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POTENTIAL HABITAT PREDICTION FOR THE CURRENT DISTRIBUTION OF *Tozzia alpina* subsp. *carpathica* IN THE ROMANIAN CARPATHIANS

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Abstract

Tozzia alpina subsp. carpathica is a rare semiparasitic plant that faces significant conservation concerns within its native range in the Carpathian Mountains of Romania. Currently classified as data deficient on the IUCN Red List, this species requires accurate habitat prediction to guide effective conservation strategies and deepen our understanding of the factors shaping its distribution. The conservation status assessment, conducted under Article 17 of the Habitats Directive, relies on presence points within 10x10 km squares. However, current estimates require a robust distribution model to assess habitat extent accurately. This plant is typically found in small patches within wet meadows and tall hydrophilous vegetation along springs and rivers in the alpine bioregion, making it vulnerable to land use and resource exploitation. Therefore, developing models to predict the habitat distribution is a priority. We employed the Maximum Entropy modeling approach to address this need and predict suitable habitats, utilizing species occurrence data in conjunction with environmental variables. This modeling method provides valuable insights for identifying areas to evaluate in the upcoming reporting period under the Habitats Directive, significantly enhancing conservation efforts.

Key words: *Carpathians, conservation, distribution, Maximum Entropy modelling, Tozzia alpina subsp. carpathica.*

INTRODUCTION

Species Distribution Models (SDMs) have become essential tools in ecology and conservation science, offering robust methods for estimating the potential geographic distribution of species based on known occurrences and associated environmental conditions (Austin, 2007; Elith & Leathwick, 2009; Guisan et al., 2017)

These models are particularly useful for rare, data-deficient, or ecologically specialized taxa, for which direct field observations are often spatially limited (Wang et al., 2015; Mousikos et al., 2021; Bao et al., 2022; Ramírez-Rodríguez et al., 2025). SDMs help identify priority areas for species monitoring, guide conservation action, and support ecological reporting under national and international frameworks. Their integration into biodiversity assessments has proven valuable for improving plant species conservation status evaluations, optimizing field survey design, and informing long-term habitat management strategies (Jansen et al., 2021). In the context of the Habitats Directive, SDMs are increasingly used to complement official range estimates and support reporting under Article 17 (Sousa-Silva et al., 2014).

Under Article 17, Member States assess the conservation status of species using presence data aggregated in 10 × 10 km UTM grid squares (M.O., 2023). However, this resolution and methodology, implemented through the Range tool provided by the European Commission, may significantly underestimate actual species distributions, particularly for plants with narrow ecological amplitudes or fragmented populations (Jansen et al., 2021). The coarse spatial scale and limited gap analysis functions reduce the ability to detect microhabitat-level patterns that are ecologically meaningful for habitat-restricted taxa. For species such as *Tozzia alpina* subsp. *carpathica* (Wołł.) Pawłł., which occurs in small, isolated populations confined to habitats like wet subalpine meadows, hygrophilous tall-forb communities, or spring margins, this limitation can lead to underreporting of potential distribution and habitat suitability.

The genus *Tozzia* comprises a small group of hemiparasitic plants within the Orobanchaceae family, represented by two closely related taxa: *T. alpina* subsp. *alpina*, distributed from the Pyrenees to the western Balkans, and *T. alpina* subsp. *carpathica* is restricted to the Carpathians and the southern Balkan Mountains (Kliment, 1999; Sârbu et al., 2013; POWO, 2025). *T. carpathica* is a species of community interest (code 4116) listed under Annexes II and IV of the Habitats Directive (92/43/EEC) and under the Bern Convention (Resolution 6/1998). It is also classified as Data Deficient on the IUCN Red List (Bilz, 2011). However, it is considered nationally rare or threatened in countries such as Romania (Oltean et al., 1994), Poland (Wika et al., 2014; Kazmierczakowa et al., 2016), Slovakia (Mereďa & Hodalová, 2011), and Bulgaria (Petrova & Vladimirov, 2009; Vladimirov & Assyov, 2011).

