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Forest gaps around wind turbines attract bat species with high collision risk

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ABSTRACT

The global demand for renewable energy has led to an expansion of wind energy production at forested sites. The deployment and operation of turbines requires the clearing of forest areas, resulting in significant habitat changes. To assess the consequences of these changes for forest-associated bats, we measured the acoustic activity of three foraging guilds at turbine clearings, adjacent forest edges, and above nearby closed forests. Open-space and edge-space foraging bats were more active at turbine clearings and forest edges than above closed forests. Similarly, narrow-space foraging bats tended to be more active at turbine clearings than above closed forests. Open-space and edge-space foraging bats are known to be at high risk of colliding with wind turbines and their increased activity at forest gaps around turbines may increase casualties for these guilds. Operation of wind turbines in forests may therefore require longer shutdown periods to prevent legally protected bats from colliding with turbines. Although this may impair the energy yield of wind turbines in forests, such preventive conservation measures will ultimately contribute to a sustainable transition from fossil to renewable energy sources which factors in biodiversity conservation.

1. Introduction

Between 2000 and 2012, a total of 2.3 million km^2 of global forest ecosystems were lost (Hansen et al., 2013). The quality of remaining forests is severely threatened by human activities such as logging, fragmentation, and construction of infrastructures (Grantham et al., 2020; Ibisch et al., 2016). In many parts of the world, anthropogenic pressure on forest ecosystems is now increasing due to the expansion of wind turbines to forested sites (EEA, 2009). Alone in Germany and in the USA, two of the largest markets for wind energy, several thousand turbines are operating in forests already (REN21, 2018; Xiarchos and Sandborn, 2017; FA Wind, 2022). Particularly countries with a high percentage of forest cover, where open areas for wind energy production are scarce, may need to place turbines in forests to meet the international goal of net zero carbon dioxide emissions by 2050 (Gaultier et al., 2020; UNFCCC, 2015). This development is relevant for biodiversity conservation because wind turbine deployment in forests will inevitably create forest gaps and alter sensitive ecosystems. In Germany, the construction of a single turbine at a forested site involves clear-cutting of about 0.9 ha. Half of the cleared area is permanently converted into gravel areas with compacted soil for maintenance of turbines (FA Wind, 2022). Ultimately, this alteration of vegetation and soil results in habitat changes, which can affect the biodiversity and community composition of forest animals, and their trophic networks (Fahrig, 2003; Ellerbrok et al., 2022; Scholz and Voigt, 2022). Yet, the ecological impacts of creating forest gaps for wind turbines on animals are poorly known to date, specifically for bats that are vulnerable at wind turbines (Schöll and Nopp-Mayr, 2021).

Temperate forests are important habitats for a wide range of species, among them bats. For example, 90 % of European bat species use forest structures at least temporarily for foraging and roosting (Dietz and Kiefer, 2014; Russo et al., 2016). Specifically, bats require tree cavities and standing deadwood for roosting as well as resource-rich foraging areas, which they use according to strata, structure, and vegetation density (Jung et al., 2012; Müller et al., 2013; Law et al., 2016). When forests are partially cleared for wind turbines, bats can be affected in several ways depending on their foraging and flight behaviour (Denzinger and Schnitzler, 2013; Aldridge and Rautenbach, 1987). Open-

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space foraging bats are long-range echolocators with pointed wings foraging mostly in spaces with few or no obstacles (Denzinger and Schnitzler, 2013). They hunt above treetops and in larger clearings, while they avoid dense vegetation and small clearings (Voigt and Holderied, 2012). Thus, open-space foraging bats may explore and use forest gaps associated with wind turbines in forests. Edge-space foraging bats are mid-range echolocators, which are specialized on hunting prey close to background objects (Denzinger and Schnitzler, 2013). Hence, they are often found at forest edges (Kirkpatrick et al., 2017), which are created when forest patches are clear-cut for wind turbines. Finally, narrow-space foraging bats are short-range echolocators with rounded wings that facilitate foraging in forest understorey (Denzinger and Schnitzler, 2013). Although narrow-space foragers can fly outside of forests (Heim et al., 2018), they mostly occur in the forest interior and might therefore suffer from the creation of forest gaps for wind turbines. In conclusion, open-space and edge-space but not necessarily narrow-space foraging bats can be expected to increase their activity where forest gaps are created for wind turbines.

