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Is the Northern Goshawk an Efficient Bioindicator of Avian Abundance and Species Richness in Urban Environments?

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Abstract: Monitoring of biodiversity in expanding urban areas is an essential part of wildlife conservation. There is evidence that raptors, such as Northern Goshawks (*Accipiter gentilis*), are effective bioindicator species in urban areas, however, their relationship with other bird populations is not clearly established. We asked whether activity patterns of Goshawks are a reliable indicator of wintering bird abundance and diversity in urban ecosystems. We tracked the movement of eight GPS-tagged Goshawks in the city of Tartu (Estonia) and analysed the numbers and diversity of birds in the same area using direct mapping and occasional data obtained from birdwatchers. The direct mapping approach revealed that the number of birds and avian species richness were higher in Goshawk activity hotspots than at random sites in 2022, however, no such differences were detected in 2023. Analysis of occasional citizen-collected data showed no effect of avian abundance nor species richness on the distribution of Goshawk activity. These results suggested that the movements of Goshawks may indicate the abundance and diversity of its prey, however, this relationship depends on the detection methodology. Hence, raptors are a promising bioindicator in urban environments, but results should be interpreted with caution, particularly when using citizen-collected data.

Keywords: bioindicator species; bird abundance; bird diversity; birds of prey; citizen science; GPS telemetry; raptors; sentinel species; urban biodiversity

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1. Introduction

Urbanised areas have become the most rapidly expanding habitat type worldwide [1] and urbanisation is one of the main threats to biodiversity [2–4]. However, a number of wildlife species have adapted to urban environments. Hence, preserving and monitoring biodiversity in human-dominated areas are becoming essential parts of maintaining biodiversity on the global scale [5].

Assessing total biodiversity is laborious and costly. Therefore, it is often evaluated using bioindicators, which are species or assemblages of species reactive to environmental changes [6]. Birds, for example, are highly visible and sensitive to changes in habitat structure and composition, therefore, they are excellent indicators of habitat quality, including that in urban environments [3,5,7]. However, comprehensive avifaunal inventories are often not feasible. Thus, well-chosen bioindicator species or species groups may be an efficient shortcut to evaluate ecosystem quality [8]. For example, large predators, raptors in particular, are considered good indicators of viable ecosystems [9,10]. Indeed, there is accumulating evidence that various raptor species are efficient surrogates for biodiversity in various ecosystems [11–14].

The Northern Goshawk *Accipiter gentilis* (hereafter Goshawk) is a flexible avian apex predator inhabiting various landscapes. Primarily, Goshawk is a forest-dwelling species, however, it also thrives in mosaic agricultural landscapes and has recently colonised cities [15]. Therefore, this species has been used as an indicator of biodiversity in forests [12,13], farmland [16] and urban areas [17,18]. Goshawks forage primarily on birds [15]. As the efficacy of a bioindicator is higher for taxa with a stronger ecological connection to the predator [10], Goshawk distributions are expected to effectively indicate avian abundance and diversity.

Northern bird populations, including Goshawk populations, are strongly limited by the occurrence of prey during winter [19–21]. Under harsh conditions, many birds inhabit areas in proximity to humans [19,22,23] and may even move to cities from less populated areas [24]. Goshawks, in turn, may follow the movements of their prey between habitats [15]. Hence, cities attract wintering hawks and, in addition to local residents, nonbreeding individuals may be concentrated in these areas. This situation provides an excellent chance to directly study relationships between predators and prey because associations with nests, which bias spatial behaviour, are limited or lacking. Earlier, Natsukawa [18] found that Goshawk nest site selection in a city corresponded to the habitat selection of wintering birds, indicating that Goshawk nest sites may serve as a surrogate for hotspots of avian diversity in urban environments. However, as these previous data sets were temporally separated, the direct link between Goshawks and other birds remains untested.

