



The precipitation levels during the warmest quarter are the primary factor influencing the spatial distribution of *Opatrum sabulosum*

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The present investigation aims to analyse the influence of bioclimatic predictors on the geographical distribution of the species *Opatrum sabulosum* (Linnaeus, 1761) and to predict changes in its range in the context of global warming. *Opatrum sabulosum*, a species belonging to the Tenebrionidae family, exhibits a high degree of plasticity in its environmental requirements, yet remains susceptible to the impacts of climate change. The maximum entropy algorithm (MaxEnt) was employed to model the ecological niche, with the species distribution data from the GBIF database and key bioclimatic variables such as temperature, precipitation, and their seasonality being utilised. Forecasts were made for the present and up to 2080 under four climate change scenarios: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. The results indicate that the key factors affecting the distribution of *O. sabulosum* are the minimum temperature of the coldest month, the average temperature of the coldest quarter, and the amount of precipitation in the warmest and wettest quarters. The analysis indicates that, under current conditions, the most favourable habitats for the species are located in Western Europe, southern Britain, Scandinavia and the northern Black Sea region. In the context of a moderate warming scenario (SSP1-2.6), the species' range is projected to expand in an eastward and northeasterly direction, driven by rising average temperatures and an enhanced water balance. Conversely, under extreme scenarios (SSP3-7.0, SSP5-8.5), a decline in habitat quality in the southeastern part of the species' range is projected due to elevated temperatures, reduced humidity, and instability in climatic parameters. The practical significance of these results lies in the possibility of using these data to develop adaptation strategies for biodiversity conservation and effective management of natural resources. Forecasts of the distribution of *O. sabulosum* can serve as a basis for assessing the risks of ecosystem changes and creating new protected areas. Information regarding the species' sensitivity to climate change is also important for the sustainable development of agroecosystems, in which this species plays a role in maintaining soil fertility. The findings of this study are directly pertinent to the attainment of the Sustainable Development Goals (SDGs) established by the United Nations in 2015. Specifically, the study contributes to the implementation of SDG 13 'Combat climate change' by providing a more nuanced understanding of the effects of climate change and the adaptation of ecosystems to new conditions. The findings are also pertinent to SDG 15, 'Conserve terrestrial ecosystems', as predicting species distribution helps to conserve biodiversity and restore degraded ecosystems. The integration of these findings into environmental management practices is expected to contribute to ensuring environmental sustainability, efficient use of natural resources, and the creation of a harmonious environment for future generations. Prospects for further research include long-term monitoring of *O. sabulosum* populations, integration of genetic data to assess the species' adaptive potential, and expanding the analysis to include anthropogenic factors such as land use change, urbanisation and agricultural activities. This will allow more accurate forecasting of ecosystem changes in the future.

Keywords: global warming; sustainable development; spatial modelling; bioclimatic variables; maximum entropy algorithm.

Introduction

The global climate change trends observed in recent decades have a wide range of environmental, economic and social impacts. The increase in average temperatures on Earth is one of the most prominent trends (Leakey & Lau, 2012). The global surface temperature has increased by about 1.1 °C compared to pre-industrial levels, according to the Intergovernmental Panel on Climate Change (IPCC) (Wigley & Raper, 2001). This trend is projected to continue due to anthropogenic factors such as greenhouse gas emissions (O'Mara, 2012). Rising ocean temperatures, coupled with melting glaciers and polar caps, are precipitating an increase in sea levels (Siebert et al., 2020). This threatens low-lying coastal areas where millions of people live and can lead to coastal erosion and flooding of ecosystems. Global warming is causing more frequent and intense extreme weather events, such as floods, droughts, hurricanes, tornadoes, and forest fires. This is particularly noticeable in regions where climate change exacerbates existing natural risks. Rising temperatures are changing precipitation patterns around the world (Yorkina et al., 2022). Some regions are experiencing increased precipitation, while others are experiencing drought (Pizzorni et al., 2024). Humidity is decreasing in some areas, stressing agriculture and water supplies. The melting of glaciers, especially in the Arctic and Antarctic, is one of the most

obvious signs of climate change. This contributes to rising sea levels and a decrease in the Earth's reflectivity (albedo), increasing the absorption of solar heat (Zymarioieva et al., 2019). Climate change causes changes in ecosystems and disruption of biodiversity. Climate change can affect species migration, seasonal cycles, reproduction, food chains and ecosystem structure. Many species cannot adapt to rapid changes, which can lead to their extinction (Bell & Collins, 2008). Increasing carbon dioxide concentrations in the atmosphere also lead to its dissolution in the oceans, causing them to become oxidised. This seriously affects marine ecosystems, including coral reefs, which are an important part of marine biodiversity. Increased temperatures and changes in precipitation patterns could significantly impact agriculture, including crop yields. Some areas may see an increase in yields, but others may see a sharp decline due to droughts, floods or an increase in plant diseases. Variations in temperature and humidity can lead to changes in atmospheric processes, such as air circulation, which affect weather patterns and the global heat balance. The effects of climate variability on people, the economy and global security are serious (Thornton et al., 2014). In particular, droughts, floods, sea level rise and other extreme events can lead to population displacement, reduced access to water resources, reduced food production and increased social and political conflict. The effects of climate dynamics on various aspects of life are expected to intensify

unless drastic measures are taken to reduce greenhouse gas emissions and mitigate the impact of global warming (Filonchuk et al., 2024).

Global climate change represents a significant environmental and social challenge for contemporary society, with a wide range of impacts, including rising average temperatures, changes in precipitation patterns, increased frequency of extreme weather events, rising sea levels and biodiversity disruption. The gravity of these changes renders the issue of climate change inextricably linked to the achievement of the Sustainable Development Goals (SDGs), defined by the United Nations (UN) in 2015 as part of the 2030 Agenda for Sustainable Development (Sorooshian, 2024). The Sustainable Development Goals are 17 global goals aimed at achieving social, economic and environmental balance, improving the quality of life for all people and preserving the planet for future generations. The repercussions of climate change on numerous Sustainable Development Goals underscore the imperative of combating global climate change as a pivotal component of achieving sustainable development. Goal 13, which explicitly addresses climate change and its impacts (Arora & Mishra, 2023), emphasises urgent action to mitigate greenhouse gas emissions, enhance energy efficiency, foster the development of clean and renewable energy sources, and provide support to countries in their endeavours to adapt to the consequences of climate change (Zhukov et al., 2022). Actions at the global, national, and local levels must ensure that the planet's temperature is reduced and the negative impacts on ecosystems, agriculture, and human health are minimised. Goal 7: Ensuring access to affordable, reliable, sustainable, and modern energy for all is closely linked to climate change, as a significant portion of greenhouse gas emissions comes from energy consumption, particularly fossil fuels (Jayachandran et al., 2022). To achieve sustainable development, it is imperative to transition towards cleaner, renewable energy sources such as solar, wind, hydropower and bio-energy. This transition will substantially reduce CO₂ and other greenhouse gas emissions, which are the primary drivers of global warming. Goal 6, which aims to ensure access to and sustainable management of water and sanitation for all, is fundamental (Evaristo et al., 2023). Climate change is affecting the availability of water resources, causing droughts in some regions and floods in others. This poses a threat not only to human water supplies and agricultural output but also to the health of aquatic ecosystems. Achieving this objective necessitates formulating efficacious water management strategies and implementing measures to mitigate the effects of climate change, including water conservation, water treatment, and pollution control (Budakova et al., 2021). Goal 14, which calls for conserving the oceans, seas and marine resources for sustainable development, is vital in climate change (Andriamahefazafy et al., 2022). This is because rising ocean temperatures and water acidification seriously impact marine ecosystems, including coral reefs, fisheries and biodiversity. To ensure the sustainable use of marine resources, it is necessary to reduce the impacts of climate change on the oceans, including reducing greenhouse gas emissions and maintaining ecosystems that support marine life. Goal 15, which aims to protect, restore and promote the sustainable use of terrestrial ecosystems, is also important (Kunakh et al., 2020; Walker, 2021). Climate change can lead to several adverse effects on terrestrial ecosystems, including land degradation, biodiversity loss and reduced ecosystem productivity. This phenomenon harms agricultural productivity, food security, and the livelihoods of populations, particularly in regions susceptible to droughts and floods (Yakovenko et al., 2023). Achieving sustainable development necessitates restoring degraded land, preserving forests, and maintaining biodiversity, all of which are pivotal in ensuring resilience to climate change. It is imperative to recognise the interconnected nature of the Sustainable Development Goals, with climate change exerting a profound influence on nearly all other areas (Kluza et al., 2024). These include poverty reduction (Goal 1), food security (Goal 2), health (Goal 3), gender equality (Goal 5) and other aspects. To illustrate this point, climate change has been demonstrated to engender diminished crop yields, thereby exacerbating food insecurity (Goal 2). Moreover, the dissemination of diseases such as malaria and diarrhoea, precipitated by fluctuations in rainfall and temperature patterns, can potentially compromise human health (Awad et al.,

2024). Consequently, global climate change represents a pivotal challenge requiring comprehensive and large-scale action at all levels. The attainment of the Sustainable Development Goals is unfeasible without a concerted effort to combat climate change, as it directly influences all dimensions of environmental, economic and social sustainability. To address this challenge, it is imperative to implement measures to mitigate the effects of climate change, enable adaptation to new conditions, conserve natural resources and promote sustainable use of energy and water resources (George, 2024).