Fatalities of bats after collisions with wind turbines are a known global problem (O'Shea et al., 2016; Thaxter et al., 2017). Bat casualties at wind turbines are not equally distributed across species. In Europe, for example, 95 % of bats found dead under wind turbines belonged to 6 out of 11 assessed genera (*Nyctalus, Vespertilio, Pipistrellus, Hypsugo, Miniopterus, Tadarida*; Dürr, 2022). Accordingly, bat species from these genera are commonly recognized as high-collision risk species (Rodrigues et al., 2014), which is associated with their ability to fly at the operation range of wind turbines (Reusch et al., 2022, 2023; Roeleke et al., 2016; Roemer et al., 2017). Noticeably, all bat species recognized as high-collision risk species at wind turbines are members of the open-space or edge-space foraging guild, while bat species of the narrow-space foraging guild are usually considered to be at low risk of colliding with wind turbines (Rodrigues et al., 2014). Consequently, deployment of wind turbines at forested sites might lead to more casualties at wind turbines if bat species of high-collision risk are attracted to the open and edge habitats which were created for the deployment and operation of wind turbines. Besides, bats may also respond to the operation of wind turbines. Indeed, past studied confirmed that wind turbines repel certain bat species in open landscapes (Barré et al., 2018; Leroux et al., 2022) and in forests (Ellerbrok et al., 2022; Reusch et al., 2023; Gaultier et al., 2023), depending on the size of the wind turbines.

Here, we investigated how bats of three foraging guilds respond to habitat changes associated with the creation of forest gaps for wind turbines deployment and operation. We monitored acoustic bat activity at 22 forest wind turbines, specifically at turbine clearings, at the edge between turbine clearings and forests, and above the adjacent closed forest. We estimated echolocation call activity as the number of minutes with bat calls and foraging activity as the occurrence of stereotyped call sequences associated with hunting events (hereafter: feeding buzzes, in sensu Skiba, 2009). We predicted that (i) echolocation activity and (ii) foraging activity of open-space and edge-space foraging bats but not those of narrow-space foraging bats is highest at forest gaps adjacent to wind turbines. Finally, we expected (iii) that the activity patterns of bats in the different habitats is influenced by the size of turbines, since our previous work suggested a reduced activity of some bat species at turbines with large rotors (Ellerbrok et al., 2022). With this study, we aim to contribute to evidence-based schemes for a sustainable use of wind energy which incorporates the protection of forest-associated bats.

2. Material & methods

2.1. Study area & design

We conducted acoustic surveys in 22 managed forests in the low-mountain ranges of Hesse, Central Germany. We chose twelve mixed deciduous and ten predominantly coniferous forests, which represent structurally rich and poor forests. We surveyed wind turbines of varying sizes, ranging in rotor diameter between 82 and 126 m (111 ± 11 m, mean ± one standard deviation) and in tower height between 145 and 212 m (193 ± 16 m; HLNUG, 2019). Turbines were located at the margins of multi-turbine facilities in clearings ranging from 0.2 to 6.5 ha (median: 1.0 ha). Around these focal wind turbines, we established three sampling points in distinct habitats: one at the centre of the wind turbine clearing, one at the adjacent forest edge and one in the canopy of the surrounding closed forest. Sampling points in the closed forest were chosen as close to focal wind turbine as possible without entering the forest edge zone to avoid the confounding effects of the edge habitat. As a result, sampling points in closed forests were all located at approximately 80 m distance to focal wind turbines. We did not survey the availability of tree roosts close to our sampling points. However, we do not anticipate a systematic bias caused by the presence of roosts but rather an increased unexplained variation in the recorded acoustic data. Acoustic surveys were conducted four times during the active season between May and September 2021 at each sampling point between 9 pm and 5 am, resulting in a total of 264 full night recordings (22 study sites x 3 habitat types x 4 sampling periods). Sampling points were chosen to be at a minimum distance of 150 m (one exception at 90 and two at 120 m, 540 ± 360 m) from the outer edge of the forest patch and a minimum distance of 250 m from other than the focal wind turbines to exclude edge and cumulative effects.

