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Edge of habitability: bird community on dump sites after uraninite mining

Master Thesis

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Annotation

Biota on post-mining areas is a well-examined topic in restoration ecology. However, most scientific attention focuses on large-scale opencast mining sites or spoil heaps. This study attempts to offer an insight into ecological conditions on a unique ecosystem represented by dump sites after uranium mining, using birds as a study group. We examined differences in bird abundance, species richness, community structure and habitat preferences between nine moderately sized dump sites and eight control areas. Our study can function as a pilot survey of birds of uranium mining sites, offering a broad overview of population-level effects of hostile conditions. Our findings can guide restoration practices with respect to this specific type of ecosystem.

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

Keywords
Birds, post-industrial site, uranium mining, community structure, vegetation characteristics

In České Budějovice 7.11.2023 ……………………………

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Declarations

This thesis is part of a publication in preparation entitled: Edge of habitability: bird community on dump sites after uraninite mining. The author of this thesis is also the primary author of the publication, and the corresponding author. The corresponding author confirms that this publication was also co-authored by doc. Mgr. Jan Riegert, Ph. D., and Mgr. Vojtěch Dolejšek. Study and survey design was performed together by primary author (50%) and Jan Riegert (50%). Majority of data collection was performed by the primary author (90%) and was supplemented by Vojtěch Dolejšek (10%), who assisted with the vegetation survey. Statistical analyses were performed, and first draft of manuscript was written by the primary author (100%). Subsequent edits were performed together by the primary author (50%) and by Jan Riegert (50%). All authors read and approved the final manuscript.

Manuscript

Title: **Edge of habitability: bird community on dump sites after uraninite mining**

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Abstract

Biota on post-mining areas is a well-examined topic in restoration ecology. However, most scientific attention focuses on large-scale opencast mining sites or spoil heaps. This study attempts to offer an insight into ecological conditions on a unique ecosystem represented by dump sites after uranium mining. Birds were used as a study group during field monitoring. We gathered data on differences in abundance, species richness, community structure and bird habitat preferences between nine moderately sized dump sites and eight control areas. Vegetation structure and invertivore food supply were also examined. Statistical analyses included constrained ordinations and mixed-effect GLMs. Dump sites attracted valuable bird assemblages despite extreme soil conditions, increased levels of radioactivity near ground, limited development of vegetation, and an impoverished food supply. These assemblages included primary succession specialists, declining grassland species, nomadic granivores or perching raptors. However, overall bird abundances as well as species richness were lower compared to control sites, and some species had to significantly adjust their ecological requirements for their survival. Radioactivity near exposed pieces of uraninite rocks could impact living conditions of ground-dwelling bird species, together with absorption of radionuclides by insects or vegetation. In addition, comparisons with other studies on birds in restoration science reveal key differences from opencast mining sites. Our study can function as a pilot survey of birds of uranium mining sites, offering a broad overview of population-level effects of hostile conditions. Our findings can guide restoration practices with respect to this specific type of ecosystem.

List of Abbreviations

RDA – Redundancy analysis

CCA – Canonical correspondence analysis

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1. Introduction

As habitat loss draws many organisms to the fringes of existence, post-industrial areas are becoming increasingly important for biodiversity conservation. Abandoned mines, quarries and spoil heaps are often the largest sites impacted by past industrial activity (Navarro-Ramos et al. 2022). 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, Czech Republic 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). In Central Europe, these impacts are generally addressed either by large-scale modification by heavy machinery followed by assisted revegetation (Hendrychová 2008), or by creation of artificial water reservoirs in place of mines (Molenda & Kidawa 2020) or by leaving areas to spontaneous succession (Tropek et al. 2012).

While the last approach may be suitable for maximizing biodiversity services (Tropek et al. 2010), it is often applied to areas where extreme conditions impede plant and animal colonization (Prach & Hobbs 2008). In such cases, ecosystem succession tends to proceed slowly and to a limited extent. First plant settlement is represented by pioneer grasses and forbs with very low vegetation cover (Skousen et al. 1990). Tree and shrub species follow after several years, slowly facilitating a perfunctory canopy layer (Skousen et al. 1990). In Central Europe, they are represented by hardy colonizers reliant on anemochory (*Betula* sp., *Salix* sp., Mudrák et al. 2010). Presence of vegetation is most often impacted by thickness of the fermentation layer. However, expansive grasses can arrest succession in nutrient-rich areas by outcompeting other understory species (e.g., *Calamagrostris epigejos*, Mudrák et al. 2010). Thickness of fermentation layer is closely related to the overall soil quality. Post-mining sites that do not undergo assisted revegetation or surface modification are often located on poor substrates with high concentration of basic elements (Veselá et al. 2021), poor water retention capacity (Cejpek et al. 2013) and an increased proportion of pollutants and toxic compounds (Frouz & Vindušková 2018). In addition, many unmodified sites offer little protection from weather phenomena, with high temperature variation between night and day, exposure to wind, rainfall and consequent soil erosion (Prach & Hobbs 2008). Similar to plants, animal colonization is impacted by these hostile conditions, and primary succession specialists tend to dominate (Bejček & Šťastný 1984, Šálek 2012).

A less-studied example of post-mining areas that develop extreme conditions are dump sites created by underground mining. These are mostly by-products of extraction of hard coal, ores, but also uraninite rock (Sasková 2011). Underground mining has a much lower overall ecological footprint than open-pit mines, since it does not directly strip the landscape. On the other hand, it produces coarse waste products (slag and tailing) that are deposited on the surface (Blight 2011). The resulting dump sites consist of steep heaps of rocks and mining slag, combining all previously listed extreme conditions, often with high content of toxic compounds (Peterková 2021). However, in case of some types of underground mines, there is an additional unique effect of radioactivity. Specifically, radioactivity associated with mining of thorium, or more often, uranium ores (Jull et al. 1987). This is to distinguish uranium mines from mining sites that are affected by unrelated "natural" radioactivity levels (Darko et al. 2010). Radioactivity associated with extracting these ores has been long under scrutiny, and many protective measures exist to reduce environmental contamination (Robinson 2004). Despite this, radiation levels are often increased at most sites of extraction, especially in reservoirs of runoff water and neutralization ponds (Carvalho et al. 2011). The coarse dump site material often contains residual uranium in pieces of leftover ore, facilitating increased radioactivity levels (Carvalho et al. 2007). Resulting exposure to radiation can impact organisms in abandoned mining areas (Hinck et al. 2017). Despite this, biodiversity on former uranium mining sites has not been sufficiently studied. In fact, effects of radioactivity on wildlife are much more often examined on landscapes irradiated by nuclear accidents (Wehrden et al. 2012). The associated high levels of radiation are affecting large areas and impact the environment more severely than radiation associated with mining (Friedman et al. 1987). However, findings of studies within these irradiated areas can be applicable to post-mining sites, albeit at a smaller scale.

