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Review

How far are birds, bats, and terrestrial mammals displaced from onshore wind power development? – A systematic review

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ABSTRACT

Wind power is a rapidly growing source of energy worldwide. It is crucial for climate change mitigation, but it also accelerates the degradation of biodiversity through habitat loss and the displacement of wildlife. To understand the extent of displacement and reasons for observations where no displacement is reported, we conducted a systematic review of birds, bats, and terrestrial mammals. Eighty-four peer-reviewed studies of onshore wind power yielded 160 distinct displacement distances, termed cases. For birds, bats, and mammals, 63 %, 72 %, and 67 % of cases respectively reported displacement. Cranes (3/3 cases), owls (2/2), and semi-domestic reindeer (6/6) showed consistent displacement on average up to 5 km. Gallinaceus birds showed displacement on average up to 5 km, but in 7/18 cases reported to show "no displacement". Bats were displaced on average up to 1 km in 21/29 cases. Waterfowl (6/7 cases), raptors (24/30), passerines (16/32) and waders (8/19) were displaced on average up to 500 m. Observations of no displacement were suggested to result from methodological deficiencies, species-specific characteristics, and habitat conditions favorable for certain species after wind power development. Displacement-induced population decline could be mitigated by situating wind power in low-quality habitats, minimizing the small-scale habitat loss and collisions, and creating high-quality habitats to compensate for habitat loss. This review provides information on distance thresholds that can be employed in the design of future wind energy projects. However, most studies assessed the effects of turbine towers of <100 m high, while considerably larger turbines are being built today.

1. Introduction

Wind power is one of the fastest growing energy sources globally (Bennun et al., 2021; IRENA, 2022), and with solar power, it accounted for 88 % of the added renewable capacity in 2021 (IRENA, 2022). To reach the Net Zero Emissions by 2050 Scenario, there is still a need to more than double the global addition of wind power capacity (IEA, 2022). In the coming years, the majority of the wind power addition will still be onshore, and turbines with higher towers and longer blades will be developed to increase cost-effectiveness and cope with low wind conditions. It has been estimated that globally, >11 million hectares of natural land may be lost to wind and solar power, impacting over 3.1 million hectares of key biodiversity areas and over 1500 threatened vertebrate animal species, especially in tropical areas (Kiesecker et al., 2019). Although the increase of wind power capacity is crucial in attempts to mitigate climate change, its proposed effects on biodiversity indicate a trade-off between climate change mitigation and biodiversity conservation targets.

Wind power development can influence wildlife through many mechanisms. Habitat change and fragmentation may decrease habitat suitability and resource availability near turbines (e.g., Campedelli et al., 2014). Disturbance caused by rotor movement, noise, vibration, flickering lights, and increased human presence may lead to behavioral changes such as avoidance and changes in flight paths (Drewitt and Langston, 2006; Marques et al., 2019; Schuster et al., 2015). Avoidance can occur at different scales, at the level of the entire wind farm (macro-scale), within the wind farm (meso-scale), or in the immediate vicinity of wind turbines (micro-scale, Marques et al., 2021; May, 2015). Displacement indicates principally macro- (May, 2015) and meso-scale (Marques et al., 2021) avoidance. As a result of displacement, a reduced density of wildlife near wind turbines may be observed. Knowledge of displacement can be used to estimate distance thresholds, beyond which wind power development is not expected to have remarkable biodiversity impacts. This improves the opportunities to

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mitigate the detrimental effects of wind power on wildlife.

There is abundant literature and review articles on the impacts of wind power development on the distribution, abundance, survival, behavior, and displacement of birds (e.g., Coppes et al., 2020b; Marques et al., 2014, 2021), bats (Cryan and Barclay, 2009; Guest et al., 2022) and on wildlife in general (Schuster et al., 2015; Schöll and Nopp-Mayr, 2021). Benítez-López et al. (2010) investigated displacement distances from infrastructure using meta-analysis and meta-regression. Using data from 49 studies, of which three studied the wind power, they showed that the main response of mammals and birds to infrastructure was avoidance or a reduced population density. In their analysis, Benítez-López et al. (2010) omitted the few studies not showing the negative effects of infrastructure. Their models however showed that a large number of studies reporting neutral or positive responses to infrastructure would be needed to reverse their results.

Marques et al. (2021) included 71 studies in their review and found that approximately 40 % of studied bird taxa showed displacement from onshore and offshore wind power development. They suggested improvements for study design, for example, by encouraging observations to be made before the construction of a wind power development. Schöll and Nopp-Mayr (2021) reviewed 27 studies of birds, bats, and mammals in woodland ecosystems. They concluded that displacement distances (or distance thresholds) varied temporally and spatially, even within species. They also called for the improvement of study design and suggested that BACI (before-after-control-impact) studies should be mandatory for approval and decisions related to wind power development.

The scale of the studied displacement distances and the potential reasons for observations that report no displacement have not been explicitly assessed in previous reviews. The lack of displacement may arise from methodological issues, such as study design, low sample size, short duration and choice of measured variables, but it may also indicate that some wildlife taxa are not disturbed by wind turbines, or that habitat conditions are still favorable for the species. In this study, we systematically reviewed 84 peer-reviewed studies concerning the effects of onshore wind power development on the displacement distances of birds, bats, and terrestrial mammals from all the studied terrestrial habitats. We addressed the following questions: 1) How prevalent are displacement effects due to wind power development on birds, bats, and terrestrial mammals?; 2) Which taxa show the longest displacement distances?; and 3) What are potential reasons for observations that report no displacement? Based on the results, we discussed how the information about the displacement can be utilized for mitigation of negative effects of wind power development.

2. Materials and methods

2.1. Literature search

We utilized the Web of Science (URL:https://www.webofknowledge.com) and Tethys Knowledge Base (URL:https://tethys.pnnl.gov/knowledge-base-wind-energy) as sources of peer-reviewed literature for birds, bats, and terrestrial mammals (April 5, 2023). A broad range of Boolean search terms was employed in the Web of Science literature search (Table 1). We supplemented the Web of Science search with studies from the Tethys Knowledge Base, applying the filters “wind energy content”, “land-based wind”, “journal article”, “avoidance”, and “displacement” with “birds”, “bats”, and “terrestrial mammals” respectively (search strings shown in Supplementary Material). In addition, we included relevant studies from the reference lists of the extracted studies.

