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Wetland classification and revitalisation monitoring by using drone data*

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Abstract

Wetlands are essential ecosystems increasingly threatened by human activities and climate change. This study presents a method for classifying and monitoring wetland habitats in the Čiližská Radvaň protected area (Slovak Republic) using RGB drone imagery and the Natural Numerical Network (NatNet), a mathematically based supervised deep learning approach. The primary aim was to evaluate the effectiveness of NatNet in identifying target habitat types and to assess the impact of ongoing revitalisation efforts. Habitat types were classified using RGB drone imagery and ground-truth training polygons that represented the dominant vegetation communities in Čiližská Radvaň wetland. The NatNet achieved the training classification success rate exceeding 97%, allowing the creation of relevancy maps successfully identifying spatial habitat distribution. Relevancy maps verified in the field reached classification accuracy of 0.88 and F1 score of 0.90 across all habitats together. Results showed observable shifts in habitat extent and structure after one year of restoration, confirming the suitability of the method for detecting ecological changes in wetland environments.

Keywords

Drone imagery, habitat revitalisation monitoring, Natural Numerical Networks (NatNet), remote sensing, supervised deep learning, wetland habitat classification

Introduction

Wetlands, defined as areas where the land is saturated or inundated with water and is occupied by plants adapted to water-saturated conditions (Brinson 1993), provide a wide range of ecological functions (Mitsch and Gosselink 2015). Wetlands also serve as habitat for a diverse array of plant and animal species, supporting biodiversity conservation (Davidson et al. 2014). Over the years, wetlands have faced significant degradation due to human activities, as well as climate change (Yang et al. 2023), threatening their capacity to deliver their crucial services. In the past, wetlands provided 40% of the ecosystem services value on Earth (Xu et al. 2020), but this extent has been decreasing continuously for several decades (Yang et al. 2023).

In Central Europe, during the 20th century, the melioration scheme with the aim of turning the area into agricultural land changed the lowland landscape dramatically. Artificial channels were built to drain the area, and traditional landscape management activities as grazing and

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mowing of wet meadows were replaced by intensive agriculture. Similarly, in the studied wetland – Čiližská Radvaň, where water regime degradation (decrease of groundwater table, absence of seasonal floodings), together with land-use changes, resulted in a high level of invasion of the degraded wetland habitats. The invasion of non-native plant species is considered as one of the major threats to the natural habitats (Pyšek and Richardson 2010; Rumlerová et al. 2016), including wetlands. Riparian and wetland habitats are among the most invaded ones (Walter et al. 2005; Pyšek et al. 2010; Medvecká et al. 2014) due to several reasons including high propagule pressure caused by floods (Baattrup-Pedersen et al. 2013). Species composition of riparian habitats is shaped by the combination of environmental factors such as position within alluvia (Slezák et al. 2022; de Simone et al. 2025) and alien species presence (de Simone et al. 2025). Habitats that are closest to the river are usually the most invaded (Hood and Naiman 2000), especially in anthropogenetically modified rivers (Maskell et al. 2006). However, within the same habitat type, areas with good water regime that experience frequent and dynamic floods (Rood et al. 2005) or higher groundwater table are more resistant to invasive species (Petrášová-Šibíková et al. 2017; Mikulová et al. 2020).

Scientific research has highlighted the importance of wetland restoration in combating biodiversity loss and maintaining ecosystem services (Davidson et al. 2014). Wetland restoration projects worldwide aim to recreate or enhance wetland ecosystems that were previously degraded or destroyed (Zedler and Callaway 1999). In the Pannonian region, especially the Danube inundation, several LIFE projects were implemented in the last decades, focusing on the restoration of the water regime and traditional management (e.g., LIFE Dunajské luhy, LIFE Dynamic Life Lines Danube, LIFE Resistance). The studied locality is currently in an ongoing restoration process of water regime improvement and regular mowing. The effect of this revitalization has been monitored since 2023 with the aim of identifying the changes in extent of wetland habitats continuously.

Traditional field-based monitoring is often time-consuming and limited in spatial and temporal extent. The use of remote-sensing techniques in the case of wetland monitoring provides a very promising technique that allows inundation mapping of large areas (Lefebvre et al. 2019; Jussila et al. 2024). In smaller wetlands, drones have emerged as a suitable solution, offering high-resolution, flexible, and cost-effective monitoring capabilities for sensitive marine and wetlands (Ventura et al. 2018; Bhatnagar et al. 2021; Dronova et al. 2021). Drones enable even species-level vegetation mapping using advanced image analysis and machine learning, supporting management of invasive species and habitat conservation (Ruwaimana et al. 2018). However, mapping of habitats is often more complicated due to the fact that the same species can occur in a variety of habitats. To support Natura 2000 habitat classification, the Natural Numerical Networks (NatNet) method was developed by Mikula et al. (2023b). It is a graph-diffusion-type supervised deep learning classification algorithm based on forward-backward diffusion model and its numerical discretization. Earlier, the NatNet has been successfully applied in the classification of Natura 2000 forest habitats using Sentinel-2 satellite data (Mikula et al. 2023b). However, wetland habitats are typically smaller in scale and require data with higher spatial resolution. In the present study, RGB drone imagery was used for the first time to apply the NatNet method in the wetland context. Although there exist multispectral and even hyperspectral drones, we used only RGB drones and photogrammetry to generate orthophoto images and the digital surface model (DSM), mainly due to the reason of general usage of developed methodology by stakeholders. The method is implemented within NaturaSat, a software developed to support geobotanical research through the application of modern mathematical approaches.

The main aims of the present study are: (1) to evaluate the use of the Natural Numerical Network for the automatic identification of wetland habitats from RGB drone imagery, and (2) to assess the success of revitalization by analysing changes in habitat extent between 2023 and 2024 in a recently restored wetland.

Methods

Geographic and historical context

Čiližské močiare protected area, is part of the Natura 2000 network (site code: SKUEV0227). It is located in Central Europe, Pannonian region, Slovak Republic, in the Podunajská nížina Lowland (Fig. 1). It has surface area of 4.783 km^2 and includes natural and artificial wetland habitats like Čiližský potok creek (Natura 2000 habitat 3150 Natural eutrophic lakes with *Magnopotamion* or *Hydrocharition*-type vegetation), wet meadows (Natura 2000 habitat 6440 Alluvial meadows of river valleys of the *Cnidion dubii*), melioration draining channels and small wetlands (alliances *Phragmition communis* Koch 1926 and *Magnocaricion elatae* Koch 1926). In the past, the area was part of a broad inundation area of the Danube River with a network of wetlands, meadows, and floodplain forests. In the 20th century, the melioration scheme with the aim of turning the area into agricultural land changed it dramatically. Many artificial channels were built to drain the area.

