



Original article

Reynoutria x bohemica (Polygonaceae): modeling potential changes in its secondary range in Ukraine

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ABSTRACT

Reynoutria x bohemica Chrtek et Chrtková (Polygonaceae) is one of the most aggressive invasive plant species in Europe, posing significant ecological risks to native ecosystems. In Ukraine, there is currently a more active spread of the species than of one of its parent forms (*R. japonica* Hout). In this study, species distribution modelling (SDM) was applied for the territory of Ukraine using climatic variables across three temporal projections (2025, 2021–2040, 2041–2060). Principal component analysis (PCA) and clustering of variables identified the key environmental factors shaping the species' potential distribution. The highest contribution to the models was associated with precipitation seasonality (bio_14), minimum temperature of the coldest month (bio_6), and temperature seasonality (bio_4), reflecting the species' sensitivity to the interaction between moisture availability and temperature extremes. Heat maps of percent contribution (PC) and permutation importance (PI) revealed temporal shifts in variable relevance: while precipitation-related parameters remained consistently important, temperature-related predictors gained greater influence under future climate scenarios. The results indicate that the northern and north-eastern regions of Ukraine are the most vulnerable to further invasion. The findings provide a robust methodological basis for predicting invasion risks and justify the need for regionally differentiated monitoring and biosecurity strategies.

KEY WORDS: Bohemian knotweed; species distribution modelling; Principle Component Analysis; clustering; climatic variables

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1. Introduction

Biological invasions represent a major global challenge, as they lead to substantial biodiversity losses, alter the structure and functioning of native ecosystems, and cause considerable economic damage across multiple sectors, including agriculture, forestry,

and infrastructure. In recent decades, the impacts of invasive species have been further intensified by ongoing climate change, which modifies temperature and precipitation regimes, reduces environmental barriers, and creates new opportunities for the establishment and spread of non-native organisms (DIDUKH ET AL., 2015; DIDUKH, 2023; ROY ET AL., 2024).

In this context, the development of effective strategies to prevent and control biological invasions requires the application of robust predictive approaches. Species distribution and ecological niche models make it possible to identify the key environmental factors driving the spread of invasive species, to assess their sensitivity to changing climatic conditions, and to predict future population dynamics and range shifts under different climate scenarios. One of the commonly used approaches for such modelling is the MaxEnt (Maximum Entropy Modelling) algorithm (PHILLIPS ET AL., 2006, 2023; PHILLIPS, 2017), which allows an assessment of potential species distributions based on available occurrence data and environmental variables. Its widespread application is largely due to the accessibility and ease of use of the software.

Species distribution modelling (SDM) based on environmental and climatic variables is widely used in studies of alien species (CABEZA ET AL., 2004; RUSHTON ET AL., 2004; ELITH ET AL., 2006; JOVANOVIĆ ET AL., 2018), as it predicts potential distribution ranges of invasive plants and their capacity to colonize new territories. These approaches also enable the simulation of potential climate change impacts on species distributions and the identification of areas with a high risk of invasion based on relatively limited data, such as georeferenced occurrence records. One of the commonly used algorithms for such analyses is MaxEnt. This is particularly important for the development of effective control and prevention strategies, as it allows an assessment of invasion risks and potential impact on native plant communities. Consequently, MaxEnt is widely used in invasion ecology, plant conservation biology, ecological planning, and impact assessment of invasive species (PHILLIPS ET AL., 2006; PHILLIPS & DUDÍK, 2008; CHYTRY ET AL., 2009; KUMAR & STOHLGREN, 2009; BUCKLEY ET AL., 2011; ELITH ET AL., 2011; FRANKLIN ET AL., 2013; YI ET AL., 2016; UNTALAN ET AL., 2019; BURGOS & MARTINEZ, 2019; KAKY ET AL., 2020; SARIKAYA & ORUCU, 2021; AXMANOVÁ ET AL., 2021; AOUINTI ET AL., 2022; DAI ET AL., 2022; DABA ET AL., 2023; ROY ET AL., 2024; ŠTÍPKOVÁ ET AL., 2024; DONG ET AL., 2025).

In Ukraine, MaxEnt has so far been used in only a limited number of studies to assess the potential spread of native and alien species (MOSYAKIN, 2013; MOSYAKIN & KAZARINOVA, 2014; LYUBKA, 2018; NOVIKOV & LABEL, 2020; PROKOPUK ET AL., 2023). Therefore, the application of this approach to characterize *Reynoutria × bohemica* Chrtek & Chrtková (Polygonaceae) appears highly relevant, as this species is considered

one of the most dangerous invasive plants, successfully colonizing large areas of Ukraine and other European countries (BAILEY ET AL., 2006; SHEVERA, 2017).