2.2. Study selection criteria and data extraction

A study was included if it contained original quantitative data on studied displacement distances of species or species groups from onshore wind turbines or wind farms. This included data on e.g., abundance and changes in lekking and feeding area usage, anticipatory evasion, or population changes. We also included studies which reported that there was no statistically significant displacement, or even if there was an attraction, if studied displacement distances were given. We did not include studies focusing solely on collisions because the short distance at the collision risk area could be understood as escape rather than displacement (May, 2015). Nor did we include studies of attraction if there was no information about studied displacement distances.

Table 1
Boolean search term sets used in the Web of Science literature search. Sets 1 and 2 were combined by “AND” with sets 3–5 respectively (TS = title, abstract, author keywords, and Keywords Plus; TI = title).

Nr.	Set	Search terms using “OR”
1	wind power (TS)	“wind energy*”, “wind farm*”, “wind power”, “wind turbine*”
2	effects (TS)	disturb*, displace*, avoid*
3	birds (TS)	bird*, avian*, raptor*, “bird* of prey”, eagle*, kite*, buzzard*, osprey*, owl*, harrier*, *falcon*, wader*, duck*, swan*, goose, geese, diver*, crane*, grouse*, “Gallinaceous bird*”, capercaillie*, nightjar*, gull*, tern*, passerine*, (NOT TI = offshore)
4	terrestrial mammals (TS)	mammal*, erinaceidae, erinaceus, hedgehog, talpidae, talpa, mole, soricidae, sorex, shrew, leporidae, lepus, hare, rodentia, rodent, Muridae, rat, mouse, cricetidae, vole, dipodidae, gliridae, Sciuridae, Sciurus, pteromys, squirrel, castor*, beaver, felidae, lynx, mustelidae, martes, marten, meles, badger, lutra, gulo, neovison, mustela, canidae, canis, wolf, vulpes, fox, nyctereutes, “raccoon dog”, ursidae, ursus, bear, Cervidae, rangifer, reindeer, caribou, alces, moose, elk, capreolus, Odocoileus, dama, cervus, deer, Bovidae, rupicapra, chamois, suidae, sus, “wild boar”, (NOT “grey wolf optim*”, “squirrel cage”, “squirrel-cage” (NOT TI = offshore)
5	bats (TS)	bat*, pipistrell*, barbast*, noctul*, myotis* (NOT TI = offshore)

* truncation of a search word.

2.3. Assessment of displacement distances

The displacement distances were obtained from different types of variables such as an activity or presence in a given area, behavior, lekking and nesting of birds, nest density, breeding success, alteration of flight paths, abundance of nesting birds, changes in flight activity, foraging distance, and occurrence of fecal pellets.

The studies provided individual species-specific distances or aggregated displacement distances for multiple species. We recorded all given distances, termed cases. We classified the case in the displacement category if there was a clear statistical or model result concerning displacement in one measured variable, for example, abundance of nesting birds or reduced density of individuals, at any phase of the study. We included both direct (e.g. noise) and indirect (e.g. reduced habitat quality) impacts of wind power development. Statistically insignificant cases and cases showing attraction were classified as no displacement. Despite the fact that the cases recorded within each study represented pseudoreplication, we reported them separately, as a single study could contain results for both displacement and no displacement, depending on the species or taxa.

To further analyze the studies showing no displacement, we classified them to four categories based on how the result was discussed in the respective papers: “methodological reason” such as small sample size or short duration of study, “species-specific reason” such as life-history stage or trait of the species, “habitat conditions”, such as vegetation characteristics or food availability, and reason “not assessed”, if it was not discussed in the respective study.

As the bird studies represented a wide range of families, migratory behavior, ecological niches, and flying patterns, we divided the birds into eight functional groups by their taxonomical and functional traits: gallinaceous birds, cranes, passerines, raptors, owls, waders (including orders Charadriiformes and Ciconiiformes, Bai et al., 2021; Meek et al., 1993; Niemuth et al., 2013), and waterfowl (including one case of the diver *Gavia stellata*, Meek et al., 1993). The category "several" was used if the displacement distance included aggregated information from many bird groups. Terrestrial mammals were grouped into canids (foxes, wolves), cervids (deer, elk, reindeer), and small mammals (rodents, hedgehogs, shrews). If a study contained information about both individual species and aggregated values for several species, we opted for species-level values.

Distances were presented using various measures. If a distance range was provided, e.g., 0–200 m, we recorded the maximum numeric value for that range, in this case 200 m. Sometimes, the upper distance limit was left open, for example, >1000 m, as it was assumed that the effect might extend longer than what was observed or modeled. In such cases, we used the highest given distance value, 1000 m, and assumed that displacement also occurred at lower distances. If multiple distances or distance ranges were given for a single species, we selected the maximum statistically significant distance and expected that displacement also occurred at smaller distances. After assessing all the displacement distances, we classified them in five categories: up to 100 m; up to 500 m; up to 1000 m; up to 5000 m; and over 5000 m.

We also estimated turbine tower heights when the information was available. This was done to get an overview of how the results apply to assessing the effects of large turbines constructed today. If height was provided as total height instead of tower height, we assumed that the tower height was 2/3 of the total height. If a range of turbine sizes was given, we calculated the mean value of minimum and maximum values. We thereafter classified the turbines in four categories: tower height under 50 m; 50–99 m; 100–149 m; and 150 or higher.

To assess if the study design influences the observations of displacement or no displacement results we classified the study design in three categories: 1) BACI design; 2) other studies involving before-after design (BA); and 3) other studies with no data before wind power development (NO). Other designs included studies monitoring the impact of wind power development after the construction, either with or without control sites.

We also recorded the countries where the studies had been carried out. This was done to see how the studies were distributed or concentrated to certain regions.

3. Results

3.1. General results

From an initial pool of 1206 research articles (called hereafter studies), after eliminating duplicates from two search databases, we extracted quantitative data on displacement distances from 84 studies published between 1993 and 2023 (Fig. 1). Among these, 62 studies focused solely on birds, eight on bats, ten on terrestrial mammals, one on bats and birds (Minderman et al., 2012), and three on birds and terrestrial mammals (de Lucas et al., 2005; Łopucki et al., 2017; Smith et al., 2017).

The dominant wind tower height in the studies was 50–99 m, and there were only four most recent studies with tower heights ≥150 m (Ellerbrok et al., 2022; Gaultier et al., 2023; Reusch et al., 2022; Rehling et al., 2023). The total number of studies using BACI design was 16, other BA design 15, and other design 53 studies.