To narrow down the available information, we will focus on bird response to increased radioactivity. Studies on birds from the Chernobyl area have shown a significant decrease in sperm count (Moller et al. 2014), brain size (Møller et al. 2011), and plumage quality (Møller et al. 2013), but also decreases in community metrics such as bird abundance or diversity, which were observed at a similar scale in Fukushima (Møller et al. 2012). Another source of radioactivity can be associated with nuclear bomb tests. A review by Mellinger et al. (1975) has discussed increased presence of radionuclides in the internal digestive tracts of birds as early as three years after the Trinity test (1948), and contaminated white-fronted geese (*Anser albifrons*) populations in Northern Europe after Soviet nuclear tests (1962). Indeed, in comparison with these far-reaching sources of radiation exposure, mining-related radiation is a much weaker effect, but nevertheless capable of altering living conditions for animal life (Hinck et al. 2017) and therefore worthy of study.

To conclude, there exist sample literature resources concerning the effects of radioactivity reviewed above, but these effects are mostly related to large-scale nuclear events. Concurrently, while surface post-mining areas are well-examined by ecologists, no attention is paid to dump sites after extraction of uranium. This twofold disregard can be addressed by a study that investigates ecological conditions on these sites. This can be achieved by choosing a group of organisms and gauging their response to on-site conditions. Birds can be most suitable for multiple reasons. They respond quickly to environmental changes and are relatively easy to monitor (Helms et al. 2018). At the same time, as primary, secondary, or even tertiary consumers within trophic networks, they are likely to be affected by accumulation of toxic or radioactive contaminants that may impact community metrics (Weeks et al. 2022). Lastly, enough literature exists concerning birds on non-radioactive post-mining sites (Hendrychová 2008), which can allow for comparisons.

As most studies on birds on post-mining sites were performed on Central-European spoil heaps (e.g., Šálek 2012, Moudrý et al. 2021, Korejs et al. 2023), choosing a study site from this region may increase comparability of results. Therefore, we selected an area with a rich history of underground uraninite extraction, the surroundings of the city of Příbram in the southern part of Central Bohemia. The first mines became active in 1952 (Sasková 2011). Due to mining activities, large amounts of slag and tailing have been accumulated over a 40-year period of intensive excavations, forming large and steep dump sites. By the end of the Cold War, mining operations began to slow down, and vegetation succession began to proceed on abandoned dumping sites (Peterková 2021). Then the sites were transferred under the jurisdiction of the Czech governmental organization DIAMO, responsible for management of irradiated post-industrial areas (Šimáčková 2017, DIAMO State Enterprise 2023). These dump sites are comparable to other nutrient-poor, rocky, originally barren mines and spoil heaps with no surface modifications (Prach & Hobbs 2008). However, there is an additional component of radiation. While the ambient radiation levels are negligible, small amounts of uraninite rock exist on the surface that can impact animal and plant life (Samuel-Nakamura 2013, author observations, see Methods).

This study was performed to expand known information on a set of under-investigated topics. As was reviewed above, post-mining areas after uranium extraction are not sufficiently examined by ecologists, and effects of radioactivity in general are mostly studied in relation to large events such as weapons testing or nuclear accidents. The dump sites in surroundings of Příbram are suitable study sites for examining both the general effects of dump sites on bird communities and to make comparisons other post-mining sites. The main aims were to 1) examine differences in biotic conditions such as vegetation parameters or invertebrate food supply during a preliminary survey, 2) explore how do bird community metrics (abundance, species richness, community structure) differ between dump sites and the surrounding landscape, 3) compare habitat preferences between birds on dump sites and surrounding landscape, and finally 4) discuss differences in community metrics between dump sites after uranium mining and post-mining sites in general, as well as the conservation potential of dump sites as habitats for bird species. Based on these findings, this study can function as a pilot survey for further research on birds of radiation-contaminated mining areas. In addition, results on bird community response to extreme conditions can reinforce existing knowledge on ecological management of post-mining sites.

2. Methods

The study took place on 17 survey sites located near the city of Příbram in Central Bohemia (Figure 1). We surveyed nine dumping sites after uranium mining, while eight areas in the surrounding landscape functioned as control sites. The dump sites were of varying sizes (total area: 52 ha; mean area ± s.d.: 6.5 ± 5 ha), and all contained mining tailing and slag with residual amounts of uranium dumped in different periods during the last century (Supplementary material, Table S1). Control sites were of similar sizes as dump sites (total area: 68 ha; mean area ± s.d: 8 ± 6 ha). They featured planted forests dominant in surrounding cultural landscape (Lipský 2000), interspersed with low-productivity grass patches. While the overall radioactivity levels measured at these sites are reported to not be life-threatening (Morávková 2006), these can increase near exposed pieces of uraninite rock, containing residual uranium. Using a Geiger-Müller radiometer, we found that radioactivity levels emitted by pieces of this mineral reach at least 100 μSv per hour, which is a similar radiation exposure as received during a full-body x-ray scan (Perko et al. 2015). Therefore, radioactivity may affect plant and animal life particularly on the ground near exposed uraninite. In contrast, control sites were not impacted by radioactivity and were fully integrated within the surrounding agricultural-forest mosaic. However, they can be still affected by the industrial history of the landscape, as the Příbram area has been heavily reshaped to accommodate its uranium mining infrastructure (Sasková 2011).

