



# Nine-year bird community development on Radovesická spoil heap: impacts of restoration approach and vegetation characteristics

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## Abstract

Worldwide environmental effects of anthropogenic land modification have made apparent the urgent need of ecological restoration. However, the methods employed in restoration of post-industrial sites vary across different regions. This study aims to examine the outcomes of different restoration approaches by examining avian communities inhabiting a vast spoil heap in Central Europe (1200 ha). Observations were conducted in 2012, and from 2019 to 2021. We built generalized mixed-effect linear models with spatial covariance structures to consider confounding effects of spatial autocorrelation. As restoration proceeded on the site, management techniques were employed that led to increases in bird abundances, diversity, and rarity. Forestry restoration involved tree planting and was associated with higher vegetation productivity and increased cover of understory and canopy layers. It facilitated increased bird diversity as it was preferred by many species that typically inhabit forests and shrublands. However, it attracted rare species only in areas with increased understory cover. Conversely, agricultural restoration (based on sowing of grasses) was associated with increased herb cover and attracted a species-poor, but valuable group of rare grassland birds. Some areas on the site were also left to spontaneous vegetation succession, which facilitated an increase in bird species richness and bird rarity and attracted wetland species. Given the historical context of the surrounding landscape, management that maintains the unique bird groups associated with each management type is recommended. This involves allowing spontaneous succession to proceed undisturbed, preserving shrub cover by introducing disturbances, and preventing the replacement of valuable grasslands with planted forests.

**Keywords** Ecological restoration · Revegetation · Agriculture · Bird diversity · Tree planting · Bird community

## Introduction

Anthropogenic land modification has severely altered the natural functioning of ecosystems, making apparent the urgent need of ecological restoration of impacted landscapes.

Typical examples of heavily disturbed ecosystems are post-mining sites, such as spoil heaps, strip mines and quarries. Surface mining is one of the most devastating anthropogenic activities that alters large areas globally (Slonecker and Bengler 2001). Most of the world's mining land use exists within vast, resource-rich countries such as the Russian Federation, China, or Australia, but it is also prevalent in European countries such as Germany, Czechia, or Ukraine (Maus et al. 2022). These countries have a long history of industrial development, with much of their landscapes still dealing with the ecological impacts of past mineral extraction (Krümmelbein et al. 2012). It is, therefore, critical that ecological restoration is approached correctly to maximize the potential of post-mining areas to enhance biodiversity (Larondelle and Haase 2012).

In European countries, restoration efforts commonly involve technical reclamation (Hodačová and Prach 2003). This practice consists of levelling soil surface, removal of waste products, spreading of organic topsoil rich in

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nutrients, and sowing commercial seed mixtures or planting trees in regular rows (Štýs and Braniš 1999). In many cases, site modification is a necessary measure (Prach and Hobbs 2008), for example in eroded habitats after lignite mining (Baasch et al. 2012; Hüttl and Gerwin 2005). However, there are situations where technical reclamation is not necessary for ecosystem restoration. Technical reclamation can be counterproductive when vegetation cover can establish itself spontaneously (Moreno-Mateos et al. 2015). Areas under natural revegetation are often technically reclaimed regardless of necessity, replacing unique and diverse plant communities with species-poor grass mixtures or tree plantations (Prach et al. 2013). For this reason, appropriate revegetation methods need to be considered (Tropek and Konvička 2008). Two most common revegetation practices in technical reclamation practices are a) planting of woody species and b) sowing of herbaceous species (Navarro-Ramos et al. 2022). Many studies have examined the effectiveness of these practices when influenced by different factors (Foxcroft et al. 2017; Iskandar et al. 2022 or Torres and Renison 2015). However, little information exists on which revegetation approach is more appropriate for successful restoration in terms of maximizing the capacity of a post-mining site for biodiversity conservation. As natural conditions in different post-mining regions around the world are variable, this is to be expected (Navarro-Ramos et al. 2022). However, within a specific region, comparing the effectiveness of both revegetation practices in restoration could yield results that are highly applicable worldwide.

In Central Europe, both planting of woody plant species and the sowing of herbaceous species is common (Hodačová and Prach 2003). However, most studies in the region focused on comparing restoration success of technical reclamation to spontaneous succession, and only marginally investigated revegetation practices (Hendrychová et al. 2012; Bejček and Šťastný 1984). Most valuable findings in this area are offered by Šálek (2012) and Moudrý et al. (2021). Their results showed that birds on spontaneously developed sites formed more species-rich communities with a greater proportion of rare species compared to technically reclaimed sites. However, Šálek (2012) also noted that bird species richness increased on technically reclaimed sites as herbaceous cover was replaced by woody vegetation, while the number of rare bird species decreased. While both studies highlight the importance of spontaneous succession, neither evaluated which revegetation practice is appropriate for biodiversity conservation on sites that have undergone technical reclamation. Neither study has fully examined how the bird community changes on sites undergoing restoration over a fixed time period. Moudrý et al. (2021) only examined bird community within a single year, and Šálek (2012) examined multiple different sites within varying successional stages at the same time. These sites were of different sizes, with

different management histories and located apart from one another (Šálek 2012). Studies on bird communities from unconnected landscapes are often influenced by confounding factors that distort bird distribution patterns, such as habitat isolation and edge effect (Ewers and Didham 2006). Monitoring a single post-mining site over several years could help address these issues. Another confounding factor is represented by the possible effect of spatial autocorrelation on bird abundances, which was not considered by either study. As spatial autocorrelation is nearly ubiquitous in ecological data, neglecting its effect may lead to misleading findings (Šmilauer and Lepš 2014). Lastly, neither study has incorporated information on bird habitat preferences into their statistical tests, simply preferring to discuss species-level preferences of different restoration approaches. Analyzing bird community by using functional trait information, such as typical preferred habitat, enhances understanding of ecosystem functioning, while increasing the applicability of obtained findings to other regions (Cadotte et al. 2011).