The studies were carried out in 22 countries with 23 studies in the USA, 10 in Spain and the United Kingdom, and six in Norway (for more information, see Tables S1–S3).

The studies provided aggregated displacement distances for multiple species or individual species-specific distances. We recorded all given distances and thus ended up with 160 separate displacement distances, termed cases, from the 84 studies, listed in Tables S1–S3. For birds, we found 116 cases involving individual bird species, taxa, or functional bird groups. Of these, displacement was observed in 73 cases, and no displacement in 43 cases (Table 2). The values were 21 and 8 for bats, and 10 and 5 for terrestrial mammals respectively. Number of cases was higher than the number of studies because some studies provided more than one displacement distance for different species or taxa.

Concerning the cases showing no displacement, more than one reason was often proposed for the result. Methodological reason was suggested in 33 cases, species-specific reason in 23 cases, habitat conditions in 19 cases, and the reason was not assessed in three cases

Table 2
Number of cases, i.e., taxa or functional groups, for which displacement distances were presented in the published studies. Classified as displacement/no displacement.

Taxa/functional group	Displacement	No displacement	Sum
Birds			
Cranes	3	0	3
Gallinaceous birds	11	7	18
Owls	2	0	2
Passerines	16	16	32
Raptors	24	6	30
Waders	8	11	19
Waterfowl	6	1	7
Several	3	2	5
Sum	73	43	116
Bats	21	8	29
Terrestrial mammals			
Canids	1	1	2
Cervids	8	1	9
Small mammals	1	3	4
Sum	10	5	15
Total	104	56	160

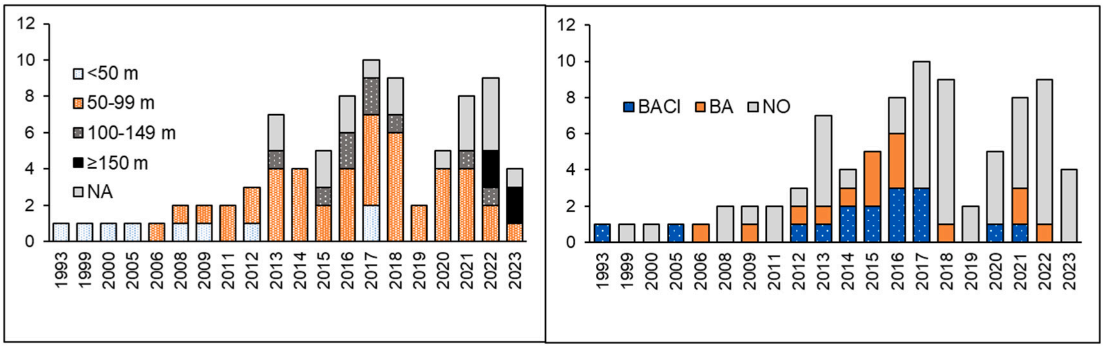

Fig. 1. Number of reviewed studies (y-axis) in different years (x-axis) in five wind tower height categories (a) and three study design categories (b).

(Tables S1–S3).

Although the result was not statistically tested due to pseudoreplication and low sample size for most of the categories, it seemed that the displacement and no displacement categories did not differ remarkably among the four wind turbine size categories (Table S4).

3.2. Birds

All three cases on **cranes** were classified as displaced by wind power development. Two studies focused on migrating whooping cranes (*Grus americana*, Ellis et al., 2022; Pearse et al., 2021). They showed 20 times more activity outside the 5000 m distance from wind turbines compared to the area inside (Pearse et al., 2021) (Fig. 2). The same displacement distance was observed when the birds looked for a stopover site to forage in the same area in the United States Great Plains (Ellis et al., 2022). GPS marked overwintering sandhill crane (*Grus canadensis*) showed potential indication of avoidance behavior <10 km distance, although this was suggested to be the result of habitat selection rather than displacement.

We classified eleven out of 18 cases of **gallinaceous birds** in the displacement category, the median distance being up to 5000 m (Fig. 2). Birds were found to reduce lekking near wind power development (LeBeau et al., 2017a; Winder et al., 2015; Zwart et al., 2015), the longest distance being >5000 m for the decreased lek persistence of greater prairie-chicken males (*Tympanuchus cupido pinnatus*, Winder et al., 2015). Greater prairie-chicken males near turbines spent less time in non-breeding behaviors than those farther away, possibly to compensate for the effects of noise disturbance (Smith et al., 2016). On the other hand, greater prairie-chicken females could nest even within a small wind power development area, but as they selected nest sites >700 m from wind power roads (Harrison et al., 2017), we classified the case as displacement. Noise was also assumed to disturb capercaillie (*Tetrao urogallus*) and reduce the success rate and time invested in breeding up to over 800 m (Taubmann et al., 2021). The species showed population declines because of reduced habitat suitability near wind power development (González et al., 2016), and there was no indication that habituation occurred eight years after construction (Coppes et al., 2020a). Chick survival in Columbian sharp-tailed grouse *(Tympanuchus phasianellus columbianus)* decreased by 50 % when there were ≥10 wind turbines within 2100 m of the nest (Proett et al., 2022). A potential reason for this was suggested to be increased predation and noise disturbance, which hindered the passing of alarm sounds to chicks by brood females (Proett et al., 2022). Summer habitat selection of greater sage-grouse (*Centrocercus urophasianus*) decreased with the increase of surface disturbance ≤1200 m from wind power development, although there was no direct effect on the nest site selection or the survival of females (LeBeau et al., 2017b).

Seven gallinaceous bird cases were classified as no displacement, two focusing on the breeding or habitat selection of greater prairie-chicken (McNew et al., 2014; Raynor et al., 2019). The lack of responses in these studies was suggested to be connected with the habitat, i.e. the avoidance of non-grassland areas instead of the displacement from wind power development. The lack of displacement in red grouse (*Lagopus lagopus scoticus*) was assumed to result from methodology, i.e. a short-term (three-year) study on a single site after wind power development was operational (Douglas et al., 2011). Even positive associations with wind turbines were found for common pheasant (*Phasianus colchicus*, Łopucki et al., 2017) and red grouse (*Lagopus lagopus scoticus*, Douglas et al., 2011). The suggested reasons for this association were linked to species and habitat through a reduced number of predatory birds and a general affinity for tracks as a source of grit, which is important for digestion (Douglas et al., 2011; Łopucki et al., 2017). Also the short duration of study on a single site was suggested to be a reason for no displacement in Douglas et al. (2011).