The species originated in Europe, most likely within the territory of the Czech Republic (town of Náchod in northeastern Bohemia), by crossing *R. japonica* Hout. and *R. sachalinensis* (F. Schmidt) Nakai, two invasive species responsible for the formation of numerous hybrids. The hybrid origin of *R. × bohemica* is considered a key factor underlying its high genetic variability, which enhances ecological plasticity and promotes successful colonization (BÍMOVÁ ET AL., 2004; TOKARSKA-GUZIK ET AL., 2017; TYNKEVICH ET AL., 2024, 2025; YAKOBYSHEN ET AL., 2025).

Reynoutria × bohemica is characterized by rapid growth, high biomass production, and pronounced allelopathic properties. It forms dense monospecific stands mainly along riverbanks, in anthropogenic habitats, and other biotopes. The species is capable of suppressing the growth of native herbaceous and woody plants, disrupting natural vegetation recovery and altering the structure of native plant communities (BAILEY & WISSKIRCHE, 2006; STRAŠIL & KÁRA, 2010; BZDEGA ET AL., 2014, 2018a, b, 2022; TOKARSKA-GUZIK ET AL., 2015; SHEVERA, 2017, etc.).

The aim of this study was to simulate the potential distribution of *R. × bohemica* in Ukraine using climate variables and to identify the key factors shaping its potential range by using integrated species distribution models combined with Principal Component (PCA) and clustering analysis.

2. Materials and methods

Data on the distribution of *R. × bohemica* in Ukraine were obtained from the analysis of herbarium collections (KW, LWKS, LWS, KRW, DNZ, UU, CHER, LW, KWU, KWH, CWU, MSUD, DSU, YALT, SIMPH, KHER, PTR, PDH), open-access databases (UkrBin, iNaturalist, GBIF) and published literature summarized in the Bibliography (ALIEN ..., 2025).

The potential distribution of the species was modelled based on bioclimatic data using the maximum entropy approach implemented in the MaxEnt 3.4.4 software package (PHILLIPS ET AL., 2006; PHILLIPS & DUDÍK, 2008) within the Java Runtime Environment.

To simulate the potential and projected distribution of *R. × bohemica* in Ukraine, 806 records of species occurrences within the study area were used (Fig. 1). When generating the *R. × bohemica* distribution model using MaxEnt, 75% of randomly selected

records were applied for model training (the "random test percentage" parameter), while the remaining 25% were used to evaluate model performance.

In ecological niche modelling (ENM), in particular applying the MaxEnt algorithm, one of the key indicator of model performance is the area under the receiver operating characteristic curve (AUC - Area Under the Curve). This indicator reflects the model's ability to correctly distinguish between sites where the species is present, and background points treated as absences. The AUC represents the integral of the ROC curve (ROC — Receiver Operating Characteristic) constructed across different species presence probability thresholds and describes the relationship between sensitivity (True Positive Rate) and specificity (1 – False Positive Rate). AUC values range from 0.5, which corresponds to a random prediction, to 1.0, which indicates a perfect model. It is generally accepted that an AUC value > 0.7 indicates a satisfactory predictive performance, whereas values of > 0.9 reflect high model accuracy.

Bioclimatic data were obtained from the WorldClim database and included 19 derived

climatic variables (Table 1) calculated from long-term monthly averages of temperature and precipitation. These variables characterize annual trends, seasonality, and extreme or limiting climatic factors relevant to species distribution modelling.

To predict the potential spread of *R. × bohemica* in Ukraine, an appropriate Global Climate Model (GCM) was selected from those available in WorldClim database. Taking into account the regional climatic features of Eastern Europe and model performance, the MPI-ESM1-2-HR model was chosen due to its high spatial and temporal resolution, reliable reproduction of present-day climatic conditions in Eastern Europe, and proven applicability in European climate change studies.

Species distribution projection was performed under the moderate climate scenario SSP2-4.5, which assumes balanced socio-economic development and mitigation efforts without radical emission reductions, resulting in a projected global temperature increase of approx. +2.7°C by 2100. This scenario is widely recommended for ecological and environmental impact assessments.

