University of South Bohemia in České Budějovice

Faculty of Science

Nine-year bird community development on Radovesická spoil heap

Bachelor thesis

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Annotation

Despite being valuable indicators of habitat change, birds are rarely used in restoration science. I surveyed birds on a large North-Bohemian spoil heap in 2012 and in 2019-21. I analysed bird community response to nine-year site development, human land use, primary vegetation productivity and proportion of senescent vegetation, vegetation age and structure, and restoration approach. My findings offer an original insight into how birds respond to habitat characteristics, and highlight the importance of birds as indicators of restoration success.

I hereby declare that the submitted Bachelor's degree thesis was written solely by me without any third-party assistance, information other than provided sources or aids have not been used and those used have been fully documented.

In České Budějovice 6. 12. 2021 …………………………….

Kryštof Korejs

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Declarations

This thesis is a part of a publication in preparation, titled: Nine-year bird community development on a North-Bohemian spoil heap: the impact of restoration approach, human land use and vegetation characteristics. The author of this thesis is also the primary author of the publication. This publication was also co-authored by doc. Mgr. Jan Riegert, Ph.D, and prof. Mgr. Miroslav Šálek, Dr. Majority of data collection was performed by primary author and was contributed to by Miroslav Šálek, who made available bird community dataset from 2012. Statistical analyses were performed and first draft of manuscript was written by the primary author, reviewed and edited by Jan Riegert. All authors read and approved the final manuscript.

Manuscript

Title: Nine-year bird community development on a North-Bohemian spoil heap: the impact of restoration approach, human land use and vegetation characteristics

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Abstract

Despite being valuable indicators of habitat change, birds are rarely used in restoration science. We surveyed birds on a large North-Bohemian spoil heap in 2012 and in 2019-2021. We gathered environmental data using both field vegetation survey and remote sensing. We analysed bird community response to nine-year site development, human land use (Corine Land Cover categories), primary vegetation productivity and proportion of senescent vegetation (represented by two vegetation indices, NDVI and PSRI), vegetation age and structure, and restoration approach (spontaneous succession, agricultural restoration, tree planting, etc.). Bird community composition was significantly affected by the site development, vegetation indices, vegetation structure and restoration approach, as well as human land use. Distinct groups of birds showed preference for specific types of restoration approach (spontaneous succession, agricultural restoration, etc.) or human land use (forest, dump site, pasture, arable land) or vegetation characteristics (tree cover and shrub cover etc.). Bird diversity, rarity and species richness increased significantly as site developed. Bird diversity was significantly lower in dump site and pasture areas than e.g. forests or arable land. Bird rarity decreased with increasing vegetation productivity, and was higher on sites with spontaneous succession than on other types of restoration. The strong response of birds to habitat characteristics and site development illustrates their value as indicators of restoration success. Highly productive areas such as forests are more diverse and species-rich than extensive pastures, but the negative effect of increased primary productivity on bird rarity emphasizes that spontaneous succession is most suitable for establishing valuable communities of rare species.

List of abbreviations

AIC = Akaike information criterion

Corine = Coordination of information on the environment

ESA = European Space Agency

GPS = Global Positioning System

NDVI = Normalized difference vegetation index

PCNM = Principal coordinates of neighbourhood matrices

PCoA = Principal coordinate analysis

PSRI = Plant senescence reflectance index

USGS = United States Geological Survey

Contents

1. Introduction

Human landscape modification continues to be a critical issue worldwide since ongoing industrial development increases the need of ecological restoration. Typical example of heavily altered areas are post-mining sites, such as spoil heaps, strip mines and quarries that drastically reshape the landscape. Reclamation approaches on post-mining sites represent a frequently discussed topic. There is a consensus in the scientific community towards spontaneous succession, yet technical reclamation remains a common practice in large-scale post-mining landscapes (Hodačová & Prach 2003, Tropek et al. 2012). These are widely known from Central Europe (Germany, Czech Republic or Poland). The process of technical reclamation consists of levelling the surface, spreading of organic material rich in nutrients and sowing commercial seed mixtures or planting trees in regular rows (Štýs & Braniš 1999). In some cases, site modification can be an effective restoration measure. For example, lignite mining leaves dry clays and mineral-poor sands that poorly retain water. Together with frequent heat, pollutant contamination and a dominance of inorganic elements at the expense of organic elements it causes extreme conditions for plant and animal colonization (Hendrychová 2008, Huttl & Gerwin 2005). Spontaneous development of vegetation under these conditions can be impeded (Prach & Pyšek 2001). Appropriate methods for such sites are to establish quickly the vegetation cover to provide basic ecosystem services (Norris et al. 2008). Conversely, assisted site recovery is recommended for habitats endangered by erosion (Baasch et al. 2012) or where rapidly expanding species threaten the vegetation development. For example, species-rich grasslands established after hay transfer and sowing are highly resistant to invasion of *Calamagrostis* grass species (Tischew & Kirmer 2007), which represent expansive grass capable of dominating early successional stages of non-reclaimed sites (Prach & Pyšek 2001).

Animal groups continue to gain importance when measuring success of restoration processes (Majer 2009). Invertebrates are closely tied to vegetation as crucial pollinators and herbivores (Losey & Vaughan 2006). Some studies on ecosystem development describe invertebrate response types of restoration management (Hendrychová et al 2012), while others emphasize the value of post-industrial sites for supplementing rare habitats (Tropek & Konvička 2008, Beneš et al. 2003). Some studies have described the benefits of spontaneous succession for amphibians (Vojar et al. 2009), but the key vertebrate group used to estimate restoration success are birds. They are suitable for the monitoring of large areas as they are easily detectable (Gardali & Holmes 2006) and respond quickly to landscape changes (Graham & Blake 2001, Helms 2018).

Birds perform key ecosystem functions (Sekercioglu 2006) and can facilitate revegetation of early successional sites via seed dispersal (McClanahan & Wolfe 1993). The surrounding landscape plays an important part in bird colonisation for restored areas (Lindenmayear et al. 2010). Birds at active industrial sites utilize extensively used areas with emergent vegetation (Krynski & Golawski 2019). Bird communities respond positively to increasing habitat heterogeneity by increasing their diversity (Šálek 2012). In heavily forested areas, bird diversity is higher at spontaneously developed sites and in ecotones compared to the forest interior (Hendrychová 2009). Characteristics of vegetation and restoration approach for studies on bird diversity are often measured in the field, but remote-sensing methods were also applied to measure habitat heterogeneity and new vegetation indices were introduced (Moudrý et al. 2021).

2. Goals

We sampled a bird community on a large North-Bohemian spoil heap. We employed both satellite data and a field survey to assess environmental data. Our study had the following goals.

1) We described the changes in bird community from 2012 to 2021 in terms of individual species as well as total abundances.

2) We analysed the response of bird community to the nine-year site development, management type (represented by Corine human land use data) primary vegetation productivity and proportion of senescent vegetation (represented by two vegetation indices), obtained using satellite imagery.

3) We calculated the effect of these variables on bird diversity, rarity and species richnesss.

4) We analysed the effect of vegetation age and structure (cover of separate vegetation layers) and restoration approach (spontaneous succession or reclamation), obtained in field survey, on bird community, diversity, rarity and species richness.

5) We discussed the preferences of community for habitat characteristics on our study site, as well as its value for spontaneous succession specialists and declining farmland species.

3. Methods

3.1 Study site

The study site consisted of the surface of the Radovesická spoil heap of area 1,200 ha (Figure 1a). It is located in the North Bohemian Lignite Basin in Czech Republic (Figure 1b).

Between 1964 and 2003, the site was used for deposition of overburden soils from the nearby surface mine. Since 1989, technical reclamation of the area has been gradually processing (Novák & Hendrychová 2021). Two mutually isolated areas with natural succession were established (4 % of study site). The rest of the area was planted with various species (e.g. *Ulmus* sp., *Quercus rubra*, *Pinus sylvestris*) or used for agriculture management (Figure 2). Agricultural restoration is most common on our study site (54 % of area), but it is gradually being replaced by tree planting to establish forested areas (26 %). In some cases, technical reclamation levelled the spoil heap surface, but no further management was performed (15 %). A few gardens and residential areas are also located on our study site (1 %).

