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Ecological restoration in the Pannonian Basin: evaluation of native species performance and implications for adaptive landscape planning

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Ecological restoration in protected areas plays a key role in halting biodiversity loss, particularly within the context of global and national biodiversity targets. This study evaluates the success of a restoration project implemented in the buffer zone of the Special Nature Reserve “Ludaš Lake” and Nature Park “Palić”, encompassing wetland and Pannonian forest-steppe habitats, potentially contributing to the resilience of the landscape in the face of ongoing climate change. The goal was to restore degraded habitats using functionally diverse native plant species to enhance ecological stability. This study evaluated the effectiveness of the initial restoration phase, focusing on a 3-year assessment of the survival and establishment of 6,310 planted native tree and shrub seedlings. The monitoring of the initial restoration phase evaluated the performance of 29 planted native species. It also aimed to identify challenges in planning and implementation and to determine which species show the best adaptation to local conditions. Climate projections, a dynamic soil–vegetation model, and the Habitat Suitability Index were used to evaluate species’ future persistence. Results from the initial monitoring phase (3-year period), indicate that *Acer campestre*, *Acer tataricum*, *Ulmus minor*, *Prunus spinosa*, *Prunus tenella*, *Viburnum lantana*, and *Ligustrum vulgare* exhibited the highest survival rates. According to projections, shrub communities will dominate, with a limited persistence of tree species. The restoration approach presented in this study supports climate-adapted species selection and provides practical guidance for planning restoration in ecologically sensitive and climatically vulnerable areas.

KEYWORDS

biodiversity, buffer zones, climate change, ecological restoration, forest steppe, protected areas, wetland

1 Introduction

Despite global efforts to conserve biodiversity and expand protected areas, species loss and habitat degradation continue to rise, particularly in ecologically significant habitats protected by the European Habitats Directive (Dirnböck et al., 2017). The importance of ecosystem restoration has been highlighted through the “Decade on Ecosystem Restoration” (from 2021 to 2030) (United Nations, 2025b), and is emphasized in the

UN Sustainable Development Goals (United Nations, 2025a) and the Convention on Biological Diversity (CBD, 2025). In line with these global commitments, the European Union has adopted environmental policies influencing both EU members and candidate countries such as Serbia, including the EU Biodiversity Strategy, the Nature Restoration Law, which prioritize the restoration of degraded habitats to enhance biodiversity and ecosystem services.

These global goals are demonstrated in local activities, as shown by the ecological restoration carried out in the area of the Special Nature Reserve “Ludaš Lake” (SNR) and Nature Park “Palić” (NP) through the planting of native tree and shrub species. Ludaš Lake, recognized as a Ramsar Site, represents an internationally significant wetland where restoration efforts conform to worldwide conservation standards (Ramsar, 2024). These activities aim to preserve the dominant vegetation types of the Pannonian ecoregion, especially the forest-steppe ecosystem (Erdős et al., 2014), and to establish a balance between forest and grassland habitats, creating a mosaic structure and contributing to the conservation of biodiversity (Erdős et al., 2017).

Buffer zones are recommended by UNESCO (1984) as protective belts that reduce pollution in riparian areas and water bodies (Lowrance et al., 2002; Dlamini et al., 2022). The concept of a vegetation buffer zone was first proposed for Palić and Ludaš areas in the 1970s for restoration purposes (Seleši, 2000) and was later acknowledged as an effective method for reducing pollutant loads and improving landscape structure through habitat restoration and preservation. This concept was implemented for the first time within this protected area through the Ecolacus project (2022), and its application and results will be presented in this research. The multifunctional importance of the buffer zone was also recognized by UNESCO (1984), and the need for its establishment was determined through the ecological risks identified in previous studies (Caković et al., 2021; Caković et al., 2023). The key ecological risks of SRP “Ludaš Lake” and NP “Palić” are diffuse pollution, through the influence of agriculture, the soil is enriched with nutrients (nitrogen, potassium and phosphorous) and the presence of heavy metals (especially cadmium), and all this has an impact on the hypereutrophic status of the lake, which represents significant limitations for the quality of the habitat and the success of ecological restoration. The project encompassed a broad range of aquatic and terrestrial ecosystem restoration activities. Ecological restoration in the Palić and Ludaš area included the establishment of a protection zone, which consisted of several components:

1. Planting a vegetation protection zone (trees and shrubs),
2. Revitalization of natural grasslands,
3. Restoration of reed beds in eroded parts of the coast.

Regarding the complexity of the restoration project, this study focuses on component I, the establishment of a vegetation protection zone. The study presents an assessment of the success of planting 29 native tree and shrub species (6,310 seedlings) within the protection zone. Monitoring the survival of planted species represents a scientific basis for planning future projects and long-term monitoring of vegetation development (Đorđević et al., 2020). The goal of this study was to apply a dynamic biogeochemical VSD + PROPS model (combining Very Simple Dynamic with Probability of

TABLE 1 Characteristics of study area.

Parameter	NP “Palić”	SNR “Ludaš lake”
Area of water body	579.77 ha	328.5 ha
Length of shoreline	28.08 km	19.2 km
Buffer area (existing)	15.1 ha	5.7 ha
Buffer area (contracted)	13.6 ha	17.3 ha
Geomorphology	Loess and sand	

Occurrence of Plant Species) and scenario analysis (RCP 8.5 climate scenarios) to determine future changes in the Habitat Suitability Index (HSI) to enable timely implementation of adequate management.

The study was guided by the following hypotheses:

1. Integrating mathematical models and climate scenario analysis into multi-species selection can improve restoration planning by enabling more precise identification of species with long-term habitat suitability and greater potential for resilience to climate change.
2. Shrub-dominated community structures, characteristic of the Pannonian forest-steppe mosaic, will show greater resilience to projected climate change than tree-dominated structures, due to their greater drought tolerance and faster establishment.