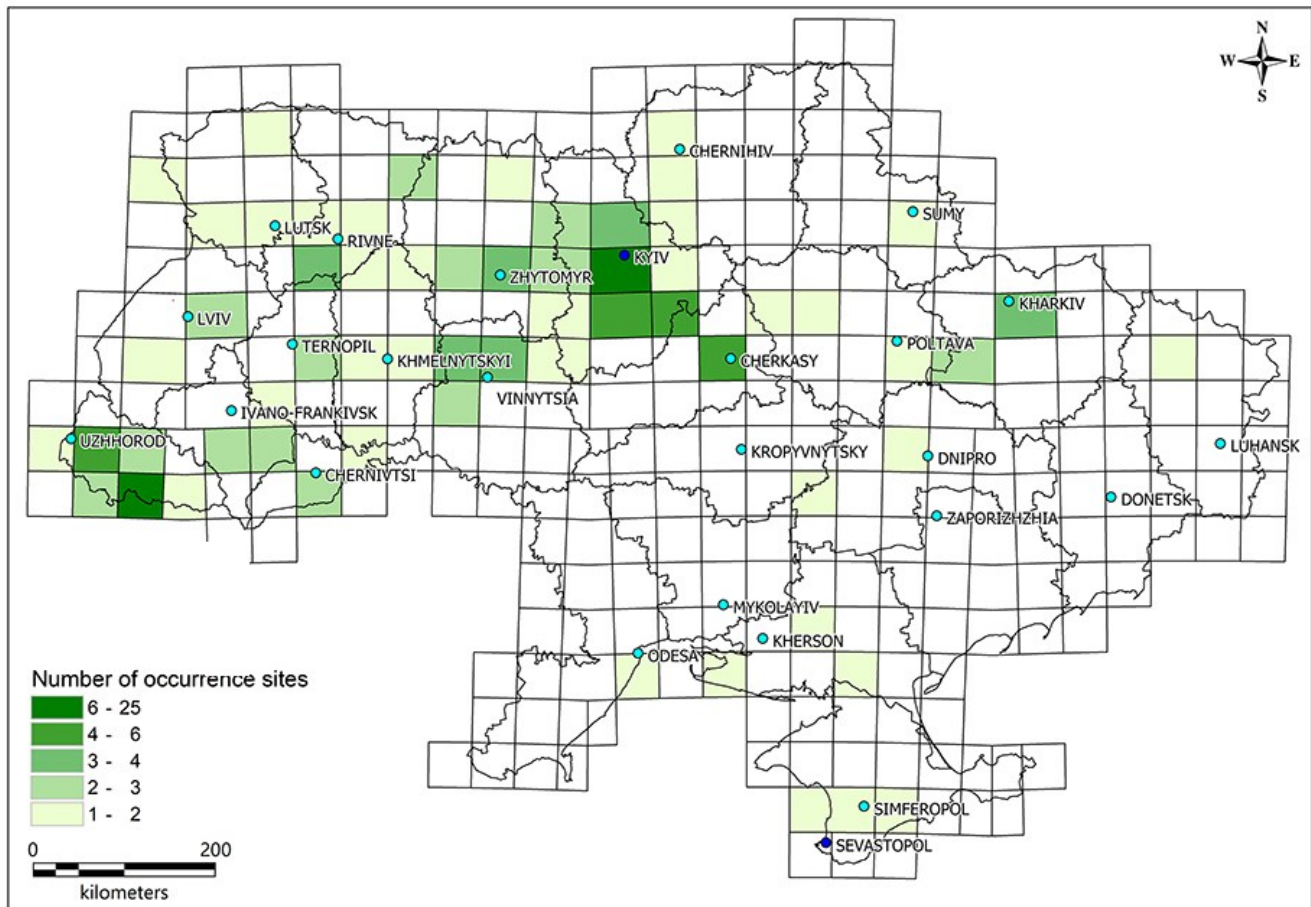


Fig. 1. Spatial distribution of *R. × bohemica* occurrence records in Ukraine based on documented localities

Table 1. Bioclimatic Indicators

Data type	Factor	Description
Temperature Indicators:	BI01	Mean Annual Temperature.
	BI02	Mean Diurnal Range: The difference between average daytime and nighttime temperatures.
	BI03	Isothermality: the ratio of BI02 to BI07.
	BI04	Temperature Seasonality: Standard deviation of temperature.
	BI05	Max Temperature of Warmest Month.
	BI06	Min Temperature of Coldest Month.
	BI07	Annual Temperature Range: The difference between BI05 and BI06.
	BI08	Mean Temperature of Wettest Quarter.
	BI09	Mean Temperature of Driest Quarter.
	BI010	Mean Temperature of Warmest Quarter.
	BI011	Mean Temperature of Coldest Quarter.
Precipitation Indicators:	BI012	Annual Precipitation.
	BI013	Precipitation of Wettest Month.
	BI014	Precipitation of Driest Month.
	BI015	Precipitation Seasonality: Coefficient of variation.
	BI016	Precipitation of Wettest Quarter.
	BI017	Precipitation of Driest Quarter.
	BI018	Precipitation of Warmest Quarter.
	BI019	Precipitation of Coldest Quarter.