The past few decades have witnessed the emergence and growth of several new scientific methods. First, several novel technologies, such as GPS-based telemetry, have seen rapid advances. Movement ecology, owing to rapid advances in telemetry technologies, is an active field of research with great potential for investigations of broad, biodiversity-scale issues [25]. This enables the replacement of landscape-level correlations with the actual pinpointing of activity centres of animals. Second, citizen science (i.e., the involvement of non-scientists in data collection for scientific research) has been expanding, in part owing to technological developments [26–28]. Citizen science provides an opportunity to conduct research at broad spatial scales, which are impossible to sample extensively using traditional field research models [29,30]. Citizen scientists, for example, collect field data related to species distributions and abundance [27,29,31]. Extensive datasets based on opportunistic observations by amateurs have contributed to faunistic surveys and correlative ecological analyses [29,31,32].

The aim of this study was to test whether Goshawk habitat use is related to the distribution of wintering birds in an urban environment. In particular, we tracked movements of eight GPS-tagged Goshawks in the city of Tartu and analysed the number and diversity of birds in the same area. We hypothesised that the activity centres of Goshawks are positively associated with avian abundance and species richness. We explored the abundance and diversity of birds in two ways. First, we mapped birds in sites preferred by GPS-tracked Goshawks and in control sites; second, we analysed occasional observations of birdwatchers. Hence, by comparison of the results obtained using the two approaches, our findings provide insight into the utility of citizen science for estimating avian abundance and diversity in urban environments.

2. Materials and Methods

This study was conducted in Tartu, Estonia, in north-eastern Europe (58°23′ N 26°43′ E). Tartu is the second largest city in Estonia with a population of c. 100,000 people. The average annual air temperature is 6.1 °C and the coldest month is February (on average −5.3 °C [33]). Tartu has rather diverse land use [34], with the dominant features being residential areas (covering 30.7% of the area), open green areas (28.7%) and roads (20.4%). Afforested areas (9.0%), open lands without vegetation (4.3%) and cultivated lands (3.5%) cover smaller portions of the landscape. Wetlands and water bodies, such as the river Emajõgi passing through the city, hold significant ecological value despite occupying a minor proportion of the area, accounting for 2.7% and 0.7% of the landscape, respectively (Figure 1).