Predicting climate change is paramount to facilitating effective management and conservation of biodiversity (Mantyka-Pringle et al., 2015). Climate change is exerting a substantial influence on global ecosystems and species. The comprehension of future climate conditions facilitates the formulation of strategies for the conservation, adaptation and mitigation of the effects of these changes on biodiversity (Weiskopf et al., 2020). By leveraging predictive models, scientists and ecologists can determine how alterations in temperature, precipitation, sea levels, and other climate variables could influence distinct ecosystem species (Bamal et al., 2024). Specifically, climate change can lead to shifts in species ranges, alterations in behaviour, a decline in population numbers, or even the extinction of certain species. This enables the identification of vulnerable species and ecosystems promptly and the development of measures to protect them. The development of forecasting models enables the formulation of science-based biodiversity conservation strategies that consider future conditions. This may encompass establishing novel protected areas, the augmentation of extant reserves, or modifications in natural resource management. Forecasting aids in identifying species that might be at risk from upcoming climate change and suggests conservation strategies them (Advani, 2023). Climate projections facilitate assessing potential ecosystem changes and developing strategies to adapt to them. This may include the implementation of measures to maintain ecosystem health, such as the improvement of soil conditions, the protection of water resources, the restoration of degraded land, or the introduction of new plant and animal species that are better adapted to changing conditions. The repercussions of climate change extend beyond wild ecosystems, encompassing significant implications for agriculture and forestry, which play a pivotal role in biodiversity (Kunakh et al., 2023). Predictive analyses facilitate adapting agricultural and silvicultural strategies to new conditions, e.g. by selecting more resilient crop varieties or tree species that can better withstand climate change (Zelenova et al., 2024). Enhanced pest and disease control is facilitated by these changes, as alterations in temperature and humidity can lead to the spread of such pests and diseases. Understanding future climate change helps anticipate environmental crises such as droughts, floods, wildfires, and water imbalances, which can substantially damage biodiversity. Forecasting allows preventative actions to be taken, thus lowering risks and mitigating environmental and societal harm (Willis et al., 2015).

Forecasting climate change informs global political decisions regarding environmental protection (Ylä-Anttila et al., 2018). Collaborative endeavours by countries, international organisations and scientists to predict climate change and identify measures to preserve biodiversity represent a significant component of global efforts to combat the effects of climate change (Kunakh et al., 2018). This collaborative endeavour has led to the establishment of international agreements, such as the Paris Agreement, which aims to limit global warming to 1.5 °C (Aggarwal, 2024). Climate change forecasting is pivotal in raising public awareness of the impacts of climate change on biodiversity (Mykhailyuk et al., 2023). This can encourage people to engage in conservation activities, such as preserving forests, maintaining ecosystem services, or reducing greenhouse gas emissions daily. Climate change forecasting is a pivotal instrument in conserving biodiversity, as it enables scientists, policymakers and the general public to respond effectively to the challenges posed by climate change, mitigate risks to species and ecosystems, and adapt conservation strategies to future conditions. Due to the swift acceleration of climate change, it is crucial to utilise scientifically informed projections and create adaptation strategies to safeguard biodiversity for future generations (Lahlali et al., 2024).

The bioclimatic habitats of agricultural pests *Zabrus tenebrioides* and *Harpalus rufipes* in the context of climate change were investigated (Avtaeva et al., 2021). These species are among the most widespread pests of cereal crops, including wheat, barley, rye and maize. The study aimed to determine how climate change affects the distribution of these species and to forecast range alterations according to the RCP 2.6 and RCP 8.5 climate scenarios. The modelling utilised the MaxEnt software, which revealed that the primary factors influencing the distribution of *Z. tenebrioides* are moisture-related parameters, including precipitation during the driest period and seasonal precipitation variability. The most favourable conditions for these species were identified in Eastern Scotland, South East England, France, the Netherlands and Germany, and the steppe zone of Ukraine. Projections indicate a potential species range decline by 2070, particularly within the eastern continental regions. *H. rufipes* was more dependent on temperature parameters, such as the annual mean and minimum temperatures of the coldest month. The current geographical distribution of *H. rufipes* encompasses most of Europe, northern Africa and Central Asia. Projections indicate that climate change will result in a contraction of its geographical distribution, accompanied by a shift towards more northerly regions. The study emphasises that global climate change will affect not only these pests' distribution but also cereals' productivity due to the reduction of suitable regions for cultivation. Consequently, the ongoing monitoring of populations of *Z. tenebrioides* and *H. rufipes*, in conjunction with the analysis of their interactions with other components of biocenoses, is imperative to ensure food security in the context of global warming (Avtaeva et al., 2021). A similar procedure was applied to analyse the impact of global climate change on the bioclimatic range of the beetle *Pterostichus melanarius* (family Carabidae). Still, four climate scenarios were considered: RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 (Avtaeva et al., 2021). The investigation revealed that the average annual temperature and the temperature of the coldest quarter are the key factors that influence the distribution of *P. melanarius*. According to the RCP 8.5 scenario, by 2070, the species' range is expected to shrink significantly, particularly in southern Europe, where areas will become unsuitable for its existence. At the same time, the range will shift to the northwest in continental regions and to the northeast in coastal regions. Mountainous regions, such as the Alps, Carpathians, Caucasus and Urals, will also become less suitable for the species. The modelling results demonstrate that climate change significantly impacts the range and abundance of *P. melanarius*, which in turn could alter the balance of pest and predator populations in forest and agricultural communities. The authors emphasise the importance of monitoring species and considering changes in bioclimatic conditions in future ecological studies (Avtaeva et al., 2021).

Opatrum sabulosum (Linnaeus, 1761) is a polyphagous species with the pronounced tendency to phytophagy of the Tenebrionidae family. This species inhabits a fairly wide range of soils and can tolerate moderate soil salinity levels. *Opatrum sabulosum* prefers chernozems and areas with sparse vegetation cover and eroded areas (Yakovenko & Zhukov, 2021). This species can engage in saprophyagy, but only as an additional trophic mode (Nazimov & Brygadyrenko, 2013). *Opatrum sabulosum* can climb stems in search of food to a considerable height of up to 1 metre. This allows them to feed on the leaves of young trees and shrubs. This species of beetle uses rotting plant parts as a source of moisture. Trees and shrubs have less metabolic value for *O. sabulosum* than grasses (Brygadyrenko & Nazimov, 2014, 2015). The wide range of trophic and biotopic preferences of this species suggests that climatic variables should play a crucial role among the factors of its distribution, making this species promising for predicting the impact of climate change on its geographical distribution. Therefore, this study aimed to fill the gap in our knowledge of the climatic factors that determine the ecological niche of *O. sabulosum* and to create projections of the geographical distribution of this species under different climate change scenarios.

Materials and methods

The present study examined the impact of bioclimatic predictors on the geographical distribution of *Opatrum sabulosum* (L.). The stu-

dy was based on modern methods of ecological modeling, spatial analysis, and bioclimatic utilization data. A particularly efficacious method is the maximum entropy algorithm (MaxEnt) (Rodríguez-Merino et al., 2020), which estimates the probability of a species presence based on bioclimatic variables and observation points. This methodological approach facilitates the construction of a model that delineates the species' potential geographical distribution, encompassing both contemporary and future climate scenarios (Avtaeva et al., 2021). The geographical distribution of the species was utilised to create the models. This data was obtained from the open database Global Biodiversity Information Facility (GBIF) (Freeman et al., 2019). In order to enhance the precision of the analysis, the data underwent a series of pre-processing steps, including the removal of duplicates, filtration, and spatial toning.

The Maximum Entropy Algorithm (MaxEnt) is a powerful method for modelling ecological niches that has been used to predict species distributions based on environmental factors (Phillips et al., 2006). The approach is based on the principle of maximising entropy, i.e. choosing the most uniform probability distribution under the constraints of the data. MaxEnt works with simple species occurrence data and uses environmental factors, including bioclimatic variables, to build a model that determines the probability of a species being found in a particular environment. The algorithm maximises entropy (uncertainty) based on these constraints, i.e. it produces a spatial distribution of species that is least biased given the environmental data. MaxEnt does not require complex statistical interpretation or large amounts of missing species data, making it attractive for ecological studies where such data are often lacking. The algorithm can work with a variety of spatial data types (global maps, raster images, etc.), allowing it to take into account different aspects of the environment. MaxEnt allows the models to be adapted to specific conditions, such as the consideration of climate or environmental change. MaxEnt models have also been used to predict the future distribution of a species under different climatic or anthropogenic scenarios, which is crucial for studying changes in biodiversity in response to global change (Wang et al., 2024).