To visualize the simulation results, raster layers with a special resolution of 2.5 arc minutes were generated and processed in QGIS version 3.34.0. Distribution maps were subsequently compiled using MapInfo Professional 7.5 software (Product – 20MIRU750WP; Sequence number – MIPWRS0750400147) (MapInfo Professional, 2010) in accordance with the methodology of the Atlas Florae Europaeae (JALAS & SUOMINEN, 1972), adapted for the study area, using a $50 \times 50 \text{ km}^2$ grid.

Taxonomic nomenclature and information on species origin followed POWO. Digital datasets were analysed using standard statistical methods (ŁOMNICKI, 2011; BUDZHAK, 2013) implementation in R (R CORE TEAM, 2025) and Microsoft Excel (CORNELL, 2007), STATISTICA 10.0 (STATSOFT, INC., 2011) and SPSS STATISTICS 17.0 (BÜHL & ZÖFEL, 2005).

3. Results

Models were developed in the MaxEnt environment to analyse the spatial dynamics of the potential spread of *R. × bohemica*. Model performance was evaluated using the Area Under Curve (AUC) indicator for both training and test datasets (Fig. 2). The mean

AUC value for the training dataset was 0.971 ± 0.001 , while that for the test dataset was 0.969 ± 0.001 . The minimal difference between these values shows high stability of the model, although the slight discrepancy indicates the possible effect of spatial or environmental heterogeneity in the data.

Overall, the obtained models demonstrate very high predictive performance ($\text{AUC} > 0.95$), which makes it possible to use them confidently to predict the future habitats of the studied species particularly taking into account the effects of climate change.

To assess the significance of 19 bioclimatic variables (BI01-BI019) in predicting the potential spread of *R. × bohemica* during three time periods (2025, 2021–2040, 2041–2060), multivariate principal component analysis (PCA) and K-means clustering were used. Both percent contribution (PC) and permutation importance (PI) were included in the analysis, allowing the direct contribution of variables to the model and their permutation stability to be integrated. The first two principal components explained the main variance in the dataset and clearly divided the variables into three functionally distinct clusters (Fig. 3).

Cluster 0 ($n = 14$ variables: bio_1, bio_2, bio_3,

bio_5, bio_7, bio_8, bio_9, bio_10, bio_11, bio_12, bio_13, bio_15, bio_16, bio_17, bio_18, bio_19). These variables characterize background temperature and precipitation parameters (average temperatures, variability, amounts of precipitation in different periods of the year), which in most scenarios demonstrate a low contribution to PC, but in some cases have a significant PI (for example, bio_1 and bio_11 in 2025).

Cluster 1 (n = 2 variables: bio_4 and bio_6). These indicators consistently exhibit high PC values across all time periods (14-24%), as well as a significant PI values in the 2021-2040 and 2041-2060 periods. They reflect critical temperature limits that restrict or enable winter survival and vegetation period of the species.

Cluster 2 (n = 1 driving variable: bio_14). This is the only variable that shows a dominant contribution to the PC (42-47%) and a high PI (15-41%) across all scenarios. Precipitation in the driest month reflects water stress in the least favourable period and represents a key factor determining the survival and spatial distribution of *R. × bohemica*.

Thus, the average temperature of the coldest quarter (bio_6), the amount of precipitation of the driest month (bio_14), and the temperature seasonality (bio_4) appear to be the most important factors that determine the potential spread of *R. × bohemica*. (Fig. 4 A, B).

Across all time periods (Fig. 4A), bio_14 maintains a leading role in PC: 44.5% (2025), 46.6% (2021-2040) and 42.4% (2041-2060), indicating the critical impact of water deficit conditions on the persistence and distribution of the species. The PI indicator for this variable is the highest in the period 2021-2040 (40.9%) (Fig. 4B) and decreases to 15.2% in 2041-2060. This trend may indicate a long-term decline in the importance of minimum precipitation due to temperature changes and altered precipitation patterns throughout the year. Such a strong influence of bio_14 can be explained by the bioecological features of *R. × bohemica*, which is able to tolerate a wide temperature range, but requires sufficient moisture during the period of active biomass accumulation and root regeneration. Reduced precipitation during the dry season can limit colonization in arid regions, while elevated minimum moisture levels during this period create conditions for active range expansion.