2.2. Bat call sampling and analysis

We used automated ultrasonic recorders (BATLOGGER A+, Elekon, Lucerne, Switzerland) with a trigger frequency between 15 and 155 kHz to cover typical call frequencies of expected local bat species. At sampling points of forest edges and closed forests, recorders were placed at canopy level, as we were particularly interested in the activity of open-space and edge-space foraging bats which occur mostly above the forest canopy (Ellerbrok et al., 2022). Additionally, most species of these two guilds are considered high-collision risk species at wind turbines (Rodrigues et al., 2014). We placed recorders in clearings adjacent to wind turbines, at the top of 2 m poles.

We used the software BatExplorer (Elekon, Lucerne, Switzerland) to convert audio recordings into spectrograms. We manually checked all sequences to identify bat calls based on typical call shape, end frequencies and peak frequencies from the literature (Barataud, 2020; LFU Bayern, 2020; Skiba, 2009) and assigned them either to the open-space (*Eptesicus* ssp., *Vespertilio* ssp., *Nyctalus* ssp.), edge-space (*Pipistrellus* ssp., *Barbastella barbastellus*) or narrow-space foraging guild (*Myotis* spp., *Plecotus* spp.). For each foraging guild, we determined bat activity minutes by dividing recording nights into 1-min intervals and counting intervals with at least one echolocation call for each foraging guild. Activity minutes were used as a proxy for the echolocation activity (Miller, 2001). Additionally, we identified call sequences with increasingly short intervals and a final drop in frequency as so-called feeding buzzes (e.g., Skiba, 2009). The presence of feeding buzzes per guild and night were used as a proxy for foraging activity.

2.3. Data analysis

All analyses were performed in R (version 4.1.3; R Core Team, 2021). We used generalized mixed models (GLMMs, glmmTMB package; Brooks et al., 2017) with a binomial error distribution and a logit link function for each bat guild separately. We analysed the effect of habitat (turbine clearing, forest edge, closed forest), forest type (deciduous, coniferous) and rotor diameter as well as the interaction of rotor diameter and habitat on echolocation and foraging activity. We did not include tower height in our model because it was strongly correlated with rotor diameter (Spearman correlation: $r = 0.72$; $p < 0.001$). Month of sampling (May, June, July, August, September) was added as fixed effect to account for temporal autocorrelation. Recording points were nested in plots, i.e., the sites of focal wind turbines (random effect).

Models were checked for homoscedasticity and normally distributed residuals with help of the DHARMa package for residual diagnostics (Hartig, 2020). As models for foraging activity were highly zero-inflated, we resorted to assessing the presence/absence of feeding buzzes (more details on methodology provided in Supporting information A).

3. Results

Overall, we recorded 28,155 activity minutes of which most corresponded to edge-space foraging bats (84 % of activity minutes), followed by open-space and narrow-space foraging bats (each 8 %). We documented foraging activity of edge-space foraging bats in 130 nights, of

