

Vegetation Islands on Continents and the Impact of Climate Change—Case Study of the Alpine-Subalpine Belt of the Romanian Carpathians, and a Flagship Species *Carex curvula*

Ilie-Adrian Stoica 

Taxonomy and Ecology Department, Institute of Biological Research—Subsidiary of the National Institute for Research and Development in Biological Sciences, Cluj-Napoca, Romania

Email: adrian.stoica@icbcluj.ro

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Abstract

Alpine and subalpine belts on continental Europe can be viewed as “islands” of cold-adapted vegetation surrounded by a “sea” of thermophilic species. *Carex curvula*, a flagship species that dominates high-elevation grasslands, provides an ideal case study for understanding the broader impacts of climate change on these alpine “vegetation islands”. We built species distribution models for *Carex curvula* using the biomod2 package in R, testing multiple modeling techniques (Random Forest, Boosted Regression Trees, XGBoost, etc.) with two uncorrelated climatic variables (mean temperature of the coldest quarter and precipitation of the driest month). Model performance, evaluated via ROC (AUC), showed Random Forest as the best algorithm. Future simulations, based on CMIP6 global circulation models (MRI-ESM2-0, UKESM1.0-LL) and mid-range (ssp245) versus high (ssp585) emissions scenarios for 2041-2060 and 2061-2080, consistently forecast significant reductions (10% - 45% to 35% - 80% lost) in climatically suitable areas for *Carex curvula*. High-elevation habitats in the Romanian Carpathians and the Alps remain potential strongholds, although intensifying competition from thermophilic species may further challenge *Carex curvula*'s persistence. These findings highlight the vulnerability of alpine “vegetation islands” to climate change and reinforce the value of *Carex curvula* as a model organism for projecting broader ecological shifts in Europe's high-altitude environments.

Keywords

Alpine and Subalpine Vegetation, *Carex curvula*, Climate Change, Species

1. Introduction

The alpine belt on the European continent can be conceptualized as a series of “islands” of specialized, cold-adapted vegetation surrounded by a “sea” of more thermophilic vegetation. Of the numerous alpine plant species, *Carex curvula* is highly relevant for studies on the effects of global warming. This species is endemic to Europe and forms climax grasslands at high elevations in the Alps, Pyrenees, and Carpathian Mountains, with sporadic occurrences also documented in the Massif Central (France) and the Balkans (Bulgaria, Macedonia, Bosnia-Herzegovina). A simulation of the future distribution of *Carex curvula* can, in many respects, provide insights into the potential trajectories for other endemic or rare alpine plants, several of which co-occur in habitats dominated by *Carex curvula* (the Natura 2000 habitat 6150). Notably, some endemics from the alpine-subalpine group of endemics of the Romanian Carpathians—such as *Achillea oxyloba* subsp. *schurii*, *Cerastium arvense* subsp. *lerchenfeldianum*, *Chrysosplenium alpinum*, *Carduus kernerii* subsp. *kernerii*, *Dianthus glacialis* subsp. *geldius*, *Doronium carpaticum*, *Erysimum witmanni* subsp. *transsilvanicum*, *Festuca porcii*, *Melampyrum saxosum*, *Papaver alpinum* subsp. *corona-sancti-stephani*, and *Phyteuma vagneri* [1]—also can occur in this habitat, or are related to similar cold adapted habitats. Consequently, *Carex curvula* can be regarded as a flagship species, suitable for modeling future scenarios applicable to a broad range of cold-adapted alpine plants.

The impact of climate change on alpine habitats has been extensively documented by a variety of studies conducted on different continents [2]-[5]. A major threat to alpine ecosystems, and the rare or endemic species they support, is the process of thermophilization [3]. Within alpine zones, thermophilization manifests through the increasing frequency and abundance of species tolerant of warmer conditions. These newly arriving species, primarily from lower elevations, introduce additional competitive pressures on the cold-adapted species that are already contending with shifting temperature and precipitation regimes.