Because of the extreme conditions of the dump sites, vegetation cover was likely to be different from control sites. These differences were quantified by a survey, which took place in early August of 2023. During this survey, the cover of different vegetation layers was noted for each study site and a 50-meter buffer zone around each mining site. Methodology on classifying vegetation structure 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. Information collected on vegetation layer cover was integrated with ArcGIS Pro (Esri 2023). Existing bodies of vegetation were recorded as polygon features, while noting down the proportional cover of each layer within their respective attribute tables as a fraction. These fractions were multiplied by the total area of each respective polygon and divided by the total area of each dump site and surrounding buffer zone. This way, final proportions of vegetation cover for each layer were reached. We also classified the dominant woody plant species for each study site by noting down their presence (0/1).

Another survey was conducted in early August 2023 to examine the differences in invertebrate community on dumps and control sites. The purpose of this survey was to determine whether there were significant differences in food supply for invertivorous bird species between dump and control sites. The survey was conducted via beating of *Petula pendula* branches reachable by hand for 30 minutes per each study site. Gathered invertebrates were then classified into orders, and their abundances on each site were recorded.

The main survey examining bird community was performed in 2022 on dump sites, and in 2023 on control sites. Birds were sampled for each study site exactly three times (late April, late May and in late June). To include birds not directly present on the sites, but close enough so their territories could encroach on them, we also sampled a 50-meter buffer zone around each dump site. Each site was surveyed while walking slowly and covering the entirety of the site interior as well as the buffering zone. All bird individuals exhibiting territorial behaviour (such as song, alarm call or continued perching) were recorded. Maximal abundances of each species on each study site and its surrounding buffer zones over all three visits were used for further analyses. We also estimated the approximate centre of each bird´s territory by observing their movements during our visit and marked down its geographical coordinates. For birds whose assumed territory centres were located directly on study sites and not within the buffer zones, we created 50-meter buffers around each centre in ArcGIS Pro. Then by intersecting the 50-meter buffers with existing polygon features delimiting vegetation cover within dump sites, we created new polygon features with information on vegetation layer cover within each territory. The final proportional covers were reached using the same methodology as in the main vegetation survey. This was done to compare bird habitat preferences on dump and control sites by using each bird territory on each visit as an independent observation in community structure analyses.

A one-tailed Mann-Whitney U-test (McKnight & Najab 2010) in R 4.3.5 software (R Core Team 2023) was used to compare the cover of all vegetation layers on dump and control sites. In addition, the dominant woody plant species on dump and control sites were used to perform a redundancy analysis (RDA) in Canoco 5 software (Šmilauer & Lepš 2014). The purpose of this analysis was to determine whether the plant community on dump sites differed from control sites, and to show which species were more likely to be present on each type of the site. The response variable was the presence/absence (1/0) of each dominant woody plant species recorded on sites, while the explanatory variable (primary predictor) specified site type (dump/control site). The RDA is a linear method of constrained ordination, which allows us to explore the proportion of variability in our dataset (presence of dominant species) that can be explained by primary predictors (site type), and simultaneously testing the null hypothesis that the perceived variability in response data results from random processes rather than environmental effects (Zuur et al. 2007).

A second RDA analysis was performed to examine how the invertebrate food supply for invertivorous birds differed between site types. We used the total number of individuals of each invertebrate order gathered on sites as a response variable, and site type (dump/control site) as explanatory variable.

The data gathered during the bird survey were used in multiple analyses, in which birds from inside the 50-meter buffer zones entered together with birds from the respective study sites. First, a one-tailed Mann-Whitney U-test (McKight & Najab 2010) in R 4.3.5 software (R Core Team 2023) was used to compare the number of bird species and total abundances of birds on dump and control sites, with site type being the explanatory variable (dump/control site). Then a canonical correspondence analysis (CCA) in Canoco 5 software was used to compare bird community structure between dump and control sites. Abundances of different bird species were used as dependent variables, while the site type was used as explanatory variable. The CCA method follows the same rationale as the RDA but is more suitable for response data with non-linear distribution (Šmilauer & Lepš 2014).

Lastly, habitat preferences of seven common bird species were examined by a set of mixed-effect linear models using the glmmTMB package (Magnusson et al. 2017) in R 4.3.5 software. The response variables were represented by proportional covers of different vegetation layers within the 50-meter radius around assumed bird territory centres. For each response variable, a separate model was built: 1) herb layer cover, 2) understory cover, 3) canopy cover. Two models (1, 3) were fitted using a negative binomial distribution with log link function, and the remaining model (2) was fitted using a gaussian distribution and identity link function (Hardin & Hilbe 2007). Each model used a single independent variable (fixed effect): site type (dump/control site), and two random effect variables: bird species to differentiate between different birds´ territories and consequent preferences of vegetation, and study site id to account for the similarity in vegetation cover for territories from same study sites.

3. Results

Our preliminary vegetation survey showed that the median covers of vegetation layers were significantly lower on dump sites compared to control sites (Figure 2). In addition, dominant woody plant genera were mostly represented by hardy colonizer species reliant on anemochory. This was in contrast with control sites, where typical forest species dominated (Supplementary material, Table S3, Figure S1). Similarly, our analysis of invertebrate community showed significant differences in invertebrate food supply between dump sites and control areas. Orders such as Diptera or Hymenoptera were more typically found on dump sites, while control sites contained more Orthoptera or Aranea (Supplementary material, Table S3, Figure S2). However, most invertebrate orders had higher abundances on control sites rather than dump sites (8 out of 12).

Our main survey of bird community revealed important differences between dump and control sites. During the survey, a total of 1293 individuals out of 58 bird species have been recorded (Supplementary material, Table S1). The most abundant bird was the chiffchaff (*Phylloscopus collybita*, N = 168), followed by Eurasian blackcap (*Sylvia atricapilla*, N = 92) and the European robin (*Erithacus rubecula*, N = 89). However, our Mann-Whitney U-tests showed that both species richness and bird abundances were significantly higher on control sites compared to dump sites (Figure 3). This means that most bird individuals were found on control sites (N = 799) compared to dump sites (N = 494). The differences between habitat types were also reflected by our CCA analysis of community structure (Table 1, Figure 4). Some species showed clear preference for dump sites (e.g., white wagtail *Motacilla alba*, black redstart *Phoenicurus ochruros*), while others were more common on control areas (e.g., Eurasian nuthatch *Sitta europaea*, Long-toed treecreeper *Certhia familiaris*).