In the recent past, the majority of the locality was covered by wet meadows (previous agricultural land was abandoned due to very low productivity), invaded by *Solidago gigantea* and *Aster lanceolatus* plant species, together with the expansive grass *Calamagrostis canescens*. The most humid parts hosted wetland habitats, the reed bed (*Phragmition communis* Koch 1926) with an admixture of *Carex* spp. and *Juncus* spp. species, as well as *Lythrum salicaria* and *Lycopus europaeus* in the lower herb layer. Recent restoration activities include improvement of the water regime by using the existing floodgate situated on the old melioration channel, and regular mowing.

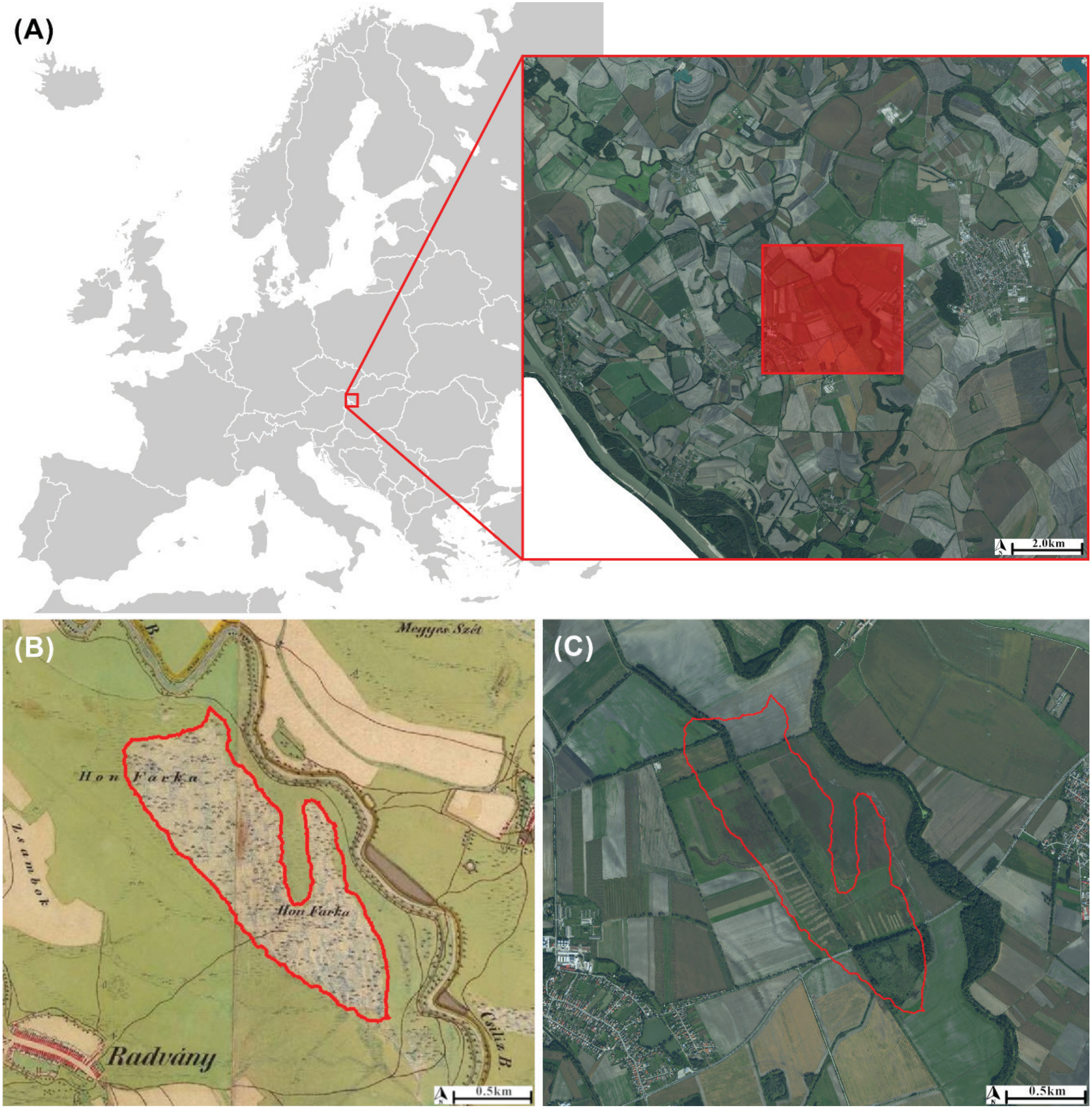

Figure 1. A. The locality Čiližská Radvaň wetland, in the Slovak Republic. The area of interest is marked by the red square. **B.** The 19th century wetland in the locality of Čiližská Radvaň segmented on the historical map of the Second military survey (1819–1869), and **C.** its transformation in an orthophoto image (2017–2019).

The historical situation of this area is depicted in Fig. 1. The wetland existed since the middle of the 19th century, next to Čiližská Radvaň village. The historical wetland was semi-automatically segmented in the software NaturaSat on the map of the Second military survey (Ministry of the Environment of the Slovak Republic 2024), then transformed to the current Open Street map by the NaturaSat Historical Maps Transformation service and superimposed with the orthophoto image (The Geodesy, Cartography and Cadastre Authority of the Slovak Republic 2025). A large part of the currently restored wetland corresponds to the historical one, which justifies the implementation of restoration activities in this region by the BROZ - Conservation Association.

Acquisition and processing of drone data

For our analysis, we used drone images captured on November 2nd 2023, and October 17th 2024. They provided sufficient distinction between habitat types and thus formed the basis for our classification algorithm and for creating the optimal Natural Numerical Network for this wetland area of interest. For both flights, we used DJI Air2S drone with Sensor dimension 1-inch CMOS, Resolution 20 MP (for photos), Field of View (FOV) 88°, Focal Length Equivalent 22 mm, Aperture f/2.8. Both flights were performed from 10:00 to 12:00 am the flight planner was Dronelink with parameters flight height 100 m, maximal flight speed 13 m/s, and area covered 72300 m^2.

The Ground Sampling Distance (GSD) was 2.91 cm/pixel. The image overlaps for both flights and are reported in Suppl. material 1: figs S1, S2.

Global navigation systems (GNSS) technologies were used to reference the ortophotomosaic in the spatial reference coordinate system. The Control points measured by the GNSS technique served directly for the transformation of photogrammetric models/ortophotomosaic into a reference system. In Suppl. material 1: fig. S3, we show 5 Control points which were also used as Check points for the November 2023 flight, and in Suppl. material 1: fig. S4, we show 6 Control points which were also used as Check points for the October 2024 flight. In Suppl. material 1: tables S1, S2 we show accuracy reports for both flights. GNSS measurements were carried out using the Slovak Positioning Observation Service SKPOS with a maximum accuracy of 0.02 m in position and 0.05 m in height. The position and height of the points were primarily determined in the ETRS89 system (EPSG:4936), while it was subsequently transformed into the primary system ETRS89-UTM34N (EPSG: 32634) in which the entire processing took place. The ellipsoidal height was transformed to elevation in the national Slovak vertical system Bpv using the DVRM quasigeoid model. Further processing took place in the Agisoft Metashape software, by a standardized workflow to create the orthophotomosaic and digital surface model in 20 cm pixel resolution. A finer resolution, e.g., corresponding to GSD, was found inappropriate due to the high level of vegetation details, which were not representative of the studied habitats and did not allow application of the classification algorithm.

