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SPATIAL ECOLOGICAL NICHES MODELLING FOR REINTRODUCTION OF *IRIS PONTICA* ZAPAŁ. (MAGNOLIOPHYTA) IN THE REPUBLIC OF MOLDOVA

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This paper presents the results of a study on spatial ecological niche modeling of a rare spontaneous vascular plant species from the Iridaceae family – *Iris pontica* Zapał. The species is protected by law and is included in the Red Book of the Republic of Moldova (2nd and 3rd editions). The aim of the study was to identify suitable habitats for subsequent reintroduction using current data on the species' distribution and stationary occurrence in the Republic of Moldova. A model generated by the MaxEnt program was used. Six final bioclimatic indexes had been used to generate the probabilistic map of spatial ecological niches for Iris Pontica. Several zones with a high probability of the presence of these ecological niches were identified. The species were reintroduced in a steppe habitat based on spatial ecological niche modeling.

Keywords: *spatial modeling, Iris pontica, Republic of Moldova, bioclimatic indexes, spatial distribution models, maximum entropy model, receiver operating characteristic, training sensitivity plus specificity.*

MODELAREA NIŞELOR ECOLOGICE SPAŢIALE PENTRU REINTRODUCEREA *IRIS PONTICA* ZAPAŁ. (MAGNOLIOPHYTA) ÎN REPUBLICA MOLDOVA

Această lucrare prezintă rezultatele unui studiu privind modelarea nişei ecologice spaţiale a unei specii rare de plante vasculare spontane din familia Iridaceae – Iris pontica Zapał. Specia este protejată prin lege şi este inclusă în Cartea Roşie a Republicii Moldova (ediţiile a II-a şi a III-a). Scopul studiului a fost identificarea habitatelor potrivite pentru reintroducerea ulterioară, utilizând date actuale privind distribuţia şi exigenţele staţionale a speciei în Republica Moldova. A fost utilizat un model generat de programul MaxEnt. Pentru generarea hartei probabilistice a nişelor ecologice spaţiale pentru Iris Pontica au fost utilizaţi şase indici bioclimatici finali. Au fost identificate mai multe zone cu o probabilitate mare de prezenţă a acestor nişe ecologice. Speciile au fost reintroduse într-un habitat de stepă pe baza modelării nişei ecologice spaţiale.

Cuvinte-cheie: *modelare spaţială, Iris pontica, Republica Moldova, indici bioclimatici, modele de distribuţii spaţiale, modelul entropiei maxime, caracteristica de funcţionare a receptorului, sensibilitatea de antrenament plus specificitatea.*

Introduction

The flora of the Republic of Moldova is characterized by the presence of a large number of rare and endangered species of vascular plants of various rarity categories. Rare species of various rarity categories currently constitute approximately 30% of the total flora [3, 11, 18, 21, 35]. The rarest taxa are included in the Lists of State Protected Species [38] and in the Red Data Book of the Republic of Moldova [4]. The conservation status of plants is one of the most widely used indicators for assessing the extent of their possible extinction in the wild. It also provides an important tool in establishing priorities for species conservation.

Vascular plants are subject to the same threats as any other wild species, which, fundamentally, are caused by the conflict between supply and demand for natural resources [28]. The species assessed are therefore mainly affected by loss, degradation and/ or increased fragmentation of their habitats that result from unsustainable human mismanagement of the environment. However, the scale of destruction of biocenoses in many regions often leaves no opportunity to preserve plants in natural conditions.

In this regard, the reintroduction of the rarest species into surviving natural areas, and in the future the restoration and reconstruction of entire communities, should be considered as promising measures to save endangered plants [34]. Reintroduction is the restoration of a species in habitats or areas that were once part of its historical range, and where it was destroyed or disappeared [5, 16, 17].

The efforts in effective in-situ conservation of rare and endangered plants require knowledge of the relationships between species habitat and the environmental factors that shapes it, in other words, their spatial ecological niche. The maximum entropy method used in MaxEnt software allows modeling the spatial distributions models of species (SDMs) based on their occurrence data and environmental variables by finding the geographic range which is closest to geographically uniform while still subjected to the constraints imposed by abiotic factors at presence locations [22]. The principle of maximum entropy states that the most characteristic probability distributions of states of an uncertain environment are those distributions that maximize the chosen measure of uncertainty given the information about the "behavior" of the environment. It uses correlational machine-learning and has a wide application in ecology, in the correlated fields of species distributions and environmental niche modelling [2, 33].