This research promotes the use of climate projections and habitat suitability modeling, integrating biogeochemical scenario-based models to assess future ecosystem conditions and to determine the optimal set of native species for restoration planning. During the implementation of the project, several challenges and limitations were identified, such as limited availability of planting material, rapid spread of invasive vegetation and site degradation. These challenges highlighted the need for model-based species suitability assessment, which directly motivated this study. In addition, this study seeks to emphasize these findings to support the refinement of methodologies and the improvement of future ecological restoration projects.

2 Materials and methods

2.1 Research area

Lake Palić and Lake Ludaš, located near the city of Subotica, are shallow, semi-static lakes of steppe areas that are among the rare and well-preserved steppe lakes of the Pannonian region (Table1; Figure 1). As such, they are protected natural areas of the Republic of Serbia. The wetland habitat complex and steppe fragments, along with Lake Ludaš, constitute the SNR “Ludaš Lake” (Official Gazette of the Republic of Serbia, 2006), a legally protected natural area (Official Gazette of Republic of Serbia, 2018). Since 1977, this area has been classified as a wetland of international importance (Ramsar Site 3YU002) (Ramsar, 2024). Lake Palić has been protected since 1996 and declared as NP “Palić” (Official Gazette of the City of Subotica, 2017). The SNR “Ludaš Lake”

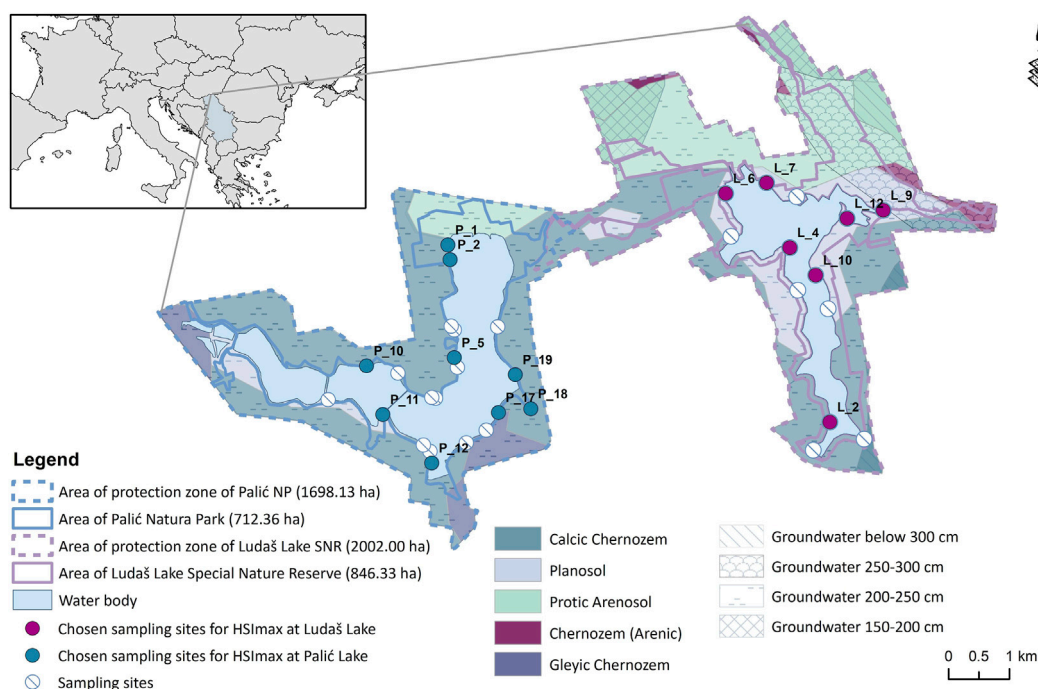


FIGURE 1
Study area (selected sampling sites are marked with "L" for Ludaš Lake and "P" for Palić Lake).

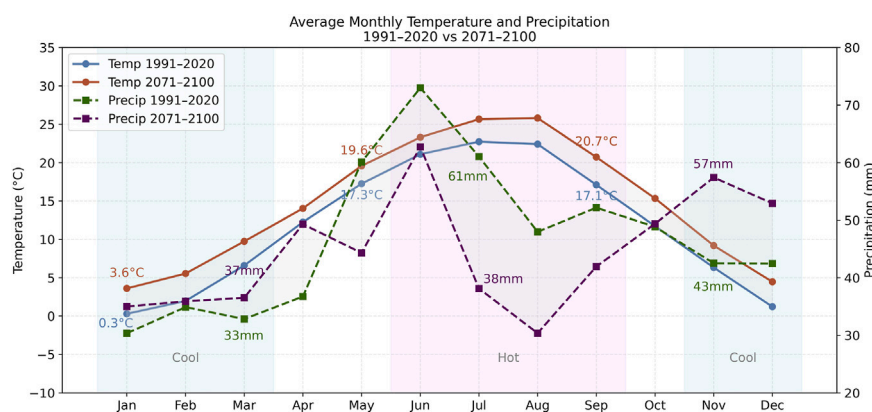


FIGURE 2
The average monthly temperatures and precipitation from 1991 to 2020 are forecasted for 2071 to 2100.

and NP “Palić” wereformally connected in 1982, establishing the Palić-Ludaš Regional Park.

The studied area is characterized by a temperate continental climate. The Digital Climatic Atlas of Serbia provided more extensive climatic data for the study sites (MEP, 2025). For the IPCC’s RCP 8.5 scenario, daily mean temperature and mean daily sum of precipitation were subsets of daily observations for 1951–2020 and projected values for the same parameters for 1951–2,100. Observed and predicted values of temperature and precipitation are presented in Figure 2, and the difference (Δ) is displayed in Supplementary Tables S1 and S2.

2.2 Vegetation and multiscale approach for ecological restoration

The studied area is part of the forest-steppe zone, characterized by a vegetation type which includes sandy and steppe components, interspersed with patches of salt marshes, meadows, wetlands, and remains of deciduous forests (Beloica et al., 2024).

