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Modelling the future distribution of solitary wasps (*Anoplius viaticus* L ., 1758, *Ammophila sabulosa* L., 1758) in relation to CMIP6 climate scenarios

Моделирование будущего распространения одиночных ос (*Anoplius viaticus* L., 1758, *Ammophila sabulosa* L., 1758), связанное со сценариями изменения климата CMIP6

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Key words: Distribution, prognosis, modeling, bioclimatic parameters, solitary wasp.

Ключевые слова: распространение, прогноз, моделирование, биоклиматические критерии, одиночная оса.

Abstract. Global climate change has become a trend and a crucial factor affecting biodiversity and species distribution. Climate change models are valuable tools in projecting the distribution of indicator animal species under different climate scenarios. Solitary wasps *Anoplius viaticus* (Linnaeus, 1758) and *Ammophila sabulosa* (Linnaeus, 1758) prefer arid habitats, which makes them ideal model objects for investigating changes in faunal structure under global climate change. Both species exhibit ecological characteristics typical of their families. The study of these wasps carried out using the ACCESS-ESM1-5 model and the SSP245 scenario showed that both species occupy the Transpalaearctic range. The range change projections for these species show a similar trend of expansion throughout the Holarctic, with potential dispersal into the Australian and New Zealand zoogeographic regions. The AUC value for both species was 0.83, indicating an 80 % probability of accurate prediction of the species' occurrence within the projected range. We analyzed 19 bioclimatic parameters. The variables bio_14, bio_2, and bio_7 are of particular significance with regard to the potential range expansion. The main variables for *Anoplius viaticus* and *Ammophila sabulosa* are the change in mean diurnal variance (permutation coefficient is 11.7 and 18.2, respectively) and temperature annual variance (permutation coefficient is 14.9 and 16.1, respectively). The other 16 variables are less significant. Both species have been shown to occupy a broad range and have the potential to further expand their range and shift it northward. Insect species with similar biological and ecological characteristics, despite different trophic preferences and systematic classification, yield similar projections, thereby enabling either species to serve as an indicator for the same objective.

Резюме. Глобальное изменение климата стало тенденцией и является одним из основных факторов, влияющих на биоразнообразие и распределение видов. Модели климатических изменений помогают предсказать распространение индикаторных видов животных в зависимости от различных сценариев изменения климата. Одиночные осы *Anoplius viaticus* (Linnaeus, 1758), *Ammophila sabulosa* (Linnaeus, 1758) — обитатели в основном аридных территорий, что делает их модельными объектами для исследования изменения структуры фауны в условиях глобального изменения климата. Оба вида с точки зрения экологических особенностей являются типичными представителями своих семейств. Исследование этих ос с использованием прогностической модели ACCESS-ESM1-5 и социоэкономического сценария SSP245 показало, что в настоящее время оба вида занимают Транспалеарктический ареал. Прогнозы изменения ареалов этих видов имеют сходную тенденцию расширения в пределах всей Голарктики, с возможностью расселения на Австралийскую и Новозеландскую зоогеографические области. Значение AUC для обоих видов составило 0,83, что означает 80 % вероятность предсказания нахождения вида в прогнозируемом ареале. Нами проанализировано 19 биоклиматических компонентов. Критерии bio_14, bio_2, bio_7 имеют ключевое значение для расширения ареала исследуемых видов. Основными предикторами для *Anoplius viaticus* и *Ammophila sabulosa* являются: изменение среднесуточной температуры (коэффициент пермутации 11,7 и 18,2 соответственно) и годовой диапазон температур (коэффициент пермутации 14,9 и 16,1 соответственно). Остальные 16 критериев менее значимы. Доказано, что оба вида занимают обширный ареал и имеют потенциал к дальнейшему расширению своих границ и его смещению на север. Виды насекомых со схожей биологией и экологией, но отличающиеся трофическими предпочтениями и систематическим положением, дают схожий прогноз, позволяя использовать любой из них как индикатор для одной и той же цели.

Introduction

As indicated in the OECD's Environment Outlook 2030 [OECD, 2008], four key pivotal issues demand immediate consideration: climate change, biodiversity, freshwater resources, and the impact of pollution on human health.

Global climate change has become a trend and a crucial factor affecting biodiversity patterns and species distribution. Many animal species either adapt to mutating environments caused by climate change or change their habitats.

A report by the Intergovernmental Panel on Climate Change (IPCC) indicated that global warming temperatures would reach 1.5 °C above pre-industrial levels by 2040. Moreover, it is projected to increase by almost 0.2 °C every ten years [Skea et al., 2022]. Climate change is regarded as one of the most significant factors affecting biodiversity patterns and species distribution. It is also a crucial concern for conservationists [Thomas et al., 2004; Araújo, Rahbek, 2006].