Only two cases addressed **owls**. Both showed that the birds abandoned their territories and nests up to 5000 m from wind power development (Husby and Pearson, 2022; López-Peinado et al., 2020). The owls were suggested to be sensitive to noise and disturbance, and open areas created by wind power development were assumed to be poor hunting habitats.

Passerines showed both displacement and no displacement in 16 cases. The median displacement distance was 500 m and was observed as avoidance behavior and reduced bird densities (Fernández-Bellon et al., 2019; Pearce-Higgins et al., 2009; Shaffer and Buhl, 2016; Stevens et al., 2013), a reduced number of breeding birds (Leddy et al., 1999; Pearce-Higgins et al., 2009), and reduced nest density (Song et al., 2021). The displacement extended up to 4500 m in a study of the endangered Dupont's lark (*Chersophilus duponti*) in Spain, where even local extinctions were suggested to occur in the presence of wind farms (Gómez-Catasús et al., 2018). Nighttime lights and the rotation of turbines were suggested to disturb birds and have adverse effects on communication (Gómez-Catasús et al., 2018, 2022; Leddy et al., 1999). It was also observed that habitat change and reduced forest cover resulted in a large reduction of safe habitats for forest-dwelling passerines (Fernández-Bellon et al., 2019; Shaffer and Buhl, 2016). In Garcia

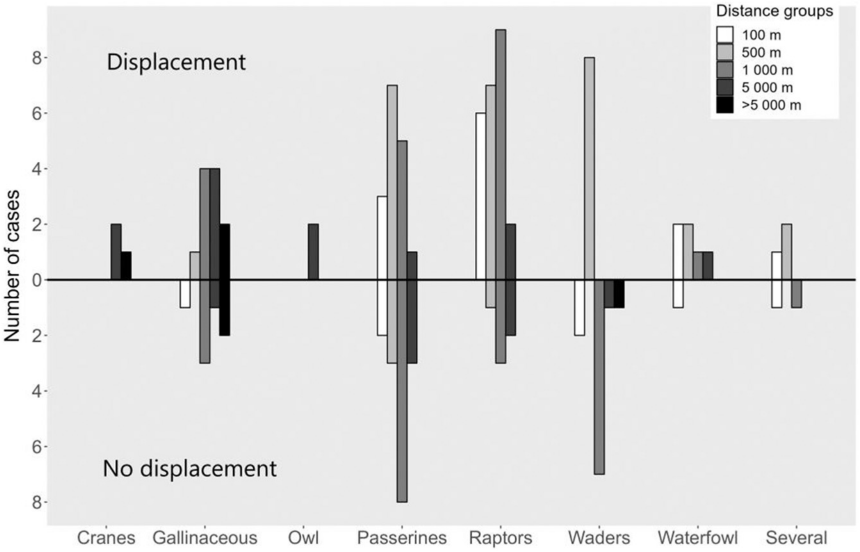

Fig. 2. Bird functional groups classified in five distance categories and according to whether displacement was observed (bars above x-axis) or not observed (bars below x-axis).

et al. (2015), decreasing population trends were observed among 12 of 15 breeding passerine species during construction, but the species were observed to return to their old nesting sites when construction was completed. We nevertheless classified Garcia et al. (2015) in the "displacement" category, since displacement was observed during the construction period.

Also no displacement was shown in 16 cases of passerines. In Hale et al. (2014), breeding grassland passerines were not observed to react to turbines, partially due to the difficulty of isolating the effect of turbine distance from other factors, such as barbed wire fences, covarying with distance. However, their conclusion was criticized by Johnson (2016), who claimed that the conclusion was based on inappropriate statistical analysis of data and that two of the three studied species might in fact show displacement. In Shaffer and Buhl (2016), the vesper sparrow (*Pooecetes gramineus*) was the only passerine species that did not respond to wind turbines, suggested reason being related to the species and habitat conditions, i.e. its life-history characteristic as the first species to occupy disturbed areas. For the nest-site selection of the grasshopper sparrow (*Ammodramus savannarum*), vegetation (i.e. habitat conditions) was assumed to play a more important role than distance from turbines, and snake predation causing failure to nesting was greater close to wooded edges than near wind turbines (Hatchett et al., 2013). In Stevens et al. (2013), three out of four passerine species showed no displacement from wind turbines, and the difference between species was assumed to be in their species-specific predator evasion strategies. Social species such as Sprague's pipit (*Anthus spragueii*), savannah sparrows (*Passerculus sandwichensis*), and meadowlarks (*Sturnella* sp.) were known to use open areas, and a high number of individuals was suggested to help in the detection of predators. In contrast, Le Conte's sparrow (*Ammodramus leconteii*) was known to hide in thick vegetation and was observed to show displacement (Stevens et al., 2013). In Devereux et al. (2008), corvids and Eurasian skylark (*Alauda arvensis*) did not show displacement and were indeed more likely to occur close to turbines than farther away. Potential reasons were suggested to be the small sampling size (methodological reason), but also higher food availability (habitat conditions) near turbines.

We found displacement in 24 cases of **raptors** (Table 2). The median distance was 500 m, ranging from 100 m for Montagu's harrier (*Circus pygargus*, Schaub et al., 2020) and the golden eagle (*Aquila chrysaetos*, Fielding et al., 2021, 2022) to 4000 m for the white-tailed eagle (*Haliaeetus albicilla*, Balotari-Chiebao et al., 2016a). Displacement was represented as changes in abundance (Campedelli et al., 2014; Garwin et al., 2011) and flight behavior near turbines (Cabrera-Cruz and Villegas-Patraca, 2016; Hull and Muir, 2013; Johnston et al., 2014; Santos et al., 2021, 2022), which were assumed to increase the birds' energy usage (Cabrera-Cruz and Villegas-Patraca, 2016). Functional habitat loss (Campedelli et al., 2014; Marques et al., 2019), and reduced breeding success were also observed (Dahl et al., 2012; Balotari-Chiebao et al., 2016a). Time could influence the results: Raptor abundances declined immediately after installation (Farfán et al., 2009) but showed some recovery, although not to the preconstruction level, 6.5 years later (Farfán et al., 2017).