The aim of this study was to model the habitat of a rare and endangered species, Iris pontica Zapał. for reintroduction into the wild with the aim of increasing the number of habitats and increasing the size of local populations.

Materials and Methods

MaxEnt takes as input a list of species presence locations, often referred to as presence-only data (PO), and a set of predictors of environmental "behavior" (e.g., precipitation, temperature) in a user-specified landscape that is divided into grid cells. The presence of a species at background locations is unknown. From this landscape, MaxEnt extracts a sample of background locations, which it compares to the presence locations. Since the total population size is unknown when modeling the ecological niches of biological species, the model generated by MaxEnt predicts a relative occurrence rate (ROR) for each grid cell, which is calculated as the relative probability that a cell in the background location sample is contained in the presence location sample. The maximum entropy model also yields species distribution models (SDMs), in which case the assumption is that we take a random sample of cells in the landscape to determine the presence of a species in them. MaxEnt then predicts the probability of the species being present in each individual cell by transforming the relative frequency of the species using a logistic function, and produces so-called logistic output for each cell in the landscape. This type of output transformation estimates the probability of the species being present between 0 and 1, with the default probability of the species being present at a "typical" presence point being 0.5. This assumption works well in the absence of so-called sampling bias, where, for example, sampling of a species is done closer to populated areas or roads because it is more convenient, and not because the species is most common in these areas.

Although there were several authors who had analyzed the Spatial Distribution Models (SDMs) for Genus *Iris*, either from the point of view of studying the expansion of invasive species [13, 24] or conservation of the rare ones [1, 22, 30, 31], there were no previous works analyzing the ecological niches of *Iris pontica* using the maximum entropy method. The synphytoindication method, which uses 12 factors characterizing soil and climate, and grades the species according to their tolerance amplitude to each of them and their occurrence in the survey, was used on *Iris pontica*, among the other species, in the works of Didukh, who is building up on the methodology of Tsyganov [29]. However, only the scales that reflect how the species are limited by the above-mentioned factors are studied there (similar to Ellenberg's scales [8, 9]).

Iris pontica EUNIS habitat type [6] was classified as continental dry grassland (true steppe) in Ukraine, although the data from the National Botanical Garden (Institute) from Republic of Moldova was not used in the research [7, 10].

It was noted that the MaxEnt software at its default cloglog transform output produces the exact same model that can also be obtained if one maximizes the likelihood of an exponential model obtained from an inhomogeneous Poisson process. In general, the cloglog output is often used both as habitat suitability index and in order to estimate the probability of occurrence [27].

The data used were 20 bioclimatic indexes recalculated for Republic of Moldova area, on the basis of raw data from State Hydrometeorological service's meteorological stations, which allowed us to increase the resolution of the predictors from 1 km (30 arc seconds) in BIOCLIM to 200 meters (9 arc seconds) (WGS 84 datum) for the author predictors. The starting raw data that we used were the monthly means of daily minimum and maximum temperatures, the monthly average temperatures and total monthly precipitation for 18 meteorological stations: (Bălţata, Bălti, Bravicea, Briceni, Cahul, Camenca, Ceadîr-Lunga, Chişinău, Codrii, Comrat, Corneşti, Dubăsari, Făleşti, Leova, Rîbnița, Soroca, Ștefan-Vodă, Tiraspol) for the period of 1991-2020.

We were using the USGS methodology [19] that had been building up on the Hijman's BIOCLIM set of predictors with some minor additions [15] (Table 1).

Table 1. List of bioclimatic predictors and their formulas used in the study

Code	Brief description	Code	Brief description
BIO1	Annual mean temperature	**BIO10**	Mean temperature of warmest quarter
BIO2	Annual mean diurnal range	**BIO11**	Mean temperature of coldest quarter
BIO3	Isothermality	**BIO12**	Annual precipitation
BIO4	Temperature seasonality (Standard deviation)	**BIO13**	Precipitation of wettest month
BIO4a	Temperature seasonality (Coefficient of variation)	**BIO14**	Precipitation of driest month
BIO5	Max temperature of warmest month	**BIO15**	Precipitation seasonality (Coefficient of variation)
BIO6	Min temperature of coldest month	**BIO16**	Precipitation of wettest quarter
BIO7	Annual temperature range	**BIO17**	Precipitation of driest quarter
BIO8	Mean temperature of wettest quarter	**BIO18**	Precipitation of warmest quarter
BIO9	Mean temperature of driest quarter	**BIO19**	Precipitation of coldest quarter