The concept of a species niche is often separated into two key components: the fundamental niche (*i.e.*, the complete range of climatic conditions in which a species can survive) and the realized niche (*i.e.*, a subset of the fundamental niche, constrained by factors such as interspecific relationships—competition, predation, etc.—as well as by dispersal limitations, including physical barriers and the species’ intrinsic capacity for propagule movement) [6]. For instance, many alpine plant species can persist at low elevations in botanical gardens, demonstrating they can endure milder conditions if competition is minimized. Under natural conditions, however, their competitiveness is significantly lower in these warm areas, and they fail to establish. Through morphological and genetic adaptations,

alpine plants are well-suited to harsher high-elevation environments, where they face less competition for resources.

Currently, considerable gaps remain regarding the potential impacts of global warming on the climatic niches of the cold-adapted plant species that characterize Europe's alpine habitats. Modeling approaches face difficulties when incorporating the species' fundamental niche, potential interspecific interactions, and dispersal barriers. Consequently, no comprehensive source exists for detailing future climate-driven scenarios of these keystone alpine species. However, developing such models—even if somewhat exploratory—remains worthwhile. They can reveal, at least qualitatively, how future climate conditions may become more adverse for a given species. Although pinpointing the precise spatial distribution of a species under future climate regimes is fraught with uncertainty, these models can suggest whether, and to what degree, a species' *in situ* fitness might either improve or decline.

2. Materials and Methods

2.1. Distribution Data

The presence points for *Carex curvula* were obtained from the GBIF database [7]. These records were carefully filtered to eliminate points with large errors or missing coordinates, and to remove erroneous points (e.g., located at sea or appearing in countries inconsistent with the data). The GBIF dataset contained only a few presence points from Romania. Therefore, additional presence points from Romania were compiled based on literature sources [8] [9] and data gathered in the field. As these records include only presence data (Figure 1), we complemented them with a set of pseudo-absences, randomly generated in a number three times greater than the presence points, following guidelines from the biomod2 package and related literature [10].

In certain regions, the abundance of species distribution data can result in multiple presence points recorded within the same grid cell of the climatic raster files. Since these points merely indicate presence (not abundance), repeated entries within one cell do not provide additional information. Indeed, using all such points might bias the models, as they could become overfit to local conditions, thereby diminishing the general predictive quality for areas with sparser data [11]. To address this, we tested various strategies for reducing multiple presence points to a single point per grid cell at scales of 5×5 km (which matches the climate dataset's resolution), 10×10 km (Kramer-Schadt *et al.* 2013), and 100×100 km [12]. We also compared these with a model version that incorporated all presence points. Ultimately, the most robust modeling outcomes arose when the data were adjusted to one presence point per 5×5 km cell.

2.2. Climate Data

We selected two climatic variables from the WorldClim 2.1 dataset [13]: one temperature variable and one precipitation variable. Specifically, we employed a uni-

variate GLM approach to identify the most important temperature variable and the most important precipitation variable, also ensuring that the correlation between these two variables did not exceed 0.7 (Pearson correlation index).

We then projected future climate conditions according to two global circulation models (GCMs) from CMIP6 [14]: an optimistic scenario (MRI-ESM2-0) [15], characterized by a lower projected temperature increase, and a pessimistic scenario (UKESM1.0-LL) [16], characterized by a stronger projected temperature increase. For both GCMs, two future periods (2041-2060 and 2061-2080) were analyzed under two different CO₂ emission pathways (ssp245, considered medium or slightly optimistic, and ssp585, considered more pessimistic).