Ecological restoration was carried out in the area of the SNR “Ludaš Lake” and NP “Palić”, following the principles of preserving forest-steppe ecosystems (Supplementary Table S6). During the planning of the restoration, all relevant legal and ecological

regulations were taken into account, including the Nature Protection Act of the Republic of Serbia, the Ramsar Convention (Ramsar, 2024), the Natura 2000 network (EEA, 2021; European Commission, 2022a; European Commission, 2022b), as well as the Detailed Regulation Plan adopted by the City of Subotica.

2.3 Multi-species selection

Species selection for the buffer zone was based on ecological site assessment, the analysis of the natural potential vegetation, and observation of existing vegetation on-site. Information about natural vegetation was found in the EuroVegMap (Bohn et al., 2004) and information about existing vegetation for Palić-Ludaš region was obtained from field observations and from documents provided by Institute for Nature Conservation of Vojvodina Province (INCS, 2004; Institute for Nature Conservation of Vojvodina Province, 2011), and information about conditions of neighboring regions, specifically region of Nyíregyháza in Hungary (Török et al., 2017).

The EuroVegMap database (Bohn et al., 2004) identifies the predominant vegetation types in this region as G4 – Pannonian mixed Tatarian maple-pedunculate oak forests, L10 – South Pannonian herb-grass steppes, L11 – Pannonian sand steppes, and P32 – Pannonian salt meadows. Based on the study of natural potential vegetation and habitat types, and in accordance with Natura 2000 guidelines, three priority habitats have been identified: 1,530 – Pannonian salt steppes (Šefferová Stanová et al., 2008b), 6,250 – Pannonian loess steppe grasslands (European Commission, 2013), and 6,260 – Pannonian sand steppes (Šefferová Stanová et al., 2008a).

Establishing the mosaic structure characteristic of forest-steppe ecosystems, the restoration was planned to achieve a ratio of 60:40 or 70:30 in favor of grassland vegetation in forest-steppe mosaic (Erdős et al., 2022), which was the composition pursued throughout the project. This approach aligns with Erdős's observation that forests typically occupy between 10% and 70% of such landscapes (Erdős et al., 2022).

The basic rules for planning the establishment of vegetation in buffer zone were:

- At least 20% of the planned species must be from the EuroVeg list for the corresponding type of natural potential vegetation, i.e., type of habitat,
- No more than 15% of woody species are allowed in the lakeshore region (the planting was planned to create smaller groups of greenery with the aim of achieving a mosaic forest-steppe structure, thus avoiding linear or dense afforestation, which is not typical for this area),
- Non-native species are not allowed (this rule also includes ornamental taxa created by crossing non-native species),

After collecting all available data, a list of species from all above-mentioned documents was extracted:

- **Tree layer:** *Acer tataricum*, *Acer campestre*, *Quercus robur*, *Quercus cerris*, *Quercus pubescens*, *Quercus petraea*, *Ulmus minor*, *Ulmus laevis*, *Frangula alnus*, *Fraxinus angustifolia*,

Pyrus pyraister, *Salix alba*, *Salix cinerea*, *Populus alba*, *Populus x canescens*, *Populus nigra* 'Italica'

- **Shrub layer:** *Cornus sanguinea*, *Viburnum lantana*, *Ligustrum vulgare*, *Euonymus verrucosa*, *Viburnum opulus*, *F. alnus*, *Berberis vulgaris*
- **Dry scrubs:** *Prunus fruticosa*, *Prunus tenella*, *Prunus spinosa*, *Rosa canina*, *Rosa gallica*, *Crataegus monogyna*

This project integrates the cultivar *P. nigra* 'Italica' planted in protective belts along the edges of agricultural fields, which are the historical element of cultural landscape of Vojvodina (Beloica et al., 2024). Supporting ecological principles by adding eco-cultural and biocultural elements into ecological restoration projects is important in the buffer zones, where local communities play a crucial role in maintaining and safeguarding landscape values (Sena et al., 2021).

2.4 Plant material procurement, planting, maintenance and monitoring

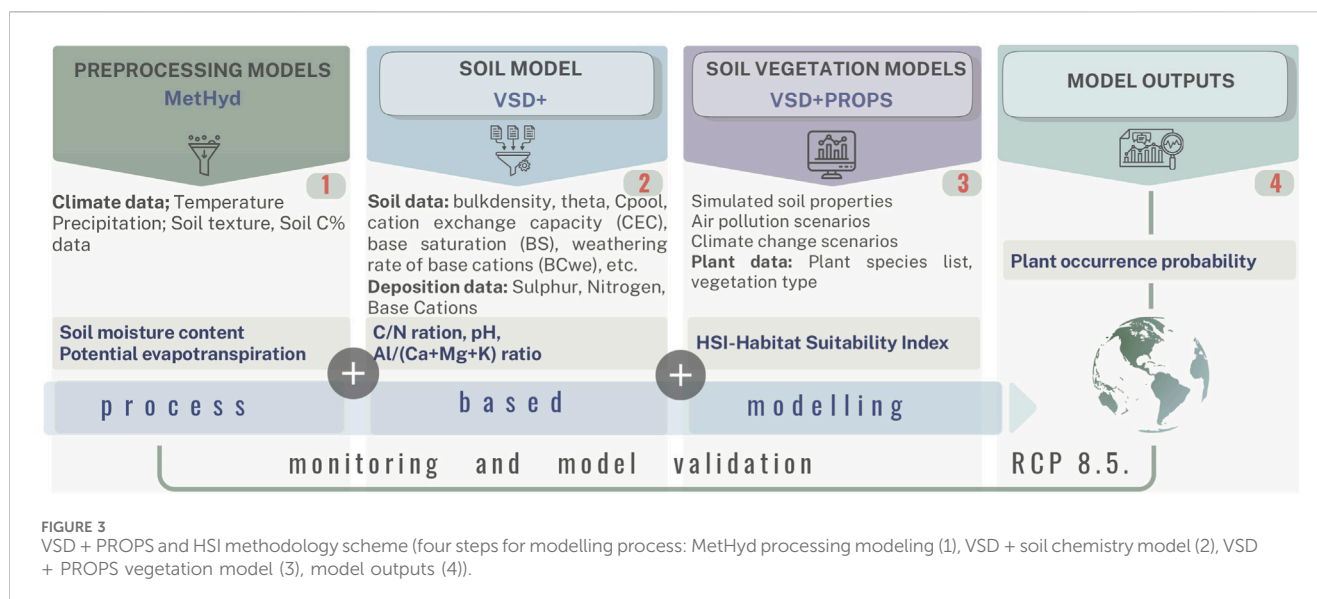
As part of this project, a total of 2,877 tree and shrub seedlings were planted around Lake Ludaš in 2020 and 2021, and 3,433 seedlings were planted around Lake Palić, forming a narrow strip ranging from 5 to 30 m in width (Supplementary Table S3). A total of 6,310 planted individuals ($n = 6,310$) were monitored in this study. The planting was designed to include keystone species (species crucial for the ecosystem), as well as plants with significant ecological functions, such as pollinator and nectar species, and species whose fruits serve as winter food for birds (Ecolacus, 2022). For the establishment of the buffer zone, species that are naturally present in the area were used, based on the assumption that all plants would successfully adapt and achieve good results.