The vegetation height was calculated by measuring differences between the digital surface model (DSM) captured with the drone and the digital terrain model (DTM), obtained from the nationwide aerial laser scanning from the years 2017–2019, which was provided by the Geodesy, Cartography and Cadastre Authority of the Slovak Republic. Only the ground class was used, from which a raster 20 cm × 20 cm was created by using kriging interpolation. In Suppl. material 1: fig. S5, we show the canopy height model (DSM-DTM) for the studied area.

NaturaSat tools and workflow

Several key workflow steps were performed in the NaturaSat software (Mikula et al. 2021). NaturaSat is a software application developed to support habitat mapping and geobotanical research through advanced mathematical methods. In this study, we used NaturaSat primarily as an environment that integrates automatic and semi-automatic image segmentation, the implementation of the NatNet classification algorithm, the creation of relevancy maps for habitats, and tools for transforming historical maps. The diagram in Fig. 2 represents the working pipeline of the complete processing workflow in the NaturaSat. The preceding steps such as the drone data acquisition, photogrammetric processing and the derivation of the canopy height are described in the previous section.

Processed drone data and field habitat information were first imported into NaturaSat. Software tools for image filtering and automatic and semi-automatic segmentations were applied to delineate polygons for the selected habitats. Within these polygons, representative squares were created, and their statistics were calculated using the software monitoring tools to construct the feature space used for NatNet training. NatNet training and classification, as well as the computation of relevancy maps, were performed using the classification tools in NaturaSat (see section "NatNet classification methodology for drone images"). Furthermore, the NaturaSat Historical Maps Transformation service was used to identify corresponding areas of interest between historical maps and the contemporary interactive map (see section "Geographic and historical context"). The subsequent workflow steps related to validation, analysis of habitat changes, and their ecological interpretation are discussed in the "Results and Discussion" section.

NatNet classification methodology for drone images

We utilised RGB drone imagery to classify wetland habitats based on their spectral characteristics. The drone images, captured over multiple dates, were composed of red, green, and blue (RGB) channels resampled to 20 cm pixel resolution. Due to seasonal variations in vegetation and environmental conditions, the winter and spring images were excluded as they were unsuitable for classification. As a result, the autumn imagery from November 2023 and October 2024 (Fig. 3A, C), which provided clear distinctions between habitat types, was selected.

To delineate the habitats, polygons were constructed by NaturaSat automatic and semi-automatic segmentation tool using the November 2023 drone data, and they were validated using GPS tracks obtained in the field (Fig. 3B). The chosen polygons represented the dominant wetland habitat of reed beds (*Phragmition communis*). Two associations are present at the locality, *Phragmitetum vulgaris* von Soó 1927 and *Typhetum angustifoliae* Pignatti 1953 together with the transitional parts where both dominant species (*Phragmites australis* and *Typha angustifolia*) occur. These communities, according to the Slovak habitat catalogue (Šuvada et al. 2023) form one habitat (reed beds – habitat Lk11, EUNIS: Q51 Tall-helophyte bed), but their physiognomy and, thus also spectral characteristics, are different. Also, shifts between two associations in the locality could bring valuable insight into the revitalisation process. For this reason, we established three classification groups: 1) *Typhetum angustifoliae* (later in the manuscript referred as "*Typha*"); 2) transitional type, "*Typha-Phragmites*"; and 3) *Phragmitetum vulgaris* (later in the manuscript referred as "*Phragmites*").

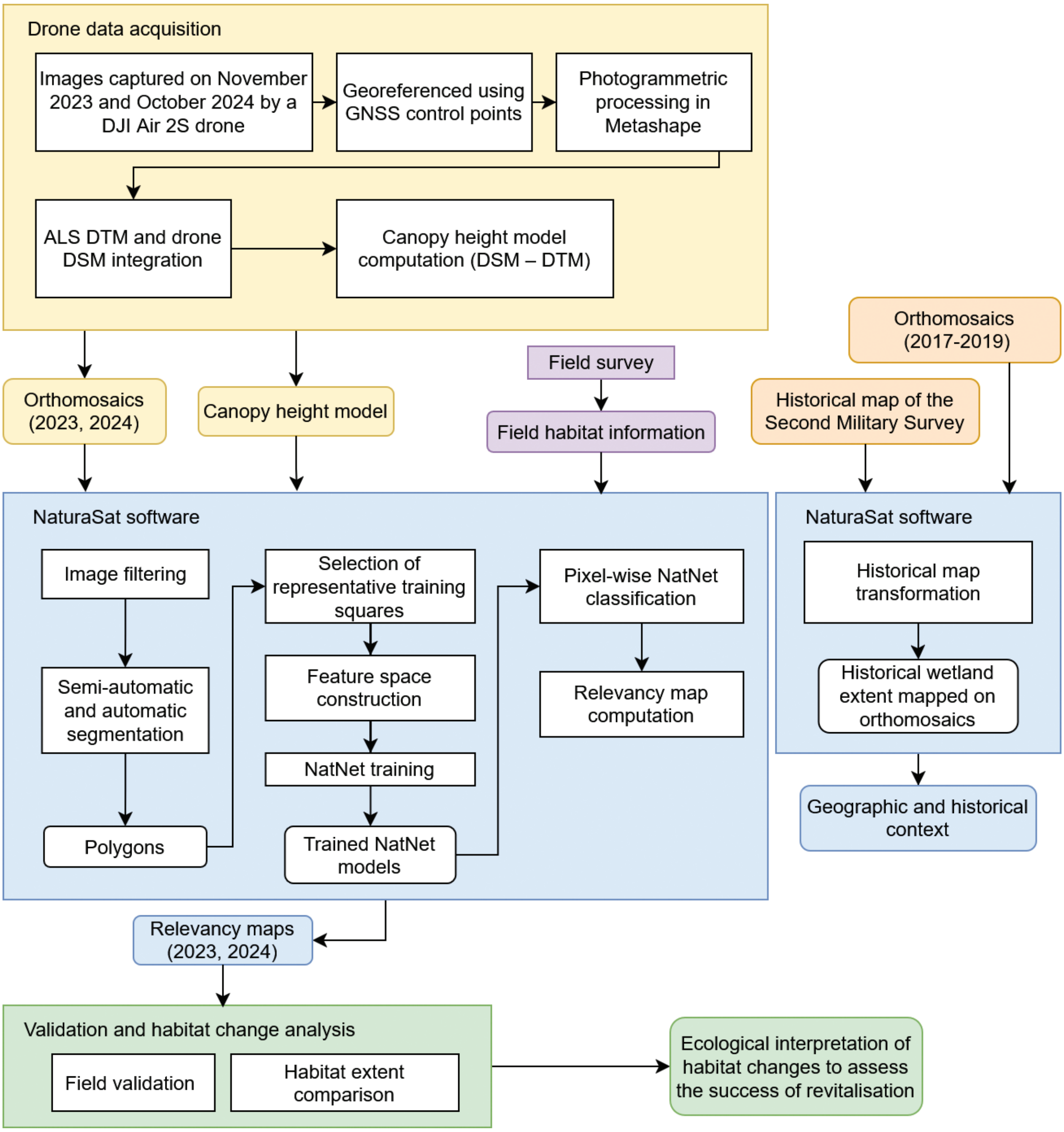

Figure 2. Working pipeline of the complete processing workflow, with key steps carried out in NaturaSat.