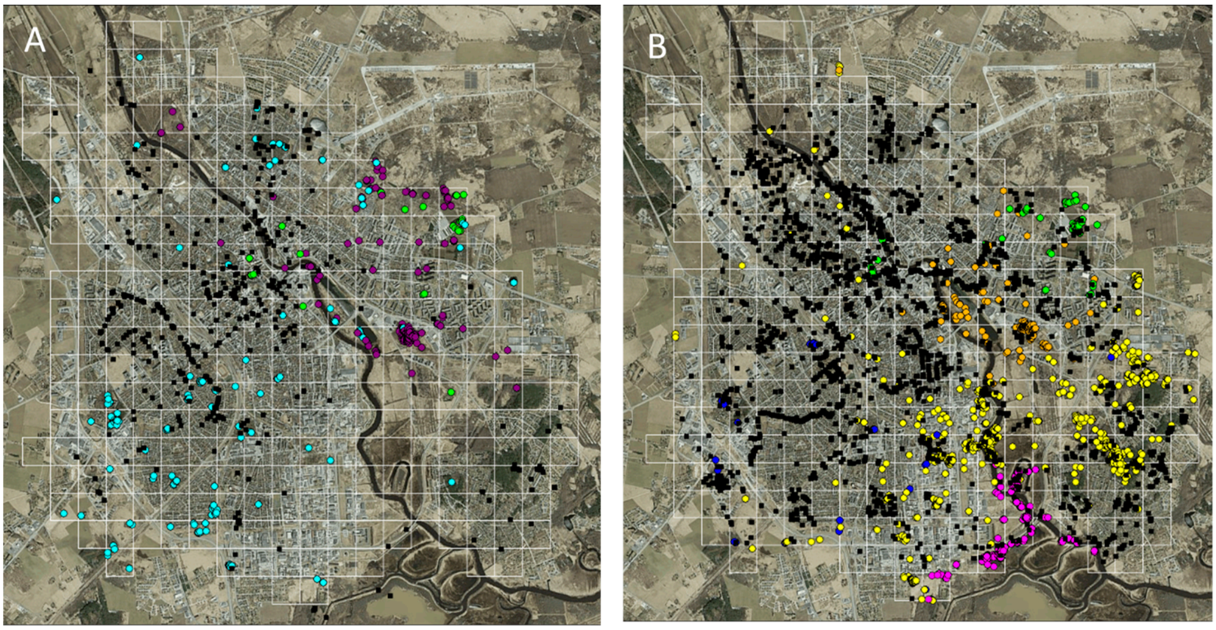

Figure 1. Citizen-collected occasional bird observations (black squares) and registered locations of Goshawks (circles, where individuals are shown in different colours) in (**A**) February 2022 and (**B**) November–February 2022/2023.

The study was conducted in two winters, in 2021/2022 (February 2022) and 2022/2023 (November 2022–February 2023). In total, seven GPS-tagged Goshawks (six males and one female) were included in the study (Table 1). Each bird was equipped with a 15–30 g (<3% of the body mass) solar-powered GSM/GPRS logger (UAB Ornitela, Vilnius, Lithuania) as a backpack using Teflon harnesses. Seven birds were followed during one winter but an adult male provided data in both study winters. All birds were followed for the entire study periods, i.e., for 28 days in 2021/2022 (84 tracking days in total) and for 120 days in 2022/2023 (600 tracking days in total). However, the datasets varied owing mainly to limited light in the winter, preventing loggers from recharging. Eventually, we used 491 Goshawk locations from 2021/2022 and 1304 locations from 2022/2023 (Table 1).

Table 1. Age, sex, tracking period and number of GPS-fixes of tracked Goshawks.

Logger No.	Age	Sex	Tracking Winter	No. of GPS-Fixes
171095	Adult	Male	2021/2022	47
190723	Immature	Male	2021/2022	205
190725	Immature	Male	2021/2022	239
171095	Adult	Male	2022/2023	60
190703	Adult	Male	2022/2023	146
190728	Adult	Male	2022/2023	30
212340	Adult	Male	2022/2023	853
212347	Adult	Female	2022/2023	215

The abundance and distribution of wintering birds in the city of Tartu was determined using two approaches. First, the authors (J.G., P.Me., T.T., and Ü.V.) mapped the birds on 14 to 20 February 2022 and on 14 to 20 February 2023 (Table 2). The city of Tartu was divided into 400 × 400 m squares (Figure 1). Out of 299 squares, 50 squares at town edges that contained >60% of land outside the borders of Tartu and nine squares that were highly (>60%) afforested and were not classified as urban were excluded. The remaining 240 grid squares were overlaid with GPS-telemetry data for Goshawks to select two independent sets (one for each season) of Goshawk activity hotspots and random squares. The hotspots were defined as the 25 grid squares with the highest number of Goshawk GPS-fixes in the given season. To avoid clustering, we selected only the squares with highest number of Goshawk locations and omitted all bordering squares (sharing a corner was allowed). To compare sites used by Goshawks with available urban sites, another 25 squares were randomly drawn from those that were not used by Goshawks. Eventually, only five hotspot squares and three random points were repeatedly selected in the two seasons; additionally, one random point from 2022 was a hotspot in 2023. In 2022/2023, most hotspots were consistent throughout the winter (Figure 2).

Table 2. Total numbers of bird individuals and species counted via direct mapping and recorded occasionally by birdwatchers.

Year	Square Type	All Birds		Medium-Sized Birds		"Local" Birds	
		Abundance	Species Richness	Abundance	Species Richness	Abundance	Species Richness
Mapping data							
2022	Hotspot	1636	30	746	12	1505	29
2022	Random	1508	27	935	11	1399	27
2023	Hotspot	1513	35	631	14	1413	33
2023	Random	1815	28	580	11	1704	26
Occasional data							
2022		7946	56	5365	23		
2023		17299	69	10382	28		