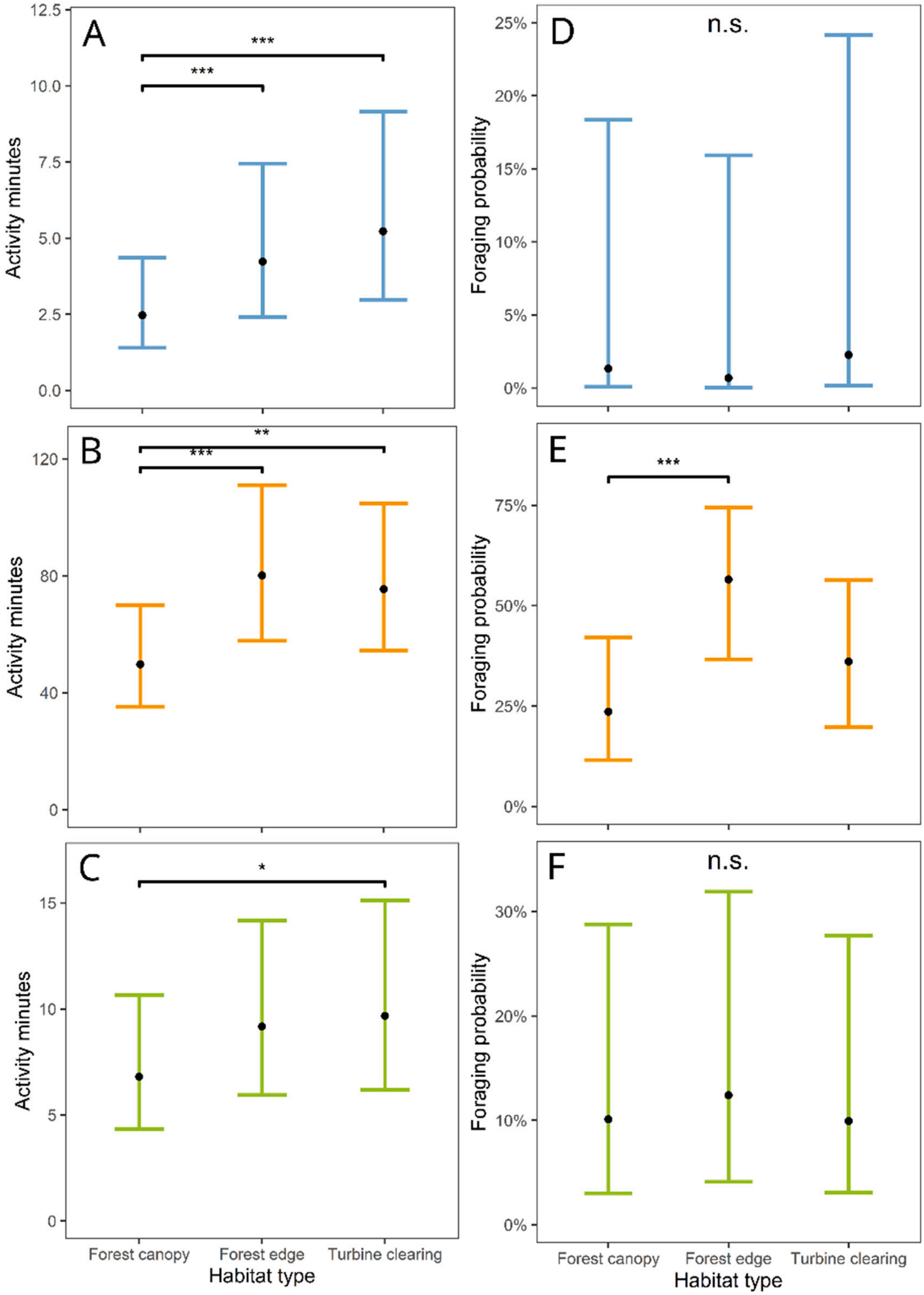

Fig. 1. Effect of habitat on (A-C) echolocation activity and (D-F) foraging activity of open-space (blue; A, D), edge-space (yellow; B, E) and narrow-space foraging bats (green; C, F). Black dots and coloured bars indicate mean ± 95 % prediction intervals. Asterisks denote the significance level of effects (*** < 0.001 < ** < 0.01 < * < 0.05 < n.s.).

narrow-space foraging bats in 26 nights and of open-space foraging bats in 13 nights. Levels of echolocation and foraging activity varied across seasons (Supporting information B).