However, even species which occurred commonly on both dump and control sites showed very different ecological behaviour between habitat types. Our analysis of habitat preferences showed significant differences in vegetation structure within the 50-meter radii around their territory centres (Table 2). For example, herb layer cover in the territories of five species was significantly lower on dump sites compared to control sites (blue tit *Cyanistes caeruleus*, great tit *Parus major*, willow warbler *Phylloscopus trochilus*, Eurasian blackbird *Turdus merula*, European robin and yellowhammer *Emberiza citrinella*, Figure 5a). In addition, understory cover also differed significantly between habitat types for territories of four species (great tit, chiffchaff, Eurasian blackbird, chaffinch *Fringilla coelebs*), being lower on dump sites (Figure 5b). Canopy cover showed a similar trend in eight species (blue tit, great tit, willow warbler, chiffchaff, Eurasian blackcap, Eurasian blackbird, chaffinch, corn bunting, Figure 5c). These results show that individual birds had to adapt to the hostile environment on the heaps by relaxing their habitat requirements.

4. Discussion

Our findings on differences in vegetation characteristics followed the trends outlined by other ecological studies on dump sites with unmodified surface areas (Bardaghi et al. 2023). Functionally, most dominant woody species recorded on dump sites are representatives of early anemochorous colonizers capable of surviving under tough environmental conditions (Hendrychová et al. 2009). Transition to competitively strong woody genera that are typically present during late successional stages on poor substrates (e.g., *Quercus* sp., *Pinus* sp., Chytrý 2017) has not yet proceeded within the 26 to 65-year period of vegetation succession. Exposure to erosion, temperature extremes and unsuitable soil conditions along with toxic elements are likely causes of delayed or arrested succession of vegetation (Novák & Prach 2003). The specificity of our study sites can also stem from accumulation of radionuclides in individual plants, especially in woody genera (Apps et al. 1988). This accumulation may further affect bird abundances since other biota consuming plants with radioactive elements, such as rodents and invertebrates, are hunted by birds (Cleveland et al. 2021). Invertivory is a key strategy for bird species within most climatic zones (Tobias et al. 2022). Thus, the suitability of dump sites for bird inhabitants may be connected with the abundance of invertebrates that serve as food supply. Our results showed that most invertebrate orders sought out control sites rather than dump sites, which might be caused by an impoverished food supply at dump sites. However, our study is not sufficiently exhaustive in its sampling methodology to fully encompass the variation of invertebrate community. A more in-depth examination was conducted by Peterková (2021) who found that invertebrate abundance was contingent on development of woody vegetation. Dump sites with increased afforestation rate were similar in their invertebrate community to the surrounding landscape. However, because vegetation cover is overall less developed on dump sites compared to control sites, it is likely that there is also a decreased availability of invertebrates for birds to exploit.

The decreased vegetation cover and insufficient food supply are then likely some of the proximate causes for the relatively low bird species richness and abundances on dump sites. Some comparisons can be made with other studies on birds on early-successional stages of post-mining sites. Šálek (2012) has examined birds of opencast coal mining pits. He found that early successional stages of unreclaimed areas characterized by high proportion of bare ground included the same bird species as dump sites within our study (for example little plover *Charadrius dubius* or white wagtail). In contrast, the bird species he found on later afforested stages were more abundant on control sites within our study (blackcap, chiffchaff). During the survey on another large, reclaimed surface mining site (Korejs et al. 2023) found some species that preferred grassland-based habitats. These species showed preference for dump sites within our study (e.g. yellowhammer or skylark *Alauda arvensis*). It appears that the lack of vegetation cover on the dump sites facilitated suitable habitat for species that either rely on bare ground or require only a semi-intact herb layer. This may enhance the conservation value of dump sites for birds, as groups of species are endangered by habitat loss due to anthropogenic interference due to removal of early-successional habitats (Korejs et al. 2023) or agricultural intensification (Reif & Vermouzek 2019). However, our results also showed that even species that preferred dump sites over the surrounding landscape were forced to modify their habitat requirements (e.g., yellowhammer used over 30% less herb cover within its dump site territories). The relative avoidance of dump sites by forest and shrub species, such as the blackcap or chiffchaff, is also not common for areas that have undergone several decades of succession. For example, Hendrychová et al. (2009) and Šálek (2012) found that even without assisted revegetation, these species sought out later successional stages on mining sites and spoil heaps. This difference calls back to the observed staggered succession of vegetation (Thrippleton et al. 2018) as well as decreased availability of invertebrates, as many shrub and forest bird species in Central Europe are opportunistic or obligatory invertivores (Tobias et al. 2022). The changes in habitat preferences also suggest increased stress stemming from insufficient proportions of understory and canopy cover that may drive avoidance of dump sites by these otherwise common species (Rosenzweig 1991).

We have found that despite being species-poor and low-abundance, bird communities on the dump sites are not without conservation value. The dump sites offer surrogate habitat for primary succession specialists or declining farmland species, but they also function as perching sites for some raptors (Eurasian hobby *Falco subbuteo*), and foraging areas for nomadic granivores (common linnet *Carduelis cannabina*). Aside from birds, they were also found to contain several endangered species of spiders and carabid beetles (Peterková 2021) as well as rare species of poor substrate herbs (dropwort *Filipendula vulgaris*, alpine willowherb *Epilobium dodonaei*, observed by authors). The current plant cover on the dump sites has also been found capable of effectively assisting in phytoremediation (Unterbrunner et al. 2007). It is likely that a full-scale restoration effort involving dump site deconstruction, surface levelling and subsequent addition of fertile soils planted with regular rows of trees, would increase overall diversity of birds (Korejs et al. 2023). However, this process would also involve disappearance of endangered habitat specialists that are responsible for the bulk of conservation value on these dump sites, as a similar development was observed on surface mining sites that underwent technical reclamation (Tropek et al. 2012). It should also be noted that the financial costs of disassembling and relocating hundreds of thousands of cubic meters of accumulated mine tailing would be exorbitant (Prach & Hobbs 2008). Therefore, we suggest that the present containment of uranium mine tailing and slag within dump sites is probably most appropriate for biodiversity conservation as well as from an economic point of view.