For the classification process, a training dataset was constructed from the polygons. Representative squares of the size 11 × 11 pixels were selected manually from each polygon to serve as training samples (Fig. 3B). These squares were chosen to capture the variability of spectral features in each habitat type (Fig. 4). Such a strategy ensured that the training dataset was homogeneous in the distribution of the samples and representative of the true spectral diversity in the habitats, thus improving the reliability of the subsequent classification.

The Natural Numerical Network (NatNet) was used for classification. It is a supervised deep learning classification algorithm designed for applications like habitat identification, particularly in environmental monitoring, such as the Natura 2000 protected areas (Mikula et al. 2023b). Its core idea was introduced in Mikula et al. (2023b), and it was further developed in Mikula et al. (2023a). In Suppl. material 1, we present the NatNet version for the classification of drone data with all necessary details.

The basic mechanism of the Natural Numerical Network can be described as follows: the forward diffusion causes the movement of points belonging to one cluster of the training set toward each other, and the opposite effect, keeping the points away from each other for different clusters of the training set, is caused by the backward diffusion. The NatNet contains a few parameters that are optimised in the training phase of the method. The training (optimization of parameters) of the NatNet yields

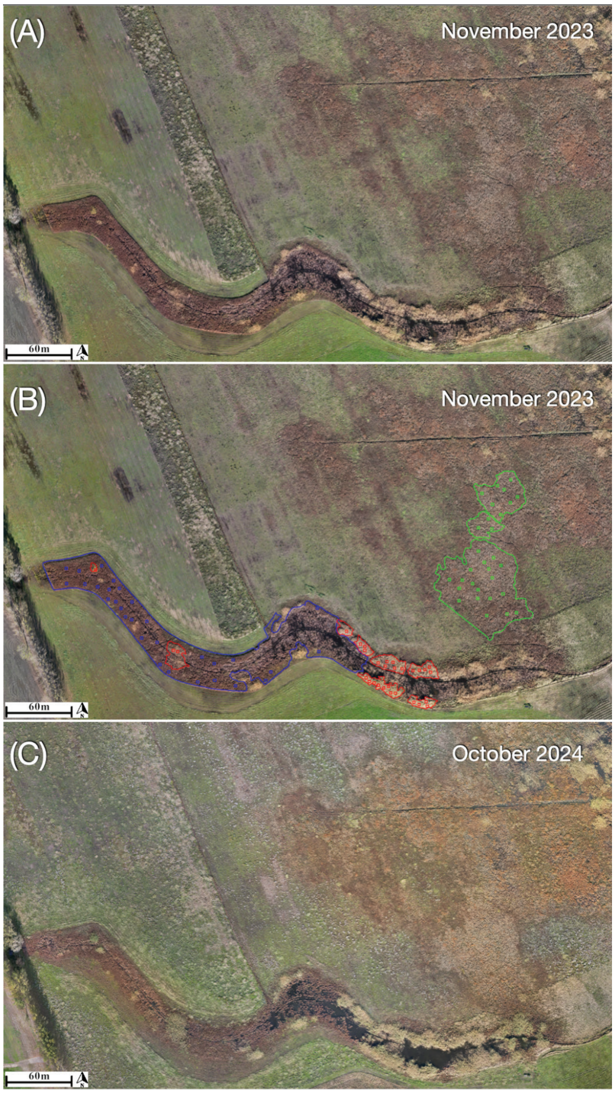

Figure 3. A. Drone imagery of Čiližská Radvaň (Slovak Republic) wetland from November 2023; **B.** drone imagery of Čiližská Radvaň wetland from November 2023 with representative squares inside the polygons of *Typha angustifolia* (green polygons), *Typha-Phragmites* (blue polygon), and *Phragmites australis* (red polygons) and **C.** drone imagery from October 2024.

the optimal dynamics of the training set vertices, i.e., the trained Natural Numerical Network. Then, by the trained network, a new observation is classified. In our case, the classification of all image pixels outside the training dataset is performed, and the relevancy map for each habitat is computed with the goal of habitat extent identification. Since the relevancy maps assign classification relevancy levels to different pixels (regions), it is also crucial in analysing degraded or transitional habitats.

The training process of the Natural Numerical Network is performed on the labelled input data, where representative squares in the imagery can be characterized by their statistical and differential values across multiple optical bands, such as mean, maximum, minimum, standard deviation, and graph-Laplacian (see also Ožvat et al. 2024). In the classification of Čiližská Radvaň wetland habitats, the training dataset consists of 150 samples. They consist of 90 samples from three target habitats with 30 representative squares for each habitat. The surrounding vegetation of the target habitats is characterized by large areas dominated by expansive species such as *Calamagrostis epigeios* and invasive species like *Solidago gigantea* and *Aster lanceolatus*. The southern part of the wetland consists of an intensively managed meadow, also dominated by *Calamagrostis epigeios*, which is mown several times a year, resulting in very uniform and short grass. To prevent misclassifications and false-positive habitat occurrences, we included these two types of surrounding vegetation as "background clusters" in the training phase. Each type of this "background" vegetation (*Calamagrostis epigeios* with invasive species and intensively mown *Calamagrostis epigeios*) was represented by 30 squares. These "background" clusters help to distinguish the habitats of interest. As mentioned above, the drone imagery consists of three optical bands and, after the extensive tests, we used only the mean of red, green, and blue channels as statistical characteristics for constructing the feature space. Throughout the training process, each sample from the training dataset is set as unlabelled and classified by NatNet dynamics, going through all possible combinations of NatNet parameters. The dynamics of the NatNet with one unlabelled point is shown in Fig. 5. The ratio between the number of correctly classified samples and number of all samples in the training dataset is set as the training success rate. The parameters that give the best success rate in the training process are taken as optimal and represent the optimal trained Natural Numerical Network.

After successful training, each pixel of the drone image is classified by the optimal NatNet, the relevancy of its classification is computed by formulas (3) and (4) in the Suppl. material 1, and the relevancy map for each habitat is constructed. The relevancy map is a greyscale image that assigns a relevancy coefficient to each pixel p by using definition (4) from Suppl. material 1, where the greyscale image intensity level indicates how strongly the pixel correlates with a specific habitat type. High intensity values, represented by bright colours in the relevancy map, suggest a substantial likelihood that a given pixel represents the target habitat, while the areas with lower intensity values may indicate transitional or degraded zones where there is still an indication of the presence of habitat characteristics. By contrast, the intensity values close to zero, given by the dark colours in the relevancy map, represent the areas with no target habitat presence.