3.2 Data collection

A matrix of 221 counting points (each 300 meters apart from other point) was established within the spoil heap (Figure 1a). The survey took place in the breeding season from late April to early June in 2012, and then in 2019, 2020 and 2021. Birds were surveyed in five-minute intervals from 6:00 to 11:00. All individuals detected within a 100-meter radius were recorded, excluding those that did not show breeding activity. We surveyed all points twice during the breeding season. The resulting data were then pooled and the maximal recorded abundances for each species on each point over the three-year period were used as response data in our analyses. Similarly, maximal abundances for each species from the 2012 dataset for each counting point were used for comparison.

Additionally, we performed a field vegetation survey in July 2020 within a 100-meter radius around each counting point (Figure 1a). For each plot, we recorded the proportional cover of herb, shrub, and tree layer. We also established the proportional share of management approaches for each point, these were: 1) unassisted spontaneous succession, 2) succession after technical reclamation (e.g. ground levelling and spreading of nutrient-rich top soil layers was performed, but no planting or sowing took place), 3) agricultural restoration (i.e. crop fields and meadows), 4) restoration based on tree planting, 5) gardens and residential areas. The proportional cover of bare ground and the water surface for each point was also recorded. For forested areas, we also established three age categories and their proportional cover: 1) young planting (saplings, no older than three years), 2) older planting (trees up to the age of ten years) and 3) old planting (fully grown trees).

We used the Arcgis Pro software (EA Desktop 2019) to gather data on development of land use and vegetation structure changes between the 2012 and 2019-21 periods. We employed the Copernicus Sentinel data, gathered by the European Space Agency's Multispectral Instrument on the Sentinel-2 satellite (ESA 2015). We used two multispectral imagery sets to determine vegetation productivity of the study area for each respective period of bird community sampling. First set was taken from 2015, the first operational year of the Sentinel-2 satellite and consequently most suitable to link with the 2012 survey. The second set was taken from the year 2020 and was linked with the 2019-2021 survey data. Each imagery set comprised of 13 spectral bands derived from reflected radiance measurements, ranging from visible and near-infrared to shortwave infrared wavelengths with varying spatial resolution (imagery datasets courtesy of USGS). Two vegetation indices were derived from each imagery set: 1) NDVI (normalized difference vegetation index), which corresponds to plant chlorophyll content and therefore to primary productivity of vegetation and 2) PSRI (plant senescence reflectance index), which is derived from carotenoid/chlorophyll ratio and corresponds with the amount of senescent vegetation. Leaf senescence is closely tied to management approach as spontaneously successional plots display a large amount of senescent vegetation in comparison to intensive restoration (Moudrý et al. 2021). Mean values of both vegetation indices were then calculated for each buffer around counting points.

These indices can be lacking when more detailed characteristics of site management and history are required (e.g., the dominant type of vegetation or human land use). The Corine Land Cover is a European programme, coordinated by the European Environment Agency, providing consistent and detailed information on land cover and land cover changes across Europe (Büttner 2014). Using freely available data for the year 2012 and 2020 (courtesy of EEA) we calculated the proportion of area covered by different categories of land use on every study plot: 1) forest, 2) industrial or urban units, 3) dump site, 4) arable land, 5) pasture and 6) transitional woodland/shrub. These categories were derived from ten separate Corine Land Cover classes, described in Supplementary material, table S2.

3.3 Statistical Analyses

Maximal recorded abundances for each survey period were used to calculate Shannon diversity index for each point for respective survey period (Shannon 1949). In addition, we used a species rarity index established previously by Šálek (2012), reflecting the scarcity of each species throughout the region with data from national quadrat mapping of birds during 2001–2003 (Šťastný, Bejček & Hudec 2006). This index was calculated using the formula 1 − N/628 where N represents the number of quadrats occupied by the species from 628 in total (Supplementary material, Table S1). If a species was recorded on a counting point, its rarity index was added to the rarity index of every other species recorded at that counting point, and the resulting sum is the rarity value for that counting point. We calculated a species richness value for each counting point as the sum of species recorded on each point.

We calculated the response of bird community (dependent variables – maximal abundances for each species on every point for each survey period) to the between year development on our study site and to different categories of land use and vegetational indices (primary predictors: survey period, PSRI, NDVI and land use categories) using variance partitioning by principal coordinate analysis of neighbour matrices (PCNM) in Canoco 5 software (ter Braak & Šmilauer 2012) that was recommended by Marrot et al. (2015). This multivariate analysis enabled us to separate the effect of geographical position (i.e., space predictors) from the effect of primary predictors (Legendre & Legendre 2012). The analysis is suitable for calculating inter-correlated variables since all these variables enter the analysis simultaneously. The analysis included nine steps: (1) primary predictor test (i.e. preliminary test of the overall effect of primary predictors on the dataset), (2) primary predictor testing by partial redundancy analysis (RDA) based on partial Monte-Carlo permutation tests (n = 499 permutations), (3) principal coordinate analysis (PCoA) based on Euclidean distances (i.e., finding the main space predictors based on GPS coordinates), (4) PCNM for all predictors (i.e., preliminary test of the overall effect of space predictors on the dataset), (5) PCNM selection (i.e., the choice of space predictors based on coordinates using forward selection and partial Monte-Carlo permutation tests), (6) spatial effects analysis (i.e., assessing the amount of variability explained by space predictors), (7) primary predictor effects analysis (i.e., assessing the amount of variability explained by primary predictors), (8) joint effects analysis (i.e., assessing the amount of variability explained by both predictor types) and (9) removal of spatial effects (Šmilauer & Lepš 2014). The effect of restoration approach, vegetation structure, as well as age of tree planting (primary predictors: types of management, cover of vegetation layers, NDVI, PSRI, planting age) on bird community from survey in 2019-2021 (dependent variable – maximal abundances for each species on every point for each survey period) was calculated in a second PCNM analysis, with the same set of geographical coordinates to allow for separation of space predictors, and the same nine step procedure.

We used the lmer function, package lme4 (Bates 2014), for building linear mixed-effects models (Pinheiro & Bates 2000, Gałecki & Burzykowski 2013) in R Software (R Core Team 2013). We calculated the effect of independent variables (fixed effects: survey period, PSRI, NDVI, Land use categories, random effects: counting point ID) on three dependent variables: 1) diversity of birds, 2) rarity of birds and 3) bird species richness. We performed forward stepwise AIC method for selection of independent variables (Yamashita et al. 2007). The resulting final models thus did not contain all predictors that entered analysis. The effect of another set of predictors (fixed effects: types of management, cover of vegetation layers, NDVI, PSRI, planting age, random effect: number of recorded individuals per sample) on bird diversity and rarity was tested using the same forward selection procedure with linear mixed-effects models using the lme4 package. We used emmeans function, package emmeans (Searle et al 1980) to calculate post-hoc tests for relevant final models. Especially, to see how diversity on areas with dump site and/or pasture land use differed from elsewhere, we redesigned the final lmer model of our diversity analysis. We converted the dump site and pasture predictors (originally numerical, describing proportion of dump site or pasture area on study plot) into two factors, describing whether either land use type was present (the possible combinations were dump site, pasture, or neither). We then performed post-hoc testing for the updated final model using the emmeans function.

4. Results

4. 1 Changes of bird community between surveys and the effect of environmental variables

During our study, 13529 individuals from 106 species were recorded. The most abundant species was Eurasian skylark (*Alauda arvensis*, 11 %), followed by Eurasian blackcap (*Sylvia atricapilla*, 5.6 %) and Yellowhammer (*Emberiza citrinella*, 4.5 %). The nine-year effect of site development between survey periods on bird community is illustrated by large differences in abundances: the number of birds detected in 2012 (4765) was much lower than was surveyed in 2019, 2020 and 2021 (7580, 7810, 7176). Some species increased their abundances between 2012 and 2021, such as the Eurasian skylark (805 to 1272) or Tree pipit (*Anthus trivialis*, 203 to 310).