Once we obtained the database for the 20 predictors, we had run the Shapiro-Wilk test. Since only 78% of the time series were normally distributed according to it was decided not to use linear regression as a method for recalculating climatic parameters from topographic and geographical parameters of the area. Using ArcGIS 10.2, environmental variables were obtained, calculated using Spline with barriers for the territory of the Republic of Moldova. We had added to the bioclimatic indexes a set of predictors for physico-geographical attributes (continuous variables, such as DEM and its derivatives) and data on the topological position (categorical variables, Topographic Positions Index (TPI) [32]). Focal statistics with a sliding window of 3000 meters was used on the DEM then the flat slope and middle slope were identified (Table 1) using the MATH->Logical->Test and EqualTo toolkit. The classification of the landforms was executed using SD (Standard Deviation), -SD, -0.5 and 0.5SD as class boundaries, which allowed identifying the basic landforms: valleys, the lower, middle and upper parts of the slope, as well as the ridges and midslopes areas with inclination values approaching zero degrees, or Flat slope (Table 2).

In order to exclude multicollinearity and model over-fitting, we had employed the following steps. First, the list of predictors was subjected to multivariate analysis in Statgraphics Centurion. All the predictors with R>=0.64 were excluded. Then the list of remaining 12 predictors were further thinned out by excluding all of the predictors with Variance inflation Factors VIF>5 (table 4), using the General Linear Models procedure. The main means for estimating the accuracy of the resulting model were the AUC, or the area under the receiver operating characteristic (ROC) curve, and TSS, or Training Sensitivity Plus Specificity criterion [14]. We had used the cloglog transform as our interpretation as it would fit better with our goal, which was to obtain the new potential sites for reintroduction of *Iris pontica* endemic species.

Table 2. Landform classification using TPI

TPI new class	TPI classification breaks	Morphometric elements of relief
1	TPI< -SD	Valley
2	-SD<TPI<-0.5SD	Lower slope
3	-0.5SD<TPI<0.5SD, if slope <=5 degrees	Flat slope
4	-0.5SD<TPI<0.5SD, if slope > 5 degrees	Middle slope
5	0.5SD<TPI<SD	Upper slope
6	TPI>SD	Ridge

Points of presence of *Iris pontica* were taken on the base of known Herbaria data, as well as our recent (2024-2025) field findings. The herbarium material of *Iris pontica* stored in the Herbarium of the National Botanical Garden (Institute) of the Republic of Moldova and the Herbarium of the Moldova State University (Chisinau) were studied to determine its distribution in the region. During field research, the identified habitats of the species were examined and new local populations were registered in previously unknown locations and the coordinates of the growing areas were recorded (Table 3). The obtained information was used to compile a map of the species distribution in the Republic of Moldova. The following symbols are used to denote the spread: ● – locality, where the species grows in the present time (from 1971 to 2021) ◆ – new locality, discovered in 2025 and ✦ – locality, where the first reintroduction of the species was carried out, taking into account spatial ecological niches modeling. The general range is indicated according to literature data [11].

According to IUCN Standards and criteria for rare species, taking into account updated data on local distribution, as well as population abundance and status, the category of rarity in the region was established. The current conservation status is shown (inclusion in the Environmental Legislation [38] of the Republic of Moldova, the 3rd edition of the Red Data Book of the Republic of Moldova [4], the 2nd edition of the Red Data Book of the Transnistria [35]), the Red Data Book of Romania [3], and the Red Data Book of Ukraine [36]). The nomenclature is indicated in accordance with the literature [12, 23, 37].

Table 3. Coordinates of confirmed locations of *Iris pontica* Zapał

Locality (district)	Coordinates		Exposition	Slope part	Abs. altitude (m)
	N	E			
Vrănești (Sîngerei)	47°36’50.16	28°5’51.76	W	middle	163
	47°36’47.79	28°5’52.13	W	middle	165
	47°36’49.00»	28°5’51.22	W	middle	154
	47°36’48.97	28°5’52.80»	W	middle	163
Sărăței (Rîbnița, UATSN)	47°49’45.35»	29°1’41.59»	SW	upper	93
Lunga Nouă (Dubăsari, UATSN)	46°93155»	29°10891»	SW	upper	93
Chirca (Anenii Noi)	46°55’52.61»	29° 6’31.45»	W	middle	62
Ciumai (Taraclia)	45°47’20.12»	28°33’14.76»	W	upper	64

The general pattern of the distribution of species’ probability presence is traced to the boundaries of the main elements of Moldova’s geomorphologic zoning [26] with the main elements of the largest river basins [25].