The planting material was nursery-grown, with seedling sizes specified in Supplementary Tables S4, S5. To ensure sustainability and success, and in accordance with the Detailed Regulation Plan and the Ecolacus project "Biodiversity and Water Protection for Lake Palić and Lake Ludaš" (Ecolacus, 2022) efforts were made to remove invasive species through clear cutting. All seedlings are protected from adverse nature and other influences after planting. To achieve this, it is necessary to provide the best possible maintenance (including watering, mulching, and pruning). Supplementary Table S6 shows terrain preparation, planting, maintenance, monitoring, and project documentation.

Observations were made on the success of 29 native tree and shrub species during 2022 and 2023 (Supplementary Table S6). The success of planted species was assessed based on visible signs of vitality, including the presence of leaves, flowering, or fruiting, and the absence of serious physical damage from wildlife or machinery. Seedlings that were dry, dead, or significantly damaged were classified as failing.

2.5 Scenario-driven planning and management

In this study, we used several coupled models that integrate climate parameters, soil characteristics, and vegetation dynamics (Figure 3). By integrating climate projections and site-specific data



into models, scenario analysis helps predict vegetation responses, optimize restoration strategies, and enhance long-term ecosystem resilience.

2.5.1 VSD + PROPS data methodology: A combined approach for ecosystem analysis

The study used coupled dynamic models MetHyd, VSD+, and PROPS in order to simulate future habitat suitability for the plant community. The MetHyd (Version 1.9.1, Alterra CEE) model, together with the VSD+ (Very Simple Dynamic model; Version 5.6.3, Alterra CEE) and the PROPS model (Probability of Occurrence of Plant Species, Version, Alterra, CCE), were applied to simulate changes in ground vegetation cover resulting from variations in climate and soil chemistry dynamics (Dirnböck et al., 2017). The change in mean monthly temperatures and precipitation was analyzed for periods 1991–2020 and 2071–2,100, under the IPCC's RCP 8.5 scenario according to EURO-CORDEX climate models (EURO-CORDEX, 2024).

MetHyd is a preprocessing model for the VSD + model, used to derive hydro-meteorological and soil-related parameters required for ecosystem simulations (Holmberg et al., 2018). In this study, monthly values of total precipitation, total insolation, and mean daily air temperature were used as meteorological inputs to the MetHyd model. In addition, data on soil particle-size distribution, soil water–air regime, and soil carbon content were included. Using the MetHyd preprocessing model, the following parameters were derived as inputs to the VSD + model: denitrification factor, percolation–runoff and soil bulk density, as well as nitrification coefficients, mineralization reduction factor (soil moisture and temperature dependent), actual evapotranspiration, photosynthetically active radiation, soil moisture content, and average annual temperature and precipitation.

The VSD + model (Reinds et al., 2012; Bonten et al., 2016) is a dynamic, biogeochemical, single-site soil model. It incorporates mass balance equations that describe soil input-output relationships, along with equations governing rate-limited and equilibrium soil processes. The PROPS vegetation model

simulates vegetation dynamics and changes in response to abiotic conditions, including nutrient availability, base cations, light, water availability, soil acidity, and temperature. Detailed soil characteristics for all sampling locations used as model inputs are presented in the Supplementary Figure S1. By integrating the PROPS model with VSD+, we estimated the probability of plant species occurrence using the Habitat Suitability Index (HSI) based on environmental factors (Figure 3) of specific micro locations in restoration area (Obratov-Petković et al., 2022).

2.5.2 Habitat Suitability Index (HSI)

The Habitat Suitability Index (HSI) is a normalized indicator used to evaluate how suitable and supportive a habitat is for a particular species, community, or ecological process. The values range from 0 to 1, allowing easy comparison across sites and conditions. HSI was calculated as the arithmetic means of probabilities that were adjusted (normalized) for the presence of the species of interest (Slootweg et al., 2014).

$$HSI = \frac{1}{n} \sum_{j=1}^n \frac{p_j}{p_{jmax}}$$

n represents the number of species, p_j is the occurrence probability of species j , and p_{jmax} is the maximum occurrence probability of species (upper value of the HSI range).

Following standard practice in HSI and VSD + modeling, habitat suitability is interpreted on a 0–1 scale, where 0 indicates low suitability for sustaining populations and 1 represents optimal environmental conditions with a strong capacity to support species persistence and ecosystem functioning.

Intermediate values could be interpreted as:

- 0–0.2: Low suitability;
- 0.3–0.4: Limited suitability;
- 0.5–0.6: Moderate-quality habitat;
- 0.7–0.8: High-quality habitat;
- 0.9–1.0: Optimal environmental conditions.



FIGURE 4 Percentage of planting success in NP "Palić" and SRP "Ludaš Lake" (blue bars represent NP "Palić", while purple bars represent SRP "Ludaš Lake").