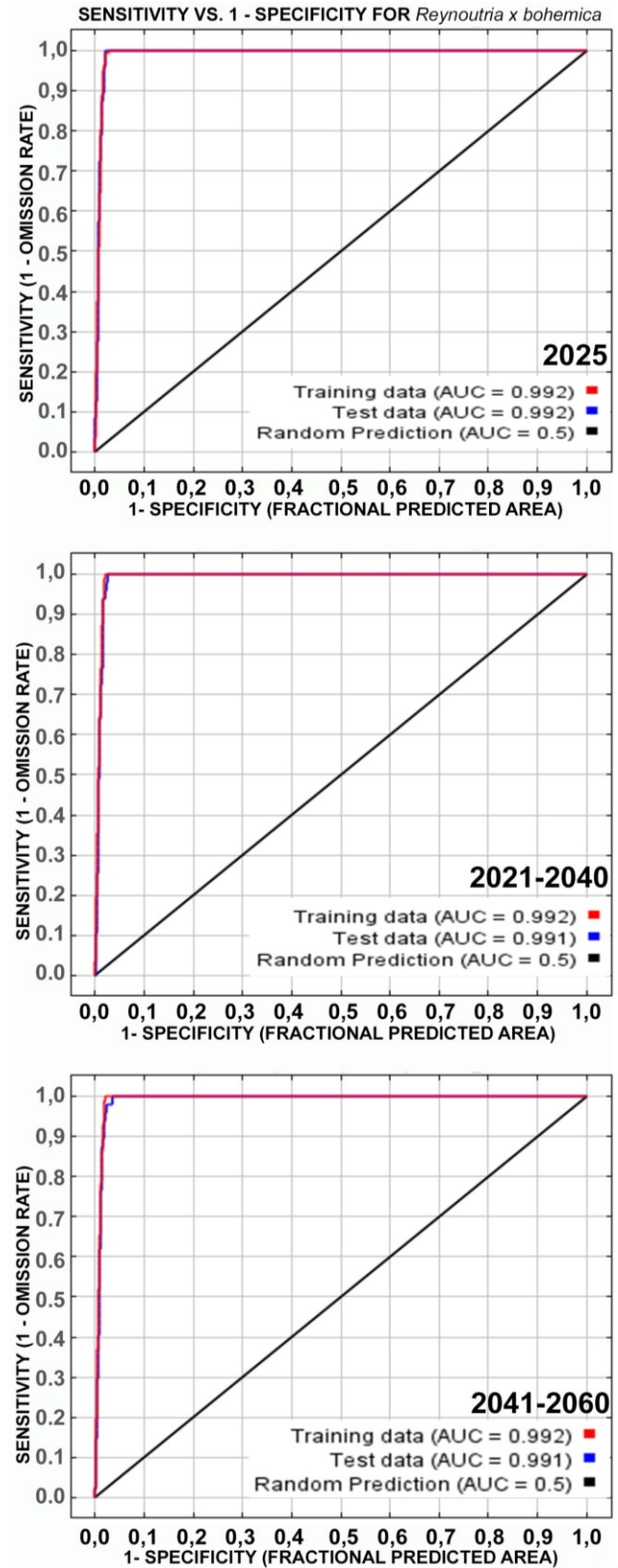


Fig. 2. Receiver Operating Characteristics curves for predictive models of *R. × bohemica* distribution in Ukraine

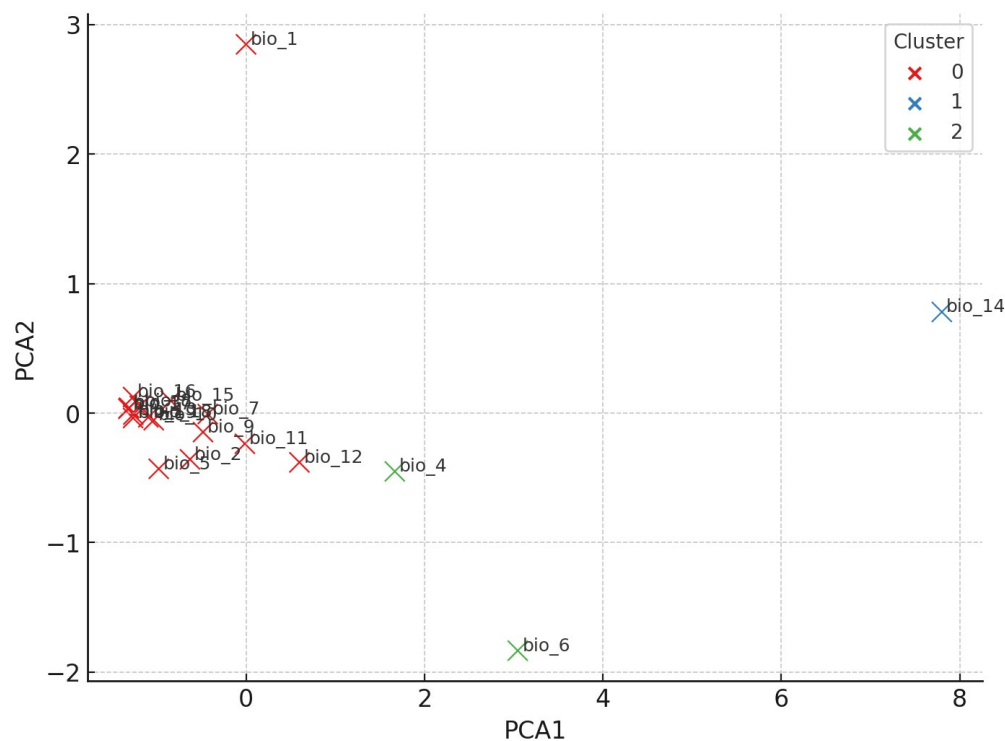


Fig. 3. Results of PCA clustering of climatic variables determining the distribution of *R. × bohemica* in different time periods (2025, 2021–2040, 2041–2060)