Results and discussion

Iris pontica Zapał. (=*Iris humilis* M.Bieb., *I. marschalliana* Bobrov, *Xyridion ponticum* (Zapał.) Rodion., *Chamaeiris pontica* (Zapał.) M.B.Crespo) – Black Sea Iris, belongs to the Iridaceae Family. It is an Endangered species [Endangered (EN)] – A4cde; B2ab(iii); D2.

Species is protected by law in the Republic of Moldova – category II. As a threatened species, it is included in the Red Book of the Republic of Moldova, as critically endangered – in the Red Book of the Transnistria [35] and Romania [3], and as a vulnerable species in the Red Book of Ukraine [36].

Perennial rhizomatous plant (Figure 1). Blooms in May-June. Propagated by seeds and vegetatively by rhizomes. It has medicinal and ornamental properties. A steppe, xeromesophilous plant. It grows as part of the steppe's grassland on slopes (Figure 2) with western exposition and forms groups or clusters of 10-30 (40) cm in diameter.

a b c d

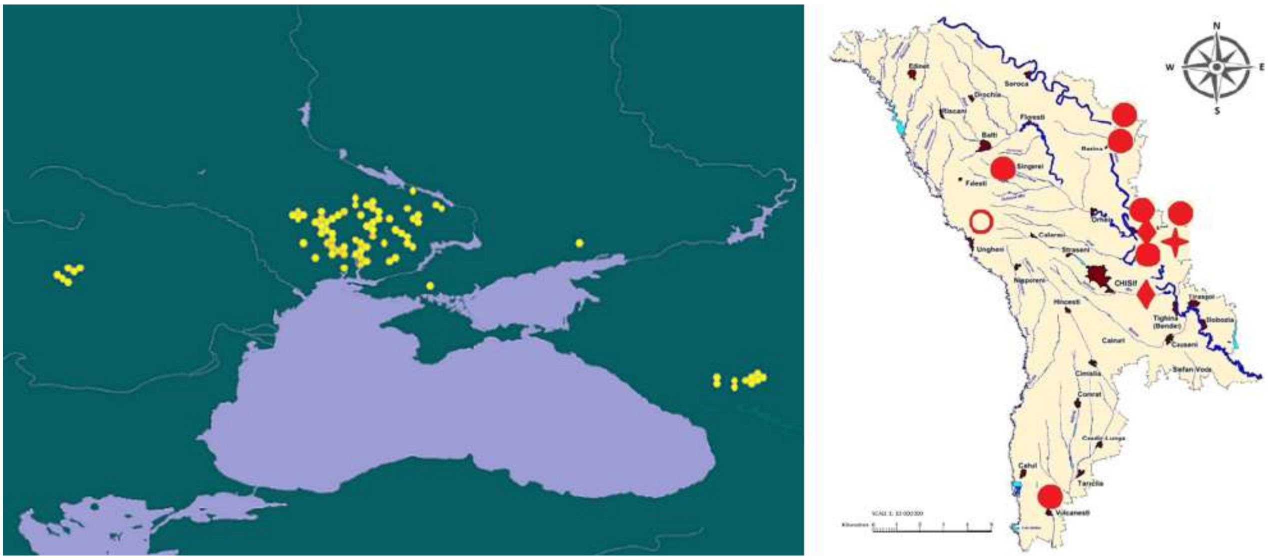
Figure 1. Iris pontica Zapał. at different stages of development: a – vegetation, b – budding, c – flowering, d – fruiting

Pontic species. Its general range covers Central (Romania) and Eastern (Republic of Moldova, Ukraine) Europe and the North Caucasus [12] (Figure 3a). In the Republic of Moldova it is found sporadically. Until now it was reliably known (based on herbarium specimens) in the districts of Sîngerei (Vrănești), Ungheni (Bumbăta), Rîbnița (Sărăței, Pîrlova), Dubăsari (Goian, Colosova), Anenii Noi (Delacău); Taraclia (Ciumai). In 2025 it was discovered in the vicinity of the village of Chirca Anenii Noi district and the village of Lunga Noua in Dubasari district (Figure 3).