In Romania, the species is included among the 90% of vulnerable Carpathian taxa covered by the national protected area network (Coldea et al., 2009). Out of the 45 Natura 2000 sites where the species has been documented across Europe, 23 are situated in Romania (EUNIS, 2025), primarily in montane and subalpine regions. Although considered well protected, the species' distribution remains fragmented and incompletely understood. Recent confirmations in protected areas such as ROSCI0225 Grădiștea Muncelului-Cioclovina (Anonymous, 2016) and ROSCI0122 Făgăraș (FCC, 2021) indicate that *T. alpina* subsp. *carpathica* may occur in additional, previously undocumented microhabitats, highlighting the need for targeted field surveys in suitable but underexplored areas.

This study hypothesises that the current distribution of *T. alpina* subsp. *carpathica* in Romania is underestimated due to the limitations of the standard reporting framework. To address this, we aim to develop a habitat suitability model using MaxEnt for the Romanian Carpathians. The objectives are: (1) to identify key environmental variables influencing habitat suitability; (2) to generate a predictive map of potentially suitable habitats; and (3) to provide spatial insights that can support future field validation, conservation planning, and reporting under the Habitats Directive.

MATERIALS AND METHODS

Study area

The study was carried out in Romania, a southeastern European country covering approximately 238,400 km² (EEA, 2020). Romania encompasses five biogeographical regions: Alpine, Continental, Pannonian, Steppic, and Black Sea, making it one of the most ecologically diverse member states of the European Union (Iojă et al., 2010; Evans, 2012). The Romanian Carpathians occupy about one-third of the national territory, being a hotspot of biodiversity and endemism, harbouring numerous relict and endemic species, particularly in alpine and subalpine habitats (Coldea et al., 2009; Biriş et al., 2011). The climate is temperate-continental, with four distinct seasons and significant regional variability, supporting a broad range of ecosystems from deciduous and coniferous forests to alpine grasslands and peatlands.

Biological characteristics

T. alpina subsp. *carpathica* is a perennial hemiparasitic plant with a distinct developmental cycle of two stages. In the initial phase, lasting up to 10 years, the plant persists underground as a rhizome with scale-like, non-photosynthetic leaves, relying entirely on its host for nutrients (McNeal et al., 2013). Only after this extended subterranean period does it emerge above ground, developing green leaves and transitioning into a hemiparasitic state, with all emerging shoots being fertile (Těšitel et al., 2010).

The plant is 10-50 cm tall, with a fragile, often branched stem that is four-angled and glabrous or sparsely hairy along the ridges; the leaves are opposite, sessile, ovate to broadly ovate, somewhat fleshy, glossy, and glabrous, with shallow coarse teeth (1-3) near the base; bracts are similar to the leaves but smaller; the inflorescence is a short, lax raceme borne at the ends of branches; the calyx is campanulate and weakly bilabiate; the corolla has five obtuse lobes forming two barely distinct lips, and is small, yellow, and tubular (6-8 mm), with reddish speckles; the plant has four didynamous stamens with filaments fused to the corolla tube; the fruit is a globular, one-chambered capsule (2-2.5 mm) enclosed within the calyx, containing one or two seeds; flowering typically occurs from July to August, in the upper areas even until September (Paucă, 1960; Sârbu et al., 2013).

Figure 1. *Tozzia alpina* subsp. *carpathica* on a riverbank in an alluvial meadow, growing among *Petasites hybridus*, its host species (Photo Nicoară R., 25.05.2023)

The typical subspecies is most commonly associated with tall perennial herbaceous hosts from the genera *Cicerbita*, *Adenostyles*, and *Petasites* (Piękoś-Mirkowa, 2004). In Romania, the Carpathian subspecies has frequently been observed parasitizing species from the Petasites genus. This relationship plays a crucial role also in determining the species distribution. Since *Petasites* thrive in moist environments such as mountain valleys and near water sources, these habitats also become the primary locations where *T. alpina subsp. carpathica* can establish itself. The presence and abundance of the host plant directly influence the occurrence of *Tozzia*, highlighting the importance of suitable hydrophilous vegetation in its habitat selection.