The conservation of biological diversity, the primary natural resource of Russia of paramount ecological, social, economic, and aesthetic importance, is a pivotal issue in the study of mechanisms for conservation of natural ecosystems in the context of climate change.

Climate change and biodiversity loss pose a significant threat to humanity and need to be tackled together. Biodiversity and climate change are interconnected in many ways. From one perspective, biodiversity is strongly affected by climate change, with adverse effects for human well-being and the long-term viability of vital ecosystems. From another perspective, the conservation of biodiversity is a critical element in the fight against climate change by supporting ecosystems. Biodiversity and ecosystems play an important role in strengthening the global response to climate change, while simultaneously providing a multitude of benefits. Climate change models facilitate the projection of distribution of indicator animal species under different climate scenarios. This enables the assessment of potential threats to ecosystems and the development of measures to mitigate them.

Solitary wasps of the families Sphecidae (digger wasps) and Pompilidae (spider wasps) are found on every continent except the Arctic and Antarctic. These two families are among the most widespread families of Hymenoptera [Antropov et al., 2017]. Due to the complexity and diversity of behavioral responses, digger and spider wasps serve as model objects for ethological and ecological studies. The significance of these wasps in pollination of flowering plants cannot be overstated [Kazenas, 2013; Loktionov, Lelei, 2014]. Wasps of the families Pompilidae and Sphecidae represent a thermophilic group of insects, with representatives most often found in open sandy areas with sparse vegetation. Adult wasps of both species feed on flower nectar of various plants. They are eurybiont insects widely distributed across the Palearctic region [Kazenas, 1998; Shlyakhtenok, Loktionov, 2016].

A distinctive biological characteristic of digger and spider wasps is their parental care, which involves the construction of specific nests and provisioning of larvae with either paralyzed or killed insects or spiders. Hunting wasps help control populations of pest insects, making them valuable in horticulture and forestry for biological pest control of species [Kolesnikov, 1973; Tobias et al., 1978].

Representatives of these families exhibit similar biological and ecological characteristics of life activity, yet they display slight differences in nesting conditions and larval trophism. *Anoplius viaticus* (Linnaeus, 1758) constructs its nests in sandy areas, primarily along forest edges, roadsides, clearings, dry meadows, and riverbanks. The prey of this species is the wolf spider of the family Lycosidae [Shlyakhtenok, Loktionov, 2016]. *Ammophila sabulosa* (Linnaeus, 1758) nests in sandy areas along forest edges, dry meadows, and riverbanks. It hunts caterpillars of geometrid and noctuid moths, which it paralyzes and then carries to the nest to feed larvae [Kazenas, 1998]. Digger and spider wasps live mainly in arid regions, and thus may be used as model objects to study changes in faunal structure under global climate change [Danilov, 2009]. To date, the only study into the distribution of digger wasps in the aridization gradient of Inner Asia is that by Danilov [Danilov, 2009]. Both species are typical representatives of their families in terms of ecological characteristics.

An insight into a life-friendly habitat for wasps and their response to future climate change is crucial for conservation of these species, which serve not only as population regulators of some arthropods, including crop pests, but also as plant pollinators. For ecological niche analysis, we chose the MaxEnt model, which performs best and is the most reliable when using species presence-only data to model potential species distributions. It is also one of the most frequently and widely used models [Zhao et al., 2024].

The aim of this study was to model a current suitable habitat and distribution of wasps *Anoplius viaticus* and *Ammophila sabulosa* in the period of 2020–2040.

Material and methods

Data on the distribution of *Anoplius viaticus* and *Ammophila sabulosa* were obtained from the GBIF (Global Biodiversity Information Facility) datasets [GBIF Data Portal, 2024] and platforms iNaturalist [iNaturalist, 2004], and also used our own data on the findings of these wasps: Republic of Altai: Kosh-Agach village — 49.996° N, 88.661° E; Republic of Tyva: Kyzyl, 51.691° N, 94.410° E; Tomskaya Oblast: Tomsk, 56.445° N, 84.847° E; Yamalo-Nenetskii Autonomnii Okrug: Khanymey village, 63.724° N, 75.975° E.

A set of 19 bioclimatic variables and elevation data was downloaded from the WorldClim database version 1.4 [WorldClim, 2024.] with a spatial resolution of 2.5 arc minutes. This data set shows current temperature and precipitation conditions, including minimum, maximum and mean temperature and precipitation values recorded from 1970 to 2000 [Hijmans et al., 2005].