The resulting model for identifying ecological niches for reintroduction of Iris pontica had demonstrated a robust accuracy and performance, having the AUC=0.955 and TSS=0.852. 25% of the existing points of presence were randomly selected as test points and 75% – as training ones. We had applied the jackknife test, the permutation importance and percent of contribution to the resulting set of predictors, and had eliminated another three. The final set of predictors is shown in table 4.

a b c

Figure 2. Steppe slopes with Iris pontica Zapał.: a – Vrănești, b – Lunga Nouă, c – Chirca



a b

Figure 3. Distribution of Iris pontica Zapał.: a – worldwide, b – in the Republic of Moldova

Table 4. Selected predictors that explain the potential distribution of *Iris pontica* Zapal in Republic of Moldova

Code	Predictor	VIF
BIO2	Annual Mean diurnal range	1.8
BIO4	Temperature seasonality (Standard deviation)	2.3
BIO8	Mean temperature of the wettest quarter	2.4
BIO19	Precipitation of coldest quarter	1.5
TPI	Topographic positions index	2.8
Aspect	Slope's orientation	2.3

The highest contribution in the model is from aspect predictor (48.5%), followed, in the descending order, by topological positions index (39.4%), diurnal range (BIO2, 8%), and precipitation of the coldest quarter (3.5%). Although BIO8 and BIO4 are showing a low percentage of contribution (0.4 and 0.3%, respectively) and relatively low permutation importance (3 and 0.2%), we kept those predictors in the model, because those predictors have a high input for jackknife test (Figure 4).

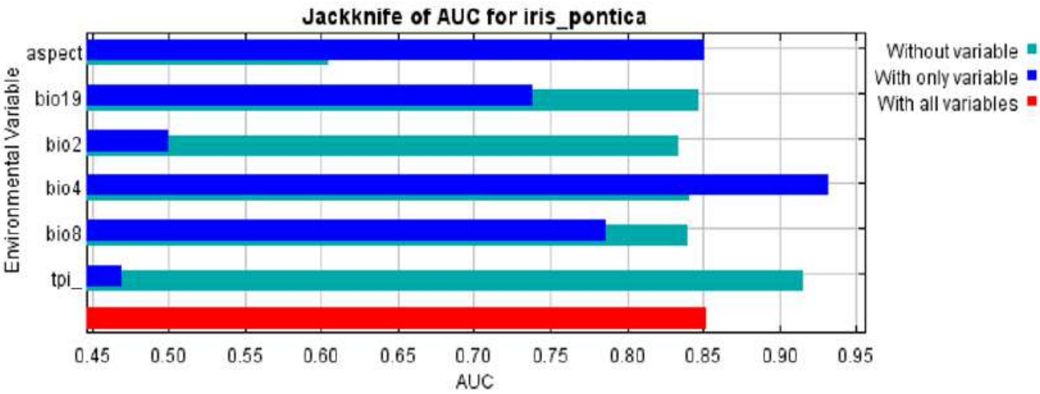


Figure 4. Specific predictors' contributions to the regularized training gain (AUC).

The response curves had demonstrated that probability of presence increases with the increase of the aspect predictor, in other words, the object of the study clearly prefers western and Southwestern parts of the slope, as the response curve is showing the most rapid increase while aspect is within the range of 200-300 degrees.

Most bioclimatic predictors, on the contrary, have a limiting effect on the distribution of the species, which is evident from the inverse relationship between the increase in the values of the bio4, bio8 and bio19 and the response of the probabilistic distribution model of the species. The only exception is the bioclimatic predictor bio2 (annual average daily temperature variation), which also increases with the probability of the species’ presence; the comfortable range of values, according to the model, fluctuates between 9 and 10 degrees Celsius. The topographic position index shows that according to the SDM, *Iris pontica* prefers the middle and upper slope, while avoiding valleys, ridges, lower parts of the slope and the so called flat slope (Figure 5).