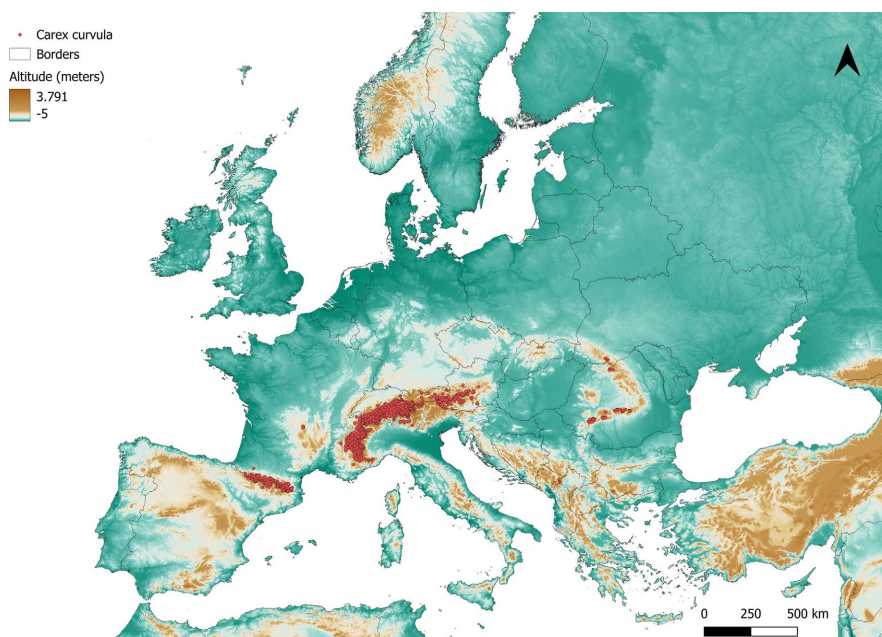


Figure 1. Occurrence of *Carex curvula* in the European alpine system.

2.3. Species Distribution Modeling

Species distribution models were generated using the biomod2 package [17] in the R programming language [18]. Several modeling algorithms available in biomod2 were used (with the respective R packages in parentheses):

- CTA: Classification Tree Analysis (rpart);
- FDA: Flexible Discriminant Analysis (fda);
- GAM: Generalized Additive Model (gam, mgcv or bam);
- GBM: Generalized Boosting Model or Boosted Regression Trees (gbm);
- GLM: Generalized Linear Model (glm);
- MARS: Multiple Adaptive Regression Splines (earth);
- RF: Random Forest (randomForest);
- SRE: Surface Range Envelope (often termed BIOCLIM; bm_SRE);
- XGBOOST: eXtreme Gradient Boosting (xgboost).

Initially, all listed modeling techniques were tested. Models for which the aver-

age ROC evaluation index (AUC—Area Under the Curve) was below 0.8 were discarded. The average AUC was calculated from three runs of the model on the same dataset, each time using a different (random) split of 80% of the data for training and 20% for testing. In the second phase, we only retained the modeling techniques with an average ROC above 0.8 and generated the final models accordingly. Although we also examined the TSS index for model evaluation, its interpretation was more variable; therefore, we placed greater emphasis on the ROC index [19].

3. Results

Based on the univariate GLM analysis, the most critical variables were bio11 (mean temperature of the coldest quarter) and bio14 (precipitation of the driest month).

A comparison of the ROC values from different modeling techniques (Figure 2) revealed that RF (Random Forest) performed best, followed by XGBOOST and then GBM, GLM, and MARS. Even the weakest method, FDA, achieved a ROC value above 0.9, indicating that all approaches provided relatively strong predictive power.

Potential viability of *Carex curvula* (1970-2000 climate data) based on the best technique (RF modeling) at the continental level depends heavily on the simulated climatic niche of the species (Figure 3).

Future simulations of the various climate change emission scenarios and global circulation models translate into a reduction of the potential cover for the species at a continental level (Figure 4).