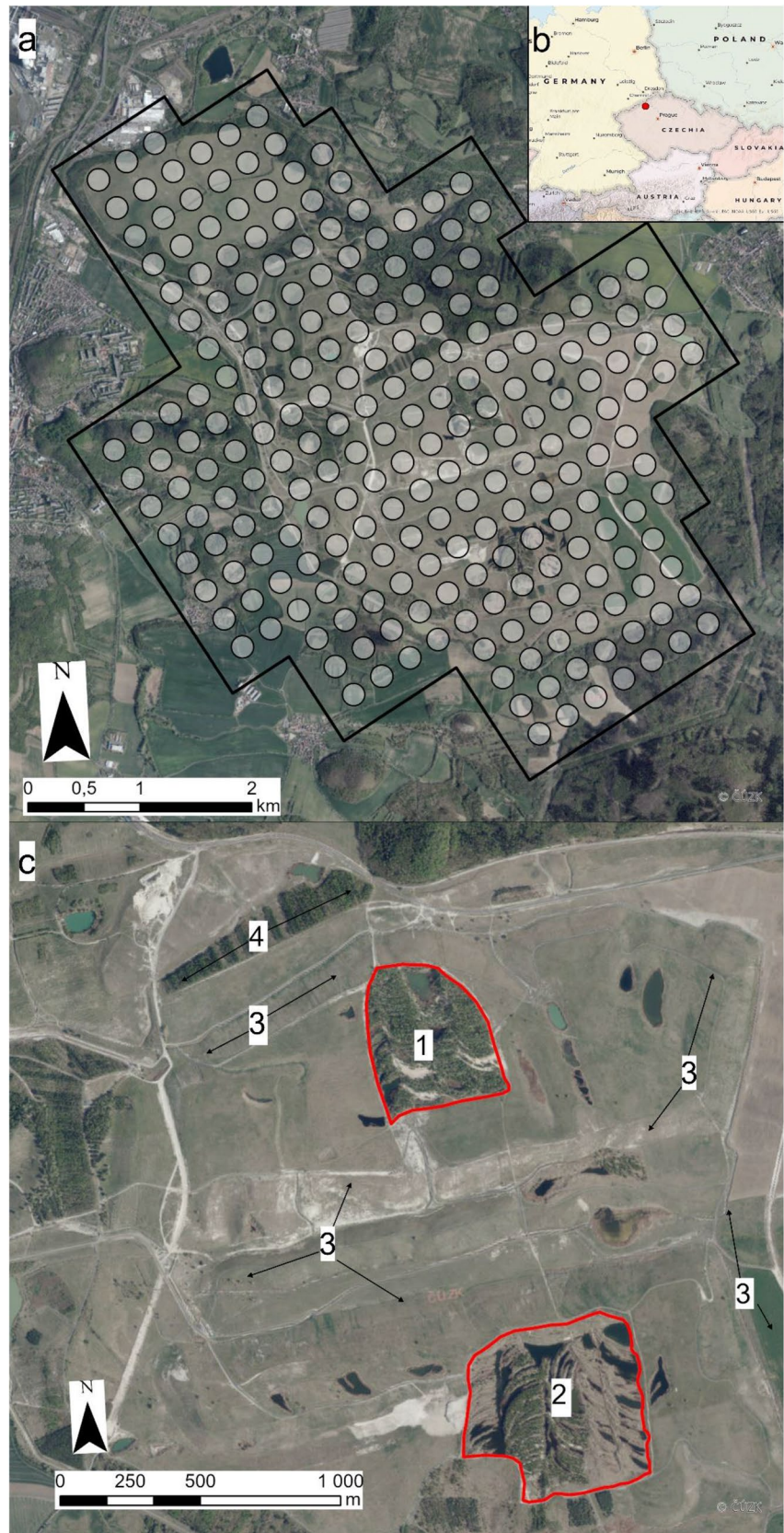
This study addresses these issues by offering a new perspective on using bird communities when evaluating success of restoration projects. We chose one of the largest post-mining sites in central Europe to conduct our field surveys and examined it over a fixed time period from 2012 to 2021. We offer an unbiased estimate of bird abundances by surveying a large area that is not burdened by variability in site history, edge effect, or disproportionate habitat isolation. We employed spatial covariance structures in statistical models to address the effects spatial autocorrelation. We included new standardized information on bird habitat preferences in our analyses by using functional trait data from the AVONET dataset (Tobias et al. 2022). Our goals were to (1) describe bird community development over the 9-year period of our study, and to (2) analyse the response of bird community to vegetation characteristics connected to different types of restoration management. We examined bird abundances by classifying species into groups based on habitat preferences (forest, grassland, shrubland and wetland species). In addition, we investigated two community indices, species diversity (represented by Shannon index values) and the occurrence of rare species (represented by rarity index values). Our results expanded the knowledge on how a bird community responds to varying types of restoration management over time, and offered information that is applicable to other similar post-mining areas.

## Materials and methods

### Study site

The study site consisted of the *Radovesická* spoil heap with an area of 1,200 ha (Fig. 1a) in North Bohemia (50.54115

**Fig. 1** **a** A map of our study site and the surrounding landscape with field survey design. All transparent white circles represent a 100-m radius around a survey point in the centre, as well as vegetation survey plots which consisted of the same areas. **b** The highlighted location of the study site in central Europe. Acquired from ArcGIS Pro basemap service. **c** A satellite image of central spoil heap area of our study site. Highlighted are (1, 2) two main spontaneously successional areas exempt from reclamation efforts, (3) areas with agricultural restoration, (4) forestry restoration. Satellite data acquired from the Czech Office for Surveying, Mapping and Cadastre (2021), <https://geoportal.cuzk.cz/>



N, 13.83000 E, Fig. 1b). Between the years 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 progressing (Novák and Hendrychová 2021). Spontaneous succession was preserved in two larger mutually isolated areas (4% of the study site area), but it also exists in various forms of scattered non-productive habitats (Hendrychová et al. 2020), in total forming 19% of the study site area. The study site is surrounded by both urban and industrial infrastructure, as well as agricultural land and forests (Fig. 1). Before spoil heap construction began in 1964, the area was mostly dominated by large farmland blocks with interspersed forests (Pilný 2011).

## Data collection

A regular grid of 221 counting points (each 300 m apart from another) was established within the spoil heap (Fig. 1a). To address dispersal of birds from the surrounding region, no counting point was located closer than 300 m from the edges of the spoil heap. This distance is sufficient to prevent most bird species whose territories surround the site from influencing abundances on counting points (Ferry et al. 1981). The survey took place in the breeding seasons from late April to early June in 2012, 2019, 2020 and 2021. Birds were surveyed during five-minute visits on each point between 6:00 and 10:00 UTC. All individuals detected within a 100-m radius were recorded, excluding those that flew over the area. We surveyed all points twice during the breeding season, at least 20 days apart. Maximum abundances for each species at each point for every breeding season were established. Birds were monitored in 2012 by five experienced ornithologists (co-authors of this study), two of whom continued bird surveys from 2019 to 2021. The data were then pooled together and used by subsequent analyses.