The increase in abundance in some species was very strong, e.g. in corn bunting (*Emberiza calandra*, 45 to 178), but others were recorded in similar numbers (Yellowhammer: 331 to 346, whinchat *Saxicola rubetra*: 147 to 154). The abundances of some species decreased, e.g. Garden warbler (*Sylvia borin*, 117 to 44), Also, many species not detected in 2012 have been recorded in the 2019-2021 breeding seasons, such as Common snipe *Gallinago gallinago*, common crane *Grus grus*, Water rail *Rallus aquaticus*, Bearded reedling *Panurus Biarmicus*, Eurasian hoopoe *Upupa epops* or Grey-headed woodpecker *Picus canus*. Especially notable was the regular occurrence of Savi´s warbler *Locustella luscinioides* at points with spontaneous succession and the consistently successful breeding of Great grey shrike *Lanius excubitor*, as both species were not detected in 2012. On the other hand, the endangered Grey partridge *Perdix perdix* has disappeared completely from the original 17 individuals recorded in 2012.

Correspondingly, our multivariate analysis (PCNM) on the effect of environmental variables to the maximal abundances of bird species showed that bird community structure was significantly affected by following primary predictors: survey period (representing site development), proportion of land use category (forest, dump site, arable land and pasture) and vegetation indices (NDVI and PSRI), (Table 1, PCNM 1). The total explained variability by the first and second ordination axes was together 14.8 %. Primary predictors explained 11.3 % of variability while space predictors explained 1.2% of variability. The shared fraction between primary and space predictors was 2.3 % of variability. The 2012 survey period was weakly correlated positively with the first ordination axis and negatively with the second ordination axis (r1= 0.1500, r2= -0.1427), while the 2019-21 survey period has the inverse relationship (r1= -0.1500, r2= 0.1427). Percentages of forest was correlated similarly with ordination axes (r1= -0.6543, r2= 0.1167). Percentages of arable land (r1= -0.1830, r2= -0.2471) and NDVI index (r1= -0.6472, r2= -0.1838) were negatively correlated with both ordination axes. On the other hand, percentages of pasture (r1= 0.6424, r2= 0.0768) and dump site (r1= 0.1487 r2= 0.2644) were positively correlated with both axes. The PSRI index (r1=0.5292, r2= -0.0444) was increased during the 2012 survey period. Each category of land use had its own distinct assortment of species (Figure 3): forest plots were occupied by forest specialists (Common firecrest *Regulus ignicapillus*, Wood warbler *Phylloscopus sibilatrix*), but were also preferred by more generalist species (Song thrush *Turdus philomelos* and Great tit *Parus major*). Arable land also hosted common generalist species (Yellowhammer and Garden warbler) that were often found on forest edges adjacent to fields. On the contrary, pastures and dump site areas were occupied by species that are common near water bodies (Eurasian reed warbler *Acrocephalus scirpaceus*, Reed bunting *Emberiza schoeniclus*), but dump site also housed birds of early successional stages (Little ringed plover *Charadrius dubius*) and heterogeneous reed growths (Savi´s warbler, Sedge warbler *Acrocephalus schoenobaenus*). The increased NDVI index (vegetation productivity) was positively correlated with increased proportion of forest and arable land. On the other hand, areas with increased PSRI index (proportion of senescent vegetation) were inhabited by species of extensively farmed areas (whinchat *Saxicola Rubetra* and Eurasian skylark). PSRI index value was also positively correlated with proportion of pastures, which were not intensively managed. There were no species that were accompanied only with one survey period, but forest species were more abundant during the 2019-2021 period (Long-tailed tit *Aegithalos caudatus*, Great tit, Chaffinch *Fringilla coelebs*) and birds of pastures and areas with increased PSRI were more abundant during the 2012 period (Eurasian kestrel *Falco tinnunculus*, Corn bunting *Emberiza calandra*).

Some environmental variables changed between the two surveys, we recorded increased proportions of pasture and arable land during the survey in 2019-2021 compared to the survey in 2012 (Figure 4). This was caused by conversion of active dump to these habitats (Figure 5). Changes in land use in turn affected general bird community variables (Table 2). Diversity of bird community was lowest at dump sites compared to pasture and other habitats (Figure 6a) Species richness was negatively affected by pasture management (Fig 6b). During the survey in 2019-2021, we recorded increased species richness compared to the survey in 2012 (Figure 7a). Diversity was significantly higher during the survey in 2019-2021 compared to the survey in 2012 (Figure 7b). Bird rarity was only significantly affected by survey period, and it was higher in 2019-21 compared to 2012 (Figure 7c).

4.2 Bird community response to restoration management and vegetation structure

The following analyses contained only data from the bird and vegetation survey in 2019-2021. In our second multivariate (PCNM) analysis, bird community composition (maximal abundances) was significantly affected by restoration approach (agricultural restoration, spontaneous succession, tree planting), the cover of the tree and shrub layers as well as the proportional area of water, forest age (proportion of middle aged and old trees) and vegetation productivity (NDVI), Table 1, PCNM 2. The total explained variability by the first and second ordination axes was together 20 %. Primary predictors explained 13.7 % of variability and space predictors explained 1.7 % of variability. The shared fraction between primary and space predictors was 4.9 % of variability. Vegetation productivity was correlated positively with the first ordination axis and negatively with the second ordination axis (r_1= 0.5946, r_2= -0.2716). Old forest had a similar relationship with both axes (r_1=0.3951, r_2= -0.0850). Shrub cover was correlated positively with both ordination axes (r_1= 0.3073, r_2= 0.0133), similarly to tree cover (r_1= 0.5553, r_2= 0.1273) and middle-aged forest (r_1=0.0809, r_2= 0.3951). Management of sites that were levelled during reclamation, but then left to develop (described as non-managed in analysis result table), was correlated positively with both ordination axes (r_1= 0.371, r_2= 0.1110). Spontaneous succession correlated negatively with first axis and positively with the second axis (r_1= -0.0573, r_2= 0.4789), similarly to water cover (r_1= -0.0437, r_2= 0.4911). Agricultural restoration correlated negatively with both axes (r_1= -0.6334, r_2=-0.3426). Tree cover was closely tied to plots where succession occurred freely after initial levelling and vegetation productivity (NDVI) was positively correlated with the proportion of older trees and shrubs. Spontaneous succession was positively correlated with water cover. It seems that some environmental variables facilitated very similar responses of bird community, while others stood out by creating a distinct assemblage of species. A few species strictly preferred sites with agricultural restoration (Eurasian skylark, Corn bunting, Whinchat) and were rarely found elsewhere. A second assemblage of species was strictly defined almost equally by increased proportion of water as by spontaneous succession (Great reed warbler *Acrocephalus arundinaceus*, Savi´s warbler, Bluethroat *Luscinia svecica cyanecula*). Some species preferred areas with increased shrub cover (European robin *Erithacus rubecula*, Song thrush), but with increasing tree cover and proportion of old trees, the habitat became suitable for common forest species (e.g. Eurasian nuthatch *Sitta europaea*, Wood warbler). Some species were common for areas with middle-aged trees (e.g. chiffchaff *Phylloscopus collybita*).

Our linear mixed effect model analysis using management approach, vegetation structure, vegetation indices and forest age as predictors showed that bird diversity was only significantly affected by shrub cover (Table 3). The results of our similar analysis on bird rarity showed that it increased with presence of spontaneous succession (Fig. 7d) and decreased with higher NDVI index (vegetation productivity, Table 2, Fig. 7e).

5. Discussion

Our analysis does not take into account the entire scope of restoration history on the Radovesická spoil heap. During the 2012 field survey, most technical reclamation processes (such as ground levelling or spreading of topsoil layers), had already been executed. However, the nine years from 2012 to 2021 were crucial for restoration of previously levelled parts of the spoil heap, where revegetation is gradually proceeding. During our vegetation survey we found many plots with relatively young growths of trees and bushes, as well as newly established planting sites with saplings. This revegetation has already impacted bird community, species of forested areas we more abundant during the 2019-2021 survey period compared to 2012.

There is a potential detriment to ongoing revegetation process since tree planting can impact extensive areas occupied by rare species that are already declining in the Czech agricultural landscape. During our vegetation survey, we marked these areas as agriculturally restored, but this characteristic is often transitional. After technical reclamation, a mixture of grasses is sown, to prevent erosion and creation of extreme conditions (Baasch et al. 2012). Such areas retain their extensive status of meadows, but they can be eventually converted into fields of forage crops or planted with a mixture of tree saplings, resulting in transition into forested areas. Birds that prefer these transitional „agriculturally restored areas" avoid forests and other areas with increased vegetation productivity. These species, such as corn bunting, Eurasian skylark and whinchat experienced declines with proceeding agricultural intensification in Central and Western Europe (Donald et al., 2006), and were more abundant during the 2012 survey period compared to 2019-2021. This result suggests that with continued tree planting and revegetation, their populations on our study site will further decline. The continuation of extensive management may be crucial for retaining the current numbers of these birds.