Preferred habitat

In Romania, *T. alpina* subsp. *carpathica* is a mesohygrophyte and microthermophyte with a narrow ecological niche, occurring predominantly in humid montane and subalpine zones of the Carpathians (Sârbu et al., 2020). The species is highly shade-tolerant and hygrophilous, typically restricted to spring-fed habitats, streambanks, wet forest clearings, and tall-herb communities that maintain stable microclimatic conditions and elevated edaphic moisture (Figure 1).

It is most frequently associated with vegetation types belonging to the classes Betulo-Adenostyletea Br.-Bl. et R. Tüxen 1943, Molinio-Arrhenatheretea R. Tüxen 1937, and Montio-Cardaminetea Br.-Bl. et R. Tüxen 1943 (Sanda et al., 2008; Neblea & Dragomir, 2015).

Within the Montio-Cardaminetea class, *T. alpina* subsp. *carpathica* occurs in spring-fed and streamside vegetation of the Montio-Cardaminetalia alliance, especially in communities such as *Cardamino–Chrysosplenietum alternifolii*, dominated by *Cardamine amara* and *Chrysosplenium alternifolium*. These vegetation types typically develop around mountain springs in beech (*Fagus sylvatica*) and spruce (*Picea abies*) forest belts, on both siliceous and calcareous substrates.

Within the Betulo-Adenostyletea class, the species is found in tall-herb communities occupying wet slopes, forest glades, and ravines between 900 and 1200 m altitude. These habitats thrive in conditions of high soil moisture and persistent atmospheric humidity. Here, *T. alpina* is considered characteristic of the Adenostyletalia alliariae order, particularly within the Adenostylion alliariae alliance - composed of hygrophilous tall-herb vegetation growing on nutrient-rich, moist colluvial soils. In these plant communities, it coexists with species such as *Adenostyles alliariae*, *Senecio nemorensis*, *Veratrum album*, *Rumex alpestris*, and *Salix hastata*.

Within the Molinio-Arrhenatheretea class, *T. alpina* subsp. *carpathica* is associated with the *Calthion palustris* alliance. It occurs in associations such as *Scirpetum sylvatici* Ralski

1931 emend. Schwich 1944 and *Chaerophyllo hirsute-Filipenduletum* Niemann et al. 1973, from the *Filipendulion* alliance (Lohmeyer in Oberdorfer et al., 1967), which develop on alluvial and pseudogley soils over siliceous rocks, typically in marshy habitats and along streams (Neblea & Dragomir, 2015).

Furthermore, the species has been recorded in several Natura 2000 habitat types characterized by consistently high soil moisture, including habitat types: 3220 Alpine rivers and the herbaceous vegetation along their banks, 4060 Alpine and Boreal heaths, 4070* Bushes with *Pinus mugo* and *Rhododendron hirsutum* (*Mugo-Rhododendretum hirsuti*), 6150 Siliceous alpine and boreal grasslands, 6170 Alpine and subalpine calcareous grasslands, and 6430 Hydrophilous tall-herb fringe communities of plains and of the montane to alpine levels (Doniţă et al., 2005; Gafta & Mountford, 2008; Drăgulescu, 2008; Brînzan, 2013; Neblea & Dragomir, 2015).

Reporting under Article 17

Monitoring species listed in Annex II and Annex IV of the Habitats Directive (92/43/EEC) is required under Article 11 and Article 17, preceding the reporting of species conservation status to the European Commission every six years. According to the Habitats Directive, measures must aim to maintain or restore species of wild flora of community interest to a favorable conservation status.

Over the past 12 years, all Member States, including Romania, have reported twice to the European Commission: first in 2013 (covering 2007-2012) and again in 2019 (covering 2013-2018). The next reporting deadline is 31 July 2025, with an updated reporting format for species types approved in 2023 (DG Environment, 2023).

The monitoring of the conservation status of plant species of community interest in Romania was structured around three key components. First, a review of all available data from scientific publications, herbarium records, and research or conservation projects were assessed in order to generate the initial inventories and distribution maps. Second, field data were collected to verify and add new data to existing records, supporting the development of comprehensive species inventories and GIS-based distribution maps. In the alpine bioregion, where *T. alpina* subsp. *carpathica* is distributed, monitoring was focused on assessing the species' range, population size and distribution, surface area of occurrence, trends in population dynamics, current conservation status, and major pressures and threats, both historical and ongoing. Finally, all data were analyzed and validated before being integrated into the national plant monitoring system.