We performed a field vegetation survey in July 2020 within a 100-m radius around each counting point (Fig. 1a). For each plot, we recorded the proportional (%) cover of herb, understory, and canopy layers, as well as the proportion of surface covered by standing water. Methodology on classifying vegetation characteristics was taken from Šálek (2012). Herb layer corresponded to the proportional cover of herbaceous plants growing directly above ground. Understory layer corresponded to the proportional cover of woody vegetation as well as young trees up to approximately four meters in height. Canopy layer cover was represented by the connectivity of the forest canopy taller than approximately four meters. We also established the proportion of employed restoration management approaches for each study plot based on the following categories: (1) spontaneous succession, (2) forestry restoration, (3) agricultural restoration. Spontaneous succession management represented the proportion of area on study plots where vegetation cover

developed without human assistance. Restoration based on forestry or agriculture are two main types of assisted revegetation practices after technical reclamation, either by planting of trees or sowing of grasses (Navarro-Ramos et al. 2022). Restoration management type classification was based on key signs, such as apparent presence of typical pioneer plant species (e.g. *Calamagrostis* sp., *Phragmites* sp., *Betula* sp., Linnaeus 1758) on clearly unmodified surface (spontaneous succession), regular rows of planted tree species (*Quercus* sp., *Acer* sp., *Pinus* sp., *Picea* sp., *Larix* sp., Linnaeus 1758) on surface modified by technical reclamation (forestry restoration) or areas sown by commercial mixes of herbs (*Trifolium* sp., *Medicago* sp., *Phleum* sp., Linnaeus 1758) on surface modified by technical reclamation (agricultural restoration). The results of the vegetation survey are available in Supplementary material, Table S4).

We used ArcGIS Pro software (Esri 2020) to gather data on vegetation structure. We employed the Copernicus Sentinel data, gathered by the European Space Agency's Multispectral Instrument on the Sentinel-2 satellite (European Space Agency 2018). The imagery dataset consisted of 13 spectral bands derived from reflected radiance measurements, ranging from visible and near-infrared to shortwave infrared wavelengths with varying spatial resolution. One vegetation index was calculated: NDVI (normalized difference vegetation index, formula taken from Huang et al. 2021), which corresponds to plant chlorophyll content and therefore to primary productivity of vegetation. Mean values of this vegetation index were calculated for each study plot in a 100 m radius and used in subsequent analyses. NDVI values range from  $-1$  to  $1$ , and in general, water bodies have negative index values, while common types of vegetation (such as forests or meadows) have positive values (Huang et al. 2021). Only positive values of mean NDVI were calculated on study plots, likely due to well-established vegetation cover.

To incorporate bird functional trait information into our analyses, we classified each bird species into one of four groups based on their habitat preferences. These groups were forest birds (birds that inhabit all types of tree-dominated areas), grassland birds (open grass-dominated landscapes), shrubland birds (low stature bushy habitats) and wetland birds (freshwater aquatic habitats). This classification is taken from the AVONET dataset, which contains standardized functional trait information for all bird species in the world (Tobias et al. 2022). Sums of abundances of each species in respective groups on each counting point for every year of survey (2019, 2020, 2021, 2012) were used as response (dependent) variables in bird abundance analyses. Information on which species belonged to each group is available in Supplementary material, Table S1. In addition to bird abundances, we used two more metrics to describe bird community response to site development and environmental

variables. First, for each year of survey, we calculated the Shannon diversity indices for birds on each counting point (Shannon 1948). We used a species rarity index formula established previously by Šálek (2012), reflecting the scarcity of each species throughout the region. We paired this formula with data from newly published national quadrat mapping of birds from 2014 to 2017 (Šťastný et al. 2022). The index was calculated as  $1 - N/628$  where  $N$  represents the number of quadrats occupied by the species from 628 in total (Supplementary material, Table S1). For every counting point and each year, the values of rarity index for all present bird species were summed up.

## Statistical analyses

To describe the relationships among environmental variables, we performed a principal component analysis (PCA) using the Canoco 5 software (ter Braak and Šmilauer 2012) with arcsine transformation for percentage data. This analysis allowed us to reduce dimensionality of variables while minimizing information loss by determining which vegetation characteristics are associated with different restoration approaches (Jackson 2005). The resulting ordination diagram highlights the relationships among them and is available in the Supplementary material (Fig. S1). We used vegetation characteristics (herb cover, understory cover, canopy cover, water cover and vegetation productivity (NDVI) as input data. Variables describing different types of management approach (spontaneous succession, forestry restoration, agricultural restoration) were also used to highlight which vegetation characteristics were associated with each management. Variables which were positively correlated with the first ordination axis were associated with restoration by forestry (canopy cover,  $r=0.76$ ; understory cover,  $r=0.63$ ; productivity  $r=0.76$ ). One variable highly positively correlated with the second ordination axis (PCA axis 2) was associated with spontaneous succession (water cover,  $r=0.78$ ). The remaining variable was highly negatively correlated with the second ordination axis (herb cover,  $r=-0.34$ ), and was associated with agricultural restoration.

We then analyzed how the listed environmental variables impacted bird community on our study site. We built generalized linear mixed-effects models using the function and package `glmmTMB` (Magnusson et al. 2017) in R 3.6.3 Software (R Core Team 2020). We built three separate models, each examining a different metric of bird community: (1) bird abundances (of each species group as defined above), (2) species diversity (Shannon index) and (3) species rarity (rarity index). We only used vegetation characteristics as fixed effects (predictors) in this analysis and omitted variables describing restoration approach. We did this because each restoration approach was highly correlated with specific vegetation characteristics (Supplementary material, Fig. S1),

and thus using these variables together as predictors would introduce multicollinearity into our models (Daoud 2017). By only using vegetation characteristics as fixed effects, we avoid this issue. In addition, we do not lose any information on the effects of restoration practices as these can be inferred from the effects of vegetation characteristics. Five fixed effect variables were used: proportional cover of understory, herb, and canopy layers, as well as the proportion of surface covered by standing water, and vegetation productivity represented by NDVI. Before entering model selection, all fixed effect variables were standardized by log-transformation. This was done to avoid any statistical errors stemming from unsupervised vegetation classification (Tichý et al. 2020). For each model, forward selection for fixed effect variables by AIC was performed (Blanchet et al. 2008) using the dredge function, package `MuMIn` (Barton and Barton 2015). The forward selection procedure represented by dredge function output for each final model for each dependent variable is available in Supplementary material, Table S2. Only variables included in the final models are reported in the results.