Ecological Niche Factor Analysis (ENFA) is a method for studying the ecological niche of species, which allows their spatial distribution to be estimated in relation to environmental conditions (Engler et al., 2004). The main feature of ENFA is that it is based on presence-only data and does not require information about places where the species is absent (Ponomarenko et al., 2021). The method compares conditions within the species' range with average conditions across the study area to determine its ecological preferences. ENFA assesses marginality, which shows how conditions in a species' range differ from average conditions in the region, and specialisation, which describes the narrowness of the species' ecological requirements. The method allows one to produce habitat suitability maps to predict the potential distribution of a species (Brotons et al., 2004). ENFA is effective where data are limited and is used to assess the condition of habitats of rare or threatened species and to develop conservation strategies (Brotons et al., 2004). At the same time, the method is dependent on the quality of the input data. It assumes that the species is in ecological equilibrium with its environment without taking into account species interactions and dynamic environmental change. Despite these limitations, ENFA is a valuable tool for analysing ecological niches and modelling species' potential range in the context of biodiversity conservation and climate change adaptation (Calenge et al., 2008).

The models are heavily reliant upon bioclimatic variables. These encompass the mean annual temperature, daily temperature fluctuations, minimum and maximum temperatures, precipitation seasonality, annual rainfall, and other parameters (Guimarães et al., 2020). The significance of these variables is then determined using the jackknifing method, which allows for the assessment of the impact of each variable on the model's accuracy (Dias et al., 2011). In instances of high correlation between variables, redundant data are excluded to enhance the model's accuracy (Dyderski et al., 2018). The results obtained allow identification of key environmental factors that limit the distribution of the species, predicting possible changes in its range,

and the assessment of risks associated with climate change. This is of critical importance for the conservation of biodiversity, the effective management of natural resources, and the adaptation to climate change (Avtaeva et al., 2021).

The sixth-generation climate model CNRM-CM6-1, developed by the French National Centre for Meteorological Research (CNRM) and Météo-France, was utilised to predict climate change (Roehrig et al., 2020). The model is part of the sixth phase of the International Climate Model Intercomparison Project (CMIP6), the purpose of which is to study the Earth's climate system and predict climate change under different greenhouse gas emission scenarios. The CNRM-CM6-1 model reflects a state-of-the-art approach to modelling the main components of the climate system, including the atmosphere, ocean, ice sheet and their interactions. The atmospheric component (ARPEGE-Climat) calculates processes related to air mass dynamics, precipitation and cloud cover, while the ocean component (NEMO) simulates heat exchange, ocean currents and ice sheet changes. The interaction between the ocean and the atmosphere is characterised by processes such as greenhouse gases, evaporation, deposition and heat transfer. The CNRM-CM6-1 is utilised to analyse global climate change, including an increase in average temperature, changes in atmospheric and oceanic circulation, and to study the impact of different socioeconomic scenarios under SSP (Shared Socioeconomic Pathways). It facilitates the analysis of extreme weather events and the prediction of climate change at the regional level. The CNRM-CM6-1 model is a key contributor to the Intergovernmental Panel on Climate Change (IPCC) reports, as it provides critical data for assessing the effectiveness of climate policies and developing adaptation strategies (Adhikari et al., 2024). The model incorporates multiple climate change scenarios. The Shared Socioeconomic Pathways (SSP) consider the following scenarios: '126', '245', '370' and '585' (Table 1). The SSP is based on a wide range of possible socioeconomic development pathways and their impact on climate change (Siabi et al., 2023).

Table 1
Shared socioeconomic pathways of projected climate change

SSP scenario	Description	Emissions trajectory	Temperature rise by 2100	Key features
SSP1-2.6 ("126")	Sustainable Development	CO ₂ emissions peak around 2020, decline rapidly, and reach net-zero by ~2050.	1.5–2.0 °C	Focus on global sustainability, strong cooperation, clean technologies, and low population growth.
SSP2-4.5 ("245")	Middle of the Road	Moderate emissions increase through mid-century, then stabilize.	~2.6–3.0 °C	Trends follow historical patterns with no major global shift toward sustainability or fossil fuel use.
SSP3-7.0 ("370")	Regional Rivalry	Increasing emissions due to nationalism, fragmented cooperation, and high fossil fuel use.	~3.8–4.2 °C	Regional competition, weak international collaboration, and higher population growth in some regions.
SSP5-8.5 ("585")	Fossil-Fueled Development (High-end)	Rapid and sustained emissions growth; economic growth relies heavily on fossil fuels.	~4.3–5.0 °C or more	"Worst-case" scenario with high energy demand and minimal investment in renewables or climate action.

SSP1-2.6 ('126') is the most optimistic scenario, assuming a global focus on sustainable development, strong international cooperation, the use of clean technologies and low population growth (Scafetta, 2024). This scenario is characterised by low emission levels, which allows for the limitation of global warming to 1.5–2.0 °C by 2100. However, the implementation of climate policies aimed at decarbonisation and reducing dependence on fossil fuels would require significant efforts. SSP2-4.5 ('245') is a moderate scenario that describes a 'middle path' in which socio-economic trends remain similar to cur-

rent ones (Mathbout et al., 2023). This scenario anticipates the stabilisation of emissions by mid-century, which is projected to result in a 2.6–3.0 °C temperature increase by the year 2100. This scenario suggests no significant changes in global climate policy, making it difficult to achieve more ambitious emissions reduction targets. SSP3-7.0 ('370') is a more pessimistic scenario, reflecting a world characterised by strong nationalism, limited international cooperation and a high dependence on fossil fuels (Wang et al., 2023). This scenario is projected to result in elevated levels of greenhouse gas emissions, leading to a global warming of 3.8–4.2 °C. This scenario also implies uneven development between regions and high vulnerability of societies to the effects of climate change. SSP5-8.5 ('585') is regarded as the worst-case scenario, with elevated emissions resulting from the extensive utilisation of fossil fuels to achieve accelerated economic growth. This approach gives rise to extremely high-temperature increases (4.3–5.0 °C or more), which could have catastrophic consequences for the climate system, ecosystems and humanity. SSP5-8.5 is frequently employed as a 'worst case' scenario for risk assessment and adaptation scenarios. In summary, SSP1-2.6 reflects a pathway to climate stability through significant decarbonisation efforts, while SSP5-8.5 is a scenario of unrestricted emissions growth with catastrophic climate consequences. Scenarios SSP2-4.5 and SSP3-7.0 occupy intermediate positions, with different levels of dependence on fossil fuels and the effectiveness of international cooperation (Fujimori et al., 2017).

A data cleaning process was implemented to ready the GBIF data for subsequent analysis in R. This procedure included the removal of duplicates, the checking of the accuracy of coordinates, and the removal of erroneous records. Duplicates may arise due to the presence of identical geographical coordinates, the utilisation of the same species name, or the existence of duplicate records. The distinct function from the dplyr package was utilised to eliminate duplicate rows. Records containing missing or erroneous coordinates (e.g., latitude and longitude of zero) were also removed. The application of GBIF data quality fields, such as basis Of Record, coordinate Uncertainty In Meters, and Georeferenced, was instrumental in refining the data. Records exhibiting substantial coordinate uncertainty (greater than 1000 m) were removed to ensure data integrity. Spatial filtering for each point within 0.5×0.5° was performed using the gridSample function from the dismo library. This procedure has been demonstrated to serve several purposes. Firstly, it reduces the excessive density of records in certain regions while maintaining data representativeness. Secondly, it helps to avoid bias due to the high concentration of observations in study areas. Finally, it improves species distribution modelling by reducing the influence of autocorrelation. This methodology has been demonstrated to be effective in preparing GBIF data for analysis, including ecological modelling and species distribution assessment.

Results

The following results were obtained after filtering the *O. sabulosum* encounter data. The initial number of records was 5,085, but following data cleansing, including the removal of duplicate data, coordinate verification, and spatial filtering, 3,558 points remained for further analysis (Fig. 1). The cleaning process was conducted using the grid Sample function with a 0.5×0.5° grid, a methodology that enabled the reduction of excessive record density in specific regions and ensured the representativeness of the data. This process helped avoid bias caused by the high concentration of observation points in the study areas and significantly improved the data quality for modelling. Following the cleaning process, the data was utilised as a foundation for ecological analyses, encompassing ENFA (Ecological Niche Factor Analysis) and assessing the species' distribution under current and future climate conditions, considering a range of SSP (Shared Socioeconomic Pathways) scenarios. The remaining 3,558 points ensured high accuracy in predicting and analysing the relationships between bioclimatic variables and the distribution of *O. sabulosum*.