The ACCESS-ESM1-5 model, one of the climate models developed to assess the impact of climate change, was employed to project range changes for the wasps. It is a component of the CMIP6 (Coupled Model Intercomparison Project Phase 6) used to project climatic conditions based on different scenarios [Ziehn et al., 2020]. The model accounts for interactions between the atmosphere, ocean, land, and biosphere, facilitating a more accurate assessment of climate change.

In addition, the study employed one of the socioeconomic scenarios, SSP245 (Shared Socioeconomic

Pathways), which describes the potential trajectory of the socioeconomic development in the context of climate change. The SSP245 scenario assumes moderate climate change mitigation efforts, resulting in an increase in greenhouse gas emissions until 2040 and their subsequent decrease.

The following gradations of model performance were used in the analysis of the obtained results: an AUC (Area Under the Curve) value of 0.50–0.60 indicates failure, 0.60–0.70 indicates poor performance, 0.70–0.80 indicates moderate performance, 0.80–0.90 indicates acceptability of the model results, and a value of >0.9 indicates high performance [Phillips et al., 2006]. The modeled species distribution results were divided into four categories of potential habitat: highly suitable habitat ($p \geq 0.6$), moderately suitable habitat ($0.4 \leq p < 0.6$), poorly suitable habitat ($0.2 \leq p < 0.4$), and unsuitable habitat ($p < 0.2$).

The present work is registered in ZooBank (www.zoobank.org) under LSID urn:lsid:zoobank.org:pub:45B95C3A-FE94-4809-972A-E24E2C4FA62F

Results

A widely used Maxent model was chosen for the wasp species *Anoplius viaticus* (Fig. 1) and *Ammophila sabulosa* (Fig. 2).

In order to elucidate the potential for entomocomplex development and trajectories of faunal response to climate change, a comprehensive analysis was conducted, and a predictive model was constructed using a global climate database [WorldClim, 2024].

The AUC value for both species was 0.83, indicating an 80 % probability of accurate prediction of the species' occurrence in the projected range.

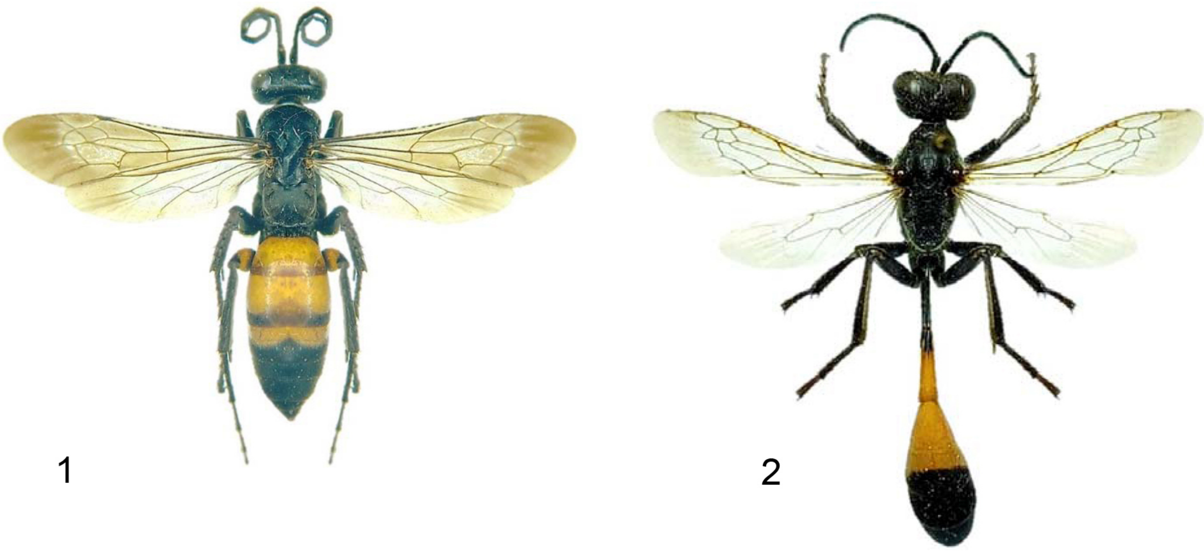
A total of 19 bioclimatic parameters were analyzed. Seven of these are of particular relevance for conservation and range expansion of both wasp species. It was found that the following parameters exert the greatest impact on species distribution: bio_2 (mean diurnal variance (mean(period max-min)) and bio_7 (annual temperature variance, bio_5-bio_6) (Table 1). The variables bio_14 (precipitation of driest period) and bio_1 (annual mean temperature) are essential for conservation of the species range; however, changes in these variables would not impede further species distribution. The diurnal and annual temperature variances are the primary parameters of distribution of the two wasp species.