Primary vegetation productivity (NDVI) was associated with tree cover and shrub cover. While there was no significant effect on bird diversity nor species richness, we found that NDVI index negatively affected bird rarity. Both covers of spontaneously developed and agricultural areas were negatively correlated with increased vegetation productivity. It appears that less productive vegetation facilitates more rare communities of birds. We compared our results on the effects of vegetation indices with those of Moudrý et al. (2021). Their study also found that primary vegetation productivity affected bird rarity significantly, but the effects of leaf senescence (PSRI) and shrub and herb cover were stronger than NDVI effect. We provided new information on vegetation indices by including the effect of NDVI and PSRI in our bird community analyses.

The proportion of variability explained by NDVI is highest of all primary predictors in both multivariate analyses, and it correlates positively with proportion of area occupied by forests, shrubs and proportion of older trees, while PSRI correlates with cover of pasture management. In addition, we included vegetation indices as predictors when analysing the effect of bird community development and human land use on species richness, diversity and rarity of birds. However, the effects of vegetation indices were not significant.

We found that bird rarity, diversity and species richness increased as the spoil heap developed. This is partly in contrast with the results of a study by Šálek (2012), where species richness also increased with time, but rarity decreased. Bird rarity was significantly higher on sites with spontaneous succession than on reclamations, which was also true for our study. We used Corine human land use data to substitute management information for the 2012 survey period. These land use categories correlated with other environmental variables in our study, and were inhabited by bird species of similar preferences. The cover of forest increased abundances of birds that also favoured areas with higher tree cover, old trees and increased NDVI. The cover of dump site was increased abundances of birds that were present on areas with increased proportion of spontaneous succession and increased water cover. Cover of pastures increased abundances of the same species, but also bird species of agriculturally restored areas. The presence of some land use categories significantly impacted bird diversity and species richness. Dump site areas showed lower bird diversity than pastures, while sites with other types of land use (forests, arable land) had significantly higher bird diversity than dump sites or pastures. In addition, areas with increased cover of pastures had lower species richness compared to non-pasture areas. It appears that extensively utilized areas were not as diverse or species rich as forests or transitional woodland-shrub. Land use categories offer information on intensity and type of human modification, rather than restoration approach. For example, arable land is more intensively managed than pasture areas by crop harvesting, and thus has a different community of birds. Dump site areas are extensive in terms of agricultural land use, but are disturbed by commercial machinery, which is why they are inhabited by primary succession specialists (Šálek 2012).

When we studied the effect of cover of each management type and vegetation structure on the bird community structure for the survey period in 2019-2021, we found several distinct groups of species. The most pronounced was a group of forest species that occupied areas with increased vegetation productivity. Most birds included in this group were also found in forested areas in the 2012 study by Šálek. Several open habitat species were most abundant on points with increased proportion of agricultural restoration. Another distinctive group of species were birds of spontaneous succession. These birds were also typical on spontaneous succession in the study by Šálek (2012). In our community structure analysis, e.g. Savi´s warbler, Sedge warbler or Reed bunting represented remnants of the original community that inhabited the active dump site on the spoil heap. The dump site was then converted to pasture in terms of land use category between the survey periods. We suggest that the combination of these processes lead to increased diversity, species rarity and species richness of our spoil heap in the survey 2019-2021 as documented by our previous analyses. Both the areas with spontaneous succession were left out of any reclamation processes that strongly modified the surrounding landscape. If the surrounding spoil heap was originally comprised of similar spontaneously developed habitats, the process of technical reclamation eradicated rare communities of birds in favour of eventually planting trees or creating arable land.

6. Conclusions

We conclude that from 2012 to 2019-2021, the bird community experienced positive changes in each of population metric, such as bird diversity, bird rarity and species richness. Also, overall bird abundances have significantly increased since new bird species inhabited the spoil heap. A mosaic of planted areas, extensively managed grasslands, and spontaneous succession, represents the current shape of our study site, offering habitat to multiple distinct and valuable groups of bird species. This study has offered detailed information into the response of a bird community to vegetation characteristics, multitude of restoration approaches and human land use in the context of the whole reclaimed spoil heap. Satellite-acquired vegetation indices provided important data on the effect of primary productivity and proportion of senescent vegetation, and we further encourage their usage in restoration research. Corine Land Cover data and derived land use categories were crucial in estimating the effect of environmental variables on bird community in the context of site development. The proceeding restoration of our study site can lead to large changes in habitat characteristics and a complex response of avian bird community. Valuable sites, such as extensively utilized grassland or spontaneous succession, should be maintained to continually offer habitats for rare or endangered bird species. An appropriate survey in the future could show how birds on the Radovesická spoil heap react to a fully restored site, and whether this process produces again more diverse or valuable bird communities compared to our present results.

7. Tables

7.1 Table 1. Effect of primary and space predictors on bird community, using response data from 2012 and 2019-2021 along with predictors established via satellite data in first analysis (PCNM 1), and response data from 2019-21 along with predictors established via field survey in the second analysis (PCNM 2).

PCNM 1			
Effects of primary predictors			
Name	**Explained variability %**	**pseudo-F**	**P**
NDVI	40.2	29.6	<0.002
Forest	18.5	14.0	<0.002
Period 2019-21	8.9	6.8	<0.002
Period 2012	8.9	6.8	<0.002
Pasture	8.8	6.8	<0.002
PSRI	8.8	6.9	<0.002
Dump site	9.0	7.2	<0.002
Arable land	4.7	3.8	<0.002
Effects of space predictors			
PCO.200	1.93	5.4	<0.002
PCO.189	1.76	5.0	<0.002
PCO.214	1.51	4.3	0.006
PCO.230	1.20	3.5	0.014

PCNM 2			
Effects of primary predictors			
Name	**Explained variability %**	**pseudo-F**	**P**
NDVI	34.45	20.8	<0.002
Agricultural restoration	18.66	11.8	<0.002
Shrub cover	11.31	7.4	<0.002
Spontaneous succession	7.45	4.9	<0.002
Water cover	4.50	3.0	<0.002
Old forest	3.86	2.6	<0.002
Middle-aged forest	3.37	2.3	<0.002
Tree cover	2.86	1.9	<0.002
Non-managed	2.34	1.6	0.026
Effects of space predictors			
PCO.9	3.9	5.8	<0.002
PCO.18	2.7	4.0	<0.003
PCO.12	2.5	3.8	<0.004
PCO.15	2.4	3.7	<0.005
PCO.5	2.2	3.4	<0.006