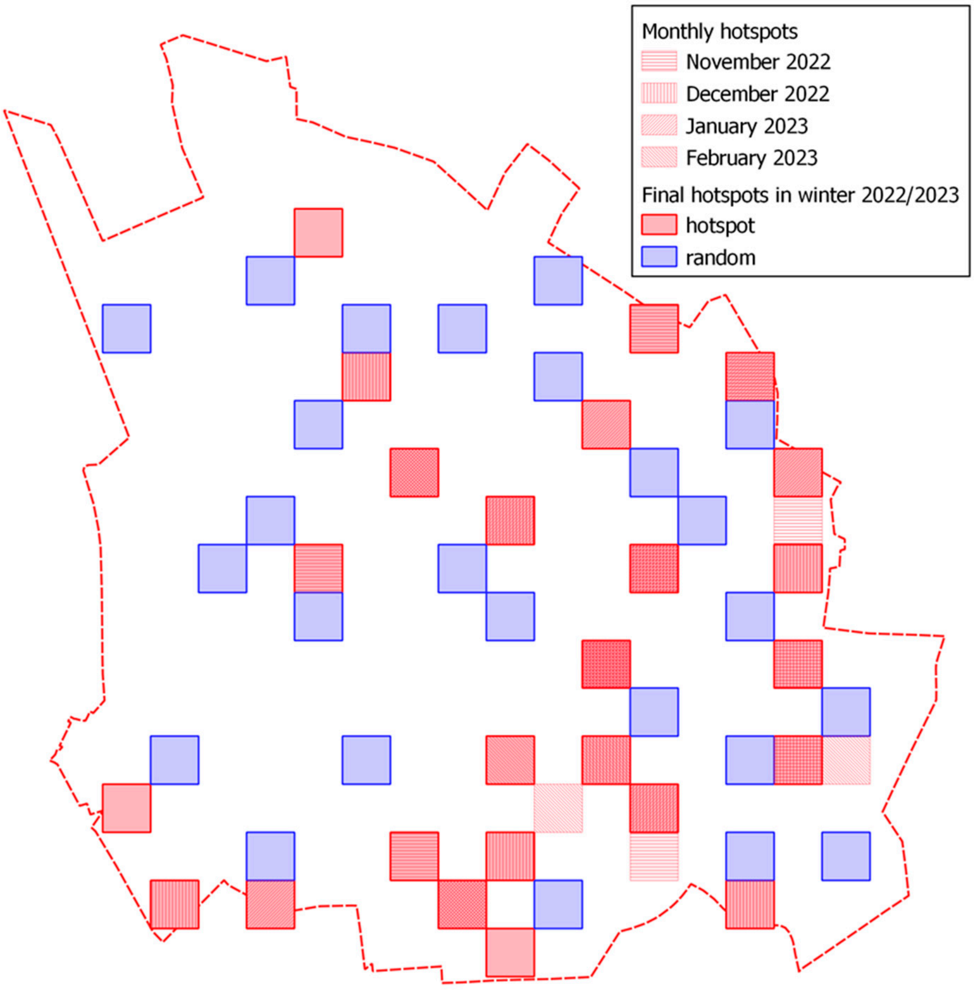

Figure 2. Distribution and consistency of Goshawk activity hotspots and the distribution of control plots in the winter 2022/2023.

Second, we used the data from citizen scientists deposited in PlutoF [35], a portal incorporating observations of Estonian birdwatchers. In early February 2022 and early November 2023, calls were published on social media platforms to encourage bird enthusiasts to collect observations in Tartu and deposit these in the PlutoF database. Collected occasional bird data (in February 2022 and November 2022–February 2023) were analysed using the same grid used in the first approach. We attempted to avoid two potential methodological caveats. First, the study area was not uniformly covered by the bird observations, nor by the home ranges of Goshawks. To avoid the effect of spatial non-overlap of the two data sets, we included only squares with at least one bird sighting and at least one Goshawk record in the analyses. Secondly, the same observers may have visited the same squares repeatedly. To avoid the cumulative effect of repeated visits, only the maximum number of each bird species in each square was included.

