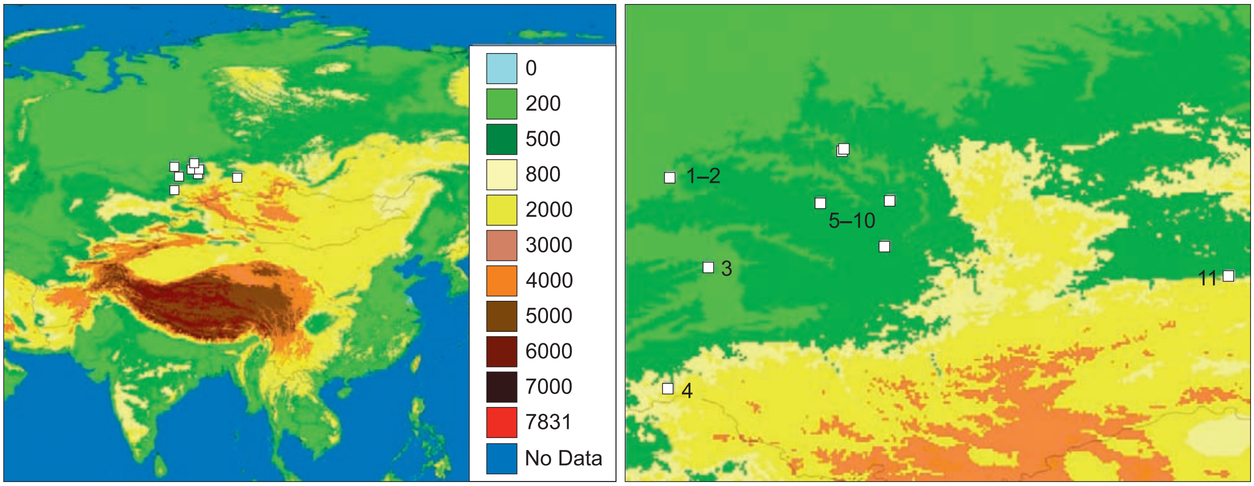

Fig. 2. Locations of *Geastrum melanocephalum* in Siberia.

a – localities on the scale of Asia, *b* – localities within the area of distribution in Asia. The colors corresponds to the height above sea level (decoding in the legend). The legend shows a scale of heights, from min to max in meters above sea level. Gradation of heights: 0–200 m – lowland, 200–500 m – upland, 500–800 m – low mountains, 800–2000 m – middle mountains, more than 2000 m – highlands.

Рис. 2. Местонахождение *Geastrum melanocephalum* в Сибири.

a – местонахождения в масштабах Азии, *b* – местонахождения в пределах области распространения в Азии. Цвета соответствуют высоте над уровнем моря (расшифровка в легенде). В легенде показана шкала высот от минимальной до максимальной в метрах над уровнем моря. Градация высот: 0–200 м – низменность, 200–500 м – возвышенность, 500–800 м – низкогорье, 800–2000 м – среднегорье, более 2000 м – высокогорье.

Distribution modeling for *Geastrum melanocephalum* in boundaries of the terrestrial ecoregions

An analysis of the distribution of *G. melanocephalum* within the boundaries of the terrestrial ecoregions of the World in Siberia shows an association with biomes of temperate grasslands, savannahs, and shrubs, as well as temperate broadleaf and mixed forests (Fig. 3).

The western distribution records is located within the Kazakh steppe (a point on the plain area near the city of Barnaul) on the border with the Kazakh forest steppe; while the habitat is located in the forest community within the pine forest and is not related to the steppe biome. The Kazakh forest-steppe also includes a point in the Altai Territory in the foothills of Tigiretsky Range near Tigirek village, on the steppe slope of the hill. Three points in the Kemerovo Region, and one in the Krasnoyarsk Territory, lay in the central and eastern parts of the species range and are located within the South Siberian forest steppe.

Distribution records in the Novosibirsk Region and three locations in the Kemerovo Region are in the Western Siberian hemiboreal forests belonging to the temperate broadleaf and mixed forests biome. Note that it is difficult to determine the point-to-biome relationship due to the vague biome boundaries in the used GIS resources. All our points are on the border in the contact zone between the Western Siberian hemiboreal forests, the Kazakh forest steppe within the Novosibirsk Region, and the South Siberian forest steppe within the Kemerovo Region.