Results and discussion

The first objective of this study was to train the Natural Numerical Network for the classification and identification of wetland habitats in the Čiližská Radvaň area, in the Sloval Republic. Three distinct wetland habitats were selected for the study, each represented by 30 representative squares. These training squares ensure comprehensive

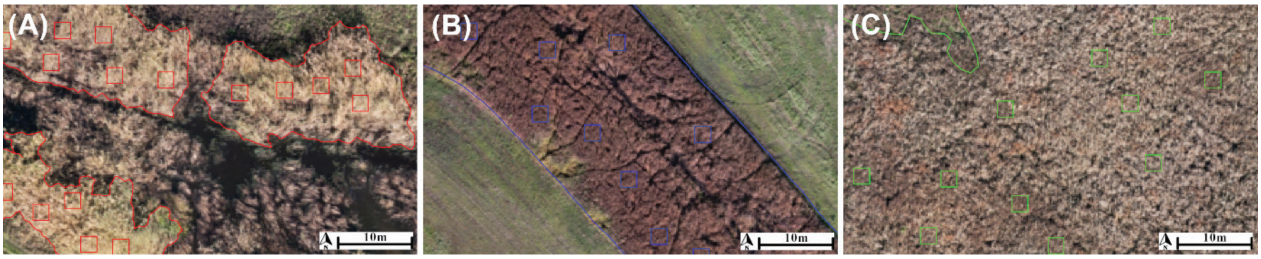

Figure 4. Detailed overview of each habitat, from left **A.** *Phragmites australis*; **B.** *Typha-Phragmites*, and **C.** *Typha angustifolia* communities.

coverage of the spectral variability in each habitat cluster, thereby enhancing the model's ability to distinguish between different habitat types. The training phase of the NatNet resulted in a high classification accuracy, achieving a success rate of 97.34%. This level of accuracy means that the algorithm was able to correctly classify most of the data points, with only four misclassified points. Notably, misclassifications occurred between the *Typha angustifolia* and *Typha-Phragmites* habitats, as well as between the *Typha-Phragmites* and *Phragmites australis* habitats. These habitats share dominant species, and the differences are mainly in the proportion of species covered. These misclassifications likely reflect overlapping characteristics of vegetation in ecotonal areas where spectral similarities disable the algorithm to find sharp distinctions.

Despite the existence of these few misclassified points, the overall success rate of 97.34% is considered sufficient for NatNet to be applied to habitat classification. The success rate was obtained with the set of parameters where $K_1 = 3800$, $K_2 = 4300$, and $\delta = 0.002$ (see also the Suppl. material 1 on NatNet mathematical details). The number of K_i-s in the diffusion coefficient (2) was reduced to two by applying a dimension reduction approach using the Principal Component Analysis (PCA), where only the first two principal components were utilized. PCA was used to catch the maximum variance in the data, thereby enabling a transformation of the coordinate system considering the direction of the maximal variance. The use of classification results and the construction of relevance maps provide valuable information on the spatial distribution of wetland habitats, allowing more precise monitoring of habitat area development in the future.

In the Čiližská Radvaň wetland, the major vegetation type is *Phragmition communis* (Lk11 – reed beds) with two associations, *Phragmitetum vulgaris* and *Typhetum angustifoliae* and transitional parts where *Phragmites australis* and *Typha angustifolia* occur together. *Typha*, as well as *Phragmites* species, are highly characteristic for wetland environments due to their ability to thrive in waterlogged soils and shallow waters. The robust root system of *Typha* helps in sediment trapping and nutrient cycling, making it a vital component of wetland ecosystems. Fig. 6 shows RGB drone imagery of Čiližská Radvaň wetland and relevancy maps for NatNet trained on November 2023 data (Fig. 6A, C, E, G) and on October 2024 data (Figs 6B, D, F, H), in rows always for one of the analysed habitats. In both columns, the results for *Phragmites australis*, *Typha-Phragmites*, and *Typha angustifolia* (with and without considering canopy height) are shown.

The pure *Phragmites* habitat in the Čiližská Radvaň wetland is a relatively rare habitat, with only a few locations identified. It occurs mainly along the water channel, on places with the highest water levels in the wetland. It occurs in shallow water and along the edges of bodies of water, contributing to the ecological health of the wetland. Despite this limited presence, the relevancy map for the *Phragmites* habitat effectively captures these areas, even identifying some regions that were not initially segmented (Fig. 6A, B). This highlights the sensitivity of the Natural Numerical Network in detecting this habitat, which is very important due to the presence of species in harder accessible terrain. The relevancy map also shows a notable transition between the *Typha angustifolia* habitat and the pure *Phragmites* habitat. This transition is visualised as black regions in the *Phragmites* polygons and white colour of the corresponding part on the *Typha angustifolia* relevancy map (Fig. 6E, F, G, H).

In our study, the *Typha-Phragmites* dominated habitat is a specific one due to its unique composition, representing a mixture of *Typha angustifolia* and *Phragmites australis*, two species commonly associated with wetland ecosystems. This mixed habitat is situated along the old channel, and also in broader surroundings, where the ecological conditions support both species (Fig. 6C, D). These two species frequently coexist in locations with oscillating water table, creating dense vegetation stands. However, the Natural Numerical Network can detect slight optical differences in the *Typha-Phragmites* mixture, enabling it to represent this habitat on the relevancy map accurately. In this representation, the interior of the *Typha-Phragmites* polygon (blue polygon) is white, indicating a high relevancy coefficient and a confident classification of this mixed habitat type.

The relevancy map for the *Typha*-dominated habitat (Fig. 6E, F) in this wetland illustrates a high degree of relevancy in the *Typha angustifolia* polygons (green polygons), which is visualised by almost all white coloration. This white colour indicates high relevancy of the presence of *Typha* species, confirming that the spectral signature closely aligns with this habitat type. Small areas in the polygons show zero relevancy in the relevancy map of the *Typha* habitat, reflecting the transitional zone between *Typha angustifolia* and *Typha-Phragmites* habitats. The relevancy map in Fig. 6E also shows regions of white colour, which extend beyond the boundaries of the