In each square, species richness and the abundance of each bird species were calculated. All bird species were included in initial analyses. Thereafter, only medium-sized birds (ducks, pigeons, most corvids, thrushes, etc.) were included as potential prey items for Goshawks. In the analysis of mapping data, the effect of "local" birds identified as potential prey in a given location was analysed separately (i.e., birds flying over were excluded). Owing to the limits of data deposition in the PlutoF database, the latter specification was not possible in the analysis of occasional data.

The bird mapping data were analysed using logistic regression models, where grid square type was a binary response variable, and avian abundance or species richness were covariates. Owing to the strong collinearity, abundance and species richness were analysed via separate models. In the analysis of occasional observations, we used linear models where the number of Goshawk GPS-fixes was a continuous response variable; again, avian abundance or species richness were covariates. Initial models included factor year and its interaction with covariates but final models were developed for each year separately. All continuous variables were log-transformed prior to analyses.

3. Results

The total number of species, but not the abundance, was always higher in squares with high Goshawk activity (hotspots) than in random squares (Table 2). According to the logistic regression analysis of bird mapping data, bird abundance was nearly significantly higher in Goshawk activity hotspots than in random squares, and the effect of year was also nearly significant (Table 3). In 2022, there were more birds in Goshawk hotspots (i.e., grid squares with high Goshawk activity) than in random squares, however, no such difference was detected in 2023 (Figure 3). Avian species richness had a nearly significant effect on the distribution of Goshawk activity and its interaction with year had a similar effect (Table 3); species richness was significantly higher at Goshawk hotspots in 2022 but not in 2023 (Figure 3). Similar tendencies were detected for the abundances (2022: t = 1.79, $p = 0.081$; 2023: t = 0.54; $p = 0.59$) and species richness (2022: t = 1.58, $p = 0.121$; 2023: t = 0.43; $p = 0.672$) of 'local' birds (Table 3). However, the abundances (2022: t = 0.84, $p = 0.631$; 2023: t = 0.78; $p = 0.438$) or species richness of medium-sized birds had no effect on Goshawk activity (2022: t = 1.07, $p = 0.292$; 2023: t = 0.14; $p = 0.886$; Table 3).

Table 3. Logistic regression models describing the effect of avian abundance and species richness (both variables log-transformed) on grid square type (Goshawk activity hotpots vs. random squares).

Variable	Estimate	SE	t	*p*
	All birds			
Intercept	−1801.1	1051.1	−1.71	0.090
Abundance	440.1	262.5	1.68	0.097
Year	0.9	0.5	1.71	0.090
Abundance × Year	−0.2	0.1	−1.68	0.097
Intercept	−1680.5	945.0	−1.78	0.079

Table 3. *Cont*.

Variable	Estimate	SE	t	*p*
Species richness	593.4	335.7	1.77	0.080
Year	0.8	0.5	1.78	0.079
Species richness × Year	−0.3	0.2	−1.77	0.081
		'Local' birds		
Intercept	−1553.7	978.9	−1.59	0.116
Abundance	388.3	250.0	1.55	0.124
Year	0.8	0.5	1.59	0.116
Abundance × Year	−0.2	0.1	−1.55	0.124
Intercept	−1051.2	834.4	−1.26	0.211
Species richness	381.3	306.2	1.25	0.216
Year	0.5	0.4	1.26	0.211
Species richness × Year	−0.2	0.2	−1.25	0.216
		Medium-sized birds		
Intercept	−4.2	532.6	−0.01	0.994
Abundance	−37.9	180.0	−0.21	0.834
Year	0.0	0.3	0.01	0.993
Abundance × Year	0.0	0.1	0.21	0.834
(Intercept)	−495.1	515.8	−0.96	0.340
Species richness	245.6	284.7	0.86	0.391
Year	0.2	0.3	0.96	0.339
Species richness × Year	−0.1	0.1	−0.86	0.391