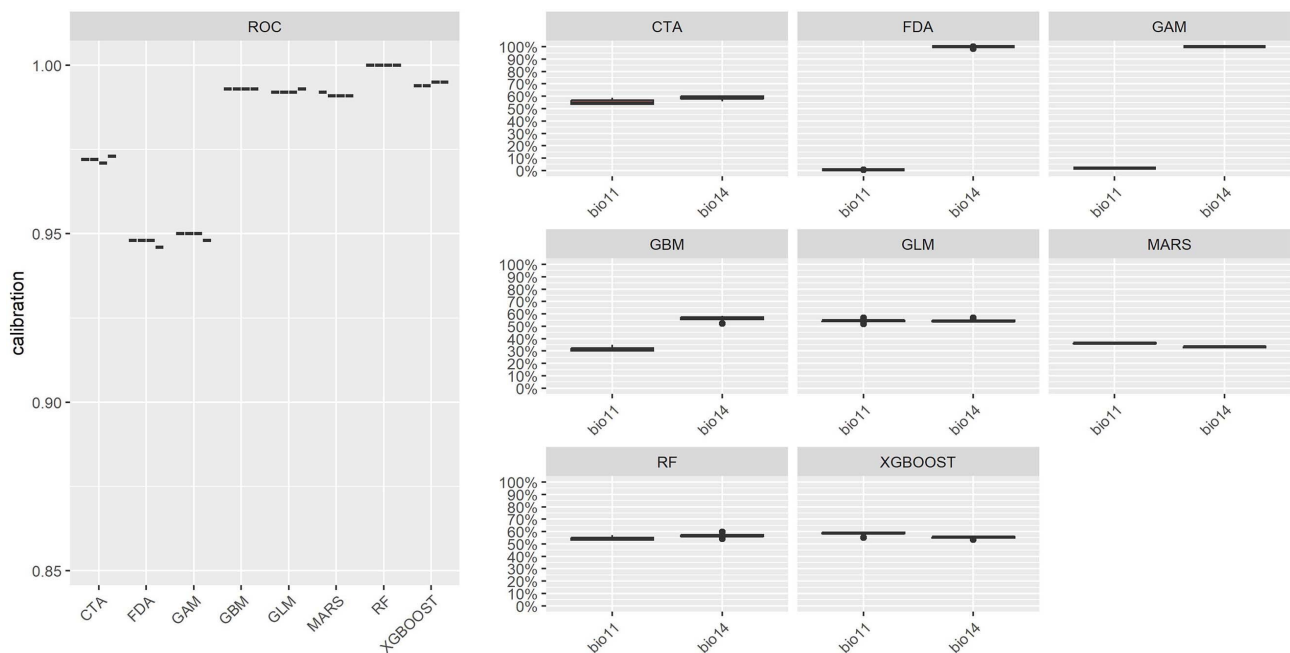


Figure 2. Left: ROC-based evaluation of the modeling techniques. Right: Variable importance for the two climatic predictors across different modeling approaches.

4. Discussions

At finer spatial scales, species distributions are influenced by topographic parameters (elevation, slope, aspect, micro-topography, etc.), while at broader scales, species distributions are predominantly governed by climatic factors (temperature, precipitation, etc.) [6]. Because we aimed to produce continental-scale models, we restricted our input variables to climatic predictors, thereby justifying the 5×5 km spatial resolution of our climate data. This approach enabled us to simulate the species' potential niche across Europe and better delineate the spatial boundaries of its suitable climatic conditions.