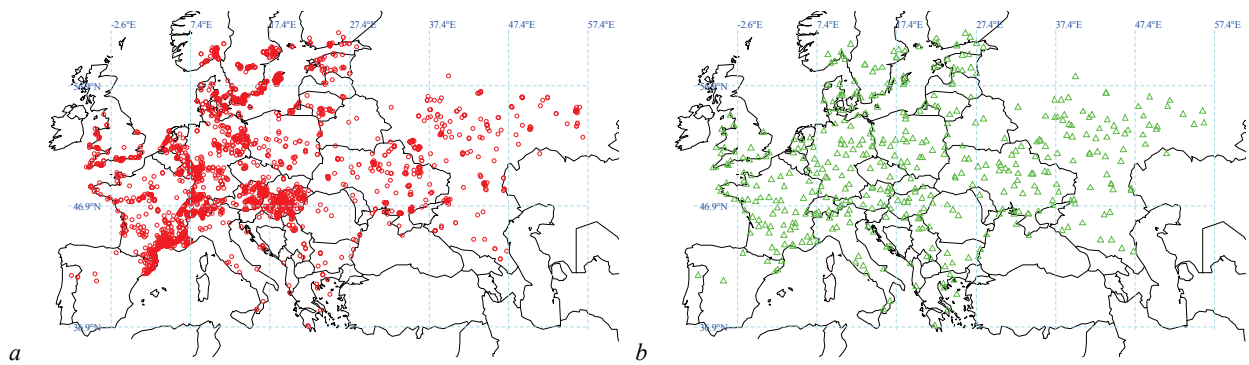


Fig. 1. 5085 *Opatrum sabulosum* occurrence points (a) and 3,558 occurrence points that were left for further analysis after filtering out duplicate data (b)

The accuracy of the MAXENT analysis was evaluated using the Receiver Operating Characteristic (ROC) curve (Fig. 2). This allowed us to obtain the AUC (Area Under the Curve), which is a standard indicator for assessing the quality of a classification model. The AUC is 0.764. This indicates the high accuracy of the MAXENT model since an AUC value of more than 0.7 indicates acceptable classification quality. Thus, the model demonstrates an adequate match between predicted and actual data. Bioclimatic predictors such as precipitation of the warmest quarter, precipitation of the wettest month, and minimum temperature of the coldest month make the greatest contribution to explaining the spatial variability of *O. sabulosum*. ENFA allowed us to estimate the parameters of marginality and specialisation of the *O. sabulosum* ecological niche regarding bioclimatic variables (Table 2). The estimates of ecological niche marginality and specialisation can also be illustrated by comparing the overall distributions of bioclimatic predictors and their partial distributions only in the occurrence points of the studied species (Fig. 3). Quantitative indicators of the marginality of the ecological niche of *O. sabulosum* indicate that the species prefers ecological regimes with higher values of the minimum temperature of the coldest month, the average temperature of the coldest quarter, precipitation of the wettest month, precipitation of the wettest quarter, and precipitation of the warmest quarter. This species tries to avoid conditions with elevated values of such environmental regimes as mean of monthly temperature ranges, seasonality of temperature, maximum temperature of the warmest month, annual temperature range, average temperature of the warmest quarter, and precipitation seasonality. Narrow specialisation of the ecological niche of *O. sabulosum* is observed in such bioclimatic variables as seasonality of temperature, average temperature of the warmest quarter, and average temperature of the coldest quarter. Thus, the approximation of environmental conditions to the optimal ones for the relevant variables is crucial for explaining the spatial variability of *O. sabulosum*. The optimal value of seasonality of temperature is 76.3 ± 76.3 °C. The optimal average temperature of the warmest quarter is 17.9 ± 0.1 °C, and the optimal average temperature of the coldest quarter is -0.8 ± 0.2 °C.

In the modern period, the most favourable conditions for *O. sabulosum* are in Western Europe, southern Britain and Scandinavia. There is also a zone of favourable conditions in the northern Black Sea region (Fig. 4). Climate change will not significantly affect the distribution of this species in western and southwestern Europe. Still, favourable conditions will be created for its spread in Eastern and Northeastern Europe. A more pronounced warming trend will cause a significant deterioration in habitat conditions in the southeast of the species' range.

Discussion

The life span of *Opatrum sabulosum* includes eggs, larvae, pupae and adult beetle (adult), and is an example of a complete metamorphosis (Munteanu et al., 2014). Females lay their eggs in the soil or the top layer of a substrate with sufficient organic residues. The eggs have a protective shell that ensures their survival in adverse condi-

tions (Fattorini, 2011). The incubation period lasts several days or weeks, depending on temperature and humidity. Larvae hatch from the eggs, and have an elongated worm-like body with well-developed jaws. The larvae feed on organic residues, contributing to soil formation, and undergo several moults during their growth. Depending on environmental conditions, the larval stage can last from several weeks to several months. After their development, the larvae move to the pupal stage, which is formed in the soil (Heneberg et al., 2016). During this stage, the body undergoes a restructuring that lasts several days to several weeks, after which the adult beetle emerges from the pupa. The adult *O. sabulosum* has a flattened, oval body adapted for movement in the soil. Adult beetles are active during the warm season, searching for food, such as organic residues, moss or plant material, and reproducing. Their lifespan is several months, depending on environmental conditions. In general, the life cycle of *O. sabulosum* demonstrates high adaptability to stressful conditions and contributes to the functioning of ecosystems through its participation in the nutrient cycle.

Analysis showed that *O. sabulosum* favours environments with warmer minimum temperatures in the coldest month. Warmer minimum temperatures lessen the chances of extreme body cooling, vital for winter insect survival. This preference helps avoid thermal stress, which is known to disrupt physiological functions or even cause death. Additionally, milder winter conditions can enhance the availability of food resources like organic matter, which these beetles depend on year-round. Elevated minimum temperatures often signal a more stable microclimate and ecosystem, aiding the species' survival. As a result, *O. sabulosum* favours environments with these thermal traits to cope with challenging winter conditions. *Opatrum sabulosum* demonstrates a clear preference for ecological regimes characterised by higher mean temperatures during the coldest quarter, a preference that is attributable to several significant ecological and physiological factors. This species is poikilothermic, which signifies that its physiological processes are contingent on the ambient temperature. Higher average temperatures in the coldest quarter reduce the risk of hypothermia and help maintain the activity of essential metabolic processes necessary for survival (Centeno Filho et al., 2022). Another significant factor is soil ecology, given that this species spends much of its life in the soil (Bhagarathi & Maharaj, 2023). In warmer conditions, soil microorganisms are more active, and organic matter is decomposed, which provides *O. sabulosum* with access to a stable food supply. The beetle's survival is enhanced by stabilising the microclimate in overwintering areas, such as soil cracks or litter, which occurs in warmer winter conditions (Vermunt et al., 2012). This adaptation likely stems from the species' evolution in temperate climates, where temperature changes are less extreme (Bodlah et al., 2023). As a result, the beetle prefers habitats with higher average temperatures in the coldest quarter, driven by the need to maintain suitable conditions throughout its life cycle and ensure the survival of its population. It was confirmed that *O. sabulosum* prefers ecological regimes with higher precipitation in the driest quarter due to its dependence on soil moisture and related environmental conditions. Since this beetle spends a significant part of its life cycle in the soil, moisture is an es-

sential factor affecting the availability of food resources and favourable conditions for the development of eggs, larvae and pupae (Knisley et al., 2018). In dry conditions, the activity of microorganisms that decompose organic residues decreases, which can limit access to food. In contrast, a stable forage base is maintained in environments with sufficient rainfall, even during the year's driest period. Increased soil moisture creates a microclimate that protects larvae and adult beetles from drying out, especially during periods of high air temperature. This is especially important for maintaining the water balance in the beetle's body, as they cannot actively regulate moisture loss. The in-

fluence of precipitation on soil structure is another significant factor (Klöffel et al., 2024). In environments with higher rainfall, the soil is usually less compact, making it easier for beetles to move and for larvae to penetrate. Such conditions also contribute to the stability of the ecosystem where *O. sabulosum* lives, reducing the risk of sudden environmental changes. Thus, the preference for ecological regimes with higher precipitation in the driest quarter is associated with ensuring favourable conditions for the species' nutrition, development and survival, even under stressful climatic conditions.