Displacement was not found in six raptor cases, in which distances up to 1000 and 5000 m (median 1000 m) were studied. Due to the lack of displacement, young white-tailed eagles were observed flying into the wind turbine areas, exposing them to the risk of collision (Dahl et al., 2013; Krone and Treu, 2018). The flying behavior was observed to vary between individual eagles and in relation to food availability (Krone and Treu, 2018). Individuals of three *Buteo* hawk species did not show displacement from wind turbines regarding the selection of their nesting territories, but as rotor speed increased, avoidance flights increased, thereby mitigating collisions (Watson et al., 2018). As the avoidance flights occurred in the immediate vicinity of turbine blades, we did not classify them as displacement. Montagu's harrier (*Circus pygargus*, was expected to choose its nesting site according to the potential of vegetation covering the nests rather than the distance to disturbing features such as wind turbines (Hernández-Pliego et al., 2015). In Campedelli et al. (2014), the sparrowhawk (*Accipiter nisus*) was the only species of seven raptors showing no significant difference in observations between pre- and post-construction. The result was not discussed. Hawks, eagles, and falcons did not display avoidance behavior around wind turbines, suggesting that their displacement might be species- and site-specific (Smith et al., 2017).

Waders were the only bird group in which we found no displacement more often than displacement (11 vs. 8 cases, respectively). Displacement effects were manifested as decreased bird density and breeding bird abundance, the median distance being 500 m from wind turbines (Pearce-Higgins et al., 2009; Sansom et al., 2016; Shaffer and Buhl, 2016). Bai et al. (2021) showed that shoreline bird groups (all four cases classified as waders in this study) avoided crossing closely spaced (200 m) turbines. However, their abundance showed no significant change in the study area compared with the control.

Eleven cases of waders showed no displacement, median studied distance across the cases being 1000 m. The longest studied distance reached beyond 5000 m for the little egret (*Egretta garzetta*) in China, where bird abundance was not influenced (Xu et al., 2021). The abundance of little egrets depended on the habitat conditions, i.e. on the land use type suitable for feeding rather than the distance to the wind farm (Xu et al., 2021). Similarly, no evidence was found for golden plovers (*Pluvialis apricaria*) avoiding wind turbines in the UK (Douglas et al., 2011) or the USA (*Pluvialis dominica*, Homoya et al., 2017). These results contradicted those of Pearce-Higgins et al. (2009) and were assumed to be partially due to a single study location and the lack of an assessment before the construction of turbines (Douglas et al., 2011). Also weather conditions between the two survey years were expected to at least partly explain the observed population increase of the golden plover (Douglas et al., 2011). An interesting observation was made for killdeer (*Charadrius vociferous*), which not only exhibited high tolerance to turbines but also increased in density near them, as turbines were assumed to provide gravel substrates for nesting (Shaffer and Buhl, 2016). Four wetland species were not observed to avoid wind turbines, but the result was thought to arise largely from the small sample size and short duration (three years) of the study, which did not cover potential lag effects on the species (Niemuth et al., 2013).

Six cases of **waterfowl** showed displacement, the median distance being 500 m from wind turbines. The greatest distance was 1300 m (classified as "up to 5000 m") for the Chinese spot-billed duck (*Anas zonorhyncha*) and mallard (*Anas platyrhynchos*, Zhao et al., 2020). Displacement was often shown as changes in the selection of resting and feeding areas (Fijn et al., 2012; Harrison et al., 2018; Larsen and Madsen, 2000; Zhao et al., 2020). To avoid the wind turbines, the birds had to fly farther, which was assumed to require more energy (Madsen and Boertmann, 2008). The associated infrastructure and fragmentation of habitats caused more displacement than the turbines themselves (Larsen and Madsen, 2000). The distance from small wind turbines decreased in 8–10 years for pink-footed geese (*Anser brachyrhynchus*, Madsen and Boertmann, 2008), and Bewick's swans (*Cygnus columbianus bewickii*), which were found to feed closer to the wind turbines according to food availability (Fijn et al., 2012). The oldest study of waterfowl, by Meek et al. (1993), indicated that the only species to respond negatively was the red-throated diver (*Gavia stellata*). The reason for its decline was however uncertain in the study. The only case for waterfowl showing no displacement was also presented in Meek et al. (1993) as an aggregated result for ducks. It was notable that most studies of waterfowl were conducted using wind turbines with tower heights of <50 m.

Three studies of **several** bird groups showed displacement, and two no displacement, with the studied distances up to 100, 500 m, or 1000 m. Displacement was expressed as reduced abundance and flight rates during a 6.5-year post-construction period (Farfán et al., 2017), a reduction in avian activity during construction (Pande et al., 2013), and changes in aerial space and flight course (Therkildsen et al., 2021). Minderman et al. (2012) did not observe displacement in terms of bird activity related to small turbines (<50 m tower height) and assumed that turbine presence did not affect habitat use, or because displacement occurred at a different spatial scale than what was studied. There was only one study focusing on tall (even above 200 m) wind turbines. It showed that small forest birds (45 species) were sensitive to forest structure, season, and rotor diameter, but not to the proximity of wind turbines (Rehling et al., 2023). We therefore classified the study as showing no displacement. Nevertheless, the study showed that the height and number of turbines, along with rotor length, reduced bird abundance and richness (Rehling et al., 2023).

3.3. Bats

Bats showed displacement in 21 cases out of 29, the median displacement distance being 1000 m, which was also the maximum distance surveyed (Fig. 3). Apart from the studies by Minderman et al. (2012, 2017) on small wind turbines (<50 m tower height), other studies were conducted on turbines taller than 50 m, extending even to over 200 m (Ellerbrok et al., 2022). None of the bat studies included observations before wind power development.

Bat responses were strongly confounded by their foraging environment (forest, edge, open) and the echolocation range of the species (short, mid, long). Especially forest species (which are also short-term ecolocators, e.g., *Myotis* sp., *Barbastella barbastellus*) showed displacement, which was expressed as reduced abundance and activity around turbines (Apoznański et al., 2018; Barré et al., 2018; Ellerbrok et al., 2022; Leroux et al., 2022; Gaultier et al., 2023). Loss in habitat quality due to greater amount of open areas (Gaultier et al., 2023), noise (Ellerbrok et al., 2022) and red aviation lights were suggested as reasons for displacement (Barré et al., 2018). Displacement was observed in their optimal foraging habitats such as hedgerows (Barré et al., 2018) and forests (Gaultier et al., 2023), while the response could be the opposite (i.e., attraction) in less optimal open habitats (Leroux et al., 2022). Reduced activity near turbines resulted in a loss of foraging habitat, which in a tropical biodiversity hotspot was considered to threaten bat conservation (Millon et al., 2018). An interesting observation was made in Reusch et al. (2022), where 70 % of common noctule bats (*Nyctalus noctula*) showed avoidance behavior toward wind turbines, but when attraction was found, it occurred toward large turbines more than small turbines.