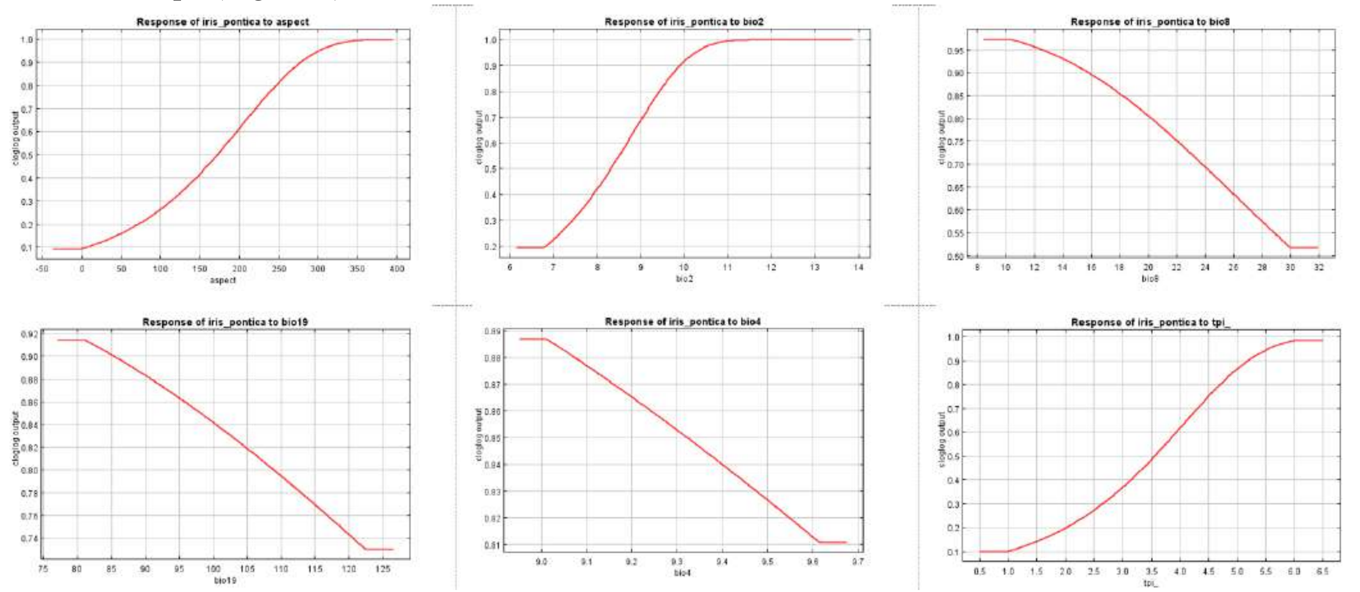


Figure 5. Response curves of the final set of predictor variables

On figure 6 is demonstrated the spatial distribution of the potential ecological niches for *Iris pontica*, the probability of presence is marked by colors, using the blue and green hues marking the low probability (less than 0.54), yellow ones- the medium probability (from 0.62-0.77) and the orange and red ones – the highly suitable areas, the potential zones for re-introduction of the species (>0.85).

The general pattern of the distribution of species’ probability presence is traced by the main elements of Moldova’s geomorphologic zoning [26], which is well-controlled by the main elements of the largest river basins [25]. The highest probability values are associated with watershed areas, the upper and middle parts of slopes (the formation of which is determined by the intensity of erosion processes) of southern points (which is determined by the direction of the hydrographic network). On gentle slopes, in river floodplains, and in the bottoms of gullies, the probability decreases significantly.

The identified patterns allowed us to identify several zones with a high probability of the presence of these ecological niches with steppe vegetation (Figure 6):

I. The Prut zone, which is in turn divided into the Middle Prut (I.1), small Nîrnova (I.2), and Lower Prut (I.3) subzones.

II. The zone of the Danube small rivers, which consists of the Cahul (II.1) and Lower Ialpuh subzones (II.2).

III. The zone of the Black Sea small rivers.

IV. The zone of the Dniester right tributaries, consisting of the Lower Bîc (IV.1), Lower Botna (IV.2), and Ştiubei (IV.3) subzones.

V. The Răut zone, including the Upper Răut (V.1), Middle-Lower Răut (V.2) subzones, as well as the subzone of the left tributaries of the middle and lower Răut (V.3). The zone of the Dniester small right tributaries, consisting of the Northern (VI.1), Central (VI.2), and Southern (VI.3) subzones.

VI. The Left Transnistria zone, which includes the Rîbniţa (VII.1) and Lower Dniester (VII.2) subzones.

Below we provide a brief description of the identified zones (Figure 7).