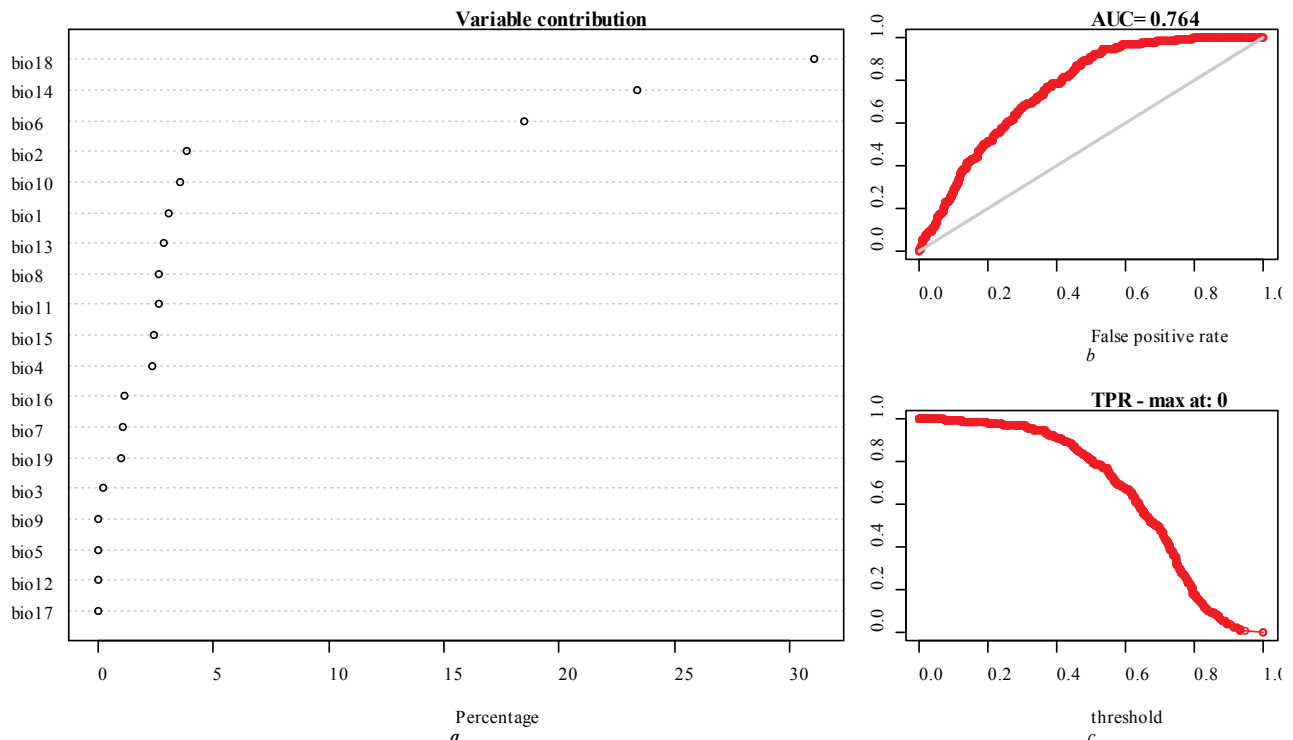


Fig. 2. Contribution of bioclimatic variables to explaining the spatial variability of *O. sabulosum* distribution according to MAXENT analysis (a), Receiver Operating Characteristic for assessing the quality of the classification model (b), Dependence of True Positive Rate (TPR) on threshold (a): bioclimatic variables: bio1 – mean annual temperature, bio2 – mean of monthly temperature ranges, bio3 – isotherm, Bio* – bioclimatic variables: bio4 – seasonality of temperature, bio5 – maximum temperature of the warmest month, bio6 – minimum temperature of the coldest month, bio7 – annual temperature range, bio8 – average temperature of the wettest quarter, bio9 – average temperature of the driest quarter, bio10 – average temperature of the warmest quarter, bio11 – average temperature of the coldest quarter, bio12 – annual precipitation, bio13 – precipitation of the wettest month, bio14 – precipitation of the driest month, bio15 – seasonality of precipitation, bio16 – precipitation for the wettest quarter, bio17 – precipitation of the driest quarter, bio18 – precipitation of the warmest quarter, bio19 – precipitation of the coldest quarter

The findings indicate that *O. sabulosum* prefers ecological regimes characterised by elevated precipitation values in the warmest quarter, attributable to the humidity levels that are conducive to ensuring favourable conditions during the period of maximum activity of the species. During the warmer months, the beetles are actively feeding, reproducing and performing other vital functions, so sufficient rainfall is crucial to maintaining their viability. Precipitation in this period ensures soil moisture, vital for the development of eggs and larvae, which are especially sensitive to desiccation (Lepage et al., 2012). The activity of soil microorganisms, which are crucial to the decomposition of organic residues and the provision of a food base for *O. sabulosum*, is supported by soil moisture. A deficiency of precipitation can lead to a decline in soil biological activity, which can adversely impact the availability of sustenance for the beetles (Saleem et al., 2024). During the warm season, higher temperatures increase the risk of dehydration for poikilothermic organisms, including *O. sabulosum*. Precipitation and the subsequent increase in humidity mitigate the risk of desiccation, enabling the beetles to function effectively even at elevated temperatures. Stable moisture conditions during the warmest quarter promote vegetation growth and preserve soil structure, providing a protective microclimate and suitable hiding places for the beetles (Chown et al., 2011). The observed preference for ecological regimes with higher precipitation during the warmest quar-

ter can be explained by the fact that such conditions create an optimal balance between resource availability, moisture conservation and maintaining the ecological stability necessary for the successful development and survival of the species.

The findings on the ecology of *O. sabulosum* are complemented by the fact that this species avoids conditions with high mean monthly temperature amplitudes, as large temperature fluctuations create stressful situations for its existence. This species depends on external temperatures, which directly impact its physiological processes, including activity, reproduction and survival (Régnière et al., 2012). Elevated temperature amplitudes can disrupt these processes due to the necessity for constant adaptation to sudden changes in the environment. Large temperature fluctuations can also compromise the beetle's ability to maintain an optimal water balance (Nervo et al., 2021). During periods of sharp temperature increases, the risk of dehydration escalates, whereas during sharp temperature decreases, metabolic activity slows down, which can lead to energy depletion and reduced viability (Sinclair et al., 2013). Significant temperature variations can also adversely affect the development of eggs and larvae in the soil. Such fluctuations have been shown to undermine the viability of beetle embryos and larvae, potentially hindering their development and activity. These temperature fluctuations have been demonstrated to disrupt the ecosystem services provided by soil microorganisms, which

are vital for the nutrition and survival of these beetles. Such conditions can affect the stability of the microclimate in the habitat, particularly in shelters used by the beetles for protection. The beetles' ability to successfully survive adverse conditions is reduced if the microclimate is not stable. The propensity of *O. sabulosum* to evade conditions characterised by elevated mean monthly temperature amplitudes can be attributed to its physiological and ecological imperatives, necessitating the maintenance of a stable environment. The results of the study are in line with findings that indicate that maintaining stable temperatures is crucial for ensuring survival at all stages of the life cycle, thereby minimising the risks associated with environmental stressors (Chen et al., 2024).

Table 2
Results of the ENFA approach and ecological niche parameters of *O. sabulosum* in terms of bioclimatic variables

Bioclimatic variables	ENFA		Parameters of the ecological niche			
	marginality	specialisation	optimum ± st. error	minimum	maximum	tolerance
bio1	0.05	0.07	8.5 ± 0.1	-1.9	16.0	2.8
bio2	-0.33	0.12	8.2 ± 0.1	3.4	11.8	1.3
bio3	0.13	-0.12	29.6 ± 29.6	19.1	44.1	4.9
bio4	-0.34	0.59	76.3 ± 76.3	27.2	131.2	20.5
bio5	-0.28	0.03	23.9 ± 0.1	9.9	31.6	3.1
bio6	0.27	0.07	-4.6 ± 0.2	-18.3	7.2	5.2
bio7	-0.41	-0.04	28.5 ± 0.3	10.9	45.5	6.1
bio8	0.13	0.01	14.2 ± 0.2	-4.6	21.8	5.0
bio9	-0.10	-0.02	4.1 ± 0.4	-10.1	24.3	7.9
bio10	-0.20	-0.51	17.9 ± 0.1	5.5	24.7	2.6
bio11	0.21	0.59	-0.8 ± 0.2	-12.5	9.4	4.8
bio12	0.13	0.00	675.4 ± 9.5	217.0	1513.0	197.8
bio13	0.05	-0.03	82.2 ± 1.1	28.0	198.0	23.9
bio14	0.27	-0.01	35.2 ± 0.6	7.0	85.0	12.5
bio15	-0.32	0.04	27.0 ± 0.4	7.7	68.8	9.0
bio16	0.06	-0.04	226.5 ± 3.3	77.0	542.0	68.1
bio17	0.27	0.01	118.3 ± 2.0	28.0	293.0	40.9
bio18	0.23	0.01	192.9 ± 2.9	28.0	542.0	59.8
bio19	0.03	0.08	151.5 ± 3.1	59.0	470.0	65.8

Notes: * – bioclimatic variables: bio1 – mean annual temperature, bio2 – mean of monthly temperature ranges, bio3 – isotherm, Bio* – bioclimatic variables: bio4 – seasonality of temperature, bio5 – maximum temperature of the warmest month, bio6 – minimum temperature of the coldest month, bio7 – annual temperature range, bio8 – average temperature of the wettest quarter, bio9 – average temperature of the driest quarter, bio10 – average temperature of the warmest quarter, bio11 – average temperature of the coldest quarter, bio12 – annual precipitation, bio13 – precipitation of the wettest month, bio14 – precipitation of the driest month, bio15 – seasonality of precipitation, bio16 – precipitation for the wettest quarter, bio17 – precipitation of the driest quarter, bio18 – precipitation of the warmest quarter, bio19 – precipitation of the coldest quarter.