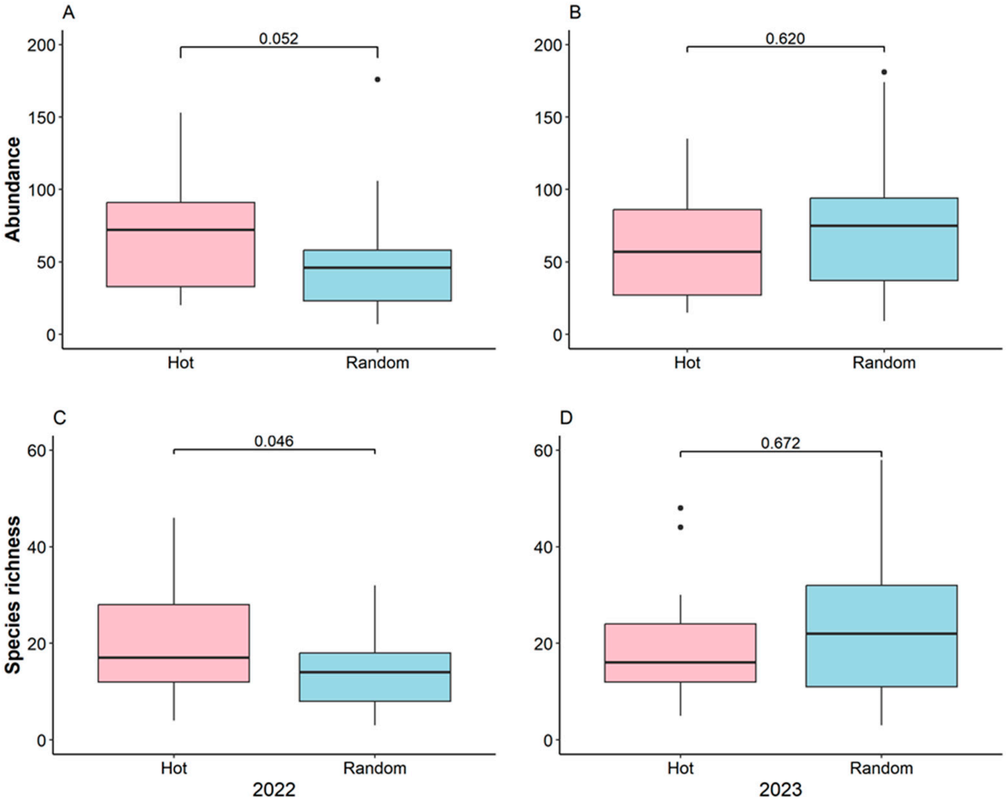

Figure 3. (**A**,**B**) Mapping-based abundance and (**C**,**D**) species richness of wintering birds in 2022 (**A**,**C**) and in 2023 (**B**,**D**) in the grid squares with high Goshawk activity (hotspots) and in random squares in Tartu. The bold line indicates the median, the box shows quartiles, the whiskers indicate the extreme data points within 1.5× the interquartile range from the quartile boundaries and dots are data points beyond that range. *p*-values for univariate logistic regression models are indicated in brackets.

In the analysis of occasional data, we did not detect an effect of total avian abundance ($F_{3,130} = 2.1$, $p = 0.101$) or species richness ($F_{3,130} = 2.0$, $p = 0.121$) on the number of Goshawk fixes in grid squares (Table 4). Additionally, there was no significant interaction with year (Table 4). Similarly, we did not detect any effects when years were analysed separately (Figure 4). We did not detect an effect of bird abundance ($F_{3,114} = 2.1$, $p = 0.102$; 2022: $F_{1,28} = 0.04$, $p = 0.836$; 2023: $F_{1,86} = 1.02$, $p = 0.315$) or richness ($F_{3,114} = 2.2$, $p = 0.097$; 2022: $F_{1,28} = 0.09$, $p = 0.771$; 2023: $F_{1,116} = 0.59$, $p = 0.445$) when only medium-sized birds were included in the analysis.

Table 4. Linear regression models describing the effect of avian abundance and species richness (both variables log-transformed) on Goshawk activity (number of GPS-fixes in grid squares).