While our results show significant changes in bird community structure and even habitat preferences, the underlying effects responsible for these changes are highly interconnected. Each dump site contains residual uranium together with previously described extreme conditions (Peterková 2021). As such, we cannot single out the effect of radioactivity without taking into consideration other drivers of extreme conditions. Moreover, dump sites around Příbram represent unique habitats, and there is no similar site within the Czech Republic replicating such environmental conditions without comparable history of uranium mining (Mihalík et al. 2011). To test specifically the effects of radioactivity, individual birds would need to be captured and examined for phenotypic effects correlated with genetic damage (Moller et al. 2013). It would be also necessary to examine the radionuclide content within bird tissues (Krivolutski et al. 1999), as other toxic elements associated with underground mining, such as lead or cadmium, may cause physiological damage (Galhardi et al. 2020).

5. Conclusions

Rather than attempting to isolate drivers of bird community changes, this study aims to give a general overview of a unique habitat created by uranium mining for birds as a study group. The characteristics of these dump sites prevent full remediation and associated surface modification, which is typical on post-mining sites within Central Europe. However, the examinations of present biotic communities reveal that this may be for the best, as they are unique and worthy of ecological conservation. Our study can serve as a pilot survey giving a first look at bird communities on dump sites after uranium mining, as well as a template for explorations of similar habitats. This study also supplies background information necessary for researching effects of radioactivity by showing how conditions on dump sites alter bird communities. The most suitable expansion of investigated topics could be based on in-depth analysis of phenotypical signs of radiation-associated damage of bird individuals. This could possibly provide a more in-depth look at the drivers of comparatively low abundance and species richness on the dump sites compared to control sites.

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7. Tables

Table 1

The effect of location (dump site or control area) on bird community structure (represented by individual species´ abundances), calculated using CCA analysis (see methods).

Dependent variable	Predictor	Adjusted explained variation (fraction)	Pseudo-F	p
Community structure	Location (Dump/Control)	0.049	38.18	0.032

Table 2

The effect of location (dump site or control area) on habitat preferences of bird species on examined sites. Dependent variables representing habitat preferences are proportional covers of different vegetation layers within the 50 m buffer around the estimated centre of individual birds´ territories (see methods). Random effects were represented by 1) site identity, grouping observations from same dump sites or control areas and by 2) bird species, grouping observations from the territory of birds from the same species.

Dependent variable	Predictor	Estimate	SE	z	p
Herb cover	Location (Dump/Control)	0.706	0.171	38.18	<0.001
Understory cover	Location (Dump/Control)	102.420	47.470	2.158	0.030
Canopy cover	Location (Dump Control)	267.530	84.620	3.162	<0.001

8. Figure captions

Figure 1

A map of our study sites and the surrounding landscape with field survey design. Highlighted are dotted lines delimiting the 50 m distance from either the border of the dump sites (black fill) or the border of the control areas (grey fill). The dump sies are also marked with numbers referring to their official ID in the Supplementary material, Table S1, where more information on their parameters is available, taken from DIAMO, state enterprise (2023). Acquired from ArcGIS Pro basemap service (Esri 2023). Mapped data were acquired from https://geoportal.cuzk.cz/.

Figure 2

a) Photography of typical vegetation cover on the dump sites (left) or the control areas (right). **b)** Comparison of the proportional covers of different vegetation layers on the dump sites or control areas. Mann-Whitney test results are displayed. Thick lines – median, boxes – 25-75% of data, whiskers – non-outlier range.

Figure 3

Boxplots comparing **a)** bird species richness and **b)** bird abundances on dump sites and control areas. Mann-Whitney test results are displayed. Thick lines – median, boxes – 25-75% of data, whiskers – non-outlier range.

Figure 4

a) Ordination diagram comparing bird community composition between dump sites and control areas. Displayed are 19 best fitting bird species. For a list explaining species name abbreviations, see Supplementary material, Table S1. The first and second ordination axes explained together 34% of variation.

Figure 5

Proportional covers **a)** the herb layer **b)** the understory layer and **c)** the canopy layer within the 50 m buffer around the estimated centre of the territories of the nine common bird species, displayed for both dump sites and control areas. Added are results of pairwise comparisons using the emmeans function (Lenth et al. 2018). Thick lines – median, boxes – 25-75% of data, whiskers – non-outlier range.