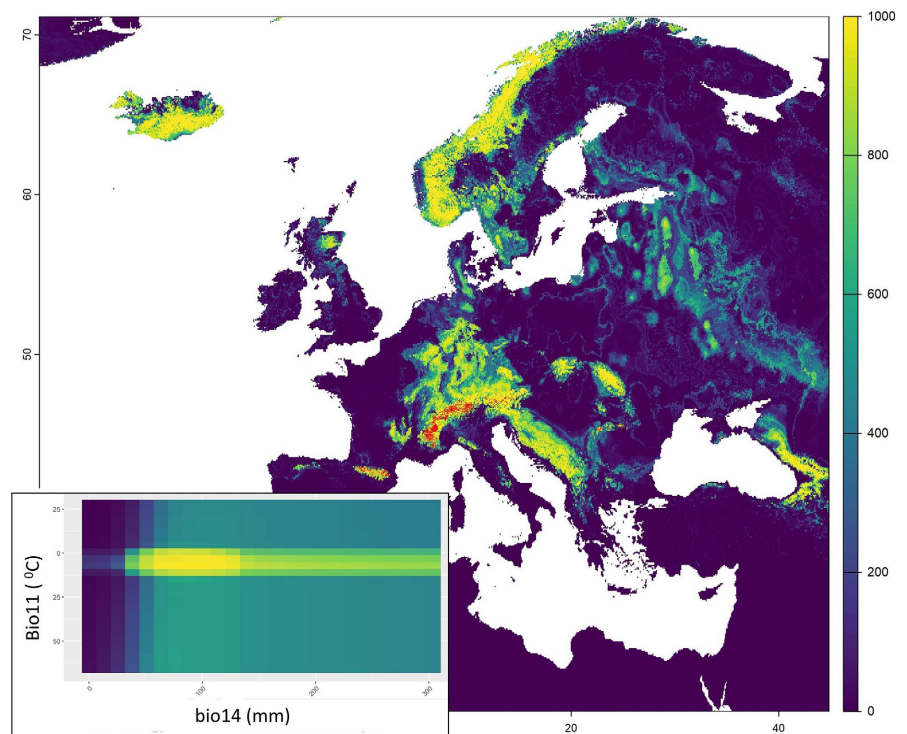


Figure 3. Potential viability of *Carex curvula* (1970–2000 climate data) based on RF modeling. Dark blue/black = 0% viability; light yellow = 100% viability. Red points = current distribution. In the medalion, the climatic envelope of the species.

According to the RF model (which exhibited the highest ROC), the current distribution of the climatic niche of *Carex curvula* is restricted to Europe's mountainous regions, excluding the mountain ranges of the Iberian Peninsula and Greece (Figure 3). The model also indicates that lower mountain ranges—such as the Ardennes, Vosges, Black Forest, Jura, and Massif Central—would have climates potentially favorable to the species, implying that *Carex curvula* could persist at elevations below strictly alpine and sub-alpine belts if competition were not limiting.

With respect to current climatic conditions, the species' optimum is positioned around mean temperatures (for the coldest quarter) of approximately -1.2 to $+0.3^{\circ}\text{C}$ and precipitation in the driest month ranging from about 35 to 135 mm

(Figure 3). Below 35 mm in the driest month, the model predicts a sharply reduced likelihood of occurrence, underscoring the significance of sufficient minimum precipitation for *Carex curvula*.