Within these framework projects, carried out between 2011-2023, the *T. alpina* subsp. *carpathica* population was inventoried in Romania and the conservation status of this species was evaluated (Mihăilescu et al., 2015a). The species identification was carried out in the field, no specimens were collected.

The concept of favourable reference values is derived from definitions in the *Habitats Directive* (DG Environment, 2023).

Overall assessment of conservation status uses four categories: "favourable" (FV), "unfavourable - inadequate" (U1), "unfavourable - bad" (U2) and "unknown" (XX), based on the evaluation matrix for assessing conservation status for a species (Table 1).

Table 1. Overall assessment of the conservation status (CS)

Status of parameters	All favourable or few favourable + one unknown	One or more inadequate, but not bad	One or more bad	Two or more unknown + favourable or all unknown
Overall assessment of CS	Favourable (FV)	Unfavourable-inadequate (U1)	Unfavourable-Bad (U2)	Unknown (XX)

Table 2. Overall assessment of the conservation status on each reporting period

Species	2013	2019	2025
	ALP	ALP	ALP
4116 *Tozzia alpina* subsp. *carpathica* (Wołł.) Pawł	FV	FV	FV

During 2007-2023, the conservation status was "favourable" (FV), due to increasing trends in the intensity of different impacts upon the species habitat (Table 2).

For the period 2013-2018 the population size measured in number of individuals was estimated between 10-400.

Under the Habitats Directive - Article 17 reporting process, these assessments have been carried out in EU25 for the period 2001-2006, in EU 27 for the period 2007-2012 and in EU28 for the period 2013-2018 (EIONET, 2019). Romania has already reported in the last two periods. The next report is due on 31 July, 2025.

During 2007-2023, the conservation status was “favourable” (FV), due to increasing trends in the intensity of different impacts upon the species habitat (Table 2).

To generate the distribution maps, we used standard methods based on occurrence data reported under Article 17. Specifically, species occurrences were aggregated within standardized ETRS89 grids (10 x 10 km and 1 x 1 km resolution, projected in ETRS LAEA 5210 (M.O., 2023). Subsequently, the Art17 reporting tool was employed to derive the species' range distribution, using a gap analysis technique integrated into the reporting tool (Figure 2).

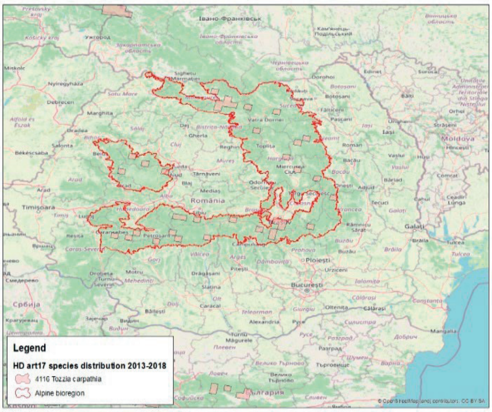

Figure 2. Habitat directive *Tozzia alpina* subsp. *carpathica* species distribution from 2013-2018 reporting period

Mapping and assessment of species state

The potential habitat distribution of *T. alpina* subsp. *carpathica* was modelled using the Maximum Entropy algorithm (MaxEnt), a species distribution modelling method especially effective for presence-only datasets and limited occurrence records. This machine-learning algorithm enabled predictions based on environmental variable similarities. Our aim was to assess whether the species distribution area previously estimated by the Article 17 reporting tool may have been underestimated.

A total of 37 validated presence plots were established by integrating distribution data from the Habitats Directive Reports (Mihăilescu et al., 2015b). Only those locations with high spatial accuracy (horizontal error <10 m for both X and Y coordinates) were selected for further analysis and used as input in the Maximum Entropy (MaxEnt) habitat suitability model.