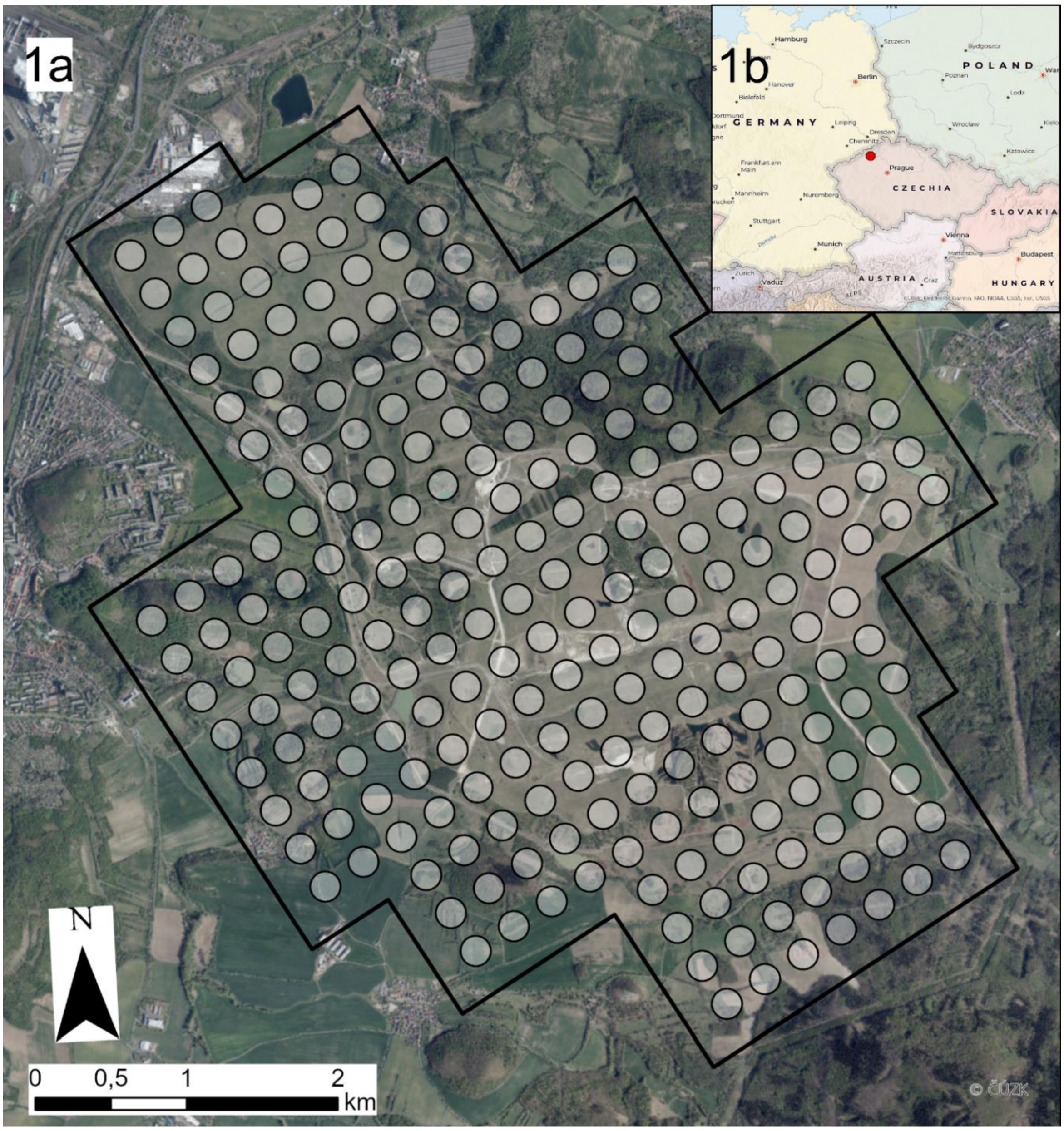
7.2 Table 2. Effect of independent variables on bird diversity, rarity and species richness, using response data from the 2012 and 2019-21 datasets. Forward model selection by AIC was performed, so only the variables present in the final model are listed. Random effects were represented by survey point id.

Dependent variable	Independent variables	Estimate	S.E.	T	P
Bird diversity	Survey period	0.698	0.03198	21.855	< 0.001
	Pasture	-0.007	0.00082	-8.330	< 0.001
	Dump site	-0.009	0.00155	-6.126	< 0.001
Bird rarity	Survey period	1.633	0.13030	12.530	< 0.001
Species richness	Survey period	9.368	0.32890	28.482	< 0.001
	Pasture	-0.039	0.00685	-5.746	< 0.001

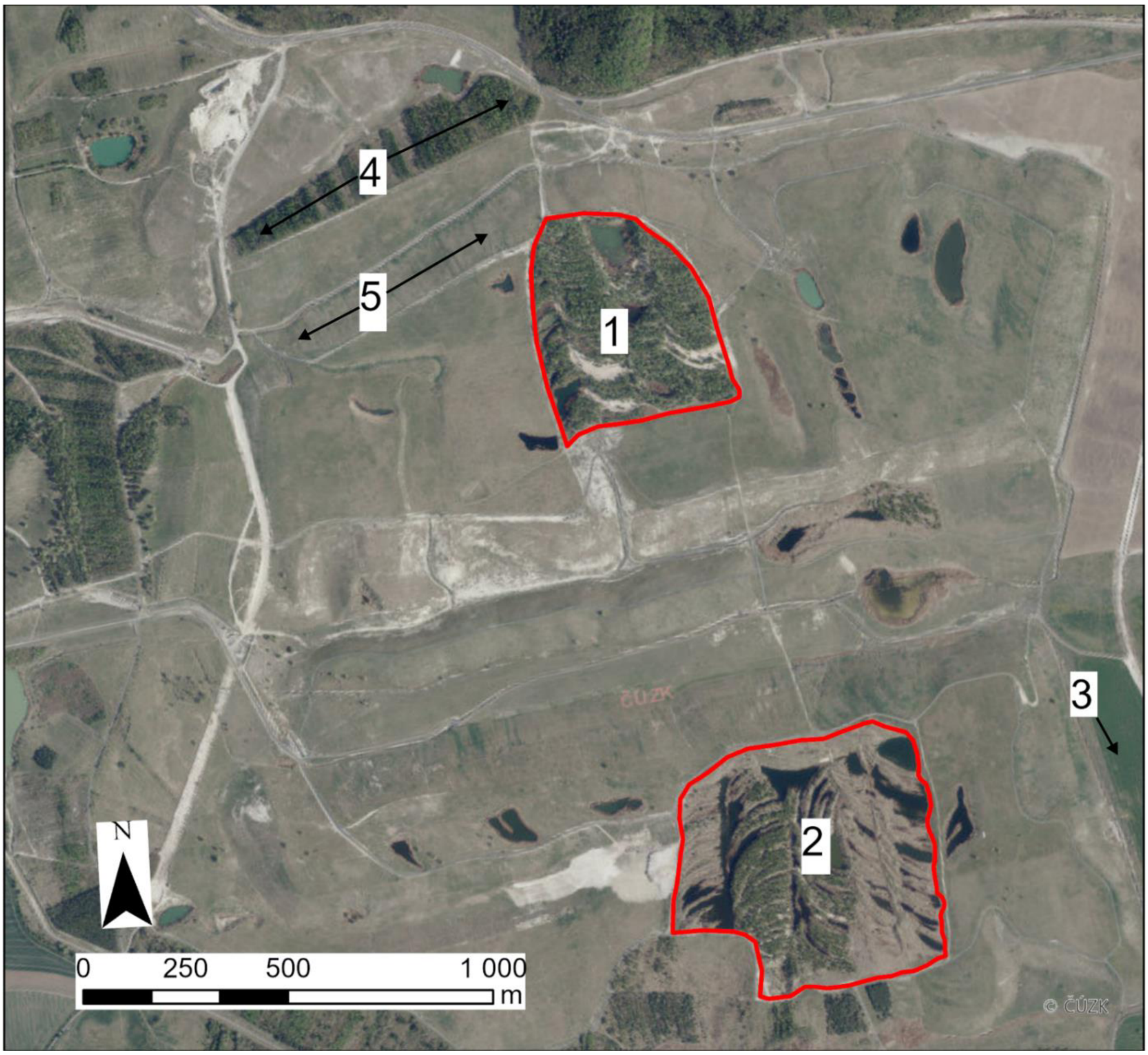
7.3 Table 3. Effect of independent variables on bird diversity and rarity, using response data from the 2019-21 dataset. Forward model selection by AIC was performed, so only the variables present in the final model are listed. Random effects were represented by species richness on survey point.