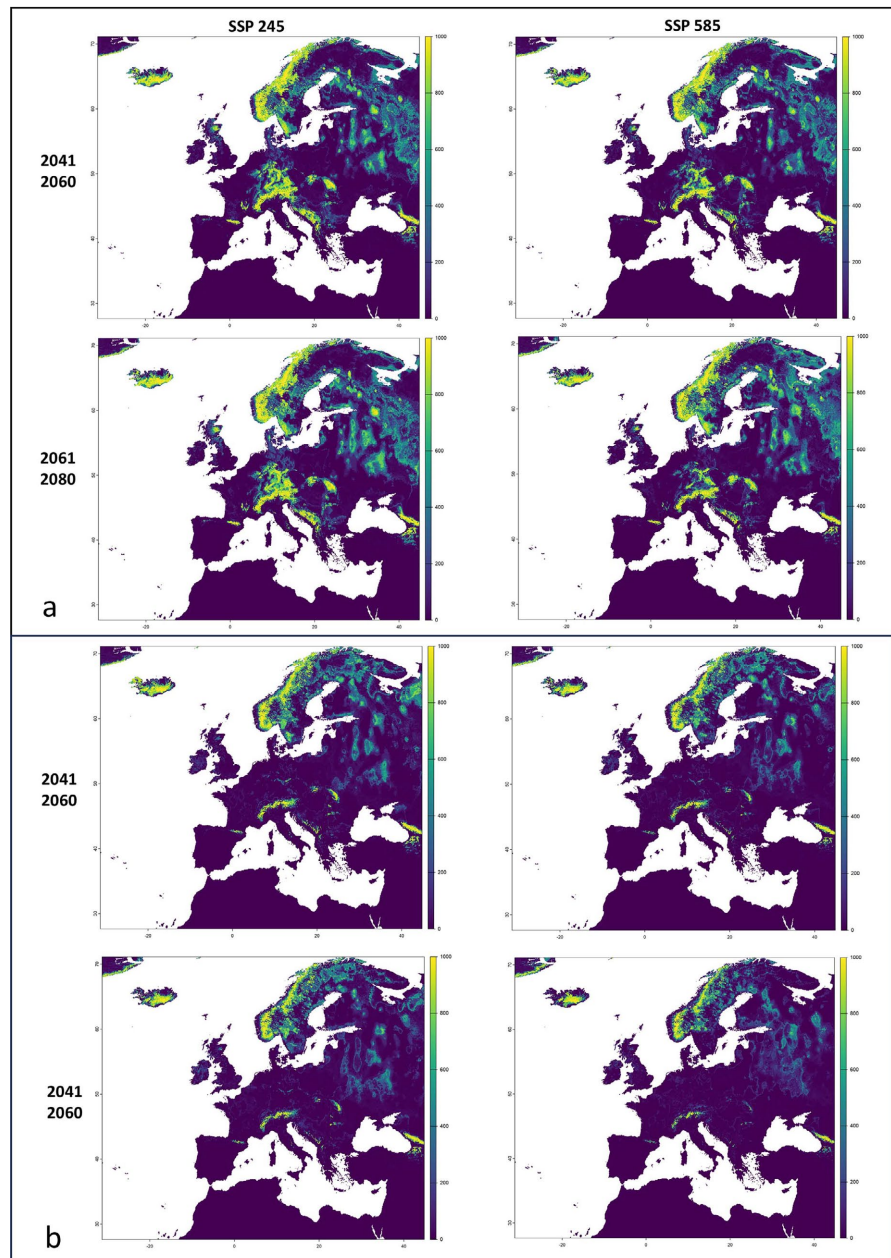


Figure 4. Potential viability of *Carex curvula* (RF model) under an optimistic GCM (MRI) (a), respectively under a pessimistic GCM (UKESM) (b). Top row: 2041-2060; bottom row: 2061-2080. Left column: ssp245 (medium emissions); right column: ssp585 (pessimistic emissions).

In future climate scenarios (Figure 4), areas at lower elevations emerge as the most vulnerable. Under all evaluated scenarios, the region in Europe offering near-optimal conditions for the species shrinks compared to its current extent.

The choice of GCM (MRI vs. UKESM) appears more influential than the emission scenario (ssp245 vs. ssp585). This trend is evident in the estimated percentages of suitable area lost (Figure 5). According to the MRI-based model projections, losses in currently suitable climate zones could average 10% - 45%, depending on the time frame and emission scenario, with an upper limit near 45%. By contrast, the more pessimistic UKESM-based scenarios suggest losses of 35% - 80%, and in some simulations, these losses exceed 80%.