2.5.3 Model validation

Model reliability and validation were evaluated using correlation analysis. For this analysis, we included only species with sample sizes exceeding 100 planted individuals, as small samples have higher statistical variance, thereby ensuring that the statistical estimates remain analytically meaningful. The analysis was performed using model-predicted values and field measurements (Supplementary Table S7).

3 Results

3.1 Establishment success—Survival rates of the planted buffer zone

At the NP "Palić" site, 85.37% of the 3,433 seedlings planted in 2020 and 2021 were found during the 2022 monitoring, and 72.15% were found during the 2023 monitoring. In 2022, 2,877 seedlings were planted in the SNR "Ludaš Lake" area, which had a planting

success rate of 90.30%. There was a decline in 2023, with the success rate dropping to 69.89%.

The radial graph (Figure 4) illustrates the prevalence of different tree and shrub species in 2023, the final year of monitoring, highlighting differences in species performance across locations. Several species have successfully adapted to the conditions in the studied area. For example, *Acer campestre* had a survival rate of 92.2% at Palić and 88.8% at Ludaš. *Acer tataricum* had a high survival rate, with 90.4% in Palić and 94.9% in Ludaš, despite numerous instances of damage caused by wild animals.

Other notably successful tree species are *Pyrus piraster* (88.9% at Palić, 77.5% at Ludaš), *Ulmus leavis* (98.4% at Palić, 74.6% at Ludaš), and *Ulmus minor* (73.1% at Palić, 94.6% at Ludaš). Despite being planted in fewer numbers, *Salix alba* shown remarkable adaptation, with a 100% survival rate at Palić and 83.3% in Ludaš. *Ligustrum vulgare* demonstrated high survival, with 87.8% at Palić and 77.1% at Ludaš. *Cornus sanguinea* adapted well on this area, with 72.6% survival rate at Palić and 71.2% at Ludaš.

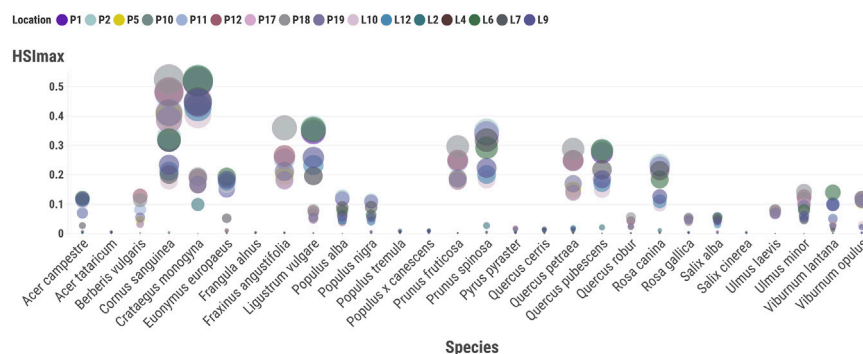


FIGURE 5
Microlocation HSI and probability of species occurrence in the area of the NP “Palić” and SRP “Ludaš Lake” (Circle size represents the HSI value for each species at each site, while colours indicate different microlocations).

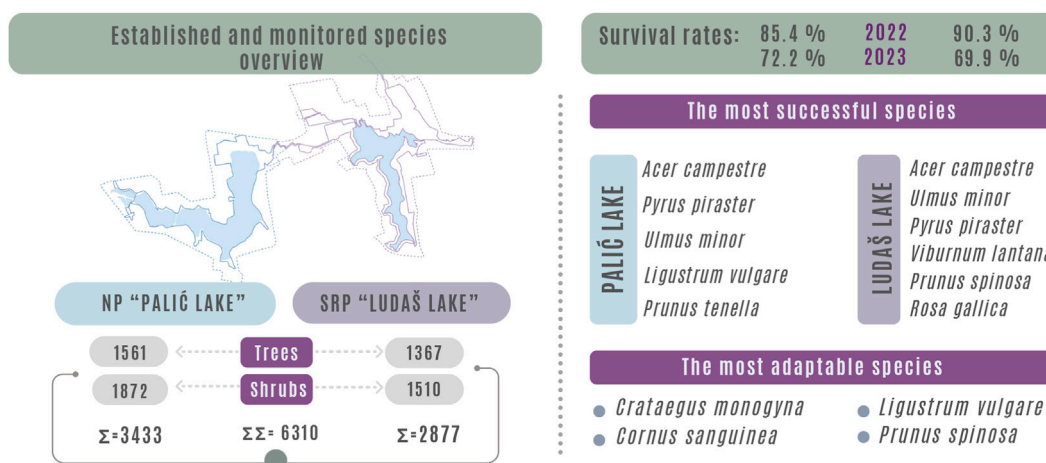


FIGURE 6
Survival and adaptation rates of the most successful planted species. Survival rates are derived from real-time field monitoring and represent the percentage of successfully established individuals, while adaptability is based on HSI modelling.

Populus alba showed a notable decrease, with survival rates falling to 50.51% in Palić as well as 39.04% at Ludaš. *Quercus robur* had significant losses, with a survival rate of 42.40% at Palić and 50.91% at Ludaš. Shrub species showed vulnerability, especially *Euonymus europaeus*, where the success rate on Palić was 60.90% and on Ludaš was 55.43%.

3.2 VSD + PROPS model analysis results

According to the analysis of the VSD + PROPS model, the species with the highest probability of occurrence (the maximum HSI) are shown in Figure 5, while specific locations are illustrated in Figure 1. Furthermore, the HSI distribution for each lake separately is provided in Supplementary Figure S2. In the area of the NP “Palić”, it is evident that the species *Crataegus monogyna* and *Cornus sanguinea* has the highest HSI index values, with a maximum value of 0.52. Also, species such as *Ligustrum vulgare*, *Prunus spinosa*, *P. fruticosa*, *Quercus petraea*, *Quercus pubescens* and *Fraxinus*

angustifolia record HSI values greater than 0.3. The most suitable locations are P1, P2, P11, P12, and P18.