Dependent variable	Independent variables	Estimate	S.E.	T	P
Bird diversity	Shrub cover	0.001	0.004	2.595	0.0102
Bird rarity	Spontaneous succession	0.034	0.008	4.157	< 0.001
	NDVI	-3.057	1.112	-2.750	< 0.006

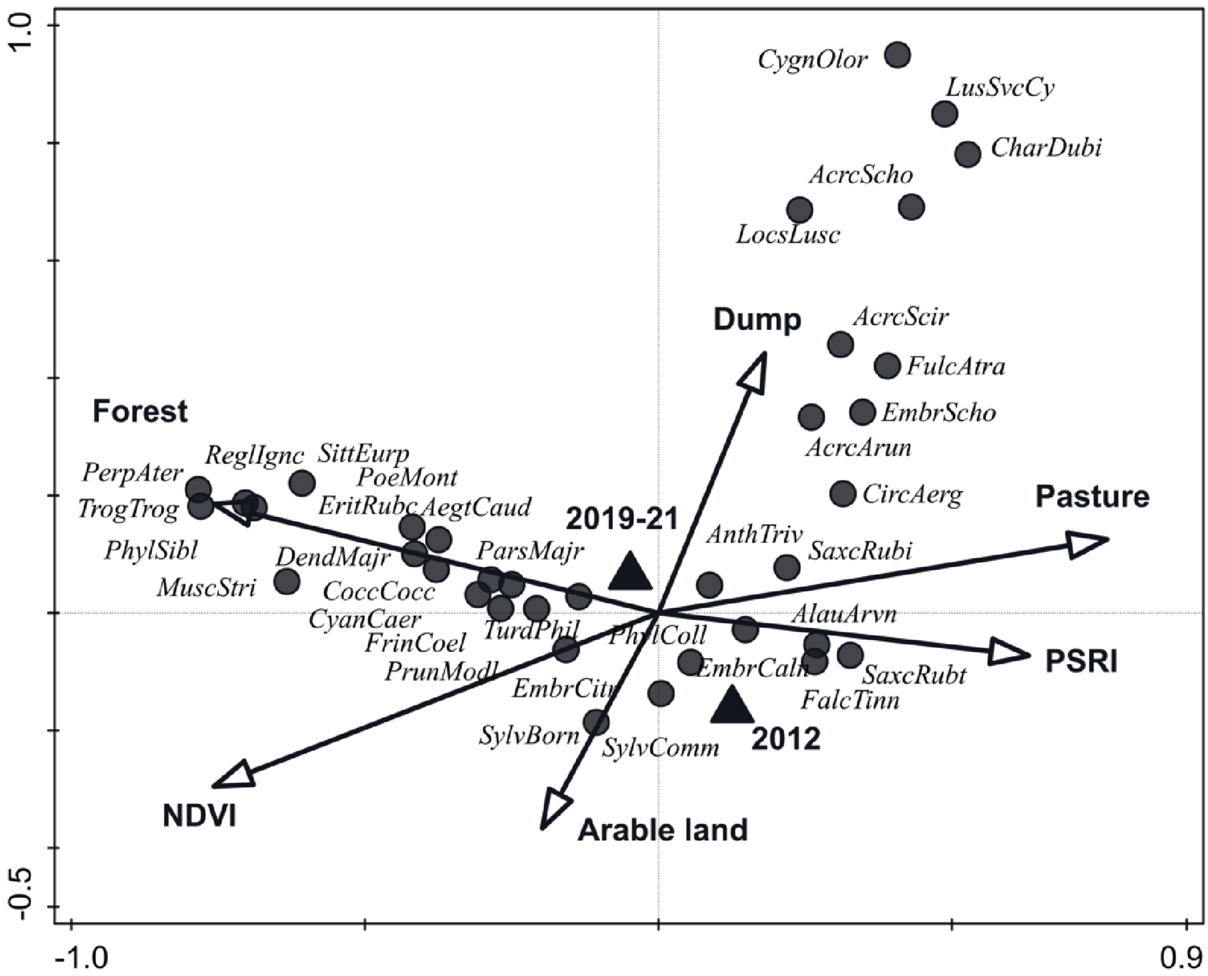
8. Figures



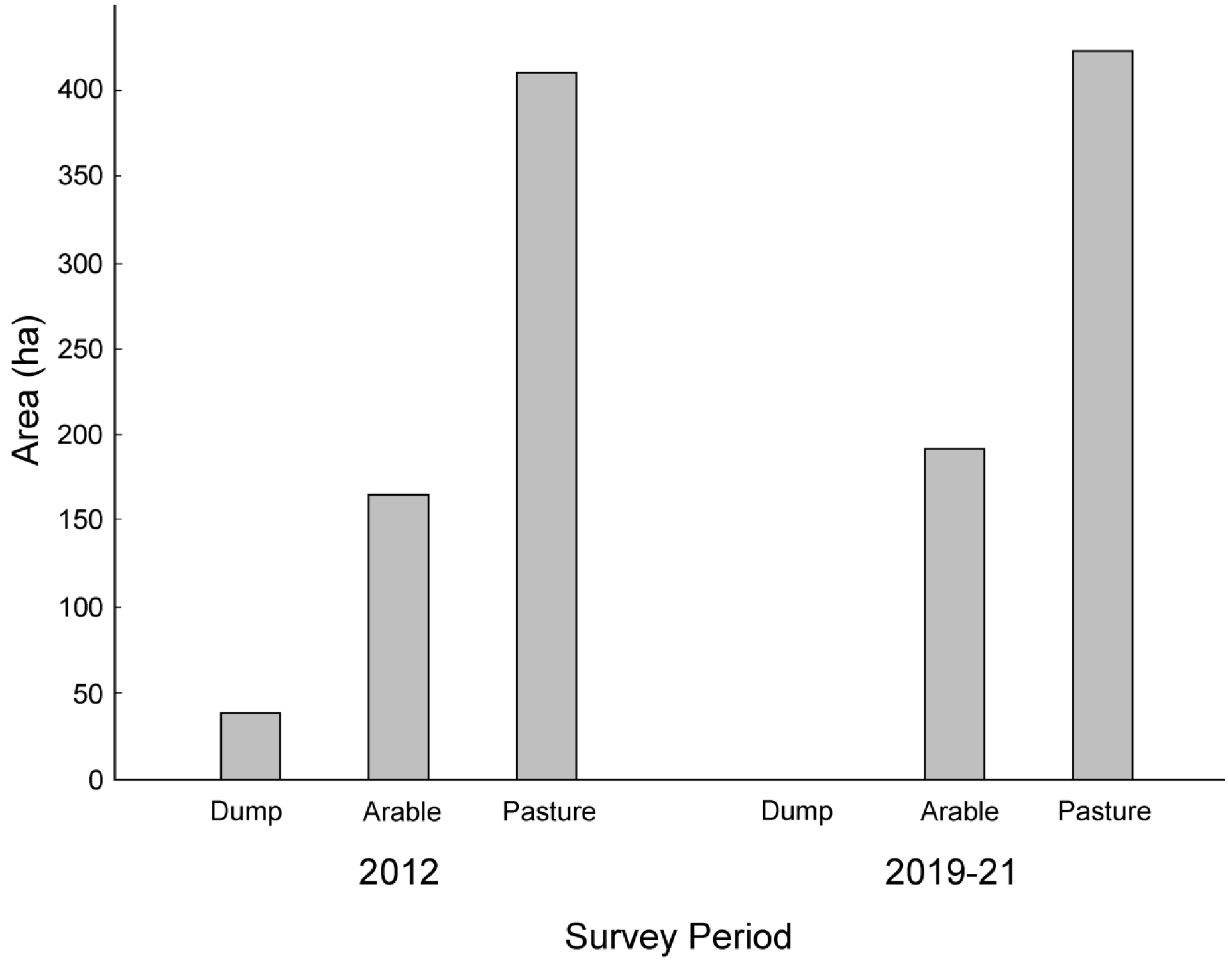
8.1 Figure 1. a) A map of our study site and the surrounding landscape with field survey design. All transparent white circles represent a 100-meter radius around a survey point in the centre, as well as vegetation survey plots which consisted of the same areas. And **b)** the highlighted location of the study site in central Europe. Acquired from Arcgis Pro basemap service. Satellite data were acquired from https://geoportal.cuzk.cz/.