Displacement was not observed in eight cases, the studied distances being up to 1000 m. Edge-space foragers (and mid-range echolocators) *Pipistrellus pipistrellus* (Ellerbrok et al., 2022) and *P. kuhlii/nathusii* (Barré et al., 2018; Leroux et al., 2022) showed no response to wind turbines in forest landscapes. The lack of responses in *Pipistrellus pipistrellus* in Ellerbrok et al. (2022) contrasted with the observation by Barré et al. (2018) and Minderman et al. (2017), who observed displacement in an open landscape. It was suggested that forest clearing for wind turbines would create ideal foraging habitats for edge-space foragers (Ellerbrok et al., 2022). Regarding the lack of response in *P. kuhlii/nathusii*, a potential explanation was the contrasting behavior (avoidance vs. attractiveness) of the species within this bat group due to their different migratory status (Barré et al., 2018; Leroux et al., 2022). Open space foragers were observed to be attracted to wind turbines in open areas (Leroux et al., 2022) or during certain seasons (Ellerbrok et al., 2022). However, the suggested reasons for this attraction were inconsistent (Ellerbrok et al., 2022).

3.4. Terrestrial mammals

There were only two studies of canids, showing displacement for the red fox (*Vulpes vulpes*) up to 700 m in Poland (Łopucki et al., 2017) but not significantly for the coyote (*Canix lastrans*), studied to almost 10,000 m in Nebraska, USA (Smith et al., 2017). Displacement for the fox was assumed to be an indirect effect of wind power development and result from lower prey availability, especially of the hare, near wind turbines (Łopucki et al., 2017) (Fig. 3). Bird carcasses killed by wind turbines were proposed to attract the foxes, but there were no observations of bird remains to support this (Łopucki et al., 2017). Coyote was assumed to have habituated to the wind turbines by the time of the study, which was started eight years after the wind turbines became fully operational (Smith et al., 2017).

Of the nine studies of cervids, six were undertaken of the semi-domestic reindeer (*Rangifer tarandus*), all showing displacement. Three studies were carried out in the same area but on different occasions in Sweden (Skarin and Alam, 2017; Skarin et al., 2015, 2018). Displacement from 100 m to the access road (Colman et al., 2013) up to 15,000 m from the wind farm (Skarin and Alam, 2017) was observed. According to Colman et al. (2013), the distribution of the reindeer was more related to habitat quality than wind power development. Displacement nevertheless occurred especially during the construction phase (Colman et al., 2013; Skarin et al., 2015), although it was observed also during operation (Skarin and Alam, 2017). Calving time was most sensitive for the reindeer (Skarin et al., 2018; Tsegaye et al., 2017). The noise generated

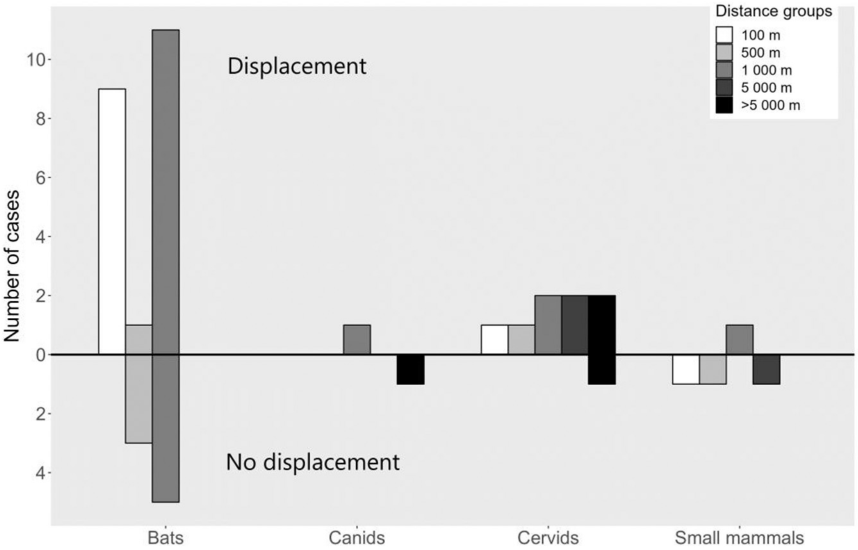

Fig. 3. Bats and terrestrial mammals classified in five distance categories and according to whether displacement was observed (bars above x-axis) or not observed (bars below x-axis).

by wind turbines was assumed to disturb the interaction between calves and mothers and negatively affect the reindeer's ability to hear predators (Skarin et al., 2018). As a consequence, displacement during operation occurred farther away than during construction (Skarin et al., 2018). Tsegaye et al. (2017) did not observe a change in the spatial use of areas near wind power development outside calving time. A high seasonal and annual variation in displacement was also observed by Eftestøl et al. (2023), and the reasons were assumed to be linked not only to natural movement patterns but also to herding activities, indicating human interference with the displacement.

Concerning wild cervids, the European roe deer (*Capreolus capreolus*) avoided wind farm interiors and proximity to turbines up to 600–700 m, potentially due to the difficulty of hearing or sensing their predators (Łopucki et al., 2017). The pronghorn *(Antilocapra americana)* showed behavioral changes during migration by avoiding turbines and moving more quickly near them, which was assumed to influence their foraging success or the availability of specific routes in the long run (Milligan et al., 2023). The Rocky Mountain elk (*Cervus elaphus*) was not adversely affected by wind power development, as evidenced by its home range, studied up to a distance of over 5000 m (Walter et al., 2006). The suggested reason was despite disturbance and habitat loss, riparian habitats that were critical seasonal habitats for the elk, were not altered by construction (Walter et al., 2006).

Of the four studies of small mammals, only European hare (*Lepus europaeus*) showed displacement up to 700 m (Łopucki et al., 2017), whereas three studies focusing on small rodents, shrews, hedgehogs, and hamsters did not show displacement (de Lucas et al., 2005; Łopucki and Mróz, 2016; Łopucki and Perzanowski, 2018). Large temporal variation of populations and difference in temporal trajectories between places (de Lucas et al., 2005), and behavioral and physiological characteristics (Łopucki and Mróz, 2016; Łopucki and Perzanowski, 2018) which were not monitored, were suggested to be reasons for the lack of responses. Also, the hamster was known to live near various types of human infrastructure, including settlements (Łopucki and Perzanowski, 2018).