Opatrum sabulosum avoids environments with high seasonal temperatures, as these ecological conditions can create unstable and stressful situations that are detrimental to the species' survival and reproduction. Temperature seasonality is characterised by substantial fluctuations between the annual maximum and minimum temperatures, which poses a significant challenge for poikilothermic organisms that cannot regulate their body temperature autonomously (Wagner et al., 2023). The high level of temperature seasonality is associated with abrupt changes in environmental conditions that can disrupt the life cycle of beetles. For instance, during frigid winters, adults may perish due to freezing, while in periods of high temperature, the risk of dehydration and heat stress escalates. Such fluctuations render the long-term survival of the species complex. The beetles' life cycle is significantly influenced by the soil conditions, which are also affected by the sharp seasonality of temperatures. Low winter temperatures can result in soil freezing, hindering the survival and activity of the beetles. This, in turn, can lead to a reduction in soil microorganisms, which are vital for decomposing organic matter and forming a food base. Conversely, during the warm season, overheating of the soil can also exert a detrimental effect on these processes. High-temperature seasonality can reduce the availability of stable microclimatic conditions where the beetles can hide (Schebeck et al., 2024). The constant change in temperature makes it difficult to maintain safe

places for wintering or protection from heat in summer. *Opatrum sabulosum* evades conditions with high-temperature seasonality due to the requirement for a stable environment conducive to completing its life cycle.

Extreme temperatures create conditions deleterious to survival, development and reproduction. Therefore, *O. sabulosum* avoids situations in which the maximum temperature of the warmest month is elevated. This species is highly sensitive to ambient temperature, with excessive heat potentially inducing heat stress, disrupting physiological processes. The increased risk of dehydration, as insects quickly lose moisture through evaporation, is another consequence of high temperatures (Riddell et al., 2023). This is particularly problematic for *O. sabulosum*, as its survival is contingent on the moisture content of the soil. In arid conditions, the soil can dry out, creating further challenges for the survival of larvae and adults (Potter & Woods, 2012). Elevated temperatures can adversely impact the development of eggs and larvae, given their heightened sensitivity to elevated temperatures (Cui et al., 2018). The consequences of soil overheating for the development of these stages can be detrimental, potentially resulting in impaired development or even death of the offspring (Jeffs & Leather, 2014). Elevated temperatures have been demonstrated to impact the insects' food supply (John et al., 2024). In extreme heat, the activity of soil microorganisms that decompose organic matter, providing food for larvae and adults, may decline (Oliver & Brooke, 2017). This may restrict food availability in crucial times. Extreme temperatures can disrupt ecosystem stability by diminishing shelters and favourable microclimatic conditions for beetles (Suggitt et al., 2011). Heat stress shortens the active lifespan of adult beetles, leading to reduced reproduction capacity (Sales et al., 2021).

Our knowledge of *O. sabulosum*'s ecology is significantly enhanced by the finding that this species tends to avoid conditions with a high annual temperature range, particularly in highly continental environments. This avoidance arises from several ecological factors linked to the notable temperature fluctuations between seasons common in climates of continental regions. Significant temperature fluctuations between winter and summer characterise continental climates (Kwiecien et al., 2022). Winter temperatures can plummet significantly in these areas, while summer brings extreme highs, resulting in considerable temperature variations. This poses a significant challenge for poikilothermic organisms such as *O. sabulosum*, as they find it difficult to adapt to such sudden changes in temperature. Very low temperatures can occur in high continental regions in winter, leading to soil freezing. This seriously threatens *O. sabulosum*, as eggs, larvae and adults may not survive such cold weather. Beetles that live in the soil are susceptible to freezing, as the soil does not provide sufficient protection against low temperatures in a high continental climate (Bale & Hayward, 2010). In the summer, when high temperatures characterise the continental climate, soil overheating is risky. This can lead to excessive evaporation of moisture, which causes dehydration of organisms, especially in the warmer months when beetles are actively feeding and reproducing. In addition, high temperatures can upset the balance in the ecosystem, reducing the activity of soil microorganisms, which limits larvae access to food. High continentality also means that conditions are highly variable across the seasons. This creates an unpredictable environment for the species' survival, as extreme temperatures can change microclimate conditions where *O. sabulosum* takes refuge from harsh conditions, such as litter or cracks in the soil. Sudden temperature changes can disrupt this stability and threaten the species' survival. *Opatrum sabulosum* avoids conditions with high continentality and large temperature fluctuations, as these conditions are stressful and can severely limit resource availability, ecosystem stability and the species' ability to survive extreme temperatures. More stable climatic conditions with moderate temperature fluctuations are much more favourable for this species.

Estivation is an essential aspect of *O. sabulosum*'s adaptation to high temperatures. This species tries to avoid conditions with elevated mean temperatures of the warmest quarter due to the peculiarities of its life cycle. *Opatrum sabulosum*, like many other insect species, has a strategic estivation mechanism that allows it to avoid high temperatures and dehydration during the hottest periods of the year. During

estivation, beetles are in a state of slow metabolism, reducing their activity and minimising their need for water and food. This allows them to survive periods of high temperatures when conditions are too harsh for active life. If the average temperature of the warmest quarter exceeds a certain threshold, conditions for estivation become more complex. High temperatures can cause overheating of the soil or surface where the beetles commonly forage, leading to moisture loss and death. It is essential for *O. sabulosum* that the conditions for foraging are stable and do not lead to temperatures rising to levels that are critical for survival. High temperatures can also affect the soil structure, where the beetles find shelter for estivation. Extremely high temperatures elevate the risk of soil desiccation, potentially resulting

in the loss of suitable hiding places. In high-temperature conditions, estivation may be less effective, as beetles may spend more energy maintaining hydration and regulating body temperature than is necessary under moderate conditions. This can lead to a decrease in the viability and reproductive capacity of the population. *Opatrum sabulosum* tries to avoid conditions with elevated mean temperatures of the warmest quarter, as high temperatures can disrupt the estivation process, lead to overheating, dehydration and reduced wintering efficiency, which in turn reduces the species' chances of successful reproduction and survival. Favourable conditions with moderate temperatures provide stability and safety for this species during estivation.

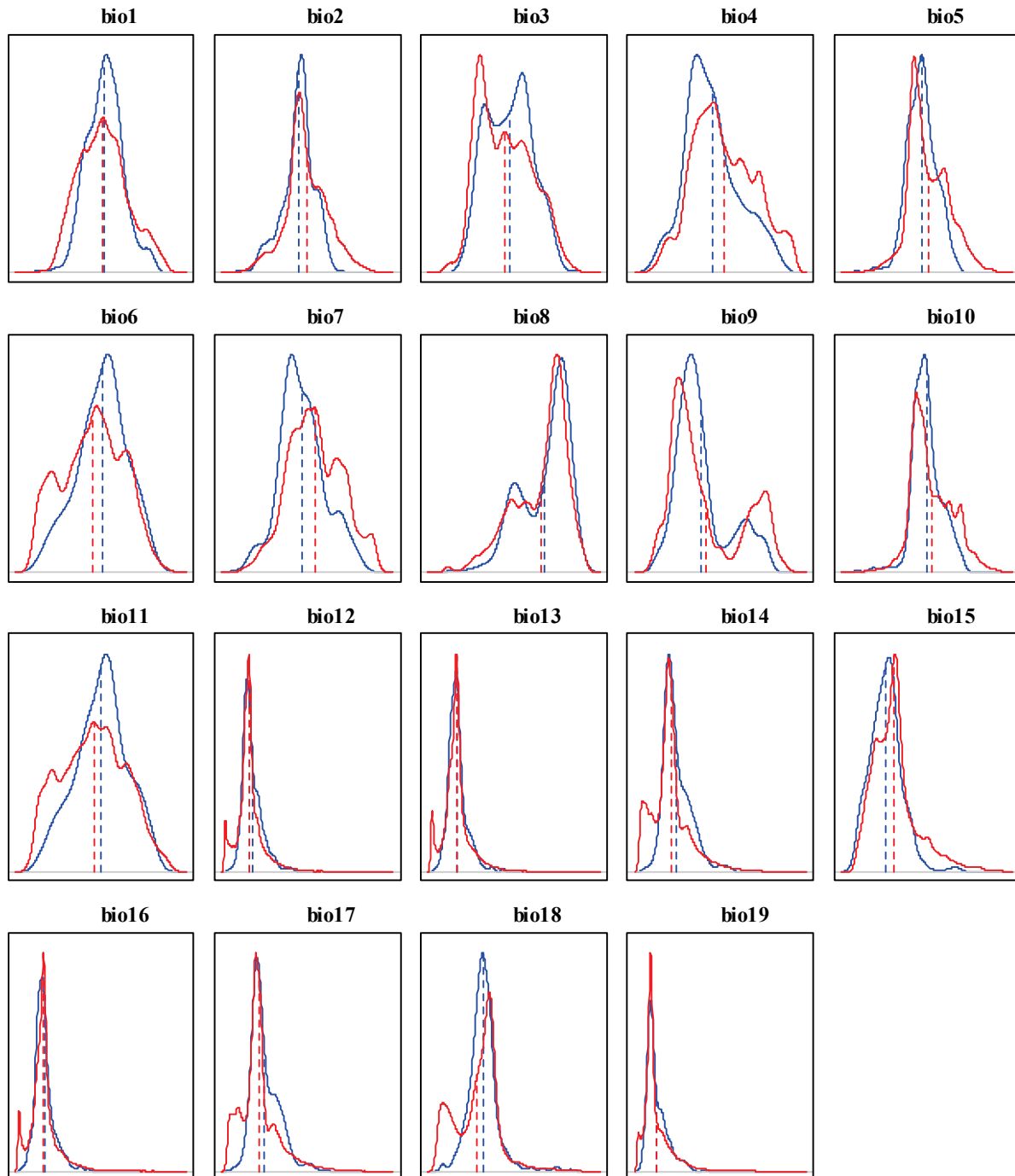


Fig. 3. Histograms of the distribution of bioclimatic variables within the polygon where *O. sabulosum* occurs (red lines) and in the locations where this species was found (blue lines)