9. Figures

Figure 1

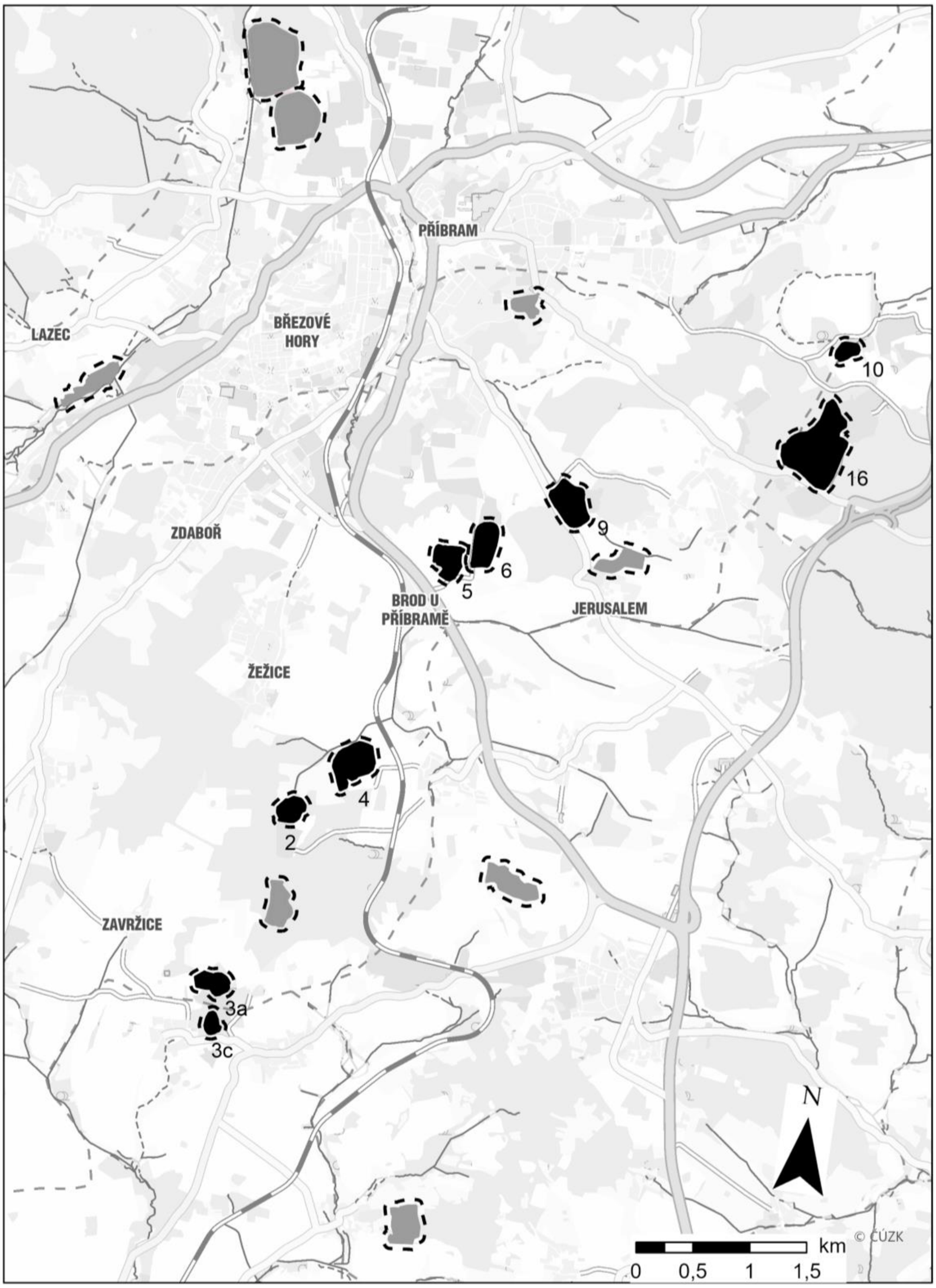


Figure 2

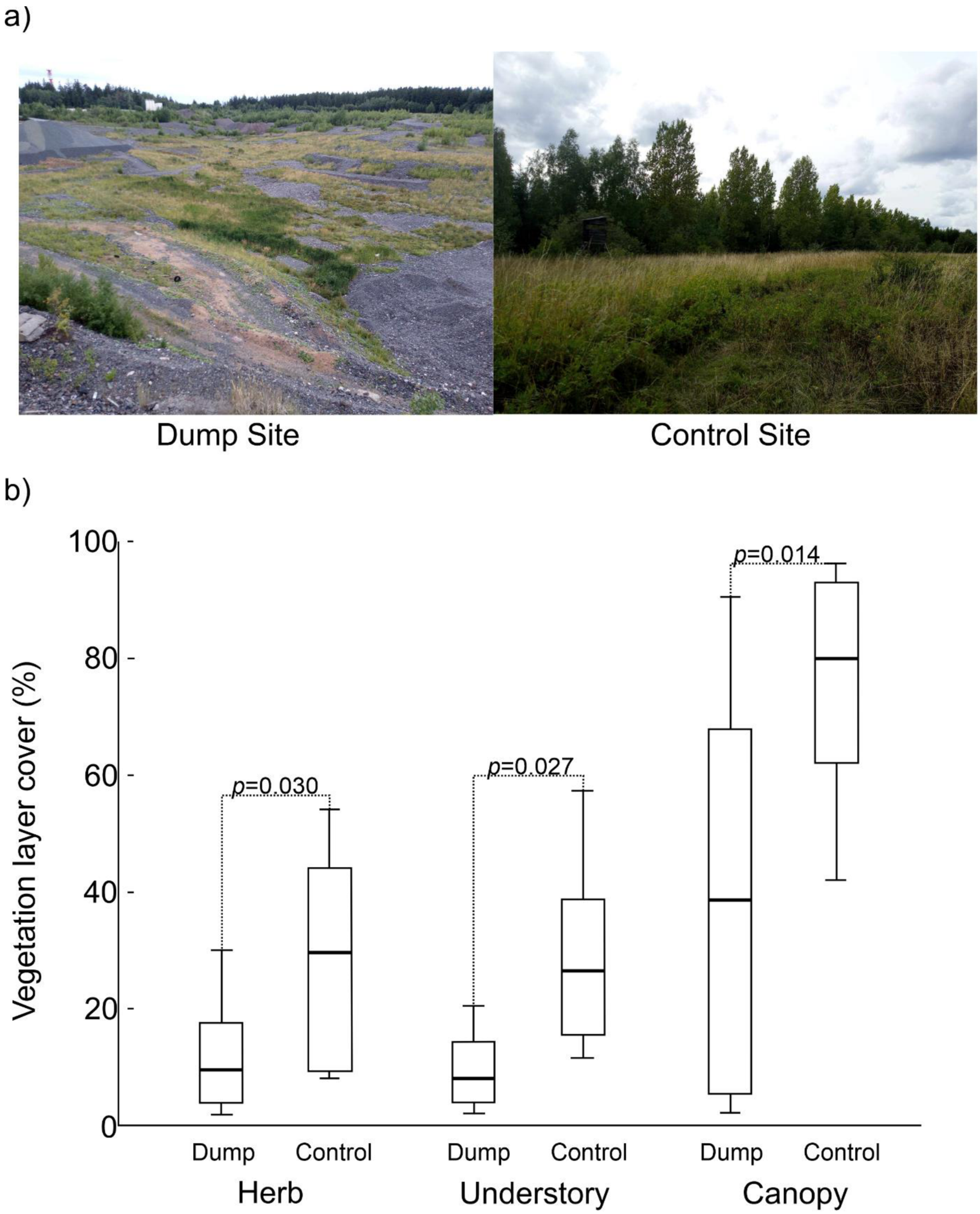