Open-space foraging bats were 111 % (95 % confidence interval [21 %, 270 %]) more active at turbine clearings and 71 % (CI [−3 %, 202 %]) more active at forest edges than at closed forest sampling points (Fig. 1A, Table 1). Foraging activity of open-space foraging bats was neither influenced by habitat nor any other predictor (Fig. 1D, Table 1). Edge-space foraging bats were 60 % (CI [15 %, 122 %]) more active at forest edges and 51 % (CI [8 %, 109 %]) more active at turbine clearings compared to closed forests (Fig. 1B, Table 1), while the foraging activity was 113 % (CI [34 %, 180 %]) higher at forest edges compared to closed forests (Fig. 1E, Table 1). Echolocation and foraging activity of narrow-space foraging bats was similar across the three habitats, but echolocation activity tended to be 42 % (CI [−9 %, 122 %]) higher in the turbine clearing than at closed forest sampling points (Fig. 1C & F, Table 1). Neither echolocation nor foraging activity of the three guilds were influenced by an interactive effect of habitat type and rotor size. However, the overall echolocation and foraging activity of narrow-space foraging bats, but not those of edge-space and open-space foraging bats, decreased by 85 % (CI [73 %, 91 %]) and 74 % (CI [5 %, 95 %]) respectively with increasing rotor diameter (Fig. 2, Table 1). The effect of rotor diameter was not confounded by forest vegetation structure, distance to the outer forest edge or forest patch size (Supporting information C).

4. Discussion

We conducted acoustic surveys at wind turbines in forests to investigate the effects of habitat conversion for turbine construction and operation on the activity of bats belonging to three foraging guilds. Bats used the forest gaps created for wind turbines, with open-space and edge-space foraging bats being more active above turbine clearings and at forest edges than above nearby closed forests. The activity of narrow-space foraging bats tended to be higher at turbine clearings than above closed forests, but the difference was less pronounced compared to those of other guilds.

Our findings are consistent with studies from managed forests without wind turbines where forest gaps created by clear-cutting were more frequently used by bats than surrounding or preceding forest habitats (Grindal and Brigham, 1998; Maki et al., 2021), especially by open-space and edge-space foraging bats (Kirkpatrick et al., 2017). In contrast to the study by Kirkpatrick and colleagues, our data also indicates an increased use of clear-cuttings by narrow-space foraging bats compared to nearby closed forests. This slight difference might be due to our recorders being installed at the canopy level of the forested sampling points but not those at the turbine clearing. We likely missed some echolocation calls of narrow-space foraging bats flying in the forest understorey, since echolocation calls of narrow-space foraging bats are emitted at lower intensities than calls of edge-space and open-space foraging bats, and they also attenuate faster in vegetation (Holderied and von Helversen, 2003; Denzinger and Schnitzler, 2013). Accordingly, echolocation calls of narrow-space foraging bats are more likely to be recorded by ultrasonic detectors at the clearing than at the forested sampling points. In contrast, open-space and edge-space foraging bats emit echolocation calls with a high sound pressure level (Currie et al., 2020; Holderied and von Helversen, 2003). Additionally, echolocation calls of these species are less attenuated in the open space, where open-space and edge-space foragers typically fly, than those of narrow-space foraging bats within the vegetation. Therefore, it is likely that we detected open-space and edge-space foraging bats with similar probability in all three habitats. Consequently, we consider our results to be robust and in line with our hypothesis that forest-associated open-space and edge-space foraging bats are more active in forest gaps next to turbines than above the canopy of nearby closed forests.