Eight environmental predictor variables were used, grouped into three main categories: geomorphological, climatic, and land use. Geomorphological variables, derived from a 10 m resolution Digital Elevation Model (DEM), included elevation, slope, aspect, and curvature (plan and profile), chosen for their relevance to the species’ known preference for humid subalpine terrain. Climatic variables included long-term annual mean temperature and precipitation extracted from the RO-ADAPT platform (1971-2005 baseline). Land use information was provided by the Corine Land Cover Plus (CLC+) dataset, capturing habitat types and anthropogenic disturbance at high spatial resolution.

MaxEnt (v.3.4.1) was run with default parameters, using 75% of the occurrence data for training and 25% for testing. Model performance was evaluated using the Area Under the receiver operating characteristic Curve (AUC), and variable contribution was assessed through percent contribution and permutation importance. The final output consisted of a continuous habitat suitability map with values ranging from 0 (unsuitable) to 1 (highly suitable), interpreted using thresholding and visualized in the geographic information software ArcGIS 8.3.

RESULTS AND DISCUSSIONS

The MaxEnt model simulation for predicting the potential distribution of *T. alpina* subsp. *carpathica* showed an accurate performance, indicated by a high area under the ROC curve (AUC = 0.950)

Potential distribution and suitable area

The habitat suitability model developed using Maxent identifies several core areas with high environmental probability for the presence of *T. alpina* subsp. *carpathica* across the alpine bioregion of the Romanian Carpathians (Figure 3).

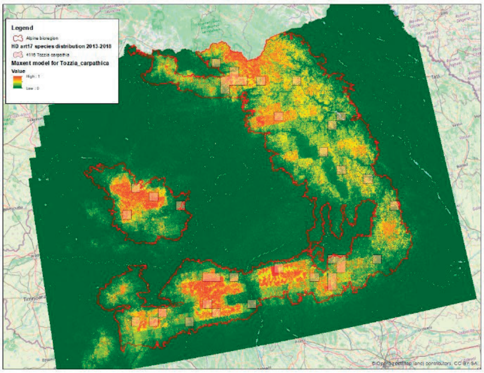

Figure 3. Modelled distribution of *Tozzia alpina* subsp. *carpathica* using Maxent in the Romanian Carpathians

The model predicted high suitability areas in the Eastern Carpathians, particularly in the Rodna and Maramureș Mountains, as well as in the Southern Carpathians, including the Făgăraș and Parâng massifs. Additionally, a significant zone of high suitability is evident in the Apuseni Mountains. These findings are consistent with the current understanding of the species' distribution in Romania. These regions include extensive or clustered patches of suitable habitat, which may support stable metapopulations. An overlay with the 2013–2018 reporting distribution under Article 17 (10 × 10 km grid) confirms the consistency between field records and predicted habitat patches. However, many suitable areas fall outside the currently reported grid cells, indicating a potential underestimation of the species' extent of occurrence. These observations highlight the need for field confirmation and improved monitoring, particularly in areas of fragmented habitat that are predicted to be suitable. Furthermore, the widespread distribution of medium to high suitability patches suggests that *T. alpina* subsp. *carpathica* may be more ecologically flexible than previously assumed but still constrained by microhabitat availability.

Environmental variables

The MaxEnt model revealed that among the eight environmental variables used, land use, elevation and precipitation were the most influential predictors of suitable habitat for *T. alpina* subsp. *carpathica* in the Romanian Carpathians (Figure 4, Table 3).

Table 3. Environmental variables in shaping the species distribution

Environmental variable	Percent contribution	Permutation importance
Land use	45.2	19.5
Elevation	33	42.1
Precipitation	17.7	23.8
Temperature	1.8	0
Exposition	1	4.9
Slope	0.9	6.1
Total curvature	0.3	3.4
Profile curvature	0	0

Land use had the highest contribution (45.2%) to the model, highlighting a strong association between *Tozzia* and specific habitat types. The land use response curve (CLC+ 2018) indicates that *T. alpina* subsp. *carpathica* is primarily associated with areas dominated by coniferous forests (class 2), followed by an association with low-growing woody vegetation (class 5) and permanent herbaceous habitats (class 6). Other land cover categories, including sealed areas, deciduous forests and sparsely vegetated areas, showed minimal influence on the predicted distribution of the species. ow and forest ecotones

Elevation is a key predictor in the habitat suitability model for *T. alpina* subsp. *carpathica*, contributing 33% to the model and showing the highest permutation importance (42.1%). The response curve indicates a lower limit starting at approximately 700–800 m where a significant increase in suitability occurs. Maximum suitability is between 1,200 and 1,800 m, which appears to be the optimal range. After 1,800 m, a significant decrease is observed, suggesting that the species avoids the alpine stage proper (usually >1,800-2,000 m in the Carpathians) and has an ecological preference for montane and subalpine altitudes rather than true alpine habitats.

