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Running title: Effects of power lines on breeding birds

Effects of overhead power-lines on the density of ground-nesting birds in open sub-arctic habitats

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Abstract

Yearly electricity production has increased steadily in the world in recent decades and the associated overhead power lines are widespread and occur across urban and natural habitats, and often in remote areas where there is little other anthropogenic influence. Here we assessed the effects of overhead power lines on the density of ground-nesting birds in the Icelandic lowlands which host several populations of international importance. The combined breeding density of the eight study species increased significantly from ~112 birds/km^2 close (<50 m) to the power lines to ~177 birds/km^2 away (450-500 m) from the power lines, with two of these species (Eurasian Whimbrel *Numenius phaeopus* and Common Redshank *Tringa totanus*) increasing significantly with distance from power lines and six species (European Golden Plover *Pluvialis apricaria,* Common Snipe *Gallinago gallinago*, Meadow Pipit *Anthus pratensis*, Black-tailed Godwit *Limosa limosa*, Dunlin *Calidris alpina* and Redwing *Turdus iliacus*) showing no changes. These findings suggest that power lines can influence the breeding density of ground-nesting bird species in their vicinity and that accounting for such effects when planning future infrastructure will be imperative.

Keywords: Anthropogenic change, waders, power lines, biodiversity, conservation, transmission lines

Human-driven land use change and infrastructure establishment are important drivers of habitat loss and degradation which can have substantial effects on native wildlife (Foley *et al*. 2005). Introducing anthropogenic structures into open habitats can result in habitat loss for wildlife populations and also affect the surrounding habitat through changes in vegetation, predation risk and pathogen invasion (Marzluff *et al*. 2001, Prugh *et al*. 2009, Runkovski & Pickering 2015, Becker *et al*. 2015). These processes can cause changes in demographic parameters such as survival and/or productivity (Lepczyk *et al*. 2004, Loss *et al*. 2015). Additionally, the presence of anthropogenic structures, or the increase in human traffic which often accompanies them, may prompt individuals to alter their patterns of use of landscapes, by avoiding or being drawn to the structures (Silva *et al*. 2010, Barrueto *et al*. 2014, Łopucki *et al*. 2017, Watts 2017).

Annual electricity production, accompanied by electrical infrastructure, has increased steadily in the world in recent decades and further increases in production are anticipated (IEA 2020). Electricity is typically generated in one area and transported to where it is used. This transportation usually goes through power lines which can be either overhead or underground (Fenrick & Getachew 2012). With the growing demand for renewable energy, the distance electricity needs to travel from energy sources to consumers may increase further (Jorge & Hertwich 2014), resulting in an increased number of power lines. Currently, the European power transmission grid contains 301,000 km of overhead lines (Jorge and Hertwich 2014) which are widespread and found across urban, semi-urban, agricultural and natural habitats, and often in remote areas where there is little other anthropogenic influence.

The introduction of power lines in open habitats could potentially provide additional places for birds to nest, for example an estimated 25% of the population of Portuguese White Storks *Ciconia ciconia* nest on transmission towers (Moreira *et al*. 2017). However, collision with power lines can be an important source of bird mortality (Bevanger & Brøseth 2001, Loss *et al*. 2015). In addition, the presence of power lines may change the distribution of mammalian predators, for example through scavenging for carcasses under power lines and using towers as cover in open habitats, and power lines and towers can be used by avian predators for perching and hunting (Ponce *et al*. 2010, DeGregorio *et al.* 2014). Such changes in predator distribution and activity may alter predation pressure and perceptions of risk in surrounding areas (DeGregorio *et al.* 2014, D'Amico *et al.* 2018). The visual obstruction, noise, presence of humans during maintenance procedures and habitat loss in areas containing the power lines (Bevanger & Brøseth 2001, D'Amico *et al.* 2018) may also make these areas less attractive for ground-nesting species. Finally, power lines emit ultraviolet light (Tyler *et al.* 2014, Engels *et al.* 2014) and generate an electromagnetic field which has been shown to affect avian behaviour, physiology and development (Fernie & Reynolds 2005, D'Amico *et al.* 2018).

In Iceland, the vast majority of electricity is produced from hydropower (~70%) or geothermal (~30%) sources (Hjaltason *et al.* 2020). Both hydro and geothermal power plants can only be established in locations where geothermal heat or large amounts of water are readily available, and the electricity produced needs to be transported to urban or industrial areas. Iceland has the highest electric power consumption per capita in the world (The World Bank 2014), with most (70-80%) being used by companies that produce either aluminium or ferrosilicon (Samtök iðnaðarins 2009, Orkustofnun 2011), and ~3% being used in data centres (KPMG 2018, Landsvirkjun 2020). With a growing human population, electrification of various systems and increasing infrastructure, along with plans for linking Iceland to electric grids in other countries, the demand for electricity is increasing in the country (Landsvirkjun 2015), and power lines in the Icelandic landscape are therefore likely to increase in the near future. Since agriculture in Iceland is not yet highly intensive or extensive and the density of anthropogenic structures is not high compared to the rest of Europe (Torres *et al.* 2016, Jóhannesdóttir *et al.* 2019), the Icelandic lowlands still contain large areas of relatively undisturbed semi-natural wetland, grassland and heathland habitats which support internationally