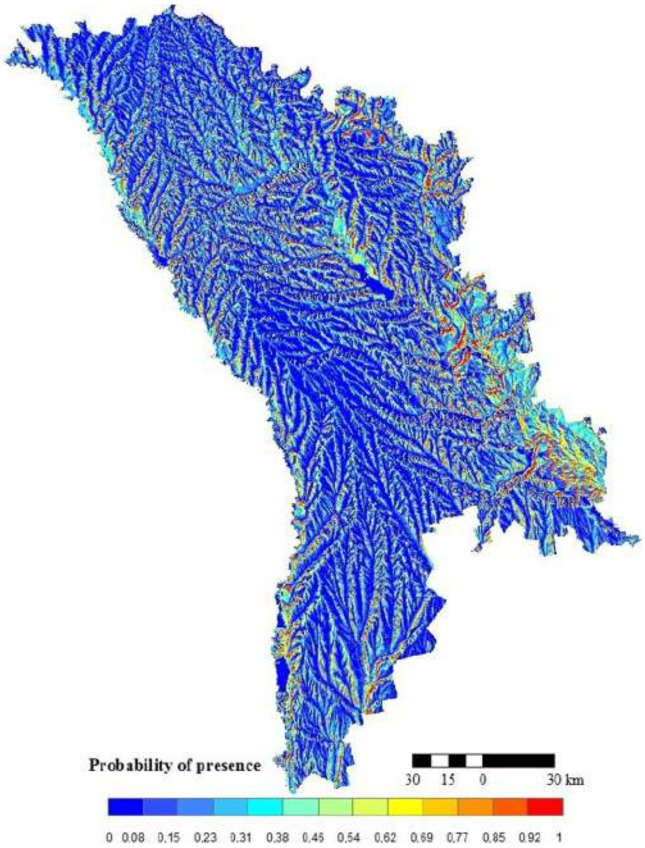


Figure 6. Potential ecological niches for Iris pontica Zapał under current (1991-2020) climate conditions for Republic of Moldova (probability of presence score (0-1.00) is given for each 200-m pixel)

Prut zone. This zone is characterized by river channels flowing from north or northeast to south or southwest. The left slopes (southeastern) of the left tributaries of the Prut River are steeper, the right slopes are gentler and longer, and in the northwestern areas, habitats with significant probability values are virtually absent or small. Habitats with a high probability of the presence of the studied species (0.85-1.0) are confined to the upper parts of the southern and southeastern slopes, as well as the watersheds of the left gullies on the eastern slopes of small Prut rivers. Less frequently, they are located directly on the southeastern slopes of the rivers. South of the Camenca River, the frequency of occurrence of such habitats increases.

In the Nîrnova subzone, areas with a high probability are characteristic of the watershed between the Prut and the Nîrnova rivers, as well as the southeastern slope of the Nîrnova in its lower reaches.

Within the Lower Prut subzone, the main river channel direction has shifted eastward, and high-probability areas are confined to the southeastern slopes of rivers and gullies.

The zone of the Danube small rivers. Within this zone, the probability has decreased somewhat (0.85-0.91). Such areas are typical of river slopes and rarely of gullies.

Zone of the Black Sea small rivers. This zone is represented by their headwaters. The main river channel direction is from north to south. Therefore, high-probability areas are confined to the southeastern slopes of gullies on the left slopes of rivers. There are slightly more areas with a probability of up to 1 here than in the previous zone.

The zone of the Dniester right tributaries. A distinctive feature of this zone is the presence of numerous tributaries and gullies extending from north to south, the southeastern slopes of which have numerous small areas with a probability of 0.77-0.85, rarely higher. An exception is the slopes of the Botna and Bîc rivers, after their flow shifted to a northwesterly direction. Here, the number of areas with probability values greater than 0.85 has increased. Within the Știubei subzone, the southeastern slopes of gullies also have high probability values.