At the Ludaš Lake region (Figure 5), *Crataegus monogyna* is distinguished as the sole species with maximum values of 0.52. Subsequently, elevated values over 0.3 are noted for the species *Ligustrum vulgare*, *Prunus spinosa*, *P. fruticosa*, and *Quercus pubescens*. The most suitable locations in this area are L6, L7, L9, L10, and L12.

The model projection indicates higher values of HSI for shrub species (*Cornus sanguinea*, *C. monogyna*, *L. vulgare*, *P. spinosa*, *Prunus fruticosa*) compared to tree species, indicating a shift towards shrub-dominated communities in future climate scenarios. Visual summary of the most successful species, based on survival and adaptation rates as shown in Figure 6.

3.3 Habitat suitability change projection

Based on the RCP 8.5 climate scenario, the projected Habitat Suitability Index (HSI) values in the study area suggest a decrease in

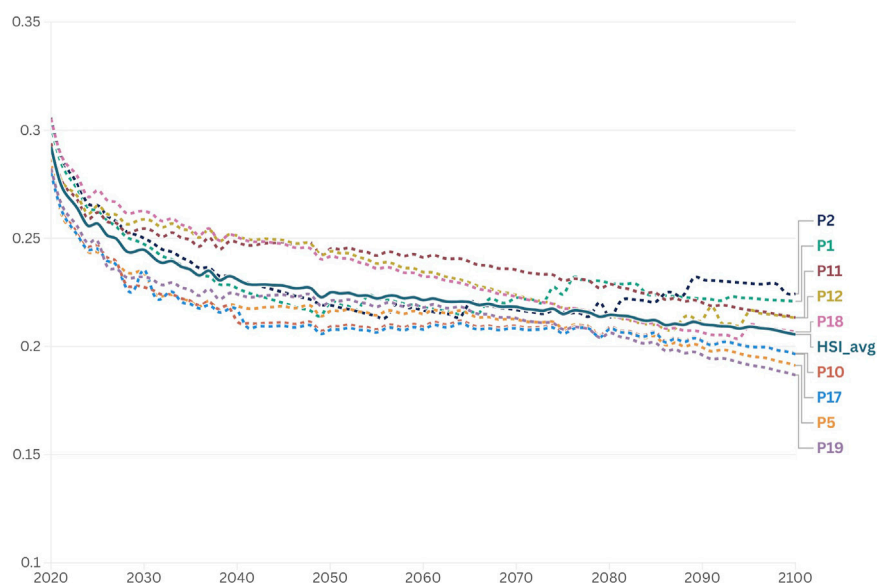


FIGURE 7
Projection of habitat suitability in the Palić area.

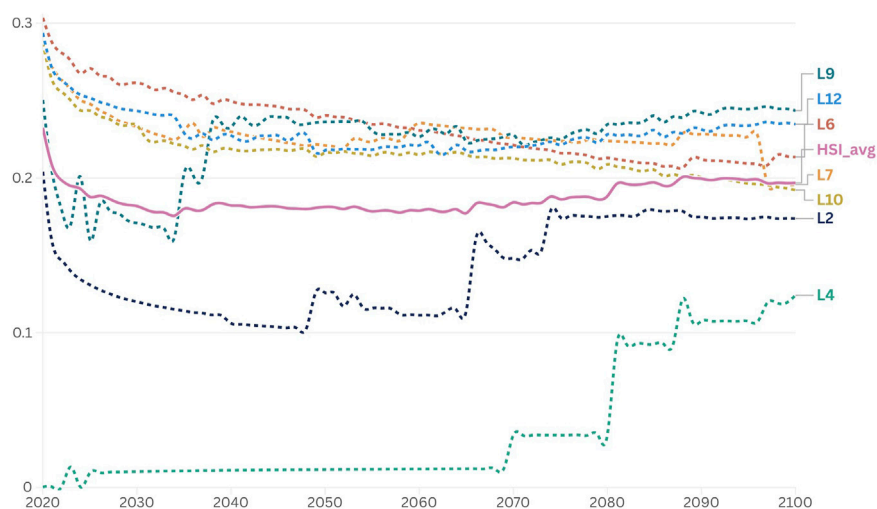


FIGURE 8
Projection of habitat suitability in the Ludaš area.

habitat suitability. The initial HSI values are approximately 0.3, declining to under 0.2 at the end of century (Figure 7). The average HSI demonstrates a progressive decline over time, with minimal variation observed in the Palić region. Similar projections are observable at the majority of monitoring sites. A progressive increase is evident at P2, whereas the most significant decrease is recorded at P19, with values falling below 0.2 by 2,100.

In the area of Ludaš, initial HSI values are around 0.3, and despite fluctuations over the years, values remain around 0.2 by the end of the century (Figure 8). A relatively stable trend is observed at several sites L9, L12, L6, L7, whereas greater variability is recorded at locations L4 and L7. Notably, location

L4 demonstrates a more distinct upward trend in habitat suitability by the end of the century.

3.4 Model validation

To minimize the influence of site-specific management practices, such as differences in maintenance intensity caused by limited accessibility of the Ludaš Lake site, correlation analyses were performed not only between the number of planted and surviving seedlings within each site, but also between the number of planted seedlings at one site and the total number of surviving seedlings

TABLE 2 Model validation: correlations between observed survival rates (site-specific and integrated) and model projections (Pearson's correlation coefficients (r) with associated p-values in parentheses).

Model scenario	SRP total	SRL total	SR 2022	SR 2023
VSD Ludaš	−0.01 (0.97)	0.08 (0.77)	0.21 (0.44)	0.08 (0.77)
VSD Palić	−0.03 (0.92)	0.03 (0.90)	0.12 (0.66)	−0.02 (0.93)
VSD Ludaš reduced	0.68 (0.02)	0.42 (0.20)	0.88 (0.00)	0.89 (0.00)
VSD Palić reduced	0.59 (0.05)	0.36 (0.28)	0.87 (0.00)	0.90 (0.00)

Bold values indicate strong and statistically significant Pearson correlations ($r \geq 0.5$, $p \leq 0.05$).

across both study areas (SR). This cross-site approach allowed partial control for human-related maintenance effects and provided a more robust assessment of planting success.