Range change projection for Anoplius viaticus. Two parameters have the greatest impact on the formation of a stable ecological niche. The first parameter is the amount of precipitation in driest period (bio_14) (from 0 to 50 mm), but the permutation coefficient for this variable is 0, which may indicate that this parameter will not play an important role in case of changed precipitation in driest period. The second parameter is annual mean temperature (bio_1) (from –10 to +30 °C) with the permutation coefficient of 2.4.

The species is least tolerant to changes in maximum temperature of warmest period (bio_5) (19–25 °C is optimal for the species) and annual temperature variance from warmest to coldest temperature (bio_7) (optimal difference does not exceed 40 °C). The mean diurnal variance (bio_2) within 8–10 °C is optimal for the species distribution, yet further increase in temperature variance will have an adverse effect.

The projected species distribution was found to depend on the amount of precipitation in wettest period and annual precipitation. This may imply that high precipitation values exceeding 700 mm (bio_12) and 80 mm (bio_13) negatively affect range expansion for *Anoplius viaticus*. This may be due to excessive soil moisture. The mean temperature of wettest quarter (bio_8) exceeding 12 °C also negatively affects the species distribution (Figs 4–5).

Currently known habitats of *Anoplius viaticus* are



Figs 1–2. External appearance of solitary wasps. 1 — *Anoplius viaticus*; 2 — *Ammophila sabulosa*.
Рис. 1–2. Внешний вид одиночных ос. 1 — *Anoplius viaticus*; 2 — *Ammophila sabulosa*.

Table 1. Estimation of the contribution of climatic parameters to the species distribution. Designations: wc2.1 — WorldClim database version, 2.5m — map resolution, bio — climatic parameters.

Таблица 1. Оценка вклада климатических факторов в распространение видов. Обозначения: wc2.1 — версия базы WorldClim, 2.5m — разрешение карты, bio — климатические компоненты.

Variable	*Anoplius viaticus* (L.)		*Ammophila sabulosa* (L.)		Bioclimatic parameters
	Percent contribution	Permutation importance	Percent contribution	Permutation importance	
wc2.1_2.5m_bio_1	20.9	2.4	21	0	annual mean temperature
wc2.1_2.5m_bio_2	1.6	11.7	3.1	18.2	mean diurnal variance (mean(period max-min))
wc2.1_2.5m_bio_3	0.2	0	0.3	12	isothermality (bio_2/bio_7) (×100)
wc2.1_2.5m_bio_4	1.8	7.4	1.4	1.9	temperature seasonality
wc2.1_2.5m_bio_5	2.7	20.4	1.7	7.6	max temperature of warmest period
wc2.1_2.5m_bio_6	4.2	0.2	1	0.5	min temperature of coldest period
wc2.1_2.5m_bio_7	8	14.9	6.7	16.1	temperature annual variance (BIO5-BIO6)
wc2.1_2.5m_bio_8	0.2	4.8	0.1	0.7	mean temperature of wettest quarter
wc2.1_2.5m_bio_9	0	4.4	0	0	mean temperature of driest quarter
wc2.1_2.5m_bio_10	0.8	4.5	0.7	17.7	mean temperature of warmest quarter
wc2.1_2.5m_bio_11	0	0	0	0	mean temperature of coldest quarter
wc2.1_2.5m_bio_12	0.5	13.9	0.3	0.1	annual precipitation
wc2.1_2.5m_bio_13	0.3	11.1	0.1	5.8	precipitation of wettest period
wc2.1_2.5m_bio_14	53.5	0	52.9	0.4	precipitation of driest period
wc2.1_2.5m_bio_15	0.1	0.7	0.4	0.9	precipitation seasonality
wc2.1_2.5m_bio_16	0.8	0	0	0	precipitation of wettest quarter
wc2.1_2.5m_bio_17	4.5	1.6	10.2	15	precipitation of driest quarter
wc2.1_2.5m_bio_18	0	1.7	0	0	precipitation of warmest quarter
wc2.1_2.5m_bio_19	0	0.3	0.1	3	precipitation of coldest quarter