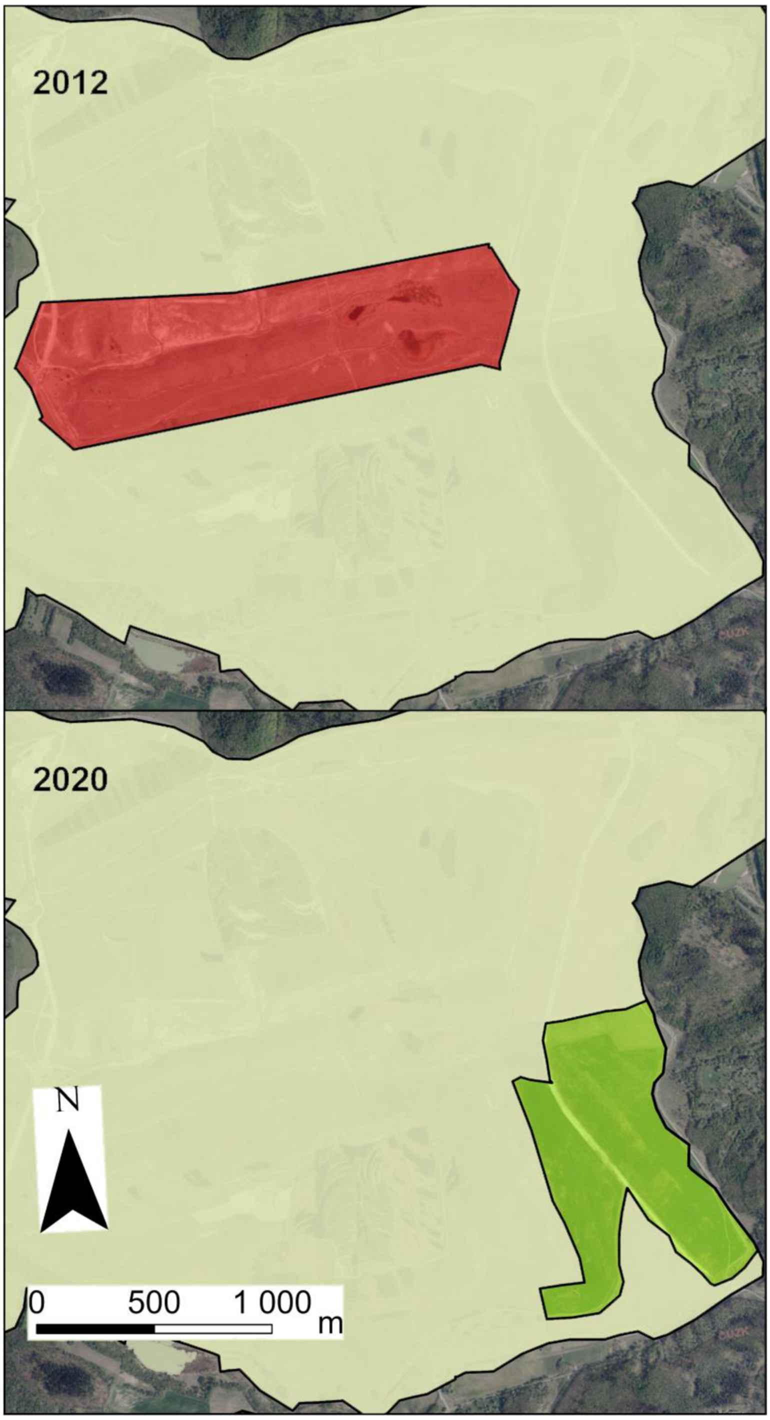
8.2 Figure 2. A satellite image of central spoil heap area of our study site. Highlighted are 1,2) two spontaneously successional areas exempt from technical reclamation, 3) area with fields and arable lands used for agriculture mainly growing of fodder crops, 4) tree planting with mature trees and 5) tree planting with saplings. Satellite data were acquired from https://geoportal.cuzk.cz/.



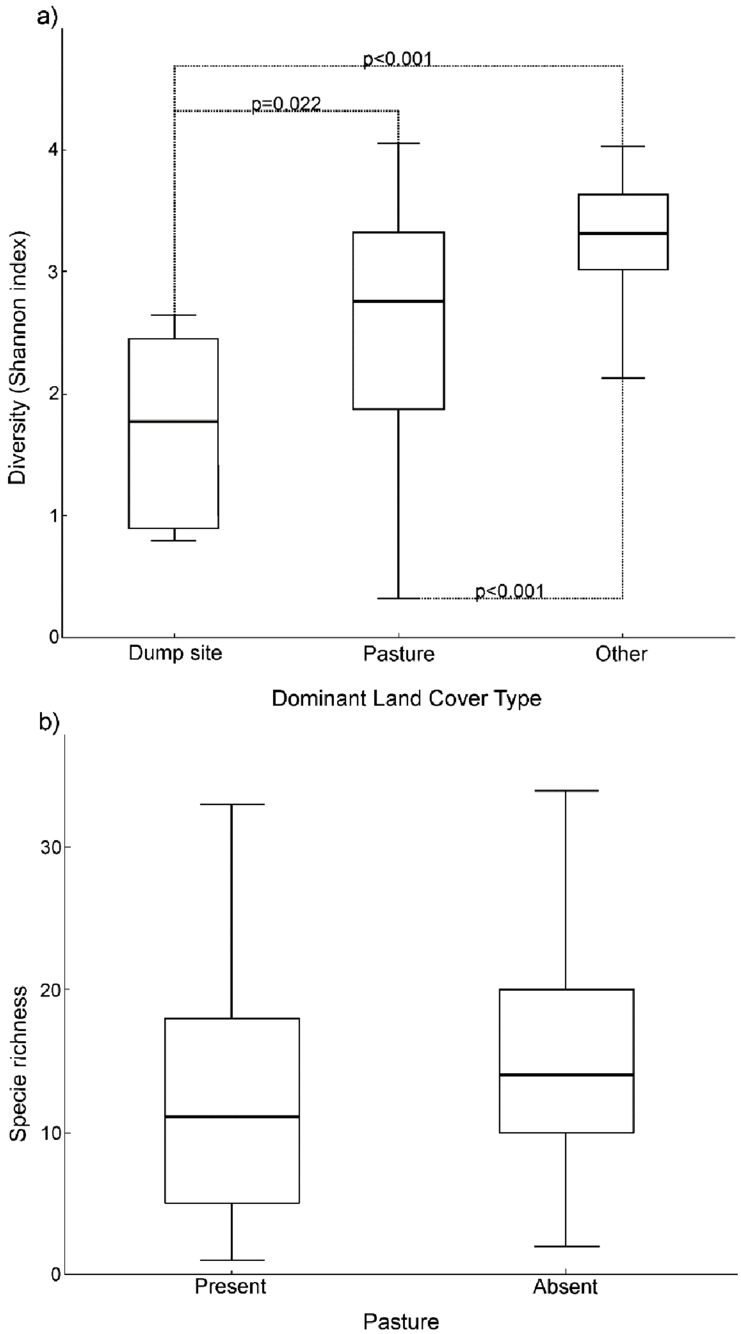
8.3 Figure 3. An ordination diagram of bird community structure with environmental variable labels describing primary predictors, using both bird community datasets from 2012 and 2019-21 and corresponding set of environmental variables. Only species that fitted the ordination axes by more than 5 % are displayed. For abbreviations of species see Supplementary material, Table S1.