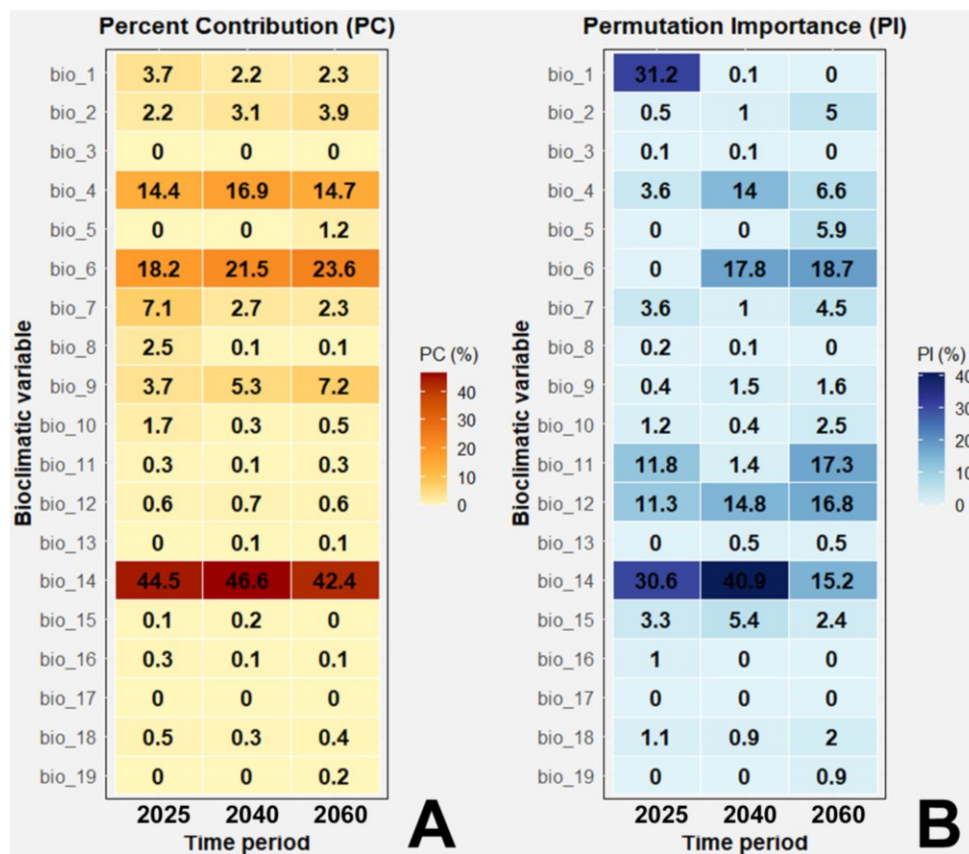


Fig. 4. Contribution of environmental variables based on the results of the distribution model *R. × bohemica* for three time slots: A - Percent Contribution (PC), B - Permutation Importance (PI)

The minimum temperature of the coldest month (bio_6) shows an increasing contribution to the overall invasion risk, accounting for 18.2% in 2025, 21.5% in 2021–2040 and 23.6% in 2041–2060, with a high PI in the medium and long term projections (17.8% and 18.7%, respectively). These results confirm the sensitivity of *R. × bohemica* to winter temperatures and show their importance for wintering and post-winter vegetative recovery. Projected warming, especially in northern and more continental regions, is expected to reduce the risks of frost damage, which will facilitate the species' expansion towards higher latitudes and continental hinterlands.

The temperature seasonality (bio_4) also occupies an increasingly high position, accounting for 14.4 - 16.9% of PC, which reflects the importance of the amplitude of temperature fluctuations for the species' ecological niche. The PI of this variable increases during the 2021–2040 period (14%) and decreases in the 2041–2060 period (6.6%), which may be due to a weakening of seasonal contrasts under the future climate conditions. Moderate temperature seasonality appears favourable for *R. × bohemica*, as it provides a well-defined growing season and sufficient time for biomass accumulation. In contrast, excessive seasonality, i.e., sharp transitions from cold to hot, can limit the development of populations in certain regions, while a reduction in the amplitude of annual temperature fluctuations under the influence of climate change could result in expansion in suitable areas.