Survey year (2012, 2019, 2020, 2021) was used as a random effect variable in all models to examine the effect of site development on bird community. In addition, another random effect variable was included in the first model analyzing bird abundances. This random effect was used to include abundances of all species groups in one dependent variable by specifying the identity of each group in the random effect term. For the specific formulation of this random effect, see Supplementary material, Table S2. We calculated Moran's  $I$  statistics for all sampling points on our study site using the ArcGIS Pro software (Esri 2020) and found significant effects of spatial autocorrelation (Moran's  $I$ : 0.98;  $p < 0.001$ ). This meant that spatial autocorrelation needed to be considered in all models. We did this by defining a numeric factor that was used to record spatial coordinates from each counting point by using the `NumFactor` function, package `glmmTMB` (Magnusson et al. 2017). Then, using a Matérn covariance structure, the numeric factor was included in the analysis as a random effect variable. Matérn covariance structures allow for reliable inclusion of spatial relationships as terms in statistical models (Bevilacqua et al. 2022). For the specific formulation of the covariance structure in each model, see Supplementary material, Table S2. For a step-by-step tutorial of building spatial models using the `glmmTMB` package, we suggest a vignette written by Lionel Herzog on the R Project forum (Herzog 2019). We used a negative binomial distribution as the family function to fit all models (Hardin and Hilbe 2007) and performed dependent variable transformations when necessary (Supplementary material, Table S2). We also performed multicollinearity tests for each model (package `performance`, Lüdtke et al. 2021). We did not find any significant effects

of multicollinearity (Supplementary material, Table S3). As part of model diagnostics, we calculated the  $R^2$  values to describe the fraction of variation explained by fixed effects only (marginal  $R^2$ ) and by both random and fixed effects (conditional  $R^2$ ). We also calculated the fraction of variation explained by only the survey year random effect.

We used the emmeans function, package emmeans (Searle et al. 1980) to perform post-hoc tests. Pairwise comparisons were made for bird abundance, species diversity and species rarity across different categories of the survey year random effect for all models (2012, 2019, 2020, 2021). This allowed us to illustrate changes in bird community over time. In addition, we calculated a Kolmogorov–Smirnov test to determine whether species that declined in their abundances from 2012 showed dissimilar values of bird rarity index than species that increased in their abundances from 2012.

## Results

### Bird community overview

During our study, 106 bird species in total were recorded. No exotic species were detected during the surveys. The most abundant species was *Alauda arvensis* (Linnaeus 1758, 11.0%), followed by *Sylvia atricapilla* (Linnaeus 1758, 5.6%) and *Emberiza citrinella* (Linnaeus 1758, 4.5%). Most species on our study site inhabited forests (56, for example *Anthus trivialis* or *Dendrocopos major*; Linnaeus 1758). Regarding other groups, there were 22 wetland species (*Acrocephalus arundinaceus*, *Locustella fluviatilis*; Linnaeus 1758), 16 grassland species (*Alauda arvensis*, *Emberiza calandra*; Linnaeus 1758) and 11 shrubland species (*Acrocephalus palustris*, *Sylvia communis*; Linnaeus 1758). Aside from containing the largest number of species, forest birds were also the most abundant group in terms of the number of individuals recorded on points each year, followed by grassland species, then shrubland species and then wetland species (Fig. 2).

Abundances of each species group also changed significantly between years. Abundances of each species group on counting points increased from 2012 to 2019, but mostly remained similar between 2019, 2020 and 2021 (Fig. 2). These changes were most apparent for forest and grassland species, but our pairwise comparisons show that abundance increases also occurred for shrubland and wetland birds (Supplementary material, Table S2). Species diversity also changed as site developed, with the 2012 values of Shannon index being lower than in 2019, 2020 or 2021 (Fig. 2). In terms of bird rarity, while the 2019 and 2020 values were significantly higher than in 2012, the 2021 values were not (Fig. 3). Abundances of each species group increased from 2012 (Fig. 2), but our Kolmogorov–Smirnov test showed

that bird species with decreasing abundances from 2012 were significantly rarer than species with increasing trends (Fig. 3). In other words, while most species from each group increased in their abundances, those that decreased were more valuable in terms of their rarity.

### Effects of vegetation characteristics

Bird abundances were significantly affected by two fixed effect variables: vegetation productivity (NDVI) and by the proportional cover of water on study plots (Table 1). This effect varied among species groups. While abundances of forest and shrubland birds showed a positive response to increased vegetation productivity, abundances of grassland and wetland birds decreased in more productive areas (Fig. 4). On the other hand, water cover had a very positive effect on abundances of wetland birds, but a negative effect on abundances of forest and shrubland birds, while grassland birds were not affected in either direction (Fig. 4).