The analysis showed that the species is associated with forest steppe and hemiboreal forests in the contact zone between the plains and foothills in Siberia.

Potential distribution modeling for *Geastrum melanocephalum* in current climate

The assessment of the contribution of variables using MaxEnt showed that for the species, the variables BIO 15 (47.5), BIO 8 (28.4), BIO 9 (15.5), BIO 2 (5.7) in percentage terms have the highest value in direct assessment of the contribution; BIO 8 (37.9), BIO 15 (19.2), BIO 9 (16.7), BIO 10 (16.3), BIO 2 (7.9) under permutation. The remaining variables made a small contribution (less than 2 %), or did not have it at all. Figure 4 shows a map of the potential distribution of the species, the probability of presence is shown in color.

Most of the territory of Siberia is unsuitable for *G. melanocephalum* presence. However, in some areas, the probability species presence in taiga flatlands of Western Siberia of the Tomsk Region can reach from

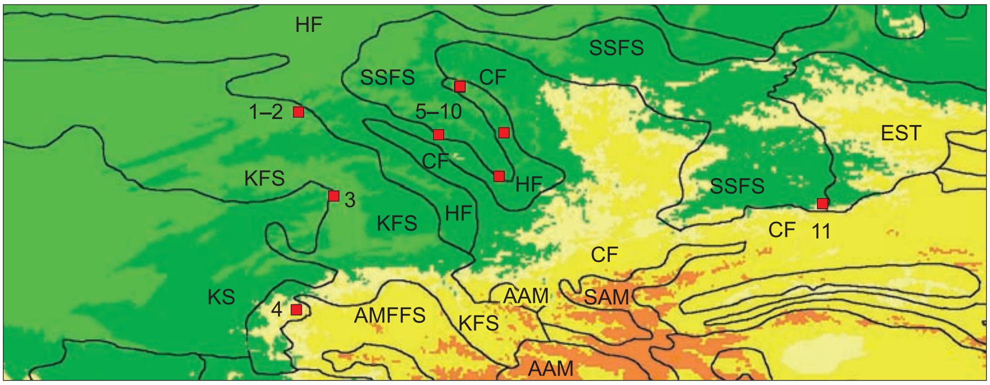

Fig. 3. The distribution of *Geastrum melanocephalum* within ecoregion boundaries. Numbers 1–11 – are distribution records. HF – Western Siberian hemiboreal forests (part of biome Temperate broadleaf and mixed forests). KS – Kazakh steppe; KFS – Kazakh forest steppe; SSFS – South Siberian forest steppe (parts of biome Temperate grasslands, savannas, and shrublands). AMFFS – Altai montane forest and forest steppe; CF – Sayan montane conifer forests (parts of biome Temperate Coniferous Forest). EST – East Siberian taiga (part of biome Boreal forests/Taiga). AAM – Altai alpine meadow and tundra; SAM – Sayan Alpine meadows and tundra (parts of biome Montane grasslands and shrublands). The height of the relief is similar to Fig. 2. Blackline – ecoregion boundaries.

Рис. 3. Распространение *Geastrum melanocephalum* в границах экорегионов. Цифры 1–11 – точки присутствия. HF – гемибореальные леса Западной Сибири (часть биома широколиственных и смешанных лесов умеренного пояса). KS – казахская степь; KFS – казахская лесостепь; SSFS – южно-сибирская лесостепь (части биома умеренных лугов, саванн и кустарников). AMFFS – алтайские горные леса и лесостепи; CF – горные хвойные леса Саян (части биома хвойные леса умеренного пояса). EST – восточно-сибирская тайга (часть биома бореальные леса/тайга). AAM – алтайские альпийские луга и тундра; SAM – саянские альпийские луга и тундра (части биома горных лугов и кустарников). Высота рельефа аналогична рис. 2. Черная линия – границы экорегионов.

50–60 to 60–70 %, and in Eastern Siberian taiga in the Krasnoyarsk Territory up to 70–80 %.

The probability of the presence of the species in the territory of western Siberia increases from north to south. The species cannot be found in tundra, forest-tundra, and taiga. The probability of its presence here is from 0–10 % to 10–50 % or 10–50 % in most parts of the taiga zone.