Variable	Estimate	SE	t	*p*
All birds				
Intercept	0.3	0.3	1.26	0.209
Abundance	0.0	0.1	0.00	0.997
Year	0.4	0.3	1.31	0.194
Abundance × Year	−0.1	0.2	−0.46	0.643
Intercept	−516.2	412.8	−1.25	0.213
Species richness	−39.8	558.3	−0.07	0.943
Year	0.3	0.2	1.25	0.213
Species richness × Year	0.0	0.3	0.07	0.943
Medium-sized birds				
Intercept	0.3	0.2	1.33	0.185
Abundance	0.0	0.1	0.15	0.879
Year	0.4	0.3	1.61	0.109
Abundance × Year	−0.1	0.2	−0.71	0.480
Intercept	−799.3	452.2	−1.77	0.080
Species richness	624.1	978.5	0.64	0.525
Year	0.4	0.2	1.77	0.080
Species richness × Year	−0.3	0.5	−0.64	0.525

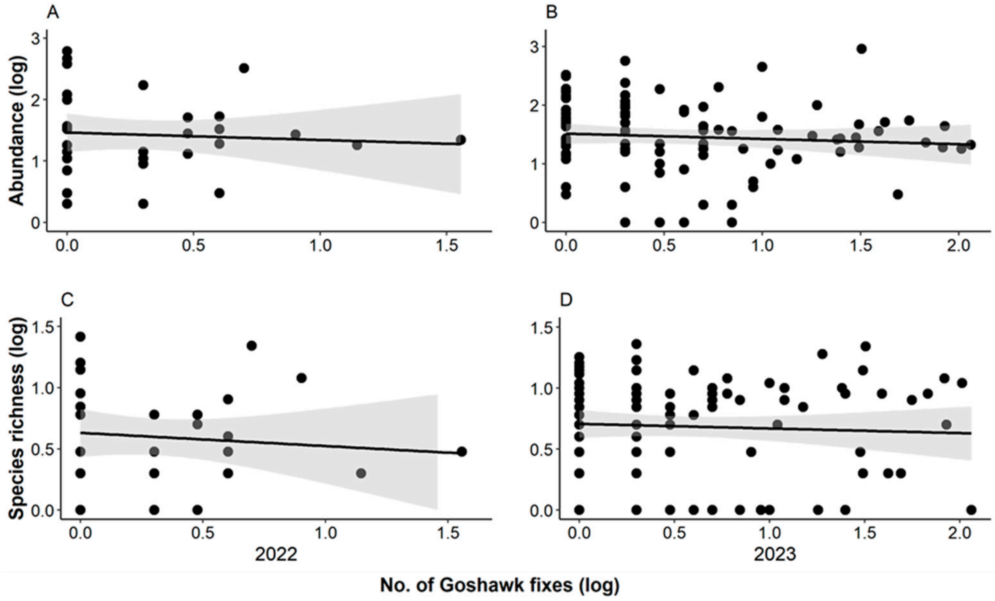

Figure 4. (**A**,**B**) Citizen-collected abundance and (**C**,**D**) species richness of wintering birds in 2022 (**A**,**C**) and in 2023 (**B**,**D**) in grid squares of Tartu in relation to the number of registered Goshawk locations.

4. Discussion

We used two different approaches to study associations between Goshawk and its prey in urban environments. In the first approach, via direct mapping, we detected a positive association in one winter but not in another. In the second approach, using occasional observations of birdwatchers, we did not detect associations between these parameters.

To address the limitations of short-term studies, we conducted this study over two winters. Variations across years may reflect the effects of weather or other features of particular winters. Furthermore, the results might have been affected by the different period of tracking and the different number (and age) of the tracked birds. However, such effects would have been detected consistently using both approaches whereas we detected differences between years only in our own mapping-based inventories but not in the analysis of citizen-collected data. This suggests that methodological differences influenced our results. Notably, total species richness (but not abundance) in both study winters was higher in Goshawk activity hotspots than in control plots.