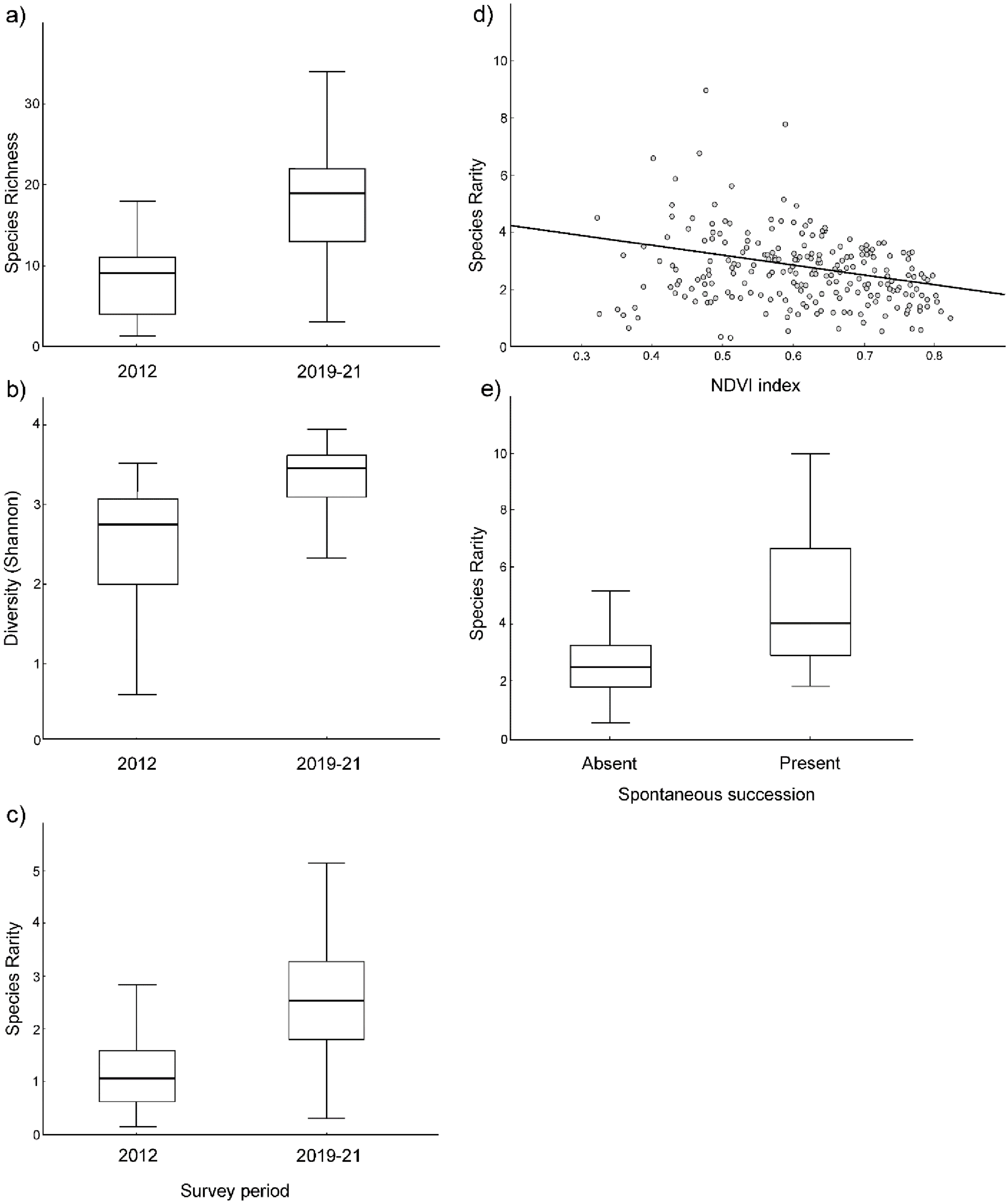
8.4 Figure 4. The changes in area occupied by different categories of human land use between survey periods. The total sums of area occupied by respective land cover categories on our study site for each survey period are displayed. Between 2012 and 2019-21, all of the dump site land use category (38 ha) was converted to pasture (26ha) or arable land (12ha).



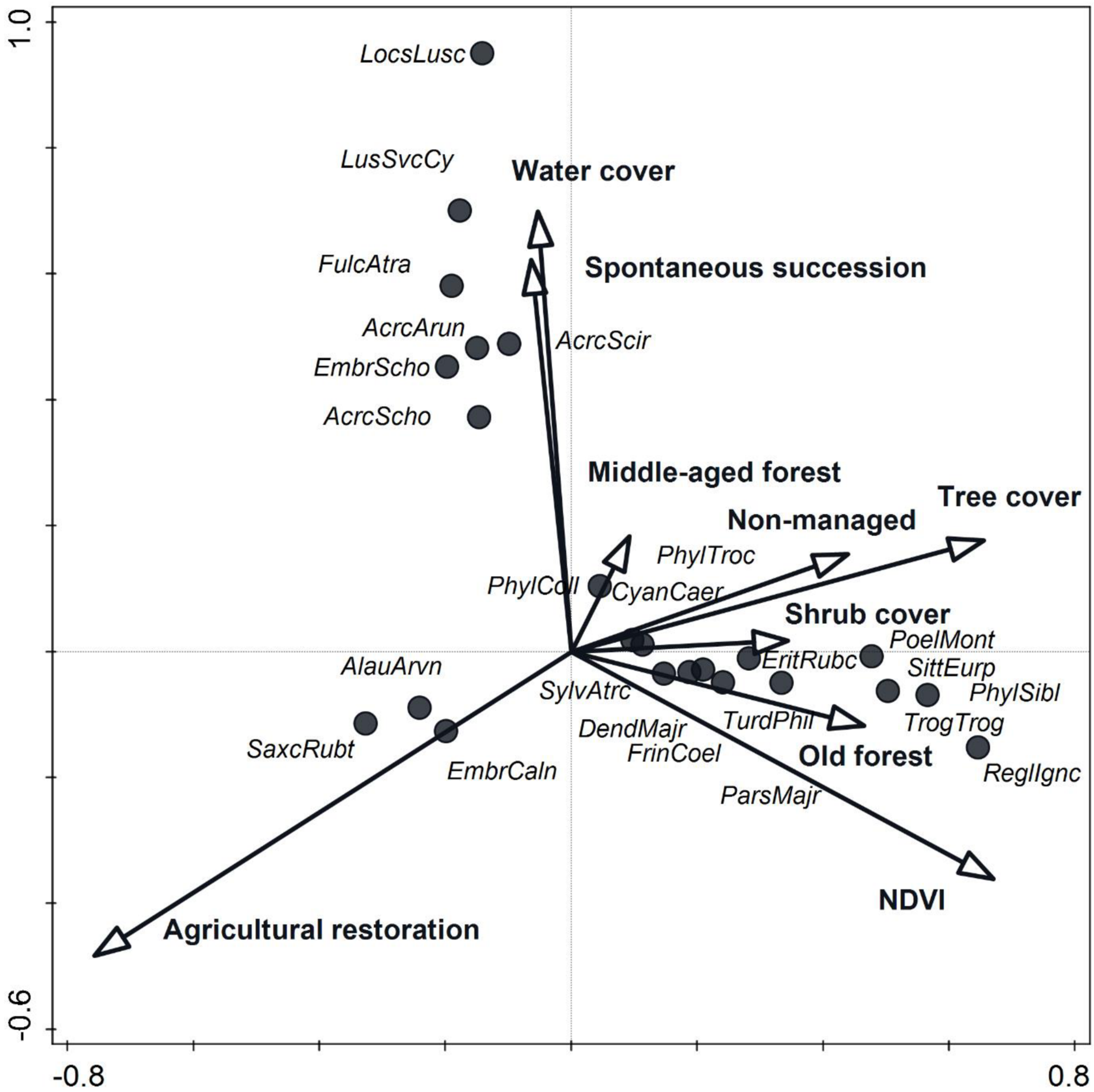
8.5 Figure 5. A satellite image of central spoil heap area of our study site with regards to land use category for each survey period. Red areas correspond to active dump site, while white areas describe pastures, green areas correspond to arable land.



8.6 Figure 6. a) Effect of site management represented by three land use categories on bird diversity, represented by Shannon index value on counting point. Highlighted are contrasts between management categories, calculated by post-hoc tests. **b)** Effect of the pasture management category on bird species richness, represented by number of species per counting point. Displaying median, boxes – 25-75 % of data, whiskers – non-outlier range.


a)
Species Richness
0
10
20
30
2012
2019-21
b)
Diversity (Shannon)
0
1
2
3
4
2012
2019-21
c)
Species Rarity
0
1
2
3
4
5
2012
2019-21
Survey period
d)
Species Rarity
0
2
4
6
8
10
0.3
0.4
0.5
0.6
0.7
0.8
NDVI index
e)
Species Rarity
0
2
4
6
8
10
Absent
Present
Spontaneous succession

8.7 Figure 7. Effect of site development represented by survey period on **a)** species richness represented by number of species on counting point, and **b)** bird diversity represented by Shannon index value on counting point and **c)** Bird rarity **d)** Effect of vegetation productivity represented by NDVI index on bird rarity on counting point. The relationship between NDVI and rarity is described by regression, while circles describe the rarity value for each counting point. **e)** Effect of spontaneous succession presence/absence on bird rarity on counting point. Bird rarity in **c,d,e)** represented by sum of rarity indices of each species present on counting point. Squares – median, boxes – 25-75 % of data, whiskers – non-outlier range. Figure displayed on previous page to this description.



8.8 Figure 8. An ordination diagram of bird community structure with environmental variable labels describing primary predictors using only the 2019-21 community dataset with corresponding set of environmental variables. Only species that fitted the ordination axes by more than 7 % are shown. For abbreviations of species see Supplementary material, Table S1.

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