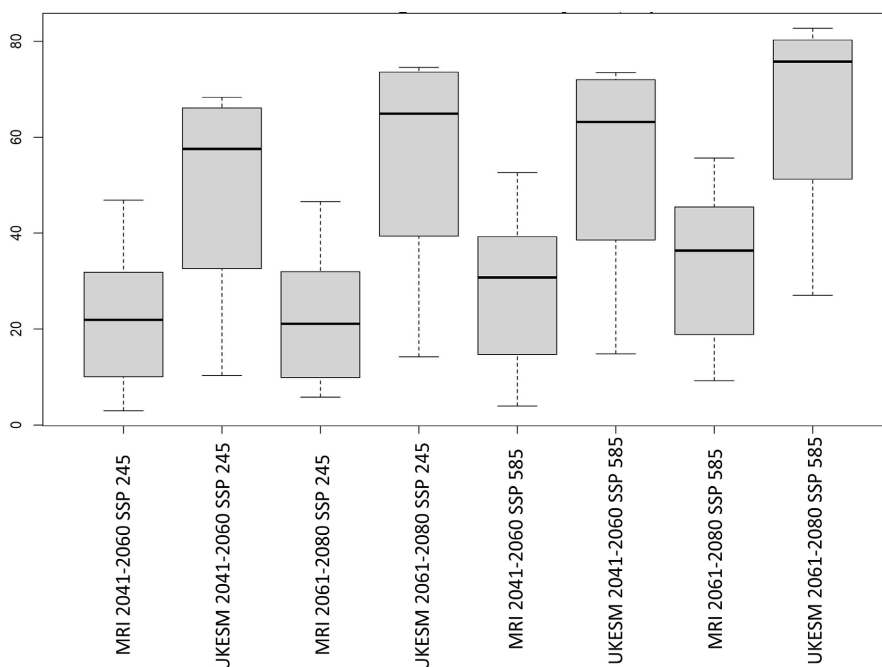


Figure 5. Percentage of the currently suitable climatic niche projected to be lost under different future scenarios (two time periods: 2041-2060, 2061-2080; two GCMs: MRI, UKESM; two SSP emission pathways: 245, 585).

Nevertheless, in most scenarios, the species' stronghold in the high-elevation pastures of the Alps remains climatically favorable. A critical consideration, however, is the potential for increased competitive pressure from more thermophilic grasses and sedges migrating upward from lower altitudes in response to warming. Although some northern regions of Europe (e.g., parts of Scandinavia) are projected to have climates that could become suitable, it is highly improbable for *Carex curvula* to disperse there naturally, given the intervening stretches of unfavorable climate and the intense competition from other species.

As the species currently occupies large areas in alpine environments across Europe, it is also included in many of the existing protected areas designated at high altitudes. However, as recent studies suggest [20], there may be a need to designate new protection areas in order to capture essential biodiversity traits in the new dynamic scenarios caused by climate change, especially in the Alps region, where for example Switzerland is considered to have a poor cover of Protected Areas at all elevations. In the Carpathian range, Natura 2000 sites cover most of the species

optimum, and conservation measures can be taken when the periodic assessments of habitat conservation state deem it necessary.

5. Conclusions

The distribution of *Carex curvula* appears to be constrained by its limited dispersal ability, by competition with other plant species, and by the historical influence of glaciation cycles in Europe. This species does not currently occupy all the regions that would be climatically suitable under present conditions, indicating the realized niche is narrower than the fundamental niche, presumably due to competitive exclusion and historical colonization patterns.

Despite modeling a range of future climate scenarios for Europe, every model suggests that some portion of the species' native range—particularly the high-elevation pastures of the Alps—will maintain suitable climatic conditions for *Carex curvula*. However, from the perspective of preserving the overall diversity of alpine plants, the majority of the simulated scenarios exhibit a contraction in the area of climatic suitability. This elicits concerns that *Carex curvula* and other cold-adapted alpine species may not persist in parts of their current range over the medium to long term.

It is very unlikely for areas identified by the models as having suitable future climate conditions in Northern Europe and in the Scandinavian peninsula to actually be colonized within the next few decades. Competition is already a limiting factor for *Carex curvula* at lower elevations, even under present climatic conditions. Thus, the fate of this species will likely hinge on a combination of ongoing climate change, increasing competition from thermophilic species, and the intrinsic dispersal constraints that characterize *Carex curvula* and many other alpine specialists.

The future may be even more grim for other rare and endemic species which are present in the *Carex curvula* grasslands. These species are already worse competitors than *Carex curvula* and are expected to have even more serious problems in competing with species adapted to warmer climates, invading the alpine habitats. The results of our study are in agreement with recent results showing that about ~70% of 1711 mountainous plant species are predicted to lose areas of suitable conditions, especially in higher mountain strata [20].

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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