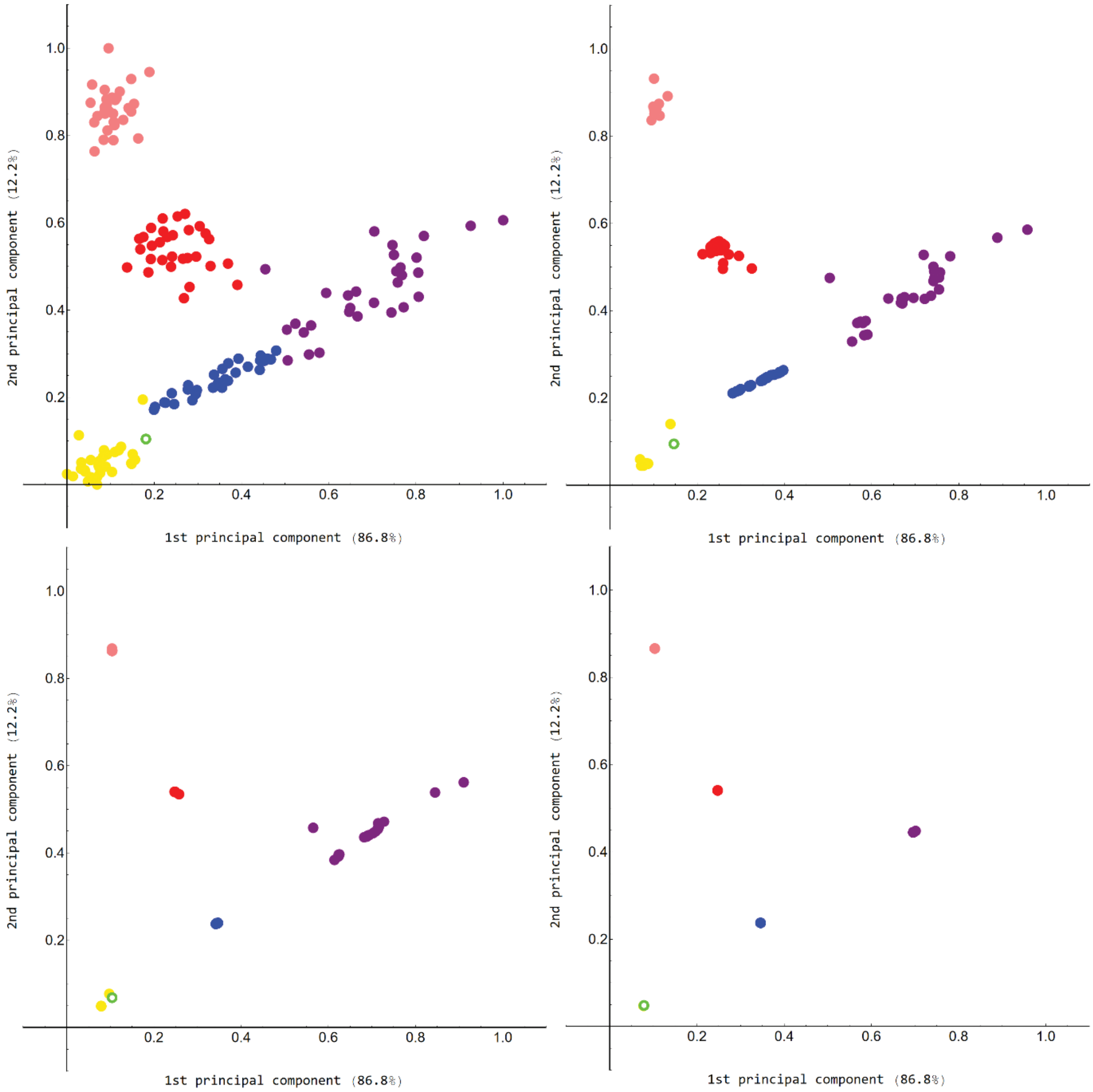

Figure 5. The dynamics of the NatNet for the learning dataset with one unlabelled point (green circle) after the dimension reduction by Principal Component Analysis. Purple, blue, and yellow points represent the points from the analysed habitats, while red and pink points are the representative squares from "background" clusters.

Typha angustifolia polygons included in the training set. However, following a comprehensive inspection of the area with high relevancy on the map, we concluded that a larger presence of *Typha angustifolia* is only partially correct and that the NatNet model trained on spectral RGB data produced for *Typha angustifolia* false positive results in certain locations.

The spectral characteristics of the *Typha* habitat exhibit similarities to those of the invasive species in the surrounding area, which leads to the tendency of the spectral model to overestimate *Typha* relevancy, highlighting the need to refine the approach. Nevertheless, a notable distinction is observed in the height of the canopy, which can thus be used as a differentiating factor. Thus, we incorporated additional structural information such as vegetation height. It was calculated using the difference of DSM and DTM models (Suppl. material 1: fig. S5) and helped us to reduce these overestimations and better delineate *Typha* stands from neighbouring habitats.

An estimated threshold value was determined for the minimum height of the *Typha* canopy, and this information was combined with the relevancy map in Fig. 6E, F. The resulting map, presented in Fig. 6G, H, indicates a significant and correct reduction in the higher values of relevancy. The integration of such data enhances the ecological accuracy of the model, thereby improving the effectiveness of the Natural Numerical Network in detecting and monitoring these typical wetland species.