Correlation values based on the full species list of modeled future occurrence probabilities (VSD Ludaš and VSD Palić) with SRP (surviving rates Palić), SRL (surviving rates Ludaš), or SR (integrated survival rates across both study areas) metrics are low and statistically non-significant (Table 2). In contrast, the reduced species list of modeled future occurrence probabilities (VSD Ludaš reduced and VSD Palić reduced) with SRP, SRL, or SR metrics shows strong and statistically significant correlations (0.59–0.90), demonstrating that removing unreliable species substantially improves the ecological signal and predictive strength of the VSD indicators. This indicates that the model provides reliable predictions for a specific subset of species, whereas certain other species may require model recalibration or the use of alternative models that incorporate additional ecologically relevant variables.

Model simulations indicate that five species (*Acer campestre*, *Acer tataricum*, *Pyrus pyraister*, *Ulmus laevis*, *Ulmus minor*) require a different set of predictor variables, suggesting that either the variable set or the model parametrization (or the input data themselves) should be improved. The discrepancy may stem from the observational datasets on which the model was originally trained, which predominantly represent conditions in Central and Northern Europe. We consider that incorporating relevé data from our study region could yield more accurate correlation patterns. Similar issues have been reported in previous studies with Ellenberg indicators (Dengler et al., 2023; Tichý et al., 2023), which subsequently led to the publication of country-specific indicator values precisely to account for such biogeographical differences. These inconsistencies suggest that additional species-specific ecological parameters may need to be incorporated to improve model performance and predictive robustness in future simulations.

4 Discussion

Ecological restoration may advance the recovery of degraded ecosystems and increase their resilience to climate change (IPBES, 2018), but its success depends crucially on the participation of all stakeholders during each phase of the project (Brancalion and Holl, 2020). This study demonstrated an acceptable level of restoration success, while survival rates change among species based on their biological characteristics and particular ecological settings, as confirmed by Liu H. et al. (2023).

In this regard, *Acer campestre* and *Acer tataricum* showed high survival rates, indicating their adaptability to local conditions and potential contribution to restoration efforts in similar environments (Halassy et al., 2020). Nevertheless, monitoring indicated substantial harm inflicted by wildlife on these species, highlighting the necessity for enhanced protection to ensure their ongoing success (Čermák and Mrkva, 2006). *Ulmus minor* and *Ulmus laevis* also showed high success, which confirms previous research from Hungary (Halassy et al., 2020). Although Halassy et al. (2020) observed low survival rates of *Pyrus pyraister* in the first year of life in their restoration experiment, our findings indicate that this species demonstrated successful adaptation.

Species selection was guided by specific assessments, including soil characteristics and groundwater levels. This approach helped establish vulnerable species like *Fraxinus angustifolia*, *Prunus tenella* and *Rosa gallica*, listed on the Red List (IUCN, 2024), have demonstrated significant success in restoration efforts in Serbia and other Pannonian Basin regions due to their well-developed root systems and belowground storage organs (Valkó et al., 2018). With the ability to thrive in a variety of conditions, as noted by Enescu et al. (2015), *Ligustrum vulgare* is characterized by a high degree of success in this area. *Cornus sanguinea* and *Prunus spinosa* also show high survival rates, indicating strong adaptation to site-specific environmental conditions. These results confirm other studies that recognize *C. sanguinea* as exceptionally adaptable to variations in the climate and many habitat types, including regions subjected to intense agricultural practices (Kollmann and Grubb, 2001). Many researchers have observed that these species not only facilitate soil stabilization but also provide essential habitat and nutritional resources for bird, insect, and various other wildlife (Kollmann and Grubb, 2001; San-Miguel-Ayanz et al., 2016). Several more shrub species like *Viburnum lantana*, *Viburnum opulus*, and *Rosa canina*, also achieved survival rates above 60%, further confirming their resilience under specified environmental conditions. Conversely, *Salix cinerea*, *Quercus robur*, and *Populus alba* had low survival rates, probably due to insufficient site conditions or planting techniques (Keenleyside et al., 2012). Annual variation in seedling survival may be attributed to climatic factors, diffuse pollution, planting techniques, or year-specific environmental factors (Keenleyside et al., 2012; Berrahmouni et al., 2015).

While the outcomes of this segment of ecological restoration, which includes the establishment of both tree and shrub layers, appear satisfactory, a longer monitoring period is needed to reliably assess whether the restoration goals have been achieved (Paolinelli Reis et al., 2024). Climate changes could have significant consequences for the success of ecological restoration, as well as for protected areas and the entire ecosystem (Liu T. et al., 2023; Young et al., 2024). Specifically, Lazić et al. (2025) state that less precipitation in spring and summer indirectly causes reduced soil moisture during the summer in this part of Europe, which will significantly affect vegetation. The VSD model simulation shows a clear contrast between the two sites: for Palić, it predicts a gradual overall decline in HSI with minor differences between locations and stable trends without major fluctuations. For Ludaš more pronounced differences and fluctuation between sites are expected, with some locations experiencing sharp changes, particularly after 2060–2070. This suggests greater variability and uncertainty in future habitat conditions. The VSD model indicates that Ludaš's higher HSI values are due to wetter conditions, especially in the northern lake,

and similar conditions are found in certain areas of Palić, particularly those with established vegetation and favorable microclimatic conditions. Additionally, these locations consistently show the highest HSI values, indicating that the model predictions align well with actual ecological conditions. Locations with specific conditions, such as high groundwater levels and areas where invasive vegetation previously existed, stood out as more suitable microlocations for the success of planted seedlings. Csákvári et al. (2022) highlight the role of site conditions, existing vegetation, and groundwater levels in successful ecological restoration within the Pannonian steppe region.