Opatrum sabulosum tries to avoid conditions with high seasonality of precipitation due to the need to ensure stable access to water and feed, as well as to adapt to conditions that minimise stress factors related to the water balance of the organism. These conditions are funda-

mental given the differences in the continental regime between Eastern and Western Europe. In regions with a high seasonality of precipitation, when most of the rain falls during specific periods (e.g. winter or early summer), *O. sabulosum* may have difficulty accessing

water in the dry-season or when precipitation is low. The beetles depend on soil moisture and the availability of decomposing organic materials, so unstable or uneven rainfall distribution throughout the year can lead to reduced resource availability and increased dehydration stress. In such conditions, beetles may have problems surviving, as there may be short periods of drought when their water balance is not maintained. In western Europe, the climate is more maritime, with a more even rainfall distribution throughout the year. This creates more stable conditions for organisms that depend on access to water and food. In such conditions, beetles can survive periods of dryness or excessive moisture without significant fluctuations in the water balance. At the same time, in Eastern Europe, where the climate is more continental, with a more pronounced seasonality of precipitation (with less rain in the summer months), conditions become less favourable for *O. sabulosum*. In such regions, dry periods in the summer can significantly reduce the availability of moisture and fodder, as well as create conditions for overheating of the soil. Under conditions of high seasonality of precipitation, where precipitation may be unevenly

distributed, the beetles may be forced to spend more energy searching for moisture and shelter, reducing their reproduction efficiency and active life. In continental regions with a high seasonality of rainfall, such as Eastern Europe, there may be greater variability between dry and wet seasons, which increases the stressful impact on the organism (Łupikasza et al., 2011). In conditions of high seasonality of precipitation, where in some periods of the year the amount of precipitation increases sharply and in others it decreases sharply, beetles may face a situation where the soil is moist during the rainy season but dries out quickly afterwards, creating conditions for dehydration and overheating during drought. Such instability in the rainfall regime makes it difficult for the species to survive, as they need more stable conditions for estivation, reproduction and feeding. *Opatrum sabulosum* avoids conditions with high seasonality of precipitation due to the need for a stable water balance and access to food, which is critical for survival. Given the differences in continentality between Western and Eastern Europe, the beetles prefer regions with more uniform and predictable rainfall conditions.

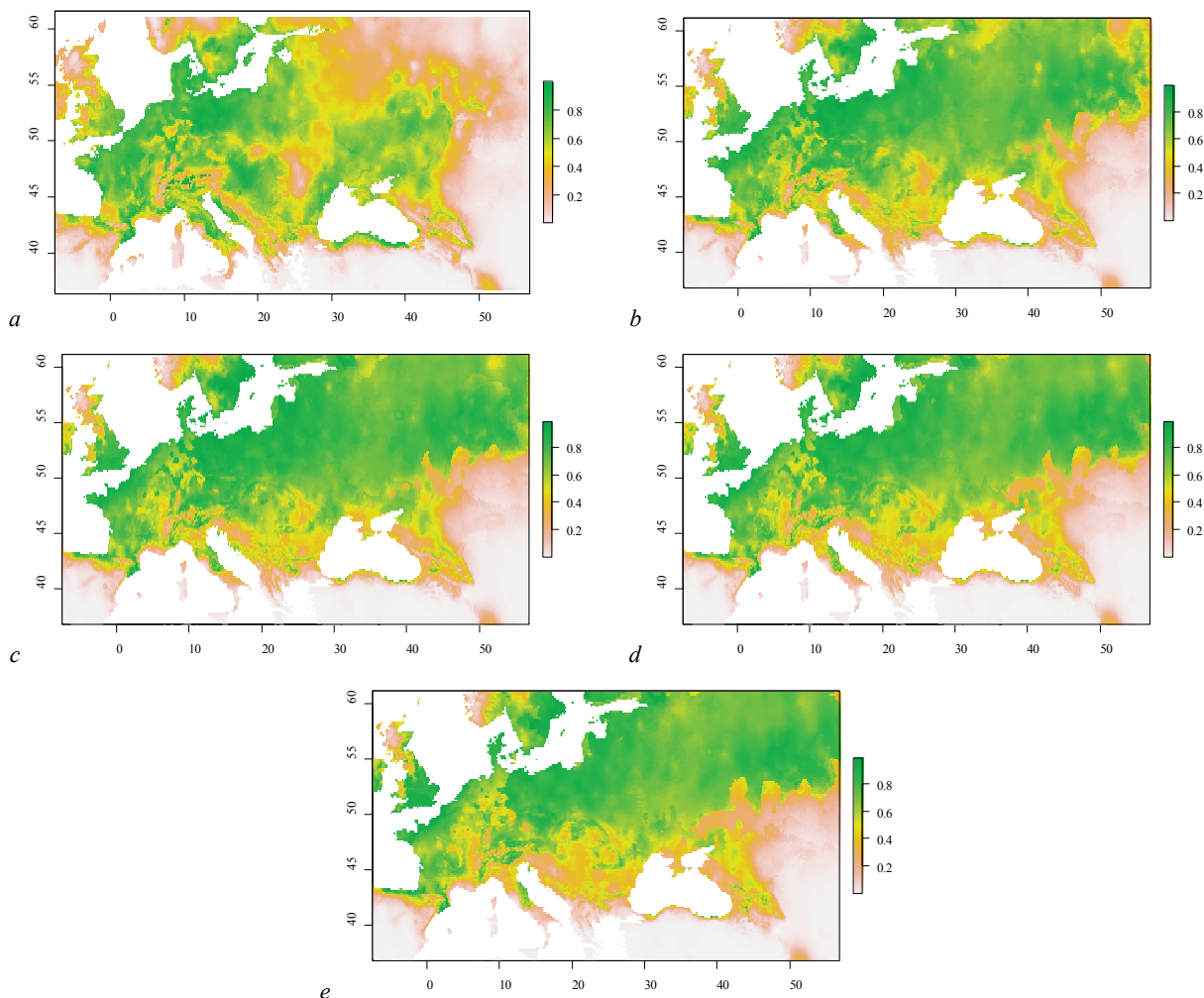


Fig. 4. Spatial variation of the Habitat Suitability Index of *O. sabulosum* estimated on the basis of bioclimatic variables in the present (a) and in the future 2061–2080 for the low emission scenario SSP1-2.6 (b), ‘middle-of-the-road’ scenario SSP2-4.5 (c), high-emission scenario SSP3-7.0 (d), very high emission scenario SSP5-8.5 (e)

The narrow specialisation of *O. sabulosum*’s ecological niche in relation to such bioclimatic variables as temperature seasonality is explained by several important aspects related to the adaptation of this species to specific climatic conditions that minimise stress factors and provide optimal conditions for their life cycle. The physiological processes of *O. sabulosum* are closely related to the temperature conditions of the environment. Seasonal temperature fluctuations can significantly affect the ability of this species to maintain its vital functions (Mugwanya et al., 2022). Abrupt changes in temperature between summer and winter can cause stress, disrupting normal metabolic processes. Therefore, a narrow specialisation in temperature seasonality

helps to maintain stable conditions for the development of the species, reducing the likelihood of such stressful situations. *Opatrum sabulosum* specialises in environmental conditions where temperature seasonality is moderate, with minimal differences between winter and summer. In such conditions, this species can effectively adapt to temperature changes, avoiding extreme fluctuations that can be dangerous for its life cycle. Sharp temperature fluctuations can make it difficult for the species to overwinter, be active or reproduce, so narrow specialisation reduces the risk of adverse effects from sudden temperature changes. *Opatrum sabulosum* has estivation mechanisms that allow it to avoid periods of high temperatures. Given the high seasonality

nality of temperatures, it is essential that this species can survive extreme temperatures without leaving the optimal conditions for estivation or wintering. To do this, they need an ecological niche where the temperature differences between summer and winter are not too sharp. Seasonal temperature fluctuations also affect the availability of food and shelter (Lownds et al., 2023). *Opatrum sabulosum* depends on organic materials and microorganisms for nutrition, and sudden changes in temperature can alter the activity of soil microorganisms, which affects the availability of food. In addition, a wide temperature range can cause changes in ecosystem structure, which reduces the ability to find shelter or places to estivate. It also favours narrow specialisation, as the species avoids conditions where temperature fluctuations can affect the foraging base or environmental micro-conditions.