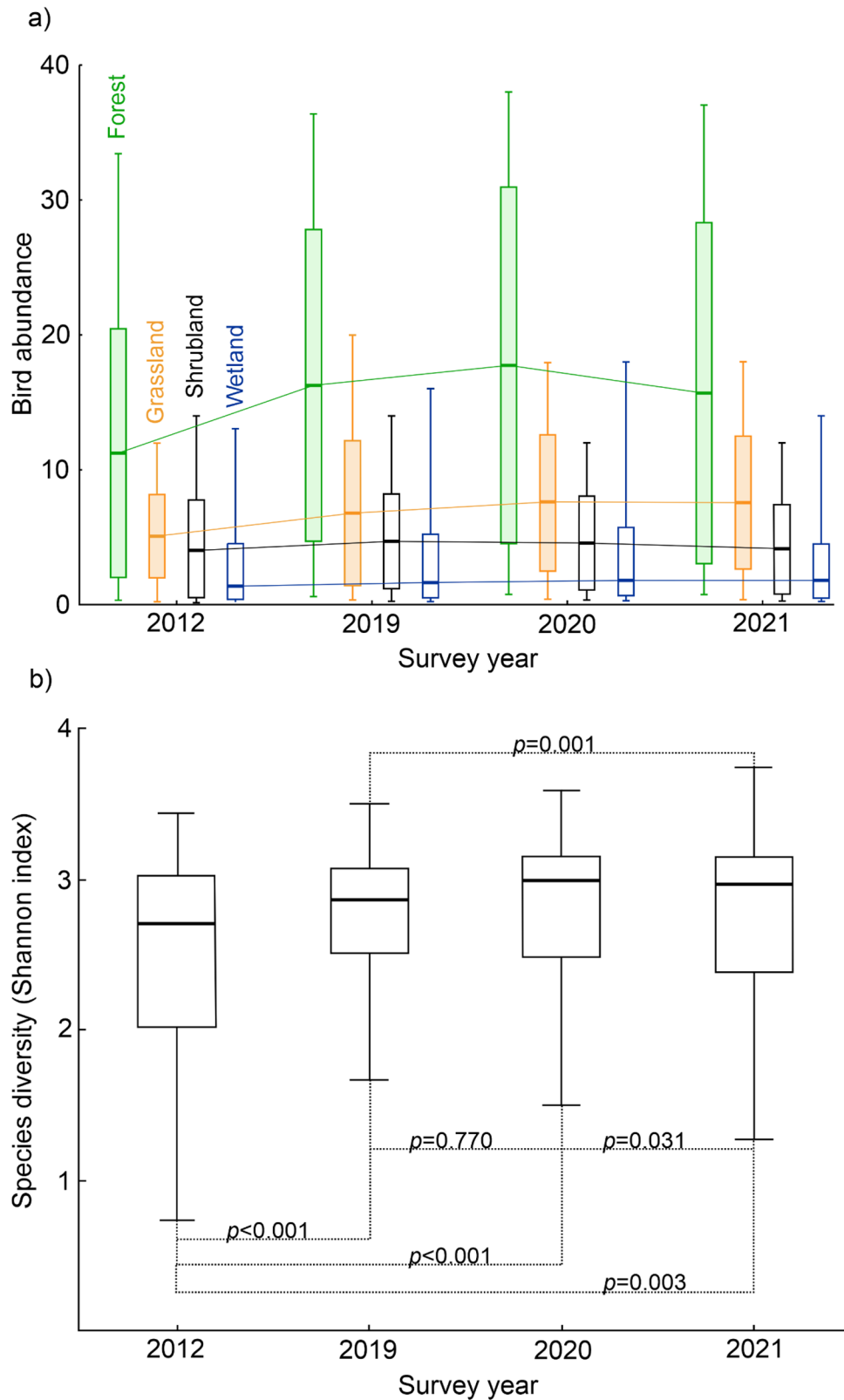
In contrast to abundances, bird diversity was not significantly impacted by vegetation productivity, but rather by the proportional cover of herb, understory, and canopy layers, as well as by water cover (Table 1). The effect of herb cover was negative, with areas with increased herb cover showing decreased diversity (Fig. 5). In contrast, the effects of understory, canopy and water cover were all positive, with increased proportions of these variables showing a positive effect on bird diversity (Fig. 5). Bird rarity was significantly impacted by vegetation productivity (NDVI), water and understory cover (Table 1). The effect of vegetation productivity was negative, showing that more productive areas were not sought out by rare bird species (Fig. 5). In contrast, the effect of water cover was positive, showing that species living near water were often rare (Fig. 5). Lastly, we found that understory cover had a positive effect on bird rarity, showing that despite having productive vegetation, areas with higher understory cover still attracted rare species (Fig. 5). In all models, the vegetation characteristics explained a significant portion of variation (up to 20% in bird abundance and rarity models and 57% in diversity model, Table 1, marginal model  $R^2$ ). However, random effects explained up to 55% of variation (Table 1, conditional model  $R^2$ ). Most of the variation explained by random effects is attributable to the spatial covariate, as the survey year random effect only explained up to 3.5% of variation (Table 1).

## Discussion

### Site development

Radovesická spoil heap features a unique mosaic of extensively managed grasslands, planted forests in various stages

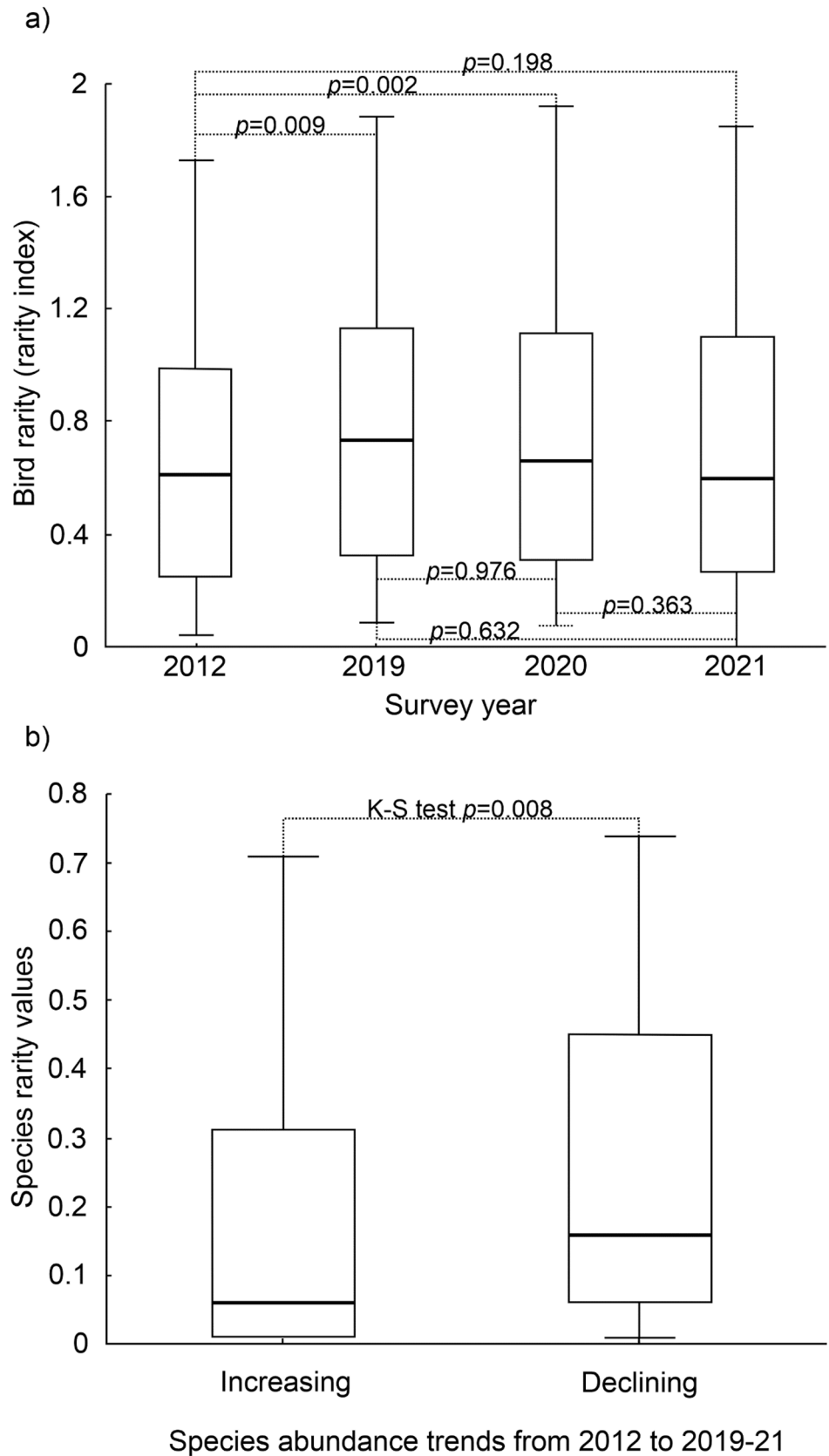
**Fig. 2 a** Effect of site development represented by survey year on bird abundances (forest, grassland, shrubland and wetland birds). Pairwise post hoc test results comparing abundances of different bird groups across all levels of the year factor are available in the Supplementary material, Table S2, as calculated by the emmeans function. Thick lines—mean, boxes—2\*standard deviation, whiskers—non-outlier range. **b** Effect of site development represented by survey year on species diversity, represented by Shannon index values. Dotted lines highlight the results of pairwise post hoc tests comparing diversity indices across different levels of the survey year factor, calculated by the emmeans function, which are also available in the Supplementary material, Table S2. Thick lines—median, boxes—25–75% of data, whiskers—non-outlier range