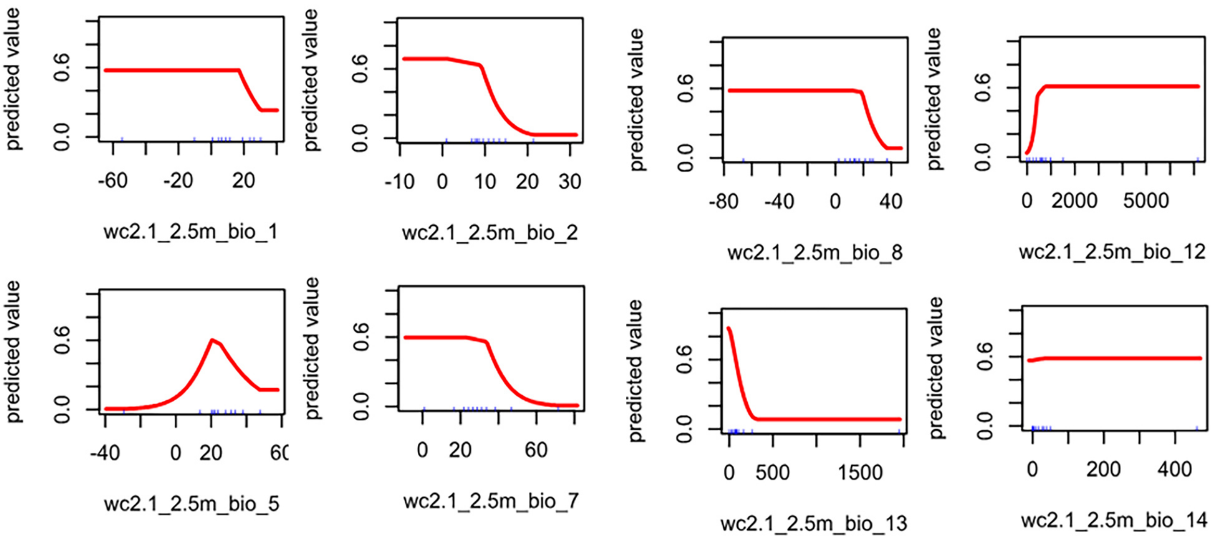
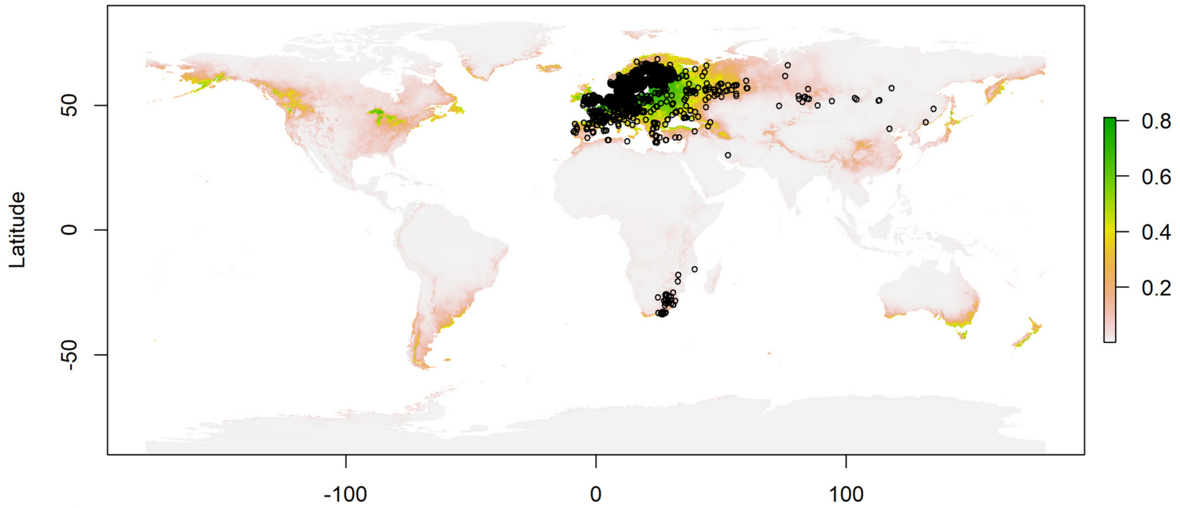


Fig. 3. Response curves of variables in the MaxEnt model for *Anoplius viaticus*. Designations: wc2.1 — WorldClim database version, 2.5m — map resolution, bio — climatic parameters. Bioclimatic parameters are arranged in order of significance for the species distribution.

Рис. 3. Кривые отклика переменных при построении модели MaxEnt для *Anoplius viaticus.* Обозначения: wc2.1 — версия базы WorldClim, 2.5m — разрешение карты, bio — климатические компоненты. Биоклиматические компоненты расположены в порядке наибольшей значимости для распространения вида.