4. Discussion

4.1. Displacement of the studied taxa

In our review, 63 %, 72 %, and 67 % of the cases concerning birds, bats, and mammals respectively showed displacement as a result of wind power development. Cranes (3 out of 3 cases), owls (2 out of 2 cases), and semi-domestic reindeer (6 out of 6 cases) showed the most consistent and longest displacement distances, on average up to or over 5000 m. Gallinaceus birds were also displaced on average up to 5000 m, but the results were strongly confounded by reports of no displacement (7 out of 18 cases). Bats showed quite consistent displacement (21 out of 29 cases), on average up to 1000 m, and waterfowl (6 out of 7 cases) and raptors (24 out of 30 cases) up to 500 m. Passerines were displaced on average up to 500 m in half of 32 cases, and waders up to 500 m, but only in 8 out of 19 cases. In general, there was a considerable variation in the results between and within taxa, study design, methodology, and the studied variables. Concerning observations of no displacement methodology was suggested to explain the results at least partially in 33 cases. Species-specific reasons and habitat conditions were suggested in 23 and 19 cases, respectively. Over half the studies had no data before the wind power development, and most studies assessed the impacts of turbine towers under 100 m in height.

We found proportionally more bird cases reporting displacement (63 %) than the review by Marques et al. (2021), who reported displacement for approximately 40 % of cases. One reason may be that we used only studies including quantitative distance data, which may have increased significant responses on displacement. Apart from waders, our observations are analogous to the meta-analysis of Stewart et al. (2007), who synthesized global data on bird abundances as a response to wind power development. In their study, waterfowl were the most sensitive group, followed by waders, raptors, and passerines. Some analogy in our results also occurs with the meta-analysis by Benítez-López et al. (2010), in which large mammals avoided infrastructures (including wind power development) at longer distances than did birds. Among birds, raptors were found to be closer to the infrastructure than other bird taxa.

We did not analyze separately whether displacement resulted from changes in area use and behavior or population abundances. Many studies combined these effects, making the separation unreasonable. Behavior and population change nevertheless go hand in hand (Bro-Jørgensen et al., 2019). Studies on birds showed that disturbance and functional habitat loss can drive species farther away, which was suggested to increase energy expenditure, and intensify competition for resources elsewhere (e.g. Fijn et al., 2012; Cabrera-Cruz and Villegas-Patraca, 2016; Harrison et al., 2018). Also other behavioral responses, such as adjustment of vocalization as a response to turbine noise, observed in passerines, may eventually have consequences at the population level (Gómez-Catasús et al., 2022). For example, turbine noise has been observed to mask territorial signals of European robin (*Erithacus rubecula*), which can reduce reproductive success because more energy is required to defend territories (Zwart et al., 2016).

The vulnerability of bird populations to wind power development can be high especially among long-lived species (Fielding et al., 2021). For example, owls and raptors have slow maturation and reproduction rates (Farfán et al., 2009; Garwin et al., 2011). If displacement influences their abundance during the breeding season (López-Peinado et al., 2020), increases the abandonment of nests (Husby and Pearson, 2022), or decreases the success of breeding (Balotari-Chiebao et al., 2016a,b), and these effects occur with increased collisions (e.g., Husby and Pearson, 2022), population effects are inevitable. Habituation to wind turbines has rarely been observed in raptors, suggesting that they do not adjust easily to the presence of a wind farm, and population changes may therefore be permanent (Campedelli et al., 2014 and the references therein).

Bats display a mixture of displacement and attraction, of which displacement occurs at longer distances and attraction around turbines (Millon et al., 2015; Reusch et al., 2022). The maximum observed displacement distance was 1000 m, but this might be an underestimate, since longer distances were not studied (Barré et al., 2018). Displacement seems to vary, depending on the preferred foraging habitat (forests or hedgerows vs. open habitats), echolocation range, and migratory pattern, but in general, the mechanisms leading to displacement remain largely unknown (Barré et al., 2018). Many studies report negative population effects, and even extinctions have been anticipated if wind power development continues to increase (Friedenberg and Frick, 2021). Despite initial population declines and changes in species diversity due to habitat change and displacement, some bat populations can recover, as shown in a study of 22 tropical bat species in Mexico (Briones-Salas et al., 2017).

There are still relatively few studies of displacement distances among terrestrial mammals. Wind power development may induce shifts in the area use and migration pattern of large mammals due to fragmentation, changed habitat quality, and disturbance. Almost half, i.e. 6 out of 15 cases, focused on semi-domestic reindeer in mountain areas of northern Scandinavia, which is a region with high potential for future wind power development. The long displacement distances to wind power indicate a further decrease in potential reindeer pasture areas, which have already been degraded due to forestry, mining, grazing, and climate change (Kivinen, 2015; Miina et al., 2020; Tonteri et al., 2021). Nevertheless, since semi-domestic reindeer are increasingly kept in enclosures and fed during the winter, their habituation to people may increase, and in the long run, they may also habituate to wind power development more than wild animals.

Small mammals are sensitive to habitat loss and fragmentation due to their limited ability to move (Merrick et al., 2021). Their displacement distance may therefore be linked to habitat specificity: If a species can use varying types of habitats, the displacement is weaker. The abundance of large mammalian predators has been observed to increase in wind power development areas due to the increased access through gravel-roads (Gómez-Catasús et al., 2021).

4.2. "No displacement" observations

Approximately one third of cases showed no significant displacement. This was most often explained by methodological reasons such as the small sample size, lack of observations before construction, short observation time, few or single observation sites, and the difficulty involved in separating distance effects from habitat conditions. BACI studies have been called for in previous reviews (Marques et al., 2021; Schöll and Nopp-Mayr, 2021), but there was no trend of increasing numbers of BACI studies in this review. One reason may be the rapid expansion of wind power, which provides limited opportunities for scientifically valid pre-construction monitoring. BACI studies also require more resources due to their longer duration and the need to harmonize between sites and periods (Christie et al., 2019). Despite its robustness, BACI may not be an optimal study design for example for small mammals, since their large annual fluctuations make it difficult to detect differences before, during and after wind farm construction (de Lucas et al., 2005; Łopucki and Mróz, 2016).