of growth, and spontaneous succession. Biological studies have examined its valuable communities of birds (Novák and Hendrychová 2021), crustaceans (Patoka et al. 2016),

or dragonflies (Tichánek and Tropek 2016). This mosaic is highly valuable for examining long-term changes in biodiversity, yet no study has yet done so.

**Fig. 3 a** Effect of site development represented by survey year on bird rarity, represented by sum of rarity indices of each species present on counting point. Dotted lines highlight the results of pairwise post-hoc tests comparing rarity indices across different levels of the survey year factor, calculated by the emmeans function. **b** The results of a Kolmogorov–Smirnov test comparing rarity index values of bird species whose abundances in 2012 were lower than the 2019–21 mean, and species whose abundances in 2012 were greater than the 2019–2021 mean. Both graphs: squares—median, boxes—25–75% of data, whiskers—non-outlier range





**Table 1** Effect of environmental variables on bird abundances, species diversity and bird rarity

Response variable	Fixed effects	Estimate	S.E.	<i>T</i>	<i>P</i>
Bird abundances	Vegetation productivity (NDVI)	−0.583	0.164	−3.558	<0.001
	Water cover	0.175	0.029	5.970	<0.001
Species diversity	Herb layer cover	−0.108	0.022	−4.790	<0.001
	Understory cover	0.027	0.007	3.754	<0.001
	Canopy cover	0.043	0.007	6.151	<0.001
	Water cover	0.024	0.011	2.241	0.025
Bird rarity	Vegetation productivity (NDVI)	−1.361	0.230	−5.894	<0.001
	Water cover	0.165	0.041	3.997	<0.001
	Understory cover	0.071	0.026	2.670	0.008
Response variable	Marginal model $R^2$	Conditional model $R^2$		Survey year contribution	
Bird abundances	0.179	0.372		0.021	
Species diversity	0.567	0.940		0.033	
Bird rarity	0.187	0.972		0.004	

Predictors were represented by vegetation characteristics as listed. Random effects were represented by survey year and a numeric factor describing spatial autocorrelation in all models (see methods). In addition, a random effect predictor representing species groups whose abundances were used to analyse bird abundances. Forward model selection by AIC was performed, so only variables with significant effect present in the final model are listed. The forward selection table output of the dredge function along with formulae of final models, used model families and model AICs, and results of tests for multicollinearity are all available for viewing in Supplementary material, Table S2–S3. The listed  $R^2$  values describe the fraction of variation explained by fixed effects only (marginal  $R^2$ ) and by both random and fixed effects (conditional  $R^2$ ), as well as the fraction of variation explained by only the survey year random effect. All reported statistical tests were performed at the <0.05 significance level

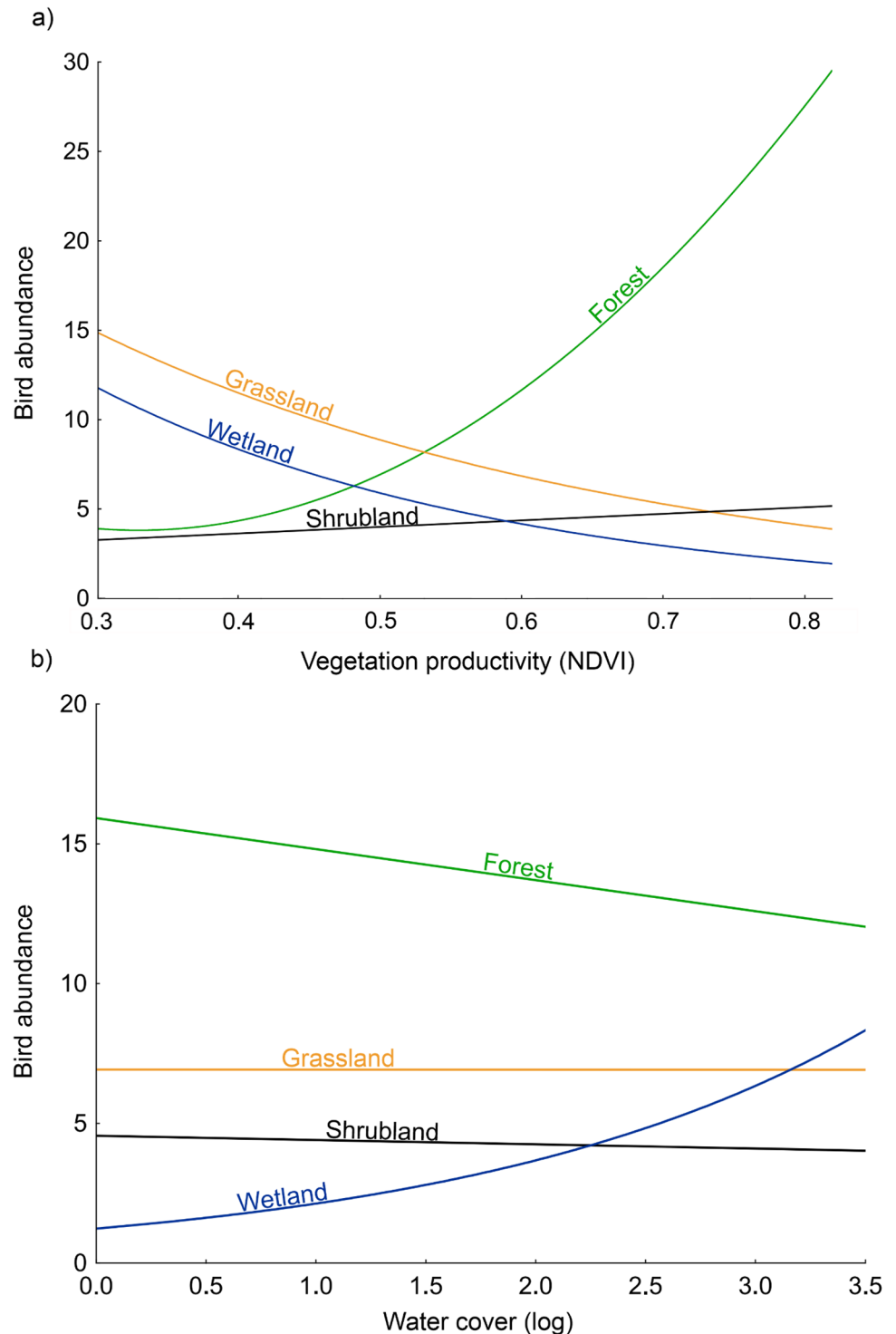
The restoration efforts had a significant impact on the bird community. Bird abundances, especially for forest and grassland species, increased since 2012. Bird diversity also showed an increase. While bird rarity was lower in 2012 compared to 2019 and 2020, there was no significant difference between 2012 and 2021. Two conflicting effects on bird rarity explain this result. Firstly, the overall abundances of all species groups increased from 2012, leading to overall increases in bird rarity as more individual birds were present on points. However, species with decreased abundances were of higher rarity compared to those with increasing abundance trends, which negatively impacted overall rarity. The significant changes in community metrics represent the onset of long-term ecosystem succession, as was observed by Šálek (2012) or by Brady and Noske (2010). As initial stages of soil modification are finished, the barren landscape is populated by young, planted forests or sown grasslands. The developing vegetation is settled by an increasingly complex community of birds, corresponding with the increased bird diversity and overall abundances (also observed by Moudrý et al. 2021). However, as revegetation continues, the site becomes similar to the pre-existing agricultural and forest mosaic of the surrounding landscape (Skaloš et al. 2012). This may result in the disappearance of early-successional habitats that are sought out by some rare species (for example *Anthus pratensis*, *Motacilla flava*, Linnaeus 1758) and a corresponding decrease in their abundances.