As predicted, edge-space foraging bats were more active hunting insects at forest gaps at wind turbines than above the adjacent closed forest, suggesting that edge-space foraging bats use turbine clearings and adjacent edge habitats as a hunting ground. Increased foraging of edge-space foraging bats especially at forest edges is in line with their elevated echolocation activity at forest edges but might be additionally promoted by a high abundance of insect prey accumulating in proximity of wind turbines (Foo et al., 2017; Cryan et al., 2014). In conclusion, we showed that edge-space foraging bats predominantly use forest gaps at wind turbines for foraging. However, we cannot disentangle the causal factor behind this pattern because we did not measure prey abundance. Although increased foraging at forest gaps is likely for open-space-foraging bats as well, it was not confirmed by our data, possibly due to the low number of feeding buzzes recorded for this foraging guild. Based on the presence of echolocation activity but relatively low number of feeding buzz recordings of narrow-space foraging bats at forest gaps around wind turbines, we suggest that narrow-space foraging bats may use forest gaps around wind turbines mainly for commuting, but not necessarily for hunting. All in all, our study shows that the activity of open-space and edge-space foraging bats is high at forest gaps created by the clear-cutting of forests for wind turbine deployments. Contrary to our expectation, this was also the case at wind turbines with large rotors, although bats of these foraging guilds are known to be repelled by turbine operation in open landscapes (Leroux et al., 2022; Reusch et al., 2022). Accordingly, we conclude that clearings around wind turbines in forests are highly attractive for open-space and edge-space foraging bats and increase the probability that these bats fly in the immediate proximity of turbines.

Bats of the open-space and edge-space foraging guild are known to fly at heights at which wind turbine rotors operate (e.g., Rodrigues et al., 2014). In our study area, the average ground clearance of the lower rotor tips of wind turbines was 82 m. The bat species with the highest mortality at wind turbines in Germany, *Nyctalus noctula* of the open-space foraging guild, flies on average below 60 m above ground but can also reach several hundred meters height (Dürr, 2022; O'Mara et al., 2019; Reusch et al., 2023). *Pipistrellus pipistrellus* of the edge-space foraging guild, a species with similarly high fatalities at wind turbines in Germany, is regularly recorded at 85 m heights (Dürr, 2022; Roemer et al., 2017). Consequently, edge-space and open-space foraging bats may

Table 1

Estimates and p-values of the effects on echolocation and foraging activity of three foraging guilds. Significant effects (p-value < 0.05) are shown in bold.

	Predictors	Df	Open-space foragers		Edge-space foragers		Narrow-space foragers	
			Chi^2	p-Value	Chi^2	p-Value	Chi^2	p-Value
Echolocation activity	Habitat	2	27.391	**<0.001**	17.102	**<0.001**	5.361	0.069
	Forest type	1	0.157	0.692	2.068	0.150	0.951	0.330
	Month	4	65.247	**<0.001**	38.524	**<0.001**	7.113	0.130
	Rotor size	1	2.137	0.144	0.357	0.550	10.75	**0.001**
	Habitat × Rotor size	2	0.993	0.609	3.134	0.371	0.808	0.668
Foraging activity	Habitat	2	0.635	0.728	12.68	**0.002**	0.176	0.916
	Forest type	1	0.142	0.707	0.258	0.612	0.166	0.684
	Month	4	2.353	0.671	9.258	0.055	2.989	0.560
	Rotor size	1	1.370	0.242	0.346	0.557	4.335	**0.037**
	Habitat × Rotor size	2	1.281	0.527	1.682	0.431	0.318	0.853