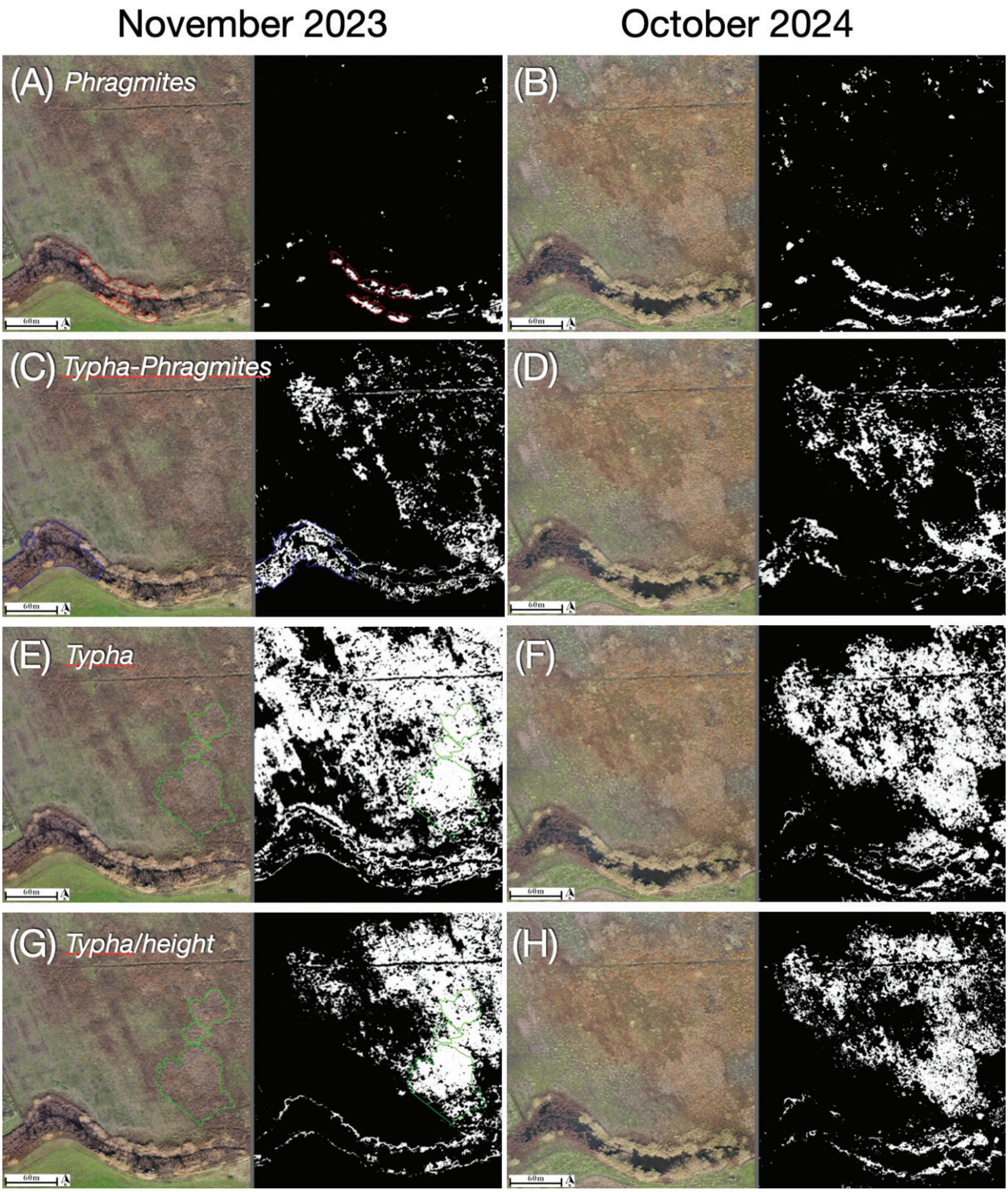

Figure 6. Part of drone imagery of Čiližská Radvaň (Slovak Republic) wetland from November 2023 and October 2024 with training polygons and relevancy maps for **A, B**. *Phragmites* habitat; **C, D**. *Typha-Phragmites* habitat; **E, F**. *Typha* habitat, and **G, H**. *Typha* habitat combined with information about vegetation height.

The second aim of our work was to compare the extent of wetland habitats after approximately one year since the initial monitoring. To accomplish a comparative analysis for the assessment of the ecological changes and evaluate the impact of restoration and management efforts on the wetland over one year, we leveraged high-resolution drone imagery collected in October 2024, along with detailed habitat relevancy maps generated from this imagery (Fig. 6B, D, F, H). These maps were calculated using the NatNet trained on representative squares created in November

2023, but using the statistical characteristics inside the squares calculated from October 2024 data. New training of the network is natural because drone images captured on different dates often suffer from inconsistent illumination, shadows, or atmospheric effects (like haze), which is important in classification tasks when using RGB imagery. The newly trained NatNet success rate was equal to 100%. Such a high success rate was obtained with a set of parameters $K_1 = 2800$, $K_2 = 2500$, and $\delta = 0.002$. That optimal NatNet was used to obtain the relevancy maps for the habitats in October 2024.

To validate these relevancy maps, a systematic approach was applied using randomly generated points in the high-relevancy (white colour) as well as in low-relevancy (black colour) areas of the map for each habitat. Field surveys were then conducted to assess the accuracy of these classifications. During the field work on November 2nd 2024, 58 validation points randomly generated in high and low relevancy areas were checked, and 7 of them were found to be inaccurate. Table 1 summarises the outcomes of the validation procedure applied to relevancy maps, including confusion matrices, and accuracy, precision, recall, and F1 scores for each habitat. For *Typha*, high-relevancy areas yielded 14 correctly classified versus 3 incorrectly classified points, while low-relevancy areas achieved full classification success (10/10). Field research indicates that misclassification occurs between the *Typha* species and invasive species due to their similar spectral characteristics when invasive species, as well as *Typha*, are not flowering. Within the *Typha–Phragmites* habitat, both high (9/9) and low-relevancy (6/6) points were classified without error. By contrast, *Phragmites* high-relevancy areas exhibited a higher misclassification rate (7 correct vs. 4 incorrect), whereas low-relevancy areas again achieved full accuracy (5/5). The incorrectly classified points were between the *Phragmites* canopy and the invasive species. Overall, when considering all habitat types, classification accuracy was 0.88 and F1 score 0.90. In Table 2, we present the same metrics – Accuracy, Precision, Recall, and F1 scores – for the classification of all habitats.

The study of the wetland habitats using relevancy maps resulting from NatNet classification is an effective tool for monitoring changes in habitat extent. We were able to observe a shift in vegetation type occurrence after one year of revitalisation activities, which could be hardly possible by using only field research and permanent plots. In Fig. 7A, C, we present three cases of expansion of the *Typha-Phragmites* transitional habitat indicated by the relevancy maps and documented by field survey and photographs of the place. The left column figures show details of the October 2024 orthophotos of Čiližská Radvaň wetland along the old channel. In the middle column, there are details of relevancy maps for the *Typha–Phragmites* habitat. The photos in the right column show the view from the red-marked location where high-relevancy pixels extend beyond the 2023 boundaries, indicating a measurable increase in *Typha–Phragmites* cover.

A quantitative comparison of the 2023 and 2024 relevancy maps indicates apparent shifts in vegetation types (Table 3). Pure *Phragmites australis* canopies were mapped over a larger area in 2024 than in 2023. As shown in Table 3, the area of high relevancy has nearly doubled. This expansion is likely linked to higher water levels in the canal due to the revitalization activities. Since *Phragmites* typically thrives in the wettest parts of wetlands, this development can be considered a natural response to changing hydrological conditions.

Table 3 also shows a modest increase in the mixed *Typha–Phragmites* habitat. The growth is limited, however, because water-level fluctuations near the canal tend to suppress this mixed community, allowing pure

Table 1. Results of the validation process for relevancy maps by randomly generated points. Confusion matrices, Accuracy, Precision, Recall, and F1 scores are presented for all three target habitats separately.

		Predicted habitat type		Accuracy	Precision	Recall	F1 score
		Typha	**Not *Typha***				
Actual habitat type	***Typha***	14	0	0.89	0.82	1	0.90
	Not *Typha*	3	10				
		Typha-Phragmites	**Not *Typha-Phragmites***				
	Typha-Phragmites	9	0	1	1	1	1
	Not Typha-Phragmites	0	6				
		Phragmites	**Not *Phragmites***				
	Phragmites	7	0	0.75	0.64	1	0.78
	Not Phragmites	4	5				

Table 2. Results of the validation process for relevancy maps by randomly generated points. Confusion matrix, Accuracy, Precision, Recall, and F1 scores is presented for wetland habitats in common.