However, it is important to note that not all areas under restoration have yet reached these late successional stages, and revegetation efforts on the site are due to continue for the foreseeable future (Pilný 2011). In addition, the decrease of some species' abundances may not be caused by changes on the study site. Many rare birds in the Czech Republic have a long-term declining population trend, and their local numbers may be affected by the collapse of the regional metapopulation (Štátný et al. 2022). Regardless of possible future decline of rare species, the observed long-term changes in community metrics are overall positive. However, it is crucial to interpret these changes with respect to used restoration management and associated vegetation characteristics, as our results show that only a small portion of variation in bird community metrics can be attributed solely to time.

### Effects of restoration management

Bird abundances were significantly influenced by two variables: vegetation productivity measured by NDVI and water cover. Water cover was specifically linked to spontaneous succession, while NDVI represented a gradient ranging from low-productivity (agricultural restoration and spontaneous succession) to high-productivity vegetation (forestry restoration). In summary, forest and shrubland species showed a preference for more productive vegetation found in forestry restoration areas, while wetland and grassland species

**Fig. 4** Scatterplots with regression lines describing the effect of **a** vegetation productivity represented by NDVI and **b** log-transformed values of the proportion of each study plot covered by standing water, on bird abundances (abundances of forest, grassland, shrubland and wetland birds). Regression lines were fitted using response variable values predicted by the corresponding glmmTMB model (Table 1), using the ggplot2 package (Wickham et al. 2016)



preferred less productive habitats. In addition, increased water cover was particularly essential for wetland species. Since different species groups favored different types of management, preserving each management type in its current state is essential to maximize the variability in bird community composition. This may be easily possible for areas with spontaneous succession inhabited by wetland

species which have been left without human intervention since 2003 (Novák and Hendrychová 2021). However, areas under forestry restoration are gradually converting from woodland-shrubs to late-stage forests. The intermediate successional stages inhabited by shrubland species may disappear unless appropriate steps are taken, such as introduction of disturbances from heavy machinery (Bušek and Reif

2017) or cattle (Konvička et al. 2021). A similar situation may occur with agricultural restoration. The anthroposoils used in the technical reclamation of Radovesická spoil heap were designed for forestry purposes (Vráblík et al. 2018) and many grassland areas on the spoil heap are scheduled for conversion to forestry in the near future (Ondráček and Lang 2009). The grassland areas on the study site are extensively managed with no application of fertilizers or grazing, and regular mowing late in the breeding season (as observed by the authors). This makes them suitable habitats for grassland species (for example *Emberiza calandra* or *Alauda arvensis*), which are declining due to agricultural intensification (Donald et al. 2001). Extensively farmed grasslands attract significantly higher abundances of these birds than intensively grazed or fertilized farmland (Verhulst et al. 2004), where the application of fertilizers can significantly decrease the food supply for many bird species (Wilson et al. 1999). To preserve such grassland habitats on the spoil heap, tree-planting efforts need to be limited.

Regarding species diversity, we observed significant positive effects of understory cover, canopy cover, and water cover. However, herb cover had a significant negative effect. Shrub cover and canopy cover were linked to forestry restoration, while herb cover was associated with agricultural restoration, and water cover was connected to spontaneous succession. In summary, forestry restoration and spontaneous succession led to an increase in bird diversity, whereas agricultural restoration was associated with a decrease in diversity. The positive effect of forestry is likely connected to increased vegetation heterogeneity, which facilitates increased bird species richness (and therefore diversity) in post-industrial areas (Šálek 2012; Moudrý et al. 2021). The beneficial effects of spontaneous succession on diversity are also likely connected to increases in habitat heterogeneity (Lengyel et al. 2023; van Turnhout et al. 2012), as well as by the presence of habitat specialists (Šálek 2012). Lastly, the negative effect of agricultural restoration on diversity is due to the homogenous, low-productivity vegetation typical for grassland habitats that cannot attract as many bird species as forests, shrublands or wetlands (Vickery et al. 1999).