In addition, several variables with lower contributions show noteworthy trends. So, the amount of precipitation in the wettest month (bio_12) increases in PI from 11.3% in 2025 to 16.8% in 2041–2060 (Fig. 3B), suggesting a growing importance of precipitation intensity for the species' distribution. The maximum temperature of the warmest month (bio_5) has almost no short-term effect, but its PI rises markedly to 5.9% in the 2041–2060 period, indicating a potential importance of summer heat in the future.

At the same time, variables reflecting the mean monthly temperature of the wettest (bio_8) and driest (bio_9) quarters show a small but gradually increasing influence, which could be a consequence of an increase in climatic extremes. The indicators bio_3, bio_13, bio_17 and bio_19 remain consistently low in all scenarios, suggesting their limited role in shaping the species' ecological niche in the study area.

The obtained results indicate that the future spatial dynamics of *R. × bohemica* in Ukraine will be

largely determined by the combined effects of winter temperatures and precipitation levels during the driest period, while the influence of temperature seasonality and summer precipitation will gradually increase over the medium and long term. This pattern is consistent with the ecological features of the species, which is known for its ability to survive under water deficit and low-temperature stress (JOVANOVIĆ ET AL., 2018), as well as with projected regional climate changes (MIROSHNYK ET AL., 2025). The pronounced role of bio_14 means that moisture availability during the driest month will remain the primary limiting factor under all climate scenarios. Predicted warming and milder winter temperatures (increasing values of bio_6 and bio_11) will likely facilitate the northward and eastward migration, while an increase in annual precipitation (bio_12) will enable colonization of the regions that were previously too dry. These findings are consistent with the results reported by Miroshnyk and co-authors (MIROSHNYK ET AL., 2025) for the distribution of *R. japonica* Houtt. in Europe. The combined effect of these factors indicates a high probability of future range expansion of species, especially under the change in climate conditions that reduce environmental restrictions and increase the climatic suitability across new territories.

Visualization of the modelled distribution of *R. × bohemica* across three time periods (2025, 2021–2040 and 2041–2060; Fig. 5) indicates an expansion of its potential range by 2040 toward northeastern, eastern and southern regions, accompanied by a reduction of suitable territories in the western part of the country. By 2060, as a result of climate change, the areas suitable for the species existence in the south-eastern regions will decrease dramatically (Fig. 5), resulting in an overall reduction in the range of the species.

By 2040, areas with a high probability ($p > 0.6$) of *R. × bohemica* occurrence are expected to increase in the central regions of Ukraine (Fig. 7). However, by 2060 the species' range, particularly areas with a high probability of *R. × bohemica* occurrence, is projected to show a declining trend and return to its current boundaries. The extend of areas characterized by a high probability of *R. × bohemica* occurrence is expected to decrease sharply (Fig. 7).

In light of the predicted changes in the range of *R. × bohemica*, it is advisable to implement systematic, integrated and multilevel monitoring of high-risk areas to enable the timely detection of new populations. Such efforts should focus particularly

on northern and northeastern regions, where the most favourable climatic conditions for further spread are projected to occur.

An important preventive measure to limit the spread of *R. × bohémica* is the restriction of its ornamental use, as well as strict control over soil movement and the transport of plant residues during construction and roadworks, which often act as a pathway for its unintentional dispersal (MIROSHNYK ET AL., 2025). For already established populations, the most effective eradication strategy involves a combination of mechanical removal of both above-ground (BIMOVÁ ET AL., 2001) and below-ground biomass and the application of herbicides. This should be followed by the restoration of native vegetation to reduce the risk of reinfestation.

Management strategies should be adaptive and region-specific. In areas where increasing winter temperatures and sufficient moisture are predicted, long-term control programs will be necessary. In contrast, in more arid regions it is advisable to focus on monitoring and rapid-response measures targeting isolated occurrences of the species.

Thus, our simulations not only describe the potential pathways of *R. × bohémica* expansion, but also provide a scientific basis for the development of a multilevel biosecurity strategy that takes into

account the spatial heterogeneity of climatic changes and the ecological characteristics of the invasive species.

At the same time, it is important to consider several limitations associated with the applied modelling approach. In particular, we now discuss that species distribution models (SDMs), including MaxEnt, are sensitive to the selection of environmental predictors and evaluation metrics, which can influence model performance and ecological interpretation. As highlighted by FOURCADE ET AL. (2018), inappropriate variable selection or reliance on certain statistical measures may lead to biased or misleading predictions. In addition, we recognize that our model may be affected by spatial sampling bias and uneven distribution of occurrence records, which can artificially inflate model accuracy or distort predicted suitability patterns. As demonstrated by DUBOS ET AL. (2022), correcting for sampling bias can substantially alter SDM outputs, and failing to account for it remains a known limitation.