		Predicted		Accuracy	Precision	Recall	F1 score
		Habitat	**Not Habitat**				
Actual	Habitat	30	0	0.88	0.81	1	0.90
	Not Habitat	7	21				

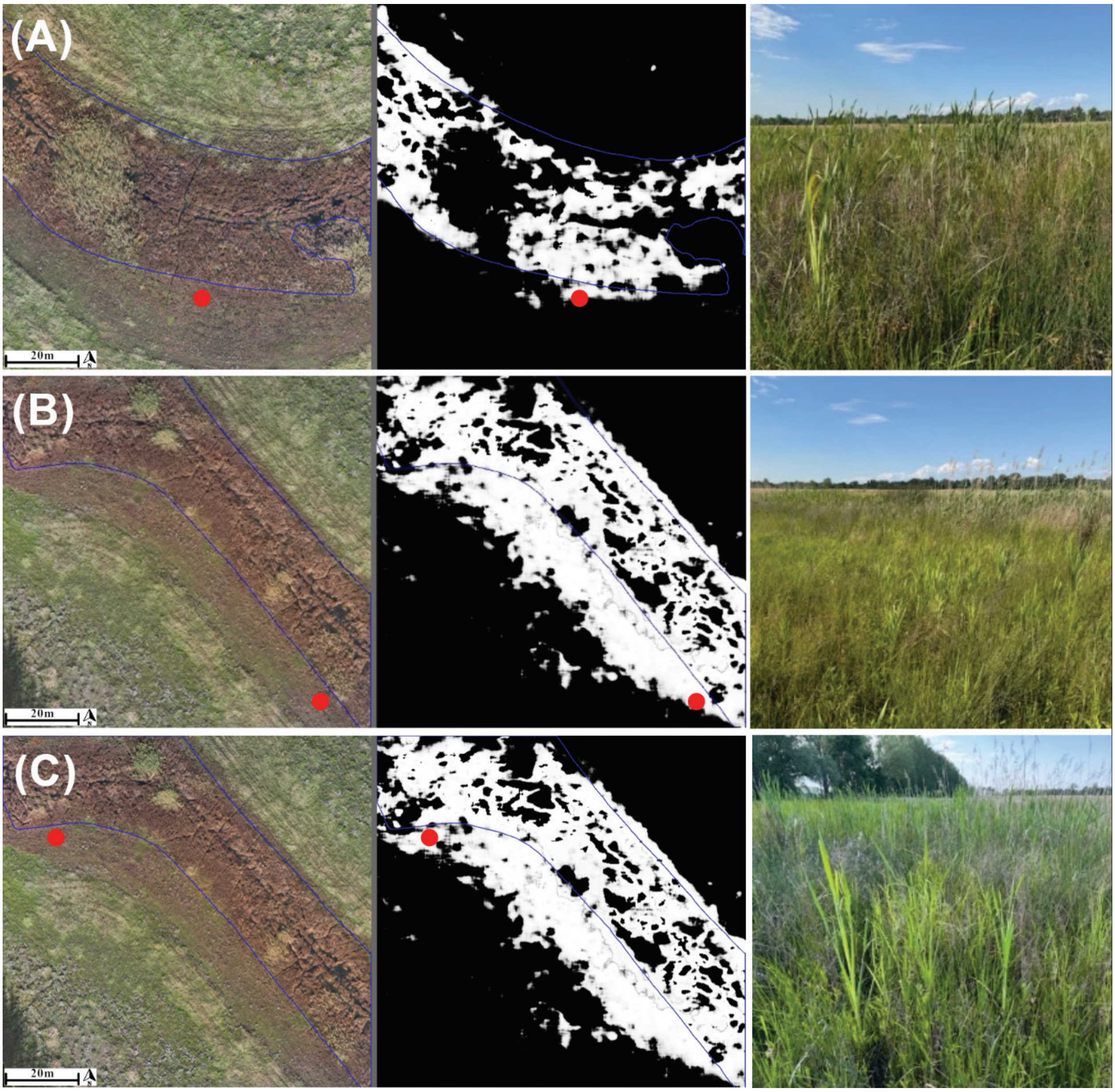

Figure 7. Part of drone imagery of Čiližská Radvaň wetland from October 2024 and relevancy maps for *Typha-Phragmites*. Relevancy maps show the enlarged area of the *Typha-Phragmites* habitat, proven by the photographs taken from the position of the red dots on the relevancy map.

Phragmites to dominate in those areas. As illustrated in Fig. 6, *Typha–Phragmites* stands have expanded mainly in the central part of the study region. The fourth column in Table 3 shows that the area covered by *Typha* has decreased. This decline appears to result from former *Typha*-dominated areas gradually transitioning to mixed *Typha–Phragmites* habitat.

Both dominant species profit from higher water levels in the locality after revitalization, which is also visible from the expansion of the *Typha–Phragmites* habitat in the central part of the wetland, where this community is slowly replacing areas dominated by *Calamagrostis epigeios* and invasive species. *Typha angustifolia* (and association *Typhetum angustifoliae*) prefers more stable waterlogged conditions (Oťaheľová 2001) in comparison with *Phragmites australis* (association *Phragmitetum vulgaris*). *Phragmites australis* can also grow in dynamically changing conditions, which are currently occurring at the revitalized site. This is reflected in the significant increase in the total area occupied by *Phragmites* habitat and the rise of mixed *Typha-Phragmites* habitats at the expense of pure *Typha* habitat.

Table 3. Comparison of habitat areas (m^2) for *Phragmites*, *Typha–Phragmites*, and *Typha* in November 2023 and October 2024.

	Phragmites	*Typha-Phragmites*	*Typha*
2023	1 729.32 m^2	10 336.84 m^2	21 459.08 m^2
2024	3 298.24 m^2	10 547.08 m^2	18 539.88 m^2

Conclusions

Our results provide spatially explicit evidence that revitalisation measures, particularly hydrological improvements and recurrent mowing, have facilitated an increase of *Typha–Phragmites* and *Phragmites*-dominated vegetation and that the drone–NatNet workflow reliably captures these changes. We confirmed that the relevancy map approach not only delineates existing habitat boundaries but also supports quantitative, year-to-year monitoring of wetland restoration outcomes.

Although the study focuses on a single area, namely the Čiližská Radvaň wetland in the Slovak Republic, and on one year of monitoring, this concentrated approach allowed for a detailed evaluation of habitat dynamics during the early phase of restoration. The area of the wetland is not large-scale, but for the purposes of revitalization monitoring we found the extent suitable, since the restoration process is challenging and is usually spatially limited to smaller areas. One year of monitoring can capture initial stages of vegetation change after revitalisation, and these trends could be different in the next years, depending on the continuous succession and other factors. Our results cannot predict the wetland development in the future, but can serve as a methodological basis for the next monitoring since we proved the possibility to identify single vegetation associations and shifts between them.

While the limited spatial and temporal extent naturally constrains broader generalisation, our study provides a solid and well-documented baseline for future multi-year and multi-site comparisons. Described methods could be transferred to other wetlands with similar habitats; however, local phenology must be considered when choosing the dates for drone data sampling.

Author contributions

All authors were involved in conceptualization and study design and methodology creation. K. Mikula led the project and M. Šibíková co-led the project. K.Mikula and A.A. Ožvat designed the NatNet classification algorithm for drone data, A.A. Ožvat and M. Kollár implemented NatNet in NaturaSat software and K. Mikula, A.A. Ožvat and M. Kollár performed all data analyses in NaturaSat software. M. Šibíková and J. Šibík were responsible for field sampling, GPS measurements, and field validation. J. Papčo and J. Sigmund were responsible for drone flights and drone data processing. All authors participated on the interpretation of results, text writing, and preparation of Figures.

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Supplementary material 1

Natural numerical network for drone data

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