The results indicate a pronounced future dominance of shrub communities, with only a small portion of forest species expected according to the modeled scenario. This observed shift is consistent with trends in other ecotones around the world, where shrubs are increasingly recognized as a significant driver of ecosystem change as a result of warmer temperatures (Sward et al., 2023). This outcome also confirms that plant species from wetland habitats are among the most vulnerable to climate change (Čavlović et al., 2017). A shift in dominance from forest to steppe vegetation within the forest-steppe ecotone would result in substantial ecological losses across multiple levels. While shrub species provide various microclimatic benefits like shelter for various species, moisture retention, and mitigation of drought stress (Kelemen et al., 2017), these benefits are inadequate to offset the impacts of climate change. As stated by Molnár et al. (2008), forest species provide vital habitats for steppe flora and fauna and are essential for sustaining the climate resilience of forest-steppe ecosystems. Taken together, these findings emphasize the importance of detailed microclimatic field analysis to inform the design of ecological restoration projects and ensure their success.

The decrease in habitat suitability is apparent but not severe, indicating that certain species may still acclimate to the changes, which highlights the need to apply adaptive management to mitigate environmental impacts. Further participatory observation is essential for the successful maintenance of this environment. This involves an active role of local people, organizations, land managers, and policymakers to ensure the enduring advantages of the executed restoration initiatives (Evans et al., 2018; Myers et al., 2023). Using adaptive leadership is crucial, as it means constantly changing strategies based on climate change and environmental conditions, informed by results from field research (Vignola et al., 2017).

4.1 Challenges and strategic improvements for ecological restoration success in Serbia

Resolution 73/284 of the United Nations declared the Decade on Ecosystem Restoration for the period from 2021 to 2030, with the aim of preventing, halting and reversing ecosystem degradation. Although actively involved in cooperation with the Food and Agriculture Organization (FAO) and the UN Economic Commission for Europe (UNECE) and promoting ecosystem restoration, the Republic of Serbia has been delayed in presenting clear regulations on how it approaches or acts in achieving this goal. In accordance with the Law on Climate Change, the Ministry of Environmental Protection has formulated the “Program of Adaptation to Climate Change for the Period 2023–2030” with the Action Plan. Additionally, through numerous regulations and reports, the Republic of Serbia is

working to improve its goals in line with the agendas of the European Union (Beloica et al., 2023).

During the project implementation, we encountered an important challenge with the lack of appropriate planting material suitable for this type of ecological restoration at national level. This deficiency highlights one of the major shortcomings in the practical implementation of the UN Decade on Ecosystem Restoration. National nurseries must be closely aligned with long-term restoration plans and adequately prepared to meet the projected needs at least a decade in advance. To improve the results of reforestation and ecological restoration itself, it is crucial to ensure the availability of high-quality planting material of native species and the implementation of effective monitoring and maintenance practices (Werden et al., 2024). After the technical restoration and species introduction phase, the ‘nature participation’ restoration phase can be expected and represents a natural and complementary stage of the restoration process. Such natural dynamics may significantly impact long-term ecosystem recovery (Kudryavtsev, 2007; Prach et al., 2013). It is crucial to monitor how restored areas continue to develop naturally, tracking the progression toward higher levels of naturalness and the dynamics of ecological succession.

An additional indicator of the long-term sustainability of such projects is the allocation of dedicated funding for site managers responsible for maintaining the restored areas. These financial resources must be carefully planned, as the costs associated with maintaining newly established restoration sites cannot be directly compared to those of previously existing, stabilized areas. Newly restored ecosystems typically require more intensive and frequent management activities, especially during the first 5 years, which are critical for the successful establishment and stabilization of these habitats. Therefore, long-term financial planning and secured budgets are essential to support the success and resilience of restoration initiatives. Short project timelines often conflict with the principles of ecological restoration, especially when complex administrative procedures and permits are required for protected or large restoration sites, a challenge, which is also widely reported in international restoration practice (Oluwajuwon et al., 2025). A further challenge in Serbia is the 5-year maintenance period: public enterprises usually lack the capacity for long-term management, which frequently results in project degradation. During the planning phase, we found that using older planting stock rather than seedlings can significantly improve establishment success and long-term survival. Solving these challenges will be essential for Serbia to achieve its ecological restoration goals during the current decade.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

MCM: Writing – original draft, Writing – review and editing, Methodology, Conceptualization, Visualization, Formal Analysis,

Data curation. JB: Data curation, Conceptualization, Methodology, Visualization, Software, Writing – review and editing. DČ: Data curation, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Correction note

A correction has been made to this article. Details can be found at: [10.3389/fenvs.2026.1792383](https://doi.org/10.3389/fenvs.2026.1792383).

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The author(s) declared that generative AI was used in the creation of this manuscript. The authors acknowledge the use of generative AI and AI-assisted technologies for processes to improve the readability and language of the manuscript. All content has been thoroughly reviewed and edited by the authors to ensure accuracy and integrity. The scientific analysis and conclusions presented in this review remain the sole intellectual contribution of the authors.

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Supplementary material

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Glossary

CBD	Convention on Biological Diversity; an international treaty for biodiversity conservation.
DRP	Detailed Regulation Plan; a municipal-level spatial planning method outlining land use, zoning, environmental protection, and development rules for targeted areas.
EU	European Union; a supranational political and economic union of 27 member states that are located primarily in Europe.
HSI	Habitat Suitability Index; a numerical index indicating how suitable a habitat is for supporting a particular species.
IPCC	Intergovernmental Panel on Climate Change; UN scientific body providing assessments of climate change and policy recommendations.
NP	Nature Park; a protected area with well-preserved natural values and predominantly natural ecosystems.
PROPS	Probability of Occurrence of Plant Species; a model that estimates species distributions based on ecological preferences.
RCP	Representative Concentration Pathway; climate change scenarios to project future greenhouse gas concentrations.
SNR	Special Nature Reserve; a protected area with unaltered natural features and representative natural ecosystems.
UN	United Nations; an international organization that promotes global cooperation and sustainability goals.
VSD+	Very Simple Dynamic; a model used to simulate soil and vegetation dynamics under various environmental conditions.