More interestingly, no displacement observations, including attraction, arose also from species-specific and individual characteristics such as the young age of raptors (Dahl et al., 2013; Krone and Treu, 2018) and predator evasion strategies such as passerines accumulating in open areas in large numbers (Stevens et al., 2013). Species-specific reasons and habitat conditions were often presented together, being related to habitat preferences, such as life-history characteristic of passerine species preferring disturbed habitats (Shaffer and Buhl, 2016), attraction to wind turbines by waders due to the utilization of gravel substrate for nesting (Shaffer and Buhl, 2016), and by gallinaceous birds due to digestion material (Douglas et al., 2011; Łopucki et al., 2017). Attraction may induce collisions, which in gallinaceous species, for example, occur toward wind towers rather than rotors (Stokke et al., 2020). Concerning bats, attraction has been suggested to result from increased foraging opportunities due to an accumulation of insects (Rydell et al., 2010) and the confusion of wind turbines with tall trees (Cryan et al., 2014; Goldenberg et al., 2021). Rehling et al. (2023) also pointed out that sensitive species might be lost during construction, and if monitoring were done during the operation phase, tolerant generalist species might show little response to wind power development.

4.3. How can information about displacement and no displacement be used for mitigation?

Guidelines for safety distances for wind power development are increasingly important due to the rapid increase of wind power capacity. The mitigation hierarchy involving avoidance, minimization, and compensation phases (BBOP, 2012) has been suggested as the strategy to minimize the negative population effects of wind power development (Rodrigues et al., 2015). Concerning the avoidance phase, displacement distances provide information on the extent of functional habitat loss of wildlife taxa. Data can be used for appropriate siting of wind power development by compiling and estimating spatial overlap with proposed wind farms. For example, the use of bird and bat migration routes and other valuable habitats can be avoided if suitable degraded and low-quality habitats and habitats located close to infrastructure are found. For example in Finland, former peat excavation sites provide potential areas for wind power production due to their high degradation (Räsänen et al., 2023).

Although displacement distances have been found to be unaffected by technical properties such as the size of turbines (Pearce-Higgins et al., 2012; Stewart et al., 2007) it is expected that increased turbine sizes and numbers will inevitably increase displacement. It is therefore probable that wind power development cannot be fully avoided at all high-quality sites. In this case the minimization phase is crucial. For example leaving small-scale high-quality habitats within wind farms has been observed to minimize the impact of habitat loss on elk (Walter et al., 2006). Concerning the prevention of collisions information about the lack of displacement is important. Painting wind towers black has been observed to partially prevent collisions of gallinaceous birds (Coppes et al., 2020b; Stokke et al., 2020), and painting the rotors decreases mortality by over 70 % for a range of birds, especially raptors (May et al., 2020). Automatic turbine shutdown during the vicinity of griffon vultures has reduced collision mortalities by over 90 %, with an estimated loss of <0.5 % in energy production (Ferrer et al., 2022). Implementing turbine curtailment has caused a 63 % decrease in bat fatalities (Adams et al., 2021), and a modern algorithm-based curtailment which uses a wide set of environmental data to predict bat activity seems even a more promising method to reduce bat fatalities (Barré et al., 2023).

Compensation is the last phase along the mitigation hierarchy and it involves restoring or creating high-quality habitats in nearby areas of wind power development. For example, protecting neighboring forests (Ellerbrok et al., 2022) and building aquaculture ponds (Xu et al., 2021) have been suggested, although they should be done taking into account the risk of collision. Bats have been shown to respond positively to fallows, hedgerows and grass strips that were used as compensation measures, but the response seems to be species-specific and season-dependent (Millon et al., 2015). Wind power companies could participate in voluntary compensation schemes, which would help alleviate negative biodiversity impacts and increase the public acceptance of wind power.

A challenge in setting safety distances and mitigation strategies is that knowledge is scattered and highly variable in behavioral responses across taxa, sexes and life-cycle stages of individuals, with responses varying between years and seasons. This variability requires studies of the physiological and behavioral mechanisms underlying displacement (and attraction), long-term monitoring of species-specific, spatial and temporal differences in responses, and research using standardized protocols and effective indicators. Consistently measured data on the mechanisms underlying displacement could be used in models that generalize responses over specific taxa and ecosystems. Linking information about displacement with economy and energy costs and benefits could then be used to optimize mitigation strategies for wind power development.

4.4. Methodological issues

Our review has many methodological limitations. The studies were manually screened based on titles, abstracts, and thereafter by reading the abstract and eventually the research article. This approach poses challenges concerning whether we accurately included or excluded each study in the review. For example, an important finding of a study could be the negative impact of proximity to wind power development on a species. If no numerical distance data was provided or could be reliably derived from figures or tables, we had to exclude such studies. This may lead to a bias in our observations, potentially underestimating studies showing displacement. Because we did not count studies showing displacement without numerical distance data, we cannot estimate how large the bias was. Moreover, the observed displacement distances did not necessarily reveal whether the displacement effects would also have occurred farther.

We considered only peer-reviewed scientific studies published in English, which ensured that they were carried out using scientifically evaluated protocols. This inevitably excluded a considerable number of potentially relevant studies published in reports and the gray literature, resulting in a bias toward European and North American studies. Nevertheless, adding the gray literature would have resulted in a new bias toward openly available studies published in a comprehensible or translatable language.

4.5. Conclusion

In our review two thirds of 160 cases show displacement, and there is large variation in the displacement distances within and among taxa. Concerning especially cranes, owls, semi-domestic reindeer and gallinaceous birds the effects of wind power development can extend for several kilometers, suggesting a significant loss of functional habitat for these species. For flying species such as raptors and bats, displacement and collisions create a double-edged sword that causes population decline regardless of whether displacement occurs. Information on displacement distances reported in this study can be used to mitigate the negative effects of wind power by avoiding high-quality areas important for threatened species, by minimizing the small-scale habitat loss and collisions caused by wind power, and by restoring or creating high-quality habitats to compensate for functional habitat loss.

CRediT authorship contribution statement

Anne Tolvanen: Conceptualization, Methodology, Investigation, Writing – Original Draft, Funding acquisition.

Henri Routavaara: Data curation, Investigation, Writing – Original Draft.

Mika Jokikokko: Data curation, Investigation, Writing – Original Draft.

Parvez Rana: Conceptualization, Methodology, Investigation, Visualization, Writing – Original Draft.

Declaration of competing interest

The authors declare no competing interests.

Data availability

Research data (the reviewed studies) are listed and described in the Supplementary Material.

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Appendix A. Supplementary data

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