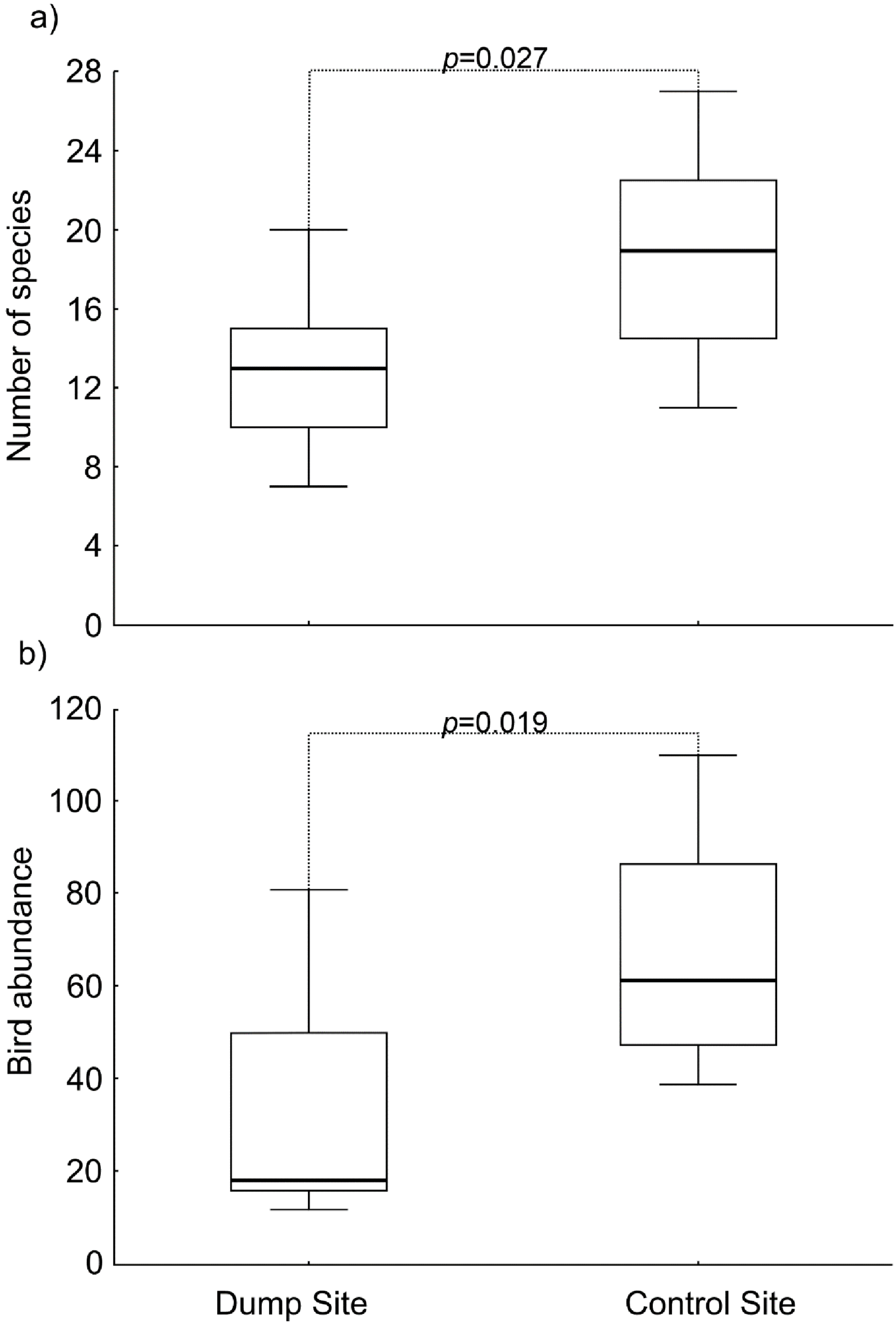
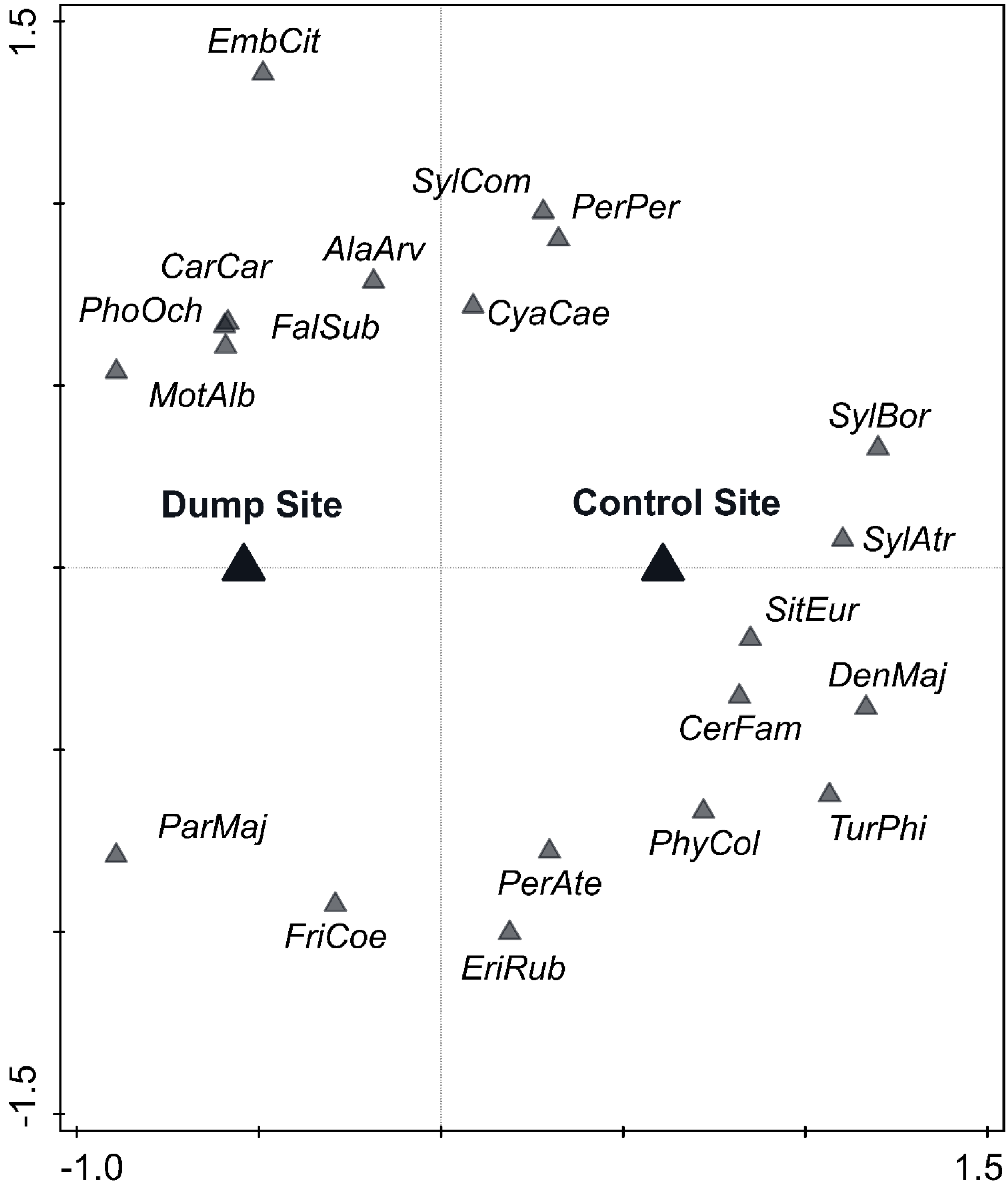