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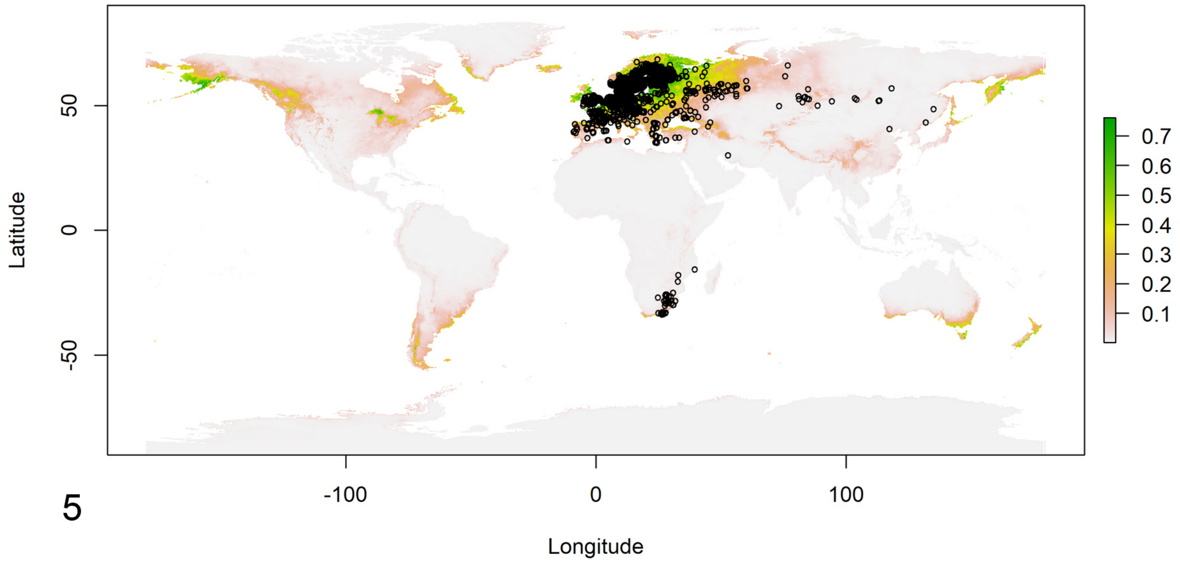

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Figs 4–5. Model of projected distribution of *Anoplius viaticus*. 4 — current suitable habitat, 5 — projected suitable habitat in 2040.

Рис. 4–5. Модель потенциального распространения *Anoplius viaticus*. 4 — пригодные территории в настоящее время; 5 — пригодные территории в прогнозе до 2040 года.

located in the boreal zone of the Palaearctic. The employed climate change model shows that the species *Anoplius viaticus* will successfully maintain its current range and will be able to spread throughout the Holarctic, with potential dispersal into the Australian and New Zealand zoogeographic regions. There is a shift of life-friendly habitats northward (Figs 4–5). Predominantly, bioclimatic parameters bio_14, bio_2, and bio_7 affect the species distribution. The altitudes from 26 to 140 m, with the mean of 121 m and the median of 64 m, are optimal for habitat.

Range change projection for Ammophila sabulosa. Two parameters have the greatest impact on the formation of a stable ecological niche. The first parameter is the amount of precipitation in driest period (bio_14) (from 0 to 50 mm), but the permutation coefficient is 0, similar to that for *Anoplius viaticus*, which indicates no effect in case of changed precipitation in driest period. The second parameter is mean annual temperature (bio_1) (from –10 to 30 °C).

The species is least tolerant to changes in mean diurnal variance (mean(period max-min)) (bio_2) (7–9 °C is optimal for the species) and annual temperature variance from warmest to coldest temperature (bio_7) (optimal difference does not exceed 30 °C). The mean temperature of warmest quarter (bio_10) is 16 °C, which is optimal