Precipitation also had a significant influence (17.7% contribution; 23.8% permutation importance), reflecting the species' preference for humid microclimates. Suitable habitats occur predominantly in areas receiving annual rainfall between approximately 600 mm and 1100 mm, with suitability stabilizing at values above this range.

The other chosen variables, such as temperature, slope and curvature, contributed less (<2%) to the model performance, suggesting that, although they modulate habitat specificity, they are not primary determinants of species distribution.

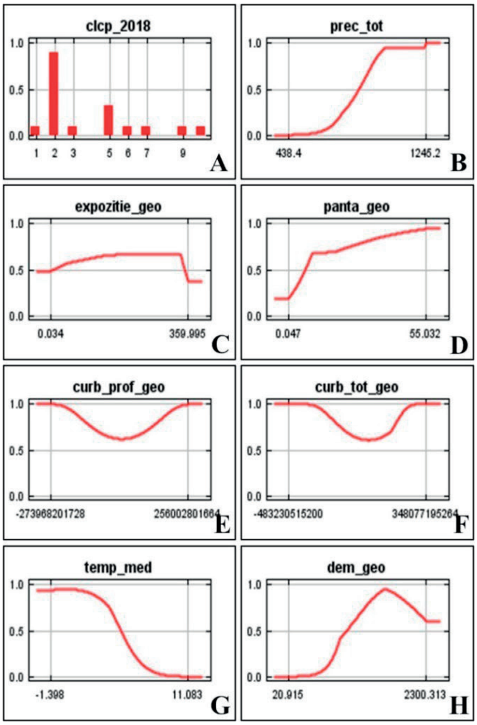

Figure 4. The influence of environmental variables on the predicted habitat suitability for *Tozzia alpina* subsp. *carpathica* in Romanian Carpathians: (A) Land use; (B) Precipitation; (C) Exposition; (D) Slope; (E) Profile curvature; (F) Total curvature; (G) Temperature; (H) Elevation

These findings align with the known ecology of the species, which typically occurs in wet meadows and high herbaceous communities in the montane and subalpine areas of the Carpathians.
The environmental variables that significantly shape the distribution of *T. alpina* subsp. *carpathica*: land use (specific habitats), elevation and precipitation are closely linked to the pressures and threats affecting the species. Given the species' preference for wet habitats with specific hydrological conditions and altitude ranges, it is particularly vulnerable to changes in water regimes, intensive logging activities, changes in land-use management, and the construction of hydropower facilities. In addition, overgrazing and uncontrolled tourist activities, such as motorized vehicles crossing rivers, further degrade the habitat.
Climate change poses another significant threat, as anticipated changes in precipitation patterns - including prolonged drought periods and increased frequency of extreme precipitation events - may lead to surface erosion, changes in soil moisture availability and degradation of suitable microhabitats. Effective conservation of *T. alpina* subsp. *carpathica* thus requires sustainable forestry practices, regulated grazing management and climate adaptive strategies to maintain suitable hydrological and microclimatic conditions within and outside designated protected areas.
List of pressures and threats and conservation measures was updated in 2024 for the period 2019-2024 (EIONET, 2025). During 2007-2023, main conservation measures according with EU code: CB01 - Prevent conversion of (semi-) natural habitats into forests and of (semi)natural forests into intensive forest plantation.

High suitability zones inside and outside the protected areas
The hotspot analysis for the estimated distribution of *T. alpina* subsp. *carpathica* examines the relationship between suitable habitat areas identified by the model, grouping them based on size and connectivity. The results of this analysis are shown in Figure 5.