a)
Dump Site
Control Site
b)
Vegetation layer cover (%)
100
80
60
40
20
0
p=0.030
p=0.027
p=0.014
Dump
Control
Dump
Control
Dump
Control
Herb
Understory
Canopy

Figure 3

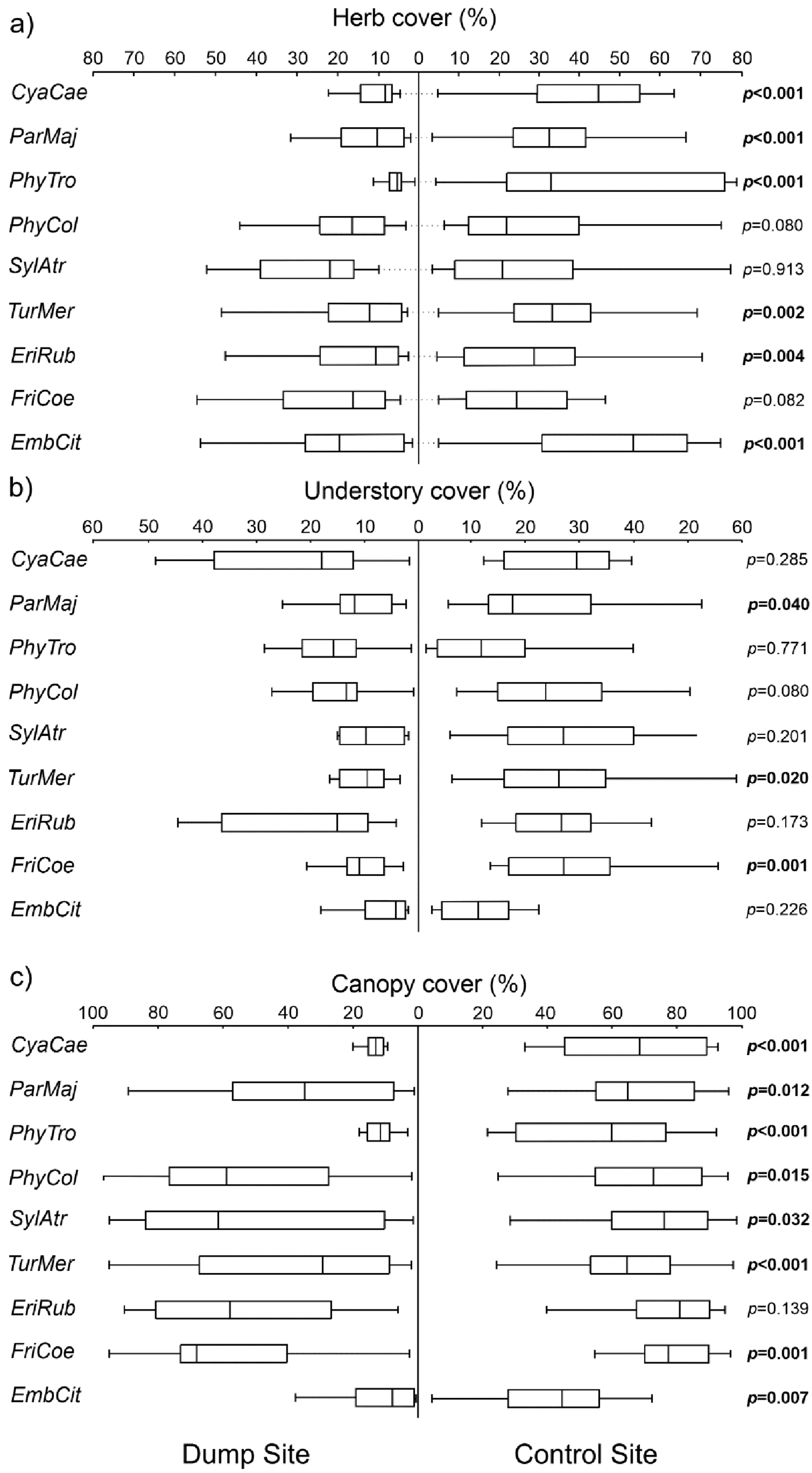

a)
p=0.027
Number of species
28
24
20
16
12
8
4
0
b)
p=0.019
Bird abundance
120
100
80
60
40
20
0
Dump Site
Control Site

557 **Figure 4**



558

Figure 5


a)
Herb cover (%)
80 70 60 50 40 30 20 10 0 10 20 30 40 50 60 70 80
CyaCae
ParMaj
PhyTro
PhyCol
SylAtr
TurMer
EriRub
FriCoe
EmbCit
p<0.001
p<0.001
p<0.001
p=0.080
p=0.913
p=0.002
p=0.004
p=0.082
p<0.001
b)
Understory cover (%)
60 50 40 30 20 10 0 10 20 30 40 20 60
CyaCae
ParMaj
PhyTro
PhyCol
SylAtr
TurMer
EriRub
FriCoe
EmbCit
p=0.285
p=0.040
p=0.771
p=0.080
p=0.201
p=0.020
p=0.173
p=0.001
p=0.226
c)
Canopy cover (%)
100 80 60 40 20 0 20 40 60 80 100
CyaCae
ParMaj
PhyTro
PhyCol
SylAtr
TurMer
EriRub
FriCoe
EmbCit
p<0.001
p=0.012
p<0.001
p=0.015
p=0.032
p<0.001
p=0.139
p=0.001
p=0.007
Dump Site
Control Site