Data for avian abundance and distribution collected by citizen scientists did not show any association with Goshawk activity centres in the first study year, which is different from the results of our mapping analysis. The citizen-collected data were rather limited in the first study winter and a substantial amount of information had to be discarded owing to the restricted spatial distribution and lack of spatial overlap with tracking data. Citizen science has other limitations, including the limited skills of participants and biases related to data collection [28,29], which could explain the conflicting results obtained via the two approaches. Evaluations of these limitations are beyond the scope of our paper, however, we stress that citizen-collected data should be analysed with caution and, if possible, results should be validated using another methodology.

Our mapping approach indicated that bird abundance and richness were significantly higher in Goshawk activity centres than in random plots in the first study season but not in the second season. The dataset for 2021/2022 was limited to late winter (i.e., February). The study period in 2021/2022 was temporally restricted and the detected association indicated a direct spatial link between Goshawk individuals and prey. In the next winter, Goshawk data were collected for 3 months, from the beginning of November to early February, and the spatial distribution of activity centres was therefore broader. Although most of the detected hotpots were the same throughout the winter, bird mapping in February may have not fully represented associations in earlier months. It is unclear why medium-sized birds, which are preferable prey for Goshawks, had no effect on its activity. The most plausible explanation is the substantially smaller sample size of this group.

Raptors are well-known indicators of biodiversity and viable ecosystems; prioritisation of conservation efforts based on their occurrence is likely to provide broad ecosystem benefits [10]. However, the efficiency of raptors as biodiversity indicators has been criticised owing to inconsistent results [36–38]. Our study, using two different approaches, suggests that conflicting results can be explained, at least in part, by methodological differences.

Raptors have been used as bioindicators at different spatial scales. On one hand, nest sites of raptors often indicate biodiversity at the microhabitat level by indirect non-causative links. For example, Goshawk nests built in diverse old-growth forest stands rich in diverse taxa, such as trees, wood-decaying fungi and butterflies [11–13]. Breeding sites of Goshawks could also serve as a useful conservation surrogate for the species richness and functional diversity of wintering birds [18]. However, this association is only correlational and it may be weaker when habitat selection by raptors differs from that of other birds [18]. On the other hand, foraging activity connects raptors directly with taxa at lower trophic levels. As many raptors cover long distances or use spatially distant sites while foraging, their movement and presence/absence data indicate ecosystem quality at the landscape (macrohabitat) scale [16,39]. However, in addition to the distribution of prey, which is determined by habitat suitability, other environmental factors, such as weather or wind conditions and the distribution of perching sites, shape the distribution of raptors [40–42]. Furthermore, intra-specific interactions, such as competition and territorialism, should be considered in data analyses. In our study, untracked Goshawks may have held territories in the western part of the town, preventing foraging by tracked Goshawks in this area.

5. Conclusions

Our data suggested that Goshawk movement patterns are potential indicators of the abundance and diversity of prey, however, the results depended on the methodological approach and should be validated in a longer survey. We emphasise that relatively costly GPS tracking can hardly be suggested as a method for bioindication; instead, information on Goshawk (or other predators') activity centres may be collected via observations by citizen scientists. Although citizen science is a promising source of data for scientific research and conservation purposes, inconsistency in data acquisition may limit its use. Our results support the view that the employment of predators as bioindicators is justified but the interpretation of results requires appropriate caution [10].

Author Contributions: Conceptualisation, Ü.V.; methodology, Ü.V.; validation, Ü.V. and P.M. (Paweł Mirski); formal analysis, Ü.V.; investigation, Ü.V., J.G., P.M. (Pelle Mellov) and T.T.; resources, Ü.V.; data curation, Ü.V.; writing—original draft preparation, Ü.V.; writing—review and editing, P.M. (Paweł Mirski); visualisation, Ü.V. and P.M. (Paweł Mirski); project administration, Ü.V.; supervision, Ü.V.; funding acquisition, Ü.V. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data collected in bird inventories and occasional records are deposited in the PlutoF data repository and available at https://plutof.ut.ee/ (accessed on 1 April 2023). The movement data of raptors is deposited in the Movebank data repository https://www.movebank.org/ (accessed on 1 April 2023).

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Conflicts of Interest: The authors declare no conflict of interest.

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