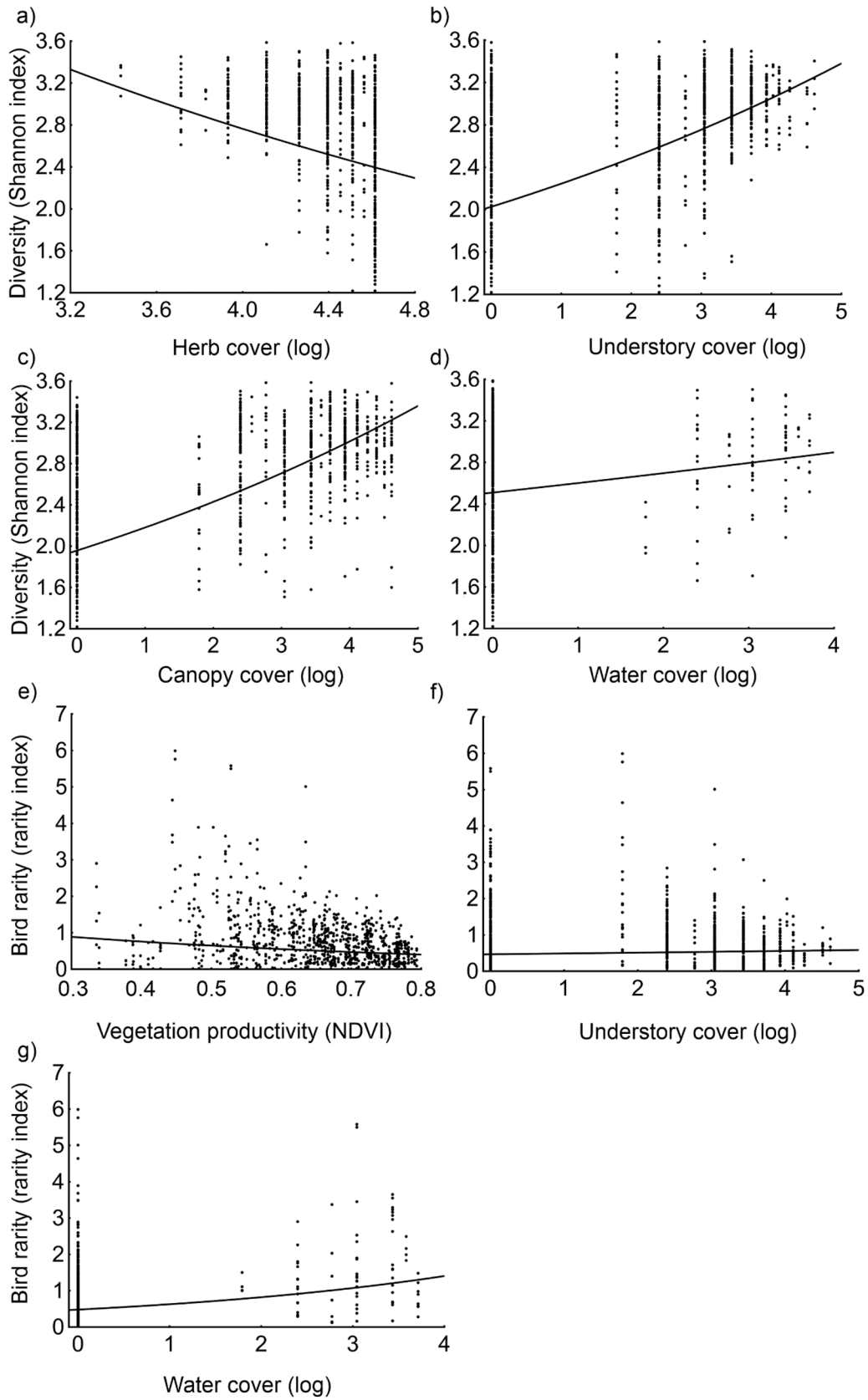
The effects of vegetation structure on bird rarity differed from those on diversity. Shrub cover and water cover had a positive impact on bird rarity, while vegetation productivity (NDVI) had a negative effect. This suggests that low-productivity grasslands resulting from agricultural restoration attract rare bird species, as do areas undergoing spontaneous succession with higher water cover. In contrast, rare birds tend to avoid forestry restoration areas characterized by higher vegetation productivity, except for intermediate successional stages that are covered by shrubs. These observed effects on bird rarity are tied to the relative regional scarcity of different

types of habitats. The Czech cultural landscape is dominated by intensive agriculture and forestry (Lipský 2000). Spontaneous succession is very scarce, estimated to have occurred on only 2% of the area of Czech Republic in the past decades (Prach et al. 2014). In contrast, the woodlands established by forestry restoration are well-represented in the general land-cover system (Skaloš et al. 2012). While full-grown forests are typical, intermediate successional stages are not maintained (Reif et al. 2007). Non-intensive agriculture is also scarce and connected with rare declining grassland species (Reif et al. 2008).

It is important to note that we only gathered vegetation data in the 2020 survey period, which may influence interpretation of the effects of vegetation characteristics. However, we suggest that within the long-term site development, these characteristics mostly remain consistent. A similar approach was taken by Moudrý et al. (2021) whose environmental dataset was taken from the same study site on 2018 and paired with response data from 2012 with no unexpected results.

## Conclusions: the end goal of restoration

Each management type had a different effect on bird community, attracting different bird groups that are valuable for their diversity (forestry restoration), rarity (agricultural restoration) or both (spontaneous succession). Which management type should we consider most appropriate? To answer this question, we need to consider the history of the study site within the context of the surrounding landscape. Before the Radovesická spoil heap was created in 1966, the area was mostly made up of large blocks of agricultural land interspersed with forests and villages (Pilný 2011). Returning the landscape to its pre-mining state may not best align with biodiversity conservation. The Czech countryside is often regarded by biodiversity researchers as particularly barren, mostly because of communist-era collectivization and pesticide overuse combined with current agricultural intensification (Reif et al. 2008). At the same time, Czech forests are mostly old-growth monocultures with low conservation value (Klimo et al. 2000), and spontaneously successional areas are routinely removed by urban and agricultural development (Prach et al. 2014). Instead of prioritizing one restoration approach, we suggest maximizing the capacity of each approach to retain their valuable bird communities. This means either not interfering with their current state (spontaneous succession), introducing disturbances that preserve shrub cover (forestry restoration), or preventing the conversion to planted forests (agricultural restoration).



**Fig. 5 a–d** Scatterplots with regression lines describing the effect of a log-transformed values of the proportion of each study plot covered by intact vegetation of the herb (ground) layer. **b** Log-transformed values of the proportion of each study plot covered by intact understorey layer vegetation. **c** Log-transformed values of the proportion of each study plot covered by intact canopy layer vegetation and **d** log-transformed values of the proportion of each study plot covered by standing water on species diversity represented by Shannon index values. **e–g** Scatterplots with regression lines describing the effect of **e** vegetation productivity represented by NDVI. **f** Log-transformed values of the proportion of each study plot covered by intact understorey layer vegetation. **g** Log-transformed values of the proportion of each study plot covered by standing water. Regression lines were fitted using response variable values predicted by the corresponding glmmTMB model (Table 1), using the ggplot2 package (Wickham et al. 2016)

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