We therefore explicitly state that our results should be interpreted with caution, particularly in regions with sparse data, and emphasize the need for further validation using independent datasets, additional predictors, and bias-correction approaches in future studies.

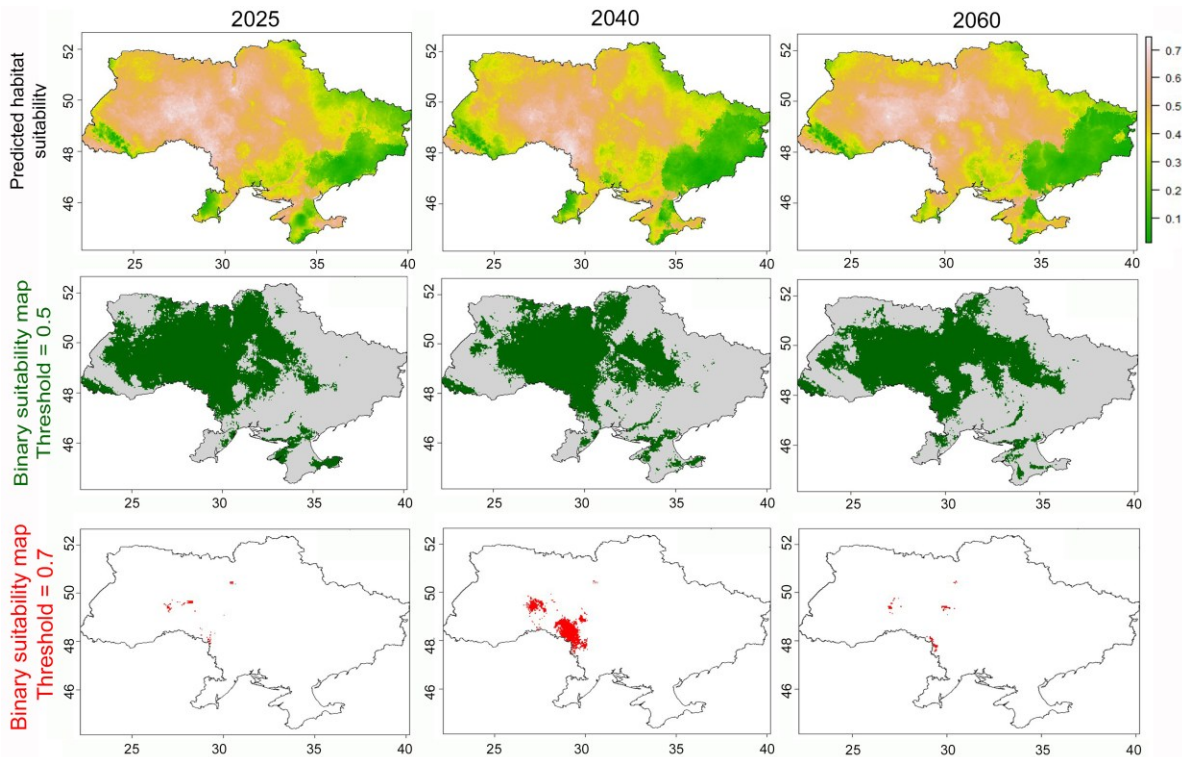


Fig.5. Predicted habitat suitability for *R. × bohémica* based on the MaxEnt model. Values range from 0 (unsuitable habitat) to 1 (highly suitable habitat)

4. Conclusions

A set of key factors determining the potential range of the species was identified through simulations of *R. × bohemica* distribution in Ukraine using bioclimatic variables combined with PCA and clustering approaches. Precipitation in the driest month (bio_14), the minimum temperature of the coldest month (bio_6), and the temperature seasonality (bio_4) made the most significant contributions to the predictive models. This highlights the critical role of the combined effects of temperature extremes and moisture availability in shaping the species' ecological niche.

Analysis of temporal dynamics showed that in the short and medium term (2025–2040), precipitation-related variables will retain their dominant influence, while the importance of temperature-related characteristics will increase in the second half of the 21st century (2041–2060). Heat maps of PC and PI confirmed the constantly high significance of precipitation variables alongside the growing role of temperature extremes, which is consistent with the projected regional climate trends.

The range of *R. × bohemica* is predicted to expand primarily in the northern and northeastern regions of Ukraine, where a favourable combination of climatic conditions will create optimal prerequisites for invasion. The obtained results are of practical importance for biosecurity management, as they enable the identification of regional risk hotspots and development of differentiated monitoring and control strategies.

Thus, the application of integrated species distribution models based on the multivariate analysis of climatic variables is an effective tool for predicting invasion processes and provides a robust scientific basis for the prevention and mitigation of the environmental threats associated with the spread of invasive species.

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