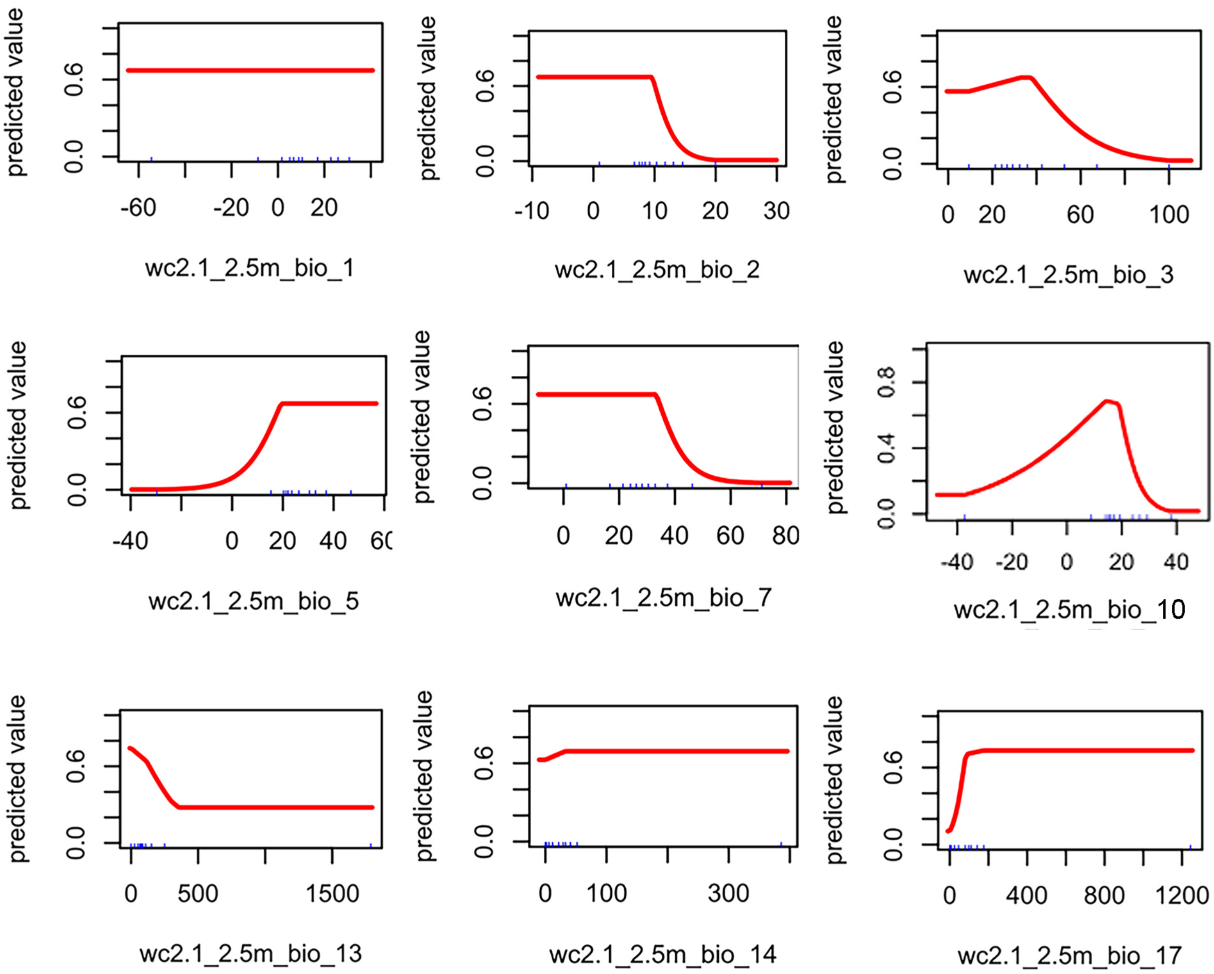


Fig. 6. Response curves of variables in the MaxEnt model for *Ammophila sabulosa.* Designations: wc2.1 — WorldClim database version, 2.5m — map resolution, bio — climatic parameters. Bioclimatic parameters are arranged in the order of significance for the species distribution.

Рис. 6. Кривые отклика переменных при построении модели MaxEnt для *Ammophila sabulosa*. Обозначения: wc2.1 — версия базы WorldClim, 2.5m — разрешение карты, bio — климатические компоненты. Биоклиматические компоненты расположены в порядке наибольшей значимости для распространения вида.

for the species distribution, yet an increase or decrease in temperature may hinder this process. The amount of precipitation in dry quarter (bio_17) (optimally 130 mm and above) is important for range expansion (Fig. 6).