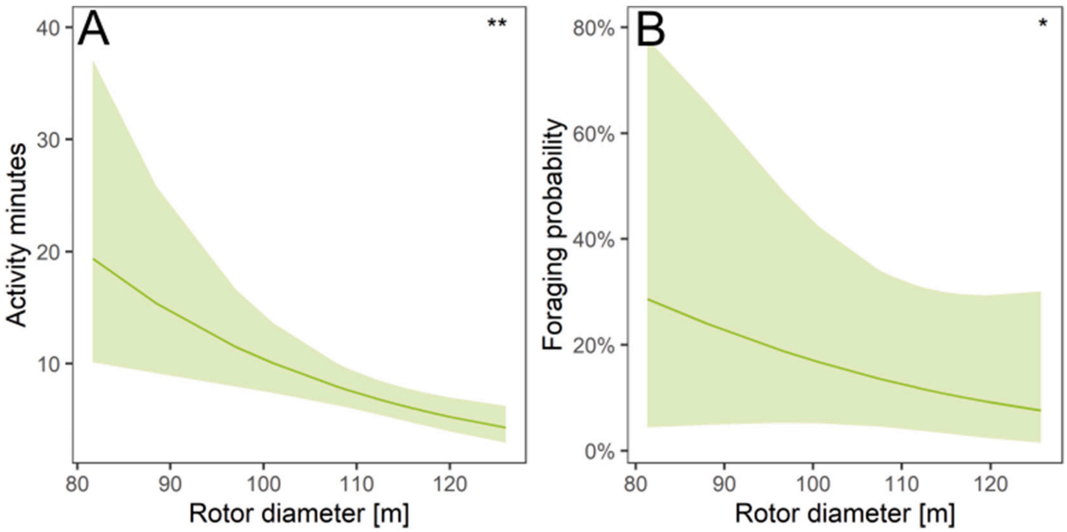

Fig. 2. Effect of wind turbine rotor size on (A) echolocation activity and (B) foraging activity of narrow-space foraging bats. The green line depicts predicted mean values, green shades indicate mean ± 95 % prediction intervals. Asterisks denote the significance level of effects (*** < 0.001 < ** < 0.01 < * < 0.05 < n.s.).

experience increased casualties at wind turbines in forests compared to those operating in open landscapes. Based on morphology, *Barbastella. barbastellus* is grouped with the edge-space foraging guild but is usually not considered a high-collision risk species at wind turbines. However, since *B. barbastellus* only comprised 8 % of recorded activity minutes in the edge-space foraging guild, their influence on our results can be neglected. In contrast, the activity of narrow-space foraging bats increased less clearly at forest gaps. Furthermore, they usually do not fly high above treetops and are rarely found dead below wind turbines (Rodrigues et al., 2014; Rydell et al., 2010). Therefore, we consider it unlikely that narrow-space foraging bats experience increased collisions at wind turbines in forests. Bats of this foraging guild are likely more affected by the direct loss of habitat caused by the clear-cutting, and by the indirect displacement that is caused by turbine operation. In fact, we confirmed our previous work that showed a reduced activity of narrow-space foraging bats in the proximity of wind turbines with large rotors (Ellerbrok et al., 2022).

5. Conclusion

Clear-cutting of forests for wind turbine construction and operation increased the activity of bats of all local foraging guilds in the newly created forest gaps. While all species might lose relevant habitat features like tree roosts as a result of clear-cutting, activity of open-space and edge-space foraging bats in particular seems to be promoted by the opening of the canopy when the forest is clear-cut for the deployment of wind turbines. Consequently, wind turbines in forests may lead to an increased number of collisions for these high-flying bat species (Rodrigues et al., 2014; Rydell et al., 2010). This might affect bat populations on the long run, because of the low reproduction rates of bats (Racey and Entwistle, 2000). To prevent this, we recommend that the operation of wind turbines in forests should be curtailed at times of high bat activity, by using algorithms that are specifically developed for wind turbine operation at forested sites. Curtailments of wind turbine operations have proven to be a promising solution to reconcile biodiversity conservation and the production of wind energy (Adams et al., 2021; Arnett et al., 2016; Whitby et al., 2021) and thus should be practiced, whenever wind turbines need to be placed in forests. Although operation curtailments may impair the efficacy of wind energy generation, such preventive measures may ultimately help to reconcile the two important goals to protect the global climate and the global biodiversity.

CRediT authorship contribution statement

Julia S. Ellerbrok: Data collection, data curation, methodology, formal analysis, investigation, writing – original draft, writing – reviewing & editing, visualization.

Finn Rehling: formal analysis, writing – reviewing & editing.

Franziska Peter: Funding acquisition, conceptualisation, supervision, writing – reviewing & editing.

Nina Farwig: Funding acquisition, conceptualisation, supervision, writing – reviewing & editing.

Christian C. Voigt: Funding acquisition, conceptualisation, methodology, supervision, writing – reviewing & editing.

Declaration of competing interest

None of the authors have a conflict of interest.

Data availability

Data is available via the Dryad Digital Repository (https://doi.org/10.5061/dryad.d2547d85q)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2023.110347.

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