The favourable conditions for *O. sabulosum* in the modern period in Western Europe, southern Britain, Scandinavia and the northern Black Sea region can be explained by several environmental and climatic factors that create optimal conditions for the species. Western Europe, southern Britain and Scandinavia have a temperate maritime climate, with more even temperature fluctuations throughout the year. This provides stable conditions for the development and activity of *O. sabulosum*. Moderate temperatures without sharp seasonal fluctuations typical of continental climates allow the species to avoid extreme temperature stresses, which can be an important factor for survival. In such conditions, the species can reproduce and develop effectively. In these regions, there is a sufficient level of precipitation, which is distributed more or less evenly throughout the year. This ensures that the soil is moist and the microclimate is stable for the development of larvae and adults. At the same time, the low seasonality of precipitation provides favourable conditions for estivation, as there are no sudden changes in soil moisture. This stability provides safe conditions for the existence of *O. sabulosum*, which requires a certain amount of moisture for its normal life cycle. The Northern Black Sea region has a temperate climate with sufficient rainfall and warm winters, which allows *O. sabulosum* to adapt to conditions with higher winter temperatures compared to more continental regions. It also has stable access to forage resources, such as organic material in the soil, which is important for this species. Elevated temperatures and sufficient moisture, combined with mild winters, allow the species to avoid extreme conditions and breed successfully. In these regions, there are suitable ecological niches for *O. sabulosum*, including dry or sandy soils, which are well suited for this species. This landscape and soil type favours the development of species that require specific conditions for breeding and resting, as well as for wintering. The spread of the species to southern Britain, Scandinavia and the northern Black Sea region may be due to the availability of such ecological niches. In the context of climate change, with rising average temperatures, *O. sabulosum* can adapt to new conditions, gradually expanding its range to the north. In particular, southern Britain, Scandinavia, and the northern Black Sea region are experiencing rising temperatures, which may be favourable for this species, as these areas are becoming more suitable for its existence due to less exposure to extreme temperatures and stable conditions for its life cycle.

Climate change may not significantly affect the distribution of *O. sabulosum* in Western and Southwestern Europe. Still, it will create favourable conditions for its spread in Eastern and Northeastern Europe due to several important factors. Western and Southwestern Europe already have a moderately warm climate with relatively stable conditions for *O. sabulosum*. The climate in these regions is already well adapted to the requirements of the species, and changes in temperature or precipitation caused by climate change may not lead to significant changes within the species' range. Because the climate in these areas is already optimal for the species, it may remain stable under climate change. And while there may be minor changes in precipitation or temperature patterns, these are unlikely to create new constraints on the species. Climate change, in particular an increase in average temperatures, may create favourable conditions for the spread of *O. sabulosum* in Eastern and Northeastern Europe. This is because temperatures in these regions may rise to a comfortable level for the species. As many parts of Eastern Europe and Scandinavia experience

extraordinary to moderately cold climatic conditions (Artmann et al., 2007), rising temperatures could make these regions more suitable for the species. The beetles may adapt to these new conditions due to increasing average temperatures, allowing them to expand their range north and east. Under climate change, precipitation levels may also change. It is essential for *O. sabulosum* that conditions are sufficiently stable regarding water balance, especially during periods of activity. In Western Europe, changes in the precipitation regime may be less noticeable, as moderate precipitation levels already characterise this region. However, Eastern and Northeastern Europe may see an increase in precipitation or a decrease in seasonal fluctuations, which could improve conditions for the species. Rising temperatures in the Northern and Eastern regions of Europe may contribute to changes in landscape conditions, opening up new ecological niches for *O. sabulosum*. For example, greater availability of dry soils, milder winters and an increase in the number of favourable ecosystems for the species could create conditions for its expansion (Dao et al., 2024). Rising temperatures and changes in seasonality in these regions may facilitate the migration of *O. sabulosum* to new areas where the former climatic conditions become more suitable for the species. The natural process of adaptation and migration may allow the species to expand its range in Eastern and Northeastern Europe, where conditions were previously less favourable. Therefore, climate change will contribute to the expansion of *O. sabulosum*'s range in Eastern and Northeastern Europe by creating conditions with higher temperatures and reduced seasonal fluctuations, essential for the species. At the same time, climate change may be insignificant in Western and Southwestern Europe and will not lead to significant changes in the distribution of this species.

A more pronounced warming trend may cause a significant deterioration in the habitat conditions of *O. sabulosum* in the southeastern part of the species' range due to several important environmental factors related to rising temperatures and changing climatic conditions. *O. sabulosum* is a species that has a certain tolerance to temperature fluctuations, but the high temperatures that occur in the context of global warming can cause overheating. Higher average temperatures already characterise the southeast of the species' range, and additional temperature increases could lead to soil overheating, negatively affecting the species' life cycle. In particular, rising temperatures may reduce soil moisture levels, making it more difficult for the species to survive as it requires moderate moisture to develop. In many southeastern European regions, the temperature is expected to rise, and changes in precipitation patterns are also likely. The warming trend could lead to drought or uneven distribution of precipitation, which would negatively affect the water balance and availability of resources for *O. sabulosum*. Increased temperatures may lead to rapid evaporation of moisture from the soil, creating conditions for water shortages, especially in summer, when the species' water requirements are most significant. This may make it difficult for the species to survive in the southeastern part of its range. Increased temperatures may disrupt the species' normal seasonal cycle. If temperatures rise, this may affect the wintering and establishment processes of *O. sabulosum*. They may become less efficient or even impossible if winter temperatures rise excessively. Such changes may result in the species being unable to adapt to new temperature conditions, making it vulnerable to extreme weather events. Increased temperatures and changes in ecosystems may lead to changes in the availability of forage resources, such as organic materials in the soil used by *O. sabulosum* for feeding. Changes in vegetation composition and a reduction in the amount of organic residues may reduce the quality of the environment for the species, which in turn will limit its ability to feed and reproduce. Increased temperatures may encourage the migration of more heat-tolerant species competing with *O. sabulosum*. This could result in species better adapted to hotter conditions replacing *O. sabulosum* in the southeast of its range, reducing its abundance and distribution. The more pronounced warming trend creates conditions that do not meet the requirements of *O. sabulosum*, in particular due to overheating of the soil, decreased moisture and changes in the precipitation regime. Increased temperatures, particularly in summer, may make the environment in the southeast of the species' range less fa-

avourable for its existence, leading to a deterioration in conditions for this species.

The practical importance of the results obtained is twofold. Firstly, they can be used to develop measures for biodiversity conservation and natural resource management in the context of climate change. Predictions of changes in the range of *O. sabulosum* can be used to assess the risks of ecosystem degradation, where this species plays an essential ecological role, particularly in soil formation and organic matter cycling. The findings are particularly relevant to agriculture, as *O. sabulosum* can influence soil conditions and agroecosystem dynamics. Information on the potential expansion or contraction of the species' range allows us to predict possible changes in the interaction of this species with other ecosystem components, which is vital for maintaining ecological balance. The research results can be utilised to develop models to assess the impact of climate change on other species with analogous ecological niches and formulate recommendations for adapting conservation strategies in diverse regions. This will improve the efficiency of environmental planning and ensure sustainable use of natural resources.

Prospects for further research include a more detailed analysis of the impact of climate change on the ecological niche of *O. sabulosum*. This analysis should utilise modern climate models and consider local environmental factors. It is recommended that research be extended on the impact of anthropogenic factors, such as land use change, agricultural activities, and urbanisation, which can significantly affect the distribution and abundance of the species. Another promising area is the study of the genetic diversity of *O. sabulosum* populations, which will allow us to assess their adaptive capacity to different climatic conditions. Integrating data obtained from ecological modelling and genetic studies will facilitate more accurate predictions of possible changes in the species' range in the future. Long-term monitoring of populations is necessary to assess the real impact of climate change and other environmental factors on their dynamics. Developing adaptation strategies based on these results will be important for biodiversity conservation and sustainable management of natural resources.

Conclusion

Investigations have revealed that the key bioclimatic indicators influencing the geographical distribution of *O. sabulosum* are the minimum temperature of the coldest month, the average temperature of the coldest quarter, and the precipitation levels in the wettest month and the warmest quarter. The species exhibits a discernible preference for ecological regimes characterised by moderate climatic conditions, marked by stable temperatures and adequate humidity. Current conditions indicate that the optimal habitats for this species are located in Western Europe, Southern Britain, Scandinavia and the Northern Black Sea region. Projections suggest that climate change will influence the species' range expansion in the eastern and northeastern directions, driven by increases in average temperatures and stabilisation of the water balance. The southeastern regions, however, are projected to experience adverse effects, including soil overheating, reduced moisture, and altered precipitation patterns, which will impose considerable stress on the life cycle of *O. sabulosum*. It is, therefore, vital to emphasise the necessity for adaptation strategies to ensure the preservation of the species' population in the future.

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