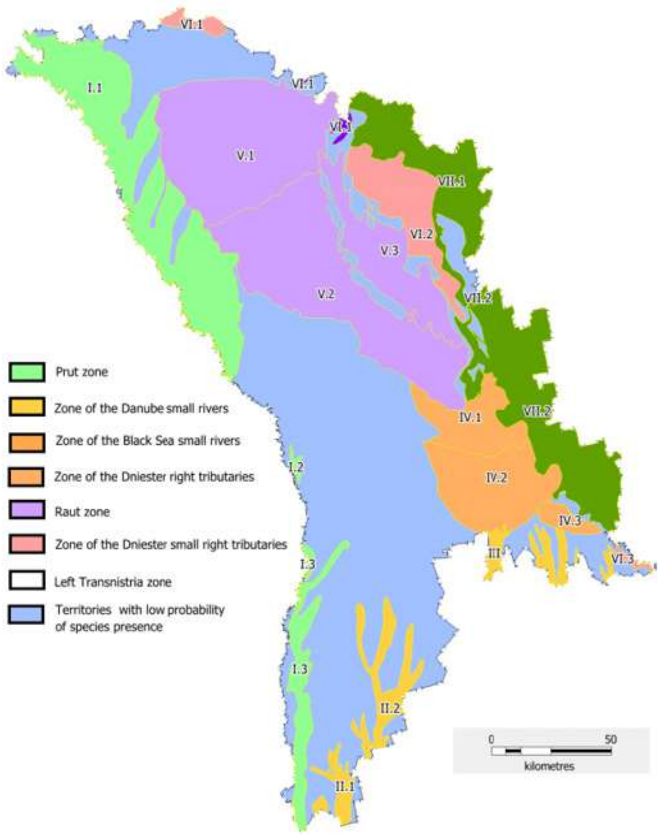


Figure 7. Zoning of the Moldova territory according to the species presence probability. Subzones are shown in Roman numerals (see text)

Răut Zone. This zone is divided into three subzones based on the flow characteristics of the Răut tributaries: Upper Răut (the main flow direction of the tributaries is northwest-southeast), Middle-Lower Răut (the main flow direction of the tributaries is almost west to east), and the Left Tributaries of the Middle and Lower Răut (the main flow direction of the tributaries is north to south).

Upper Răut Subzone. Strong valley-ravine dissection has led to the formation of a large number of small ravines with slopes where the probability of occurrence of habitats for the studied species rarely exceeds 0.85. However, these habitats are numerous and widespread throughout the subzone.

Middle-Lower Răut Subzone. High-probability habitats (greater than 0.85) are confined to the southern and southeastern slopes of ravines of the Răut tributaries, and to a lesser extent to higher-order rivers. Left Tributaries of the Middle and Lower Răut Subzone. High-probability habitats (0.85-1.0) are confined to the southeastern slopes of the Răut tributaries and the watersheds between them, and to a lesser extent to ravines.

Zone of the Dniester small right tributaries. Most of the relatively small habitats with high probability values in the central subzone are confined to gullies on the southern slopes of rivers such as the Rezina, Ciorna, Cusmirca and Jidauca. Similar habitats are absent on the northern slopes. In the northern and southern subzones, habitats with high probability values are confined to the watersheds of small Dniester tributaries up to 15 km long.

Left Transnistria Zone. The northern, Rîbniţa subzone is characterized by habitats located on the eastern and southeastern slopes of Dniester tributaries and their gullies, forming fairly large territories. Of particular note are the slopes of the Dniester valley, with probability values of 0.92-1.0. A strip with similar values connects the Rîbniţa subzone with the Lower Dniester subzone (from the Rîbniţa River valley to the Iagorlîc River valley). The distribution pattern of habitats within the Lower Dniester subzone is similar to that of the Rîbniţa subzone. However, it should be noted that the area of habitats with a probability of 0.62-0.79 is significantly larger here.

Figure 8. Iris pontica Zapał. on the experimental plot in the National Botanical Garden (Institute)

For propagation purposes, including for subsequent introduction and restoration of small populations, several specimens were planted and successfuly multiplied in the rare plant sector of the National Botanical Garden (Figure 8). The plants were taken from a locality near the village of Lunga Nouă (Dubăsari district).

Pilot reintroduction efforts for *Iris pontica* (Figure 9b) into suitable steppe habitats were carried out on October 16, 2025, when 15 specimens from the rare plant sector of the National Botanical Garden were planted on a steppe slope near the village of Hlinaia in the Grigoriopol district (Figure 9a). The habitat was selected based on spatial ecological niche modeling. Long-term monitoring of the planted samples and the formation of a new local population has begun. Reintroduction efforts will continue in the selected areas using spatial ecological niche modeling in 2025.

a **b**

Figure 9. Reintroduction of Iris pontica Zapał.: a – a sector of steppe vegetation near the village of Hlinaia in Grigoriopol district; b – planted samples

Conclusions

1. The distribution patterns of habitats with a high probability of *Iris pontica* Zapał. presence are determined by the geomorphologic conditions of the area and the structure of the hydrographic network.
2. Habitats with a high probability of *Iris pontica* presence are confined to watershed areas and the upper parts of southern slopes.
3. Depending on the main direction of river flow, such slopes may be confined to slopes and watersheds of erosion forms of varying order.
4. River floodplains, gulch bottoms, and areas with low dissection have a low probability of *Iris pontica* presence.
5. The spatial ecological niches modeling method allows us to identify the most suitable habitats for the reintroduction and expansion of the geographic distribution of the rarest plant species protected at the national and international levels throughout the territory of the Republic of Moldova.

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