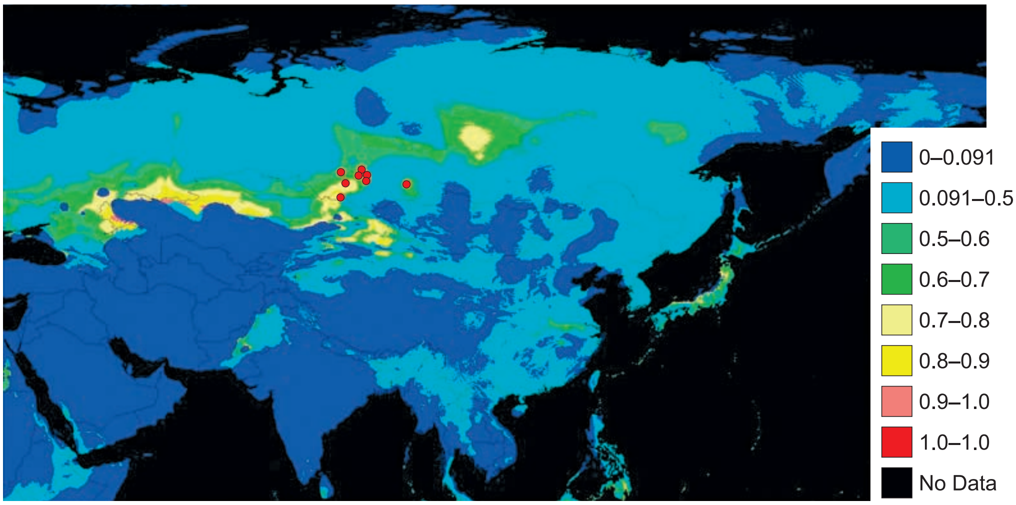

Fig. 4. Potential distribution of *Geastrum melanocephalum* in current climate (~1950–2000 years). MaxEnt results are given in logistic format (values in the legend from 0 to 1). 1–1 – observed presence points.

Рис. 4. Потенциальное распространение *Geastrum melanocephalum* в современном климате (~1950–2000 гг.). Результаты MaxEnt представлены в логистическом формате (значения в легенде от 0 до 1). 1–1 – наблюдаемые точки присутствия.

The constructed MaxEnt Model showed that all presence points in Asia are in areas with a relatively favorable climate for the species. The identified points of species presence in Siberia are in the zone with 50–60 % probability (these are all points in Novosibirsk, near the Tigirek village, and all points in the Kemerovo Region). A point in the Krasnoyarsk Territory is in the zone with a 60–70 % probability of presence. A point near Barnaul is in the zone with a 70–80 % probability of presence.

In the southeast of Western Siberia, the probability of species presence gradually increases in the forest-steppe and steppe zones in the sub-taiga. At the same time, this increase is by no means connected to specific biomes. It occurs from northwest to southeast as it approaches mountain systems (Altai, Salair).

The Kemerovo Region, the central part and the entire eastern part of the Novosibirsk Region, the whole territory of the Altai Territory (except for the territories where the spurs of the ridges of the Northwestern Altai enter) are in the zone of the most favorable climate for the studied species in Siberia. The presence probability for the species here reaches 50–90 %. The area with the best climate for the species with an 80–90 % presence probability is in the Altai Territory. It includes territories at the junction of the flatlands on the northwestern Altai border, including foothills area.

In foothills, the probability of species presence decreases from a maximum of 80–90 % to 70–80 % and 60–70 %, up to 50–60 % as the altitude rises, and is less than 50 % at the border with mountains.

Mountain areas – Altai, Kuznetsk Alatau, and Western Sayan – are unfavorable for the species. The probability of its presence here is only up to 50 %. Salair area is an exception, as it includes hemiboreal and taiga parts located in the foothills and low mountains zone. At the same time, the probability species presence is 60–70 % in the zone of hemiboreal forests and decreases to 50–60 % in the zone of taiga forests as the altitude increases.

A similar pattern of increasing the probability of species presence is observed in the southwestern part of Western Siberia, in the forest-steppe and steppe zones, at the foot of the Ural Mountains, and to the east from them. The southern part of the Ural Range, like the Salair in the southeast, is favorable for the development of the species; the probability of the presence of the species here is 50–80 %, increasing to the south, reaching 80–90 % in the forest-steppe and steppe zones.

The most favorable area with a 90–100 % probability of the species presence is in the sub-latitudinal zone to the south of the spurs of the Ural Range – Mount Mugodzhary in the Aktobe region in Kazakhstan. The second zone with a high probability of the presence of the species in Kazakhstan is located at a considerable distance, to the southwest, in the Caspian region, in the Caspian lowland desert zone. To the south, the Central Asian deserts are unfavorable for the species. The probability of its presence there is less than 50 %, while most of the territory is in the zone beyond the threshold value.

In the Krasnoyarsk Territory, the region with the highest probability of species presence is at the border between the South Siberian forest steppe with the Sayan montane conifer forests and the East Siberian taiga. Still, it does not exceed 60–70 %.

The Inner Asian area, covering most of Mongolia, is unfavorable for the species. For half of its territory, the probability of the species presence does not exceed 10 %, and no more than 50 % for another half.

Potential distribution modeling for *Geastrum melanocephalum* in future climate

The assessment of the contribution of variables using MaxEnt showed that for the species, the variables BIO 15 (52.6), BIO 8 (15.8), BIO 9 (8.6), BIO 2 (4.8) in percentage terms have the highest value in direct assessment of the contribution; BIO 5 (36.7), BIO 10 (33.9), BIO 9 (15.9), BIO 15 (9.7) under permutation. The remaining variables made a small contribution (less than 4 %), or did not have it at all. Figures 9 and 10 show a map of the potential distribution of the species, the probability of presence is shown in color.

We modelled the future distributions of *G. melanocephalum* in 2100 AD (Fig. 5). Modeling has shown that under this scenario, the areas with marginal habitats in Siberia and Asia will increase in size. Areas of suitable habitats will change in size and be subject to displacement. In some places, areas of suitable habitats will grow larger. Before 2100, the areas with the species presence probability of less than 50 % will increase, both in Siberia and in Asia in general.

Until 2100, the area with a probability of the presence of the species less than 50 % will increase, both in Siberia and in Asia as a whole.

On the flatland taiga territory in Western Siberia, the areas with a 50–80 % presence probability will be reduced, while areas with a maximum presence probability will be fragmented. Since the species has never been found in the taiga, these changes will not affect its distribution in any way.

The most interesting forecast is obtained for the territory of the modern range of the species in southern Siberia (Fig. 6).

The area with a favorable climate for the species will reduce. It will somewhat compress from the north, but the probability will increase from northwest to

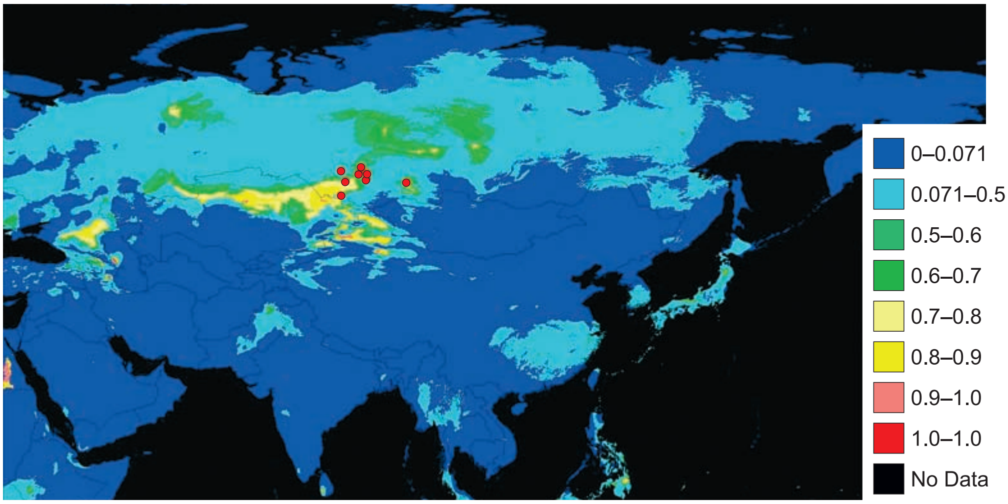

Fig. 5. Potential distribution of *Geastrum melanocephalum* in future climate (2100 AD). MaxEnt results are given in logistic format (values in the legend from 0 to 1). 1–1 – observed presence points.

Рис. 5. Потенциальное распространение *Geastrum melanocephalum* в будущем климате (2100 г. н.э.). Результаты MaxEnt представлены в логистическом формате (значения в легенде от 0 до 1). 1–1 – наблюдаемые точки присутствия.

southeast as it approaches the mountain systems (Altai, Salair), as in the current climate. The probability of the species presence in the forest steppe will reach 50–60 % only in some areas in the Novosibirsk region. The points the species presence near Novosibirsk will be in the areas with a less than 50 % probability. The territories of the Altai Territory will become more favorable for the development of the species, especially the steppe zone with an 80–90 % presence probability. The southern areas of the Altai Territory, in the zone of contact between the flatlands and Fasa Altai, and especially in the zone of foothills up to the Tigirek village, will become more favorable for the studied species. The probability of the species presence in the steppe areas of the mountains will increase from 60–70 to 70–80 %.

Area with a 90–100 % probability of the species presence will appear south of the Russian border in the Altai Territory and Kazakhstan, at the Kazakh steppe and Kazakh semi-desert junction. Territories of mountain systems will remain unsuitable for the species. In the north and northwest of Altai, the situation will not change much in the future climate. The area with the probability of the species presence below the threshold

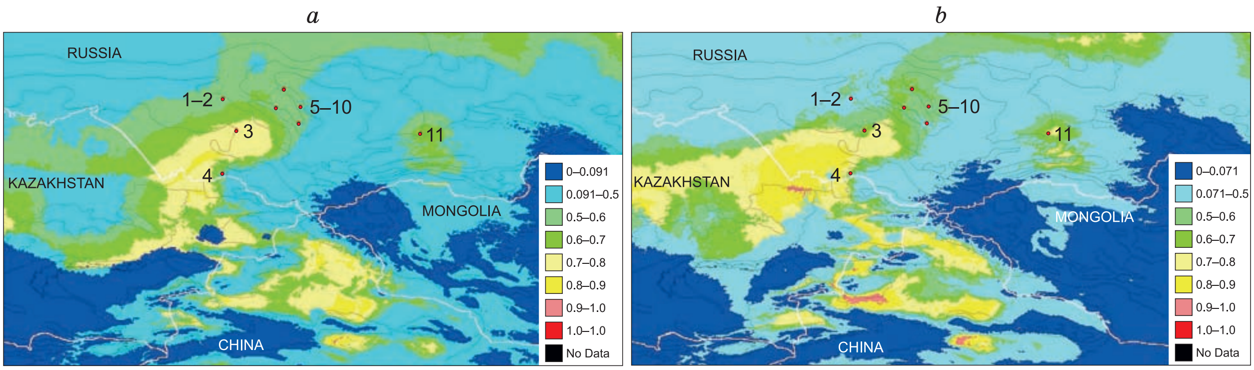

Fig. 6. Potential distribution of *Geastrum melanocephalum* in current climate (~1950–2000 years) and future climate (2100 AD) in the south of Siberia and adjacent parts of Inner Asia.

a – current climate, *b* – future climate. MaxEnt results are given in logistic format (values in the legend from 0 to 1). 1–1 – observed presence points. Black line – boundaries of ecoregions. White line – borders of countries.

Рис. 6. Потенциальное распространение *Geastrum melanocephalum* в современном климате (~1950–2000 гг.) и в будущем климате (2100 г. н.э.) на юге Сибири и прилегающих частях Внутренней Азии.

a – текущий климат, *b* – будущий климат. Результаты MaxEnt представлены в логистическом формате (значения в легенде от 0 до 1). 1–1 – наблюдаемые точки присутствия. Черная линия – границы экорегионов. Белая линия – границы стран.

value will increase significantly and move northward from Mongolia, reaching the border with the Kazakh forest steppe.

On the Salair and in the areas of hemiboreal forests in Kuznetsky Alatau, the probability of the species presence will also decrease, but only from the north. In general, in the zone of hemiboreal forests and the South Siberian forest steppe, the distribution pattern of the species will not change significantly, except for a decrease in the probability of presence from the northern side. In the Krasnoyarsk Territory, at the border between the South Siberian forest steppe and taiga biome, the probability of the species presence will increase from 60–70 to 70–80 %.

Areas with a 90–100 % probability of the species presence in the current climate, south of the Ural Mts and in the Caspian Sea on the territory of Kazakhstan, will be unfavorable for the species, and the probability of its presence here will be less than 50 %. The zone in the southern part of Ural Mts, with 50–80 % to 80–90 % probabilities of the species presence in the sublatitudinal direction in the forest-steppe and steppe zone, will remain. At the same time, it will narrow and shift to the south, occupying only a small local area on the Russian territory.

The territory to the west, located in Russia and Kazakhstan, from the southern spurs of the Ural Mts, will become entirely unfavorable for the species. At the same time, the area of favorable climate will shift to the southwest of Kazakh semi-deserts. The probabilities of species presence in some places there are up to 70–80 % and even 80–90 %.

The area favorable for the species will increase in the vicinity of Lake Ebi-Nur in the Junggar Basin semi-deserts in northwest China and south of the Bogdo-Ula ridge (Eastern Tian Shan, near the city of Urumqi) in the Taklimakan desert.

As a result, among the bioclimatic variables, the species is more influenced by seasonality (precipitation seasonality), quarter trends (mean temperature of wettest quarter and mean temperature of driest quarter) and to a lesser extent daily trends (Mean Diurnal Range). The contribution of bioclimatic variables remains practically unchanged in the model for the future climate.

The obtained modeling results objectively characterize the ecological specificity of *G. melanocephalum* in Siberia and explain the reasons for its geographical distribution. In Siberia, the species occurs at altitudes of 200–500 meters above sea level, which are typical for uplands. The species is more characteristic of arid biomes. Habitats of the species are represented in the Kazakh forest-steppe, South Siberian forest-steppe, and hemiboreal forests of Western Siberia, in the zone of contact between the plains and foothills. Modeling the potential distribution of the species under the selected climatic scenario showed the dynamics of changes in its range. Climate change in the future in the south of Siberia and adjacent parts of Inner Asia, will lead to a change in the boundaries of the area of potential distribution of the species. Modeling showed that in the future in the south of Siberia there will be areas with a high probability of finding the species, which may be caused by the appearance of suitable habitats for the species as a result of aridization and desertification processes.

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ОСОБЕННОСТИ ГЕОГРАФИЧЕСКОГО РАСПРОСТРАНЕНИЯ *GEASTRUM MELANOCEPHALUM* (GEASTRACEAE, BASIDIOMYCOTA) В СИБИРИ В УСЛОВИЯХ СОВРЕМЕННОГО И БУДУЩЕГО КЛИМАТА

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Выявление особенностей географического распределения редких видов грибов позволяет понять, какие факторы окружающей среды оказывают на него решающее влияние. Моделирование пространственного распределения видов, проведенное методом максимальной энтропии (MaxEnt), помогает выявить эти факторы. Таким образом, на основе данных о встречаемости редких видов можно выявить закономерности их географического распределения в зависимости от условий окружающей среды. С помощью метода MaxEnt мы построили карту современного и потенциального географического распространения редкого вида *G. melanocephalum*. Для выявления закономерностей географического распространения изучаемого вида в Сибири на основе объективных данных были созданы модели потенциального распространения вида с использованием биоклиматических данных и программного обеспечения MaxEnt для моделирования пригодности местообитаний вида в текущих условиях (~1950–2000 гг.) и при прогнозируемых изменениях будущего климата (2100 г. н.э.) на основе 11 точек пространственного распространения изучаемого вида. Большинство местонахождений *G. melanocephalum* в Сибири расположены на высотах 200–500 м над ур. м. Проведенное моделирование показало, что оптимальные климатические условия для *G. melanocephalum* в Сибири характерны для местообитаний, представленных в казахской лесостепи, южно-сибирской лесостепи и гемибореальных лесах Западной Сибири в зоне контакта равнины и предгорий.

Ключевые слова: *моделирование распространения видов, Азия, редкие виды.*

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