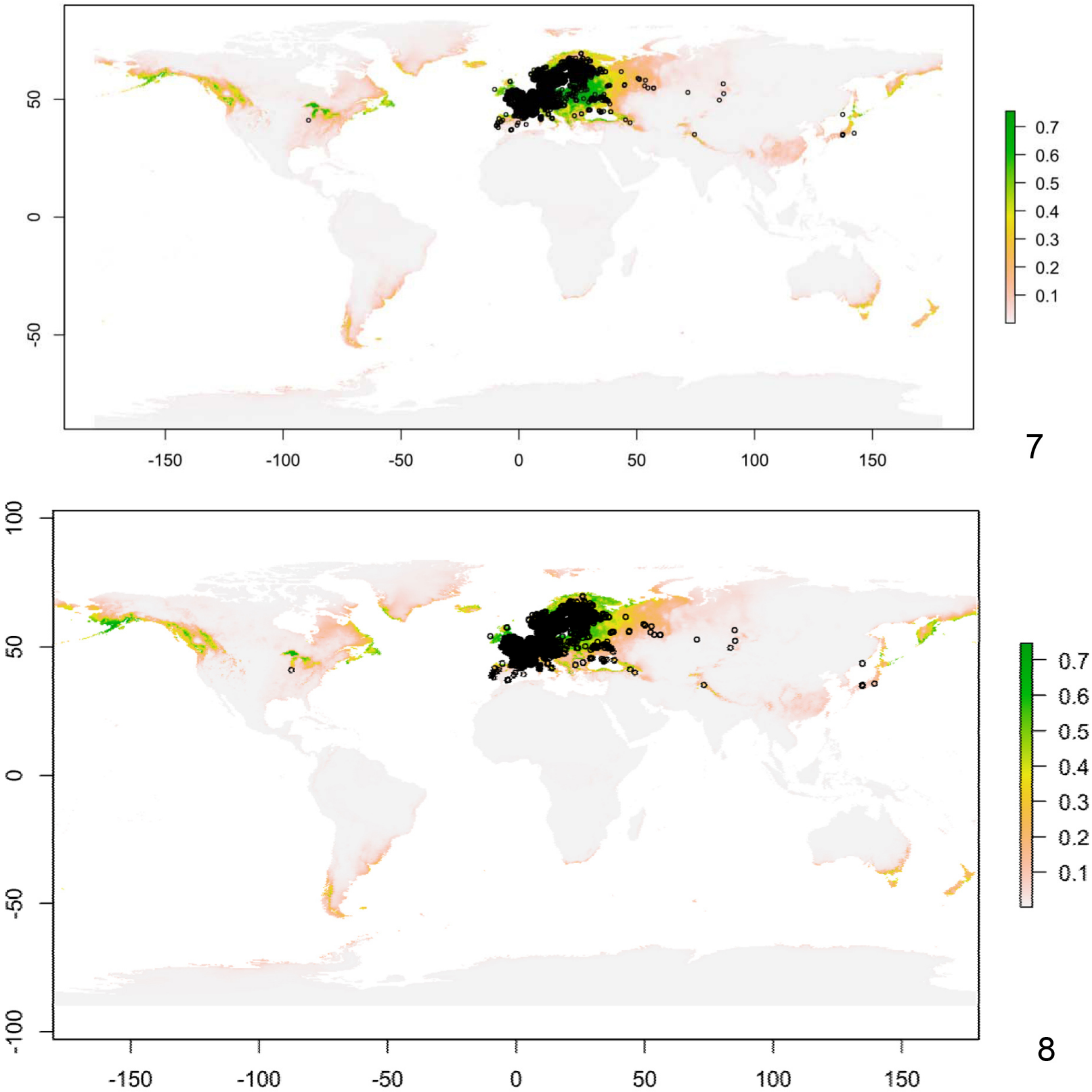
At present, *Ammophila sabulosa* and *Anoplius viaticus* are Transpalearctic species (Figs 7–8).

The study has shown that *Ammophila sabulosa*, similar to *Anoplius viaticus,* will successfully maintain its current range and will be able to spread throughout the Holarctic. Compared to *Anoplius viaticus,* the Australian and New Zealand zoogeographic regions are less suitable for *Ammophila sabulosa*. There is a shift of life-friendly habitats northward (Figs 7–8). Predominantly, bioclimatic parameters bio_14, bio_2, and bio_7 affect the species distribution. Optimal altitudes for this species are 25 to 161 m, with a mean of 143 m and a median of 71 m.

Thus, the distribution of both wasp species is significantly affected by the same bioclimatic parameters. The least significant variables also coincide. Under this climatic scenario, the studied wasp species will be able to change their range within similar boundaries. Consequently, species with similar biological and ecological characteristics, despite different trophic preferences and systematic position, yield similar projections, thereby enabling either species to serve as an indicator for the same objective.

Conclusion

The study of two eurybiont wasp species, typical representatives of the families Pompilidae and Sphecidae, performed using the ACCESS-ESM1-5 model and the SSP245 socioeconomic scenario showed that both species currently occupy the Transpalaearctic range. The range change projections for these species have a similar trend of expansion throughout the Holarctic, with potential dispersal into the Australian and New Zealand zoogeographic regions.



Figs 7–8. Model of projected distribution of *Ammophila sabulosa*. 7 — current suitable habitat; 8 — Projected suitable habitat in 2040.

Рис. 7–8. Модель потенциального распространения *Ammophila sabulosa*. 7 — пригодные территории в настоящее время; 8 — пригодные территории в прогнозе до 2040 года.

Bioclimatic variables bio_14, bio_2, and bio_7 are of paramount importance for range expansion of the studied species. The decisive variable for *Anoplius viaticus* and *Ammophila sabulosa* is temperature, namely the change in mean diurnal temperature (permutation coefficient is 11.7 and 18.2, respectively) and annual temperature variance (permutation coefficient is 14.9 and 16.1, respectively). The other 16 variables are less significant or insignificant.

Both species occupy an extensive range and have the potential to further expand their range and shift it northward. They can equally be used as indicators of the environmental change.

We have obtained preliminary data for projecting range changes for ecologically similar species, which show similar patterns of their distribution. Further projections will be developed for species confined to different climatic zones based on a number of climatic models and scenarios.

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