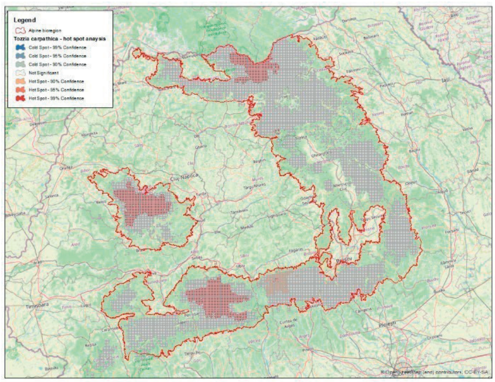

Figure 5. The hotspot analysis for estimated *Tozzia alpina* subsp. *carpathica* areal

A comparative analysis of the two approaches used to estimate the distribution and population of *T. alpina* subsp. *carpathica* (Table 4) highlights the potential advantages of integrating additional modelling techniques into the Art.17 reporting process. While the Art.17 method provides valuable distribution data at a broad spatial scale (5300 km²), the MaxEnt model suggests a slightly larger potential distribution area (6007 km²) at a significantly finer resolution (0.6 ha versus 100 km²).

Table 4. Comparative analysis on distribution areal of specie *T. alpina* subsp. *carpathica* estimates

Characteristics	**MAXENT**	**Art. 17**
Areal distribution	6007 km^2	5300 km^2
Minimum habitat units	0.6 ha	100 km^2
Population size estimates	2.973.017 individuals	300 locations 1x1 km

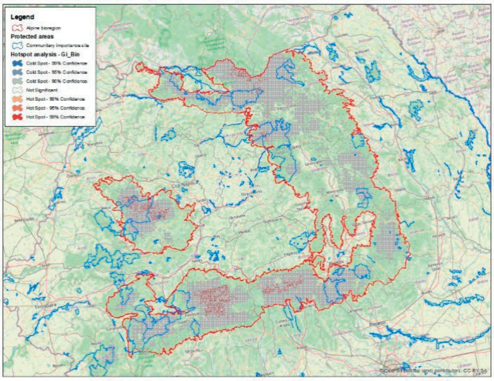

Figure 6. Distribution areal hotspot of species *Tozzia alpina* subsp. *carpathica* in relation with protected areas

By overlapping the distribution area of the suitable habitats with Special Areas of Conservation (SACs) we were able to evaluate the representation proportion for each hotspot class category: "high-confidence" (HC) (>90%), corresponding to extensive areas with favorable conditions for the target species, and the "not significant" category (NS), minor, fragmented patches with limited connectivity potential (Figure 6).

Table 5. Zonation of specific measures on species *Tozzia alpina* subsp. *carpathica* distribution areal

Hotspot class category	**Inside SACs**	**Outside SACs**
HC >90	58.87%	41.13%
NS	25.53%	74.47%

The spatial analysis highlights that the distribution of suitable habitats for *T. alpina* subsp. *carpathica* exist both inside and outside SACs. 58.87% of the high-confidence habitats (HC > 90%) are contained in existing SACs, but also a significant proportion (41.13%) remains unprotected.

In contrast, areas designated as "not significant" (NS), predominantly occur outside protected areas (approximately 74%). Only about a quarter (26%) of these NS habitats currently fall within SACs (Table 5).

These results highlight the existence of large and favourable habitat coverage within the SACs.

However, there is a clear need for extended protection or targeted conservation measures to address habitat fragmentation and limited connectivity in areas outside the current SAC boundaries.

CONCLUSIONS

Although the initial hypothesis regarding the underestimated habitat extent was not supported by the MaxEnt analysis, the model makes an important contribution, as it provides higher spatial resolution and precise numerical estimates of potential populations, allowing a more realistic and precise assessment of the conservation status of the species.

Areas identified as “hotspots” can serve as conservation priorities, guiding future monitoring and management measures.

The difference between the reported area (Art.17) and the predicted area (MaxEnt) highlights the need to update monitoring methodologies, including the use of additional predictive models to improve reporting on the status of species of Community interest.

Maintaining the favourable conservation status still depends on the continued application of conservation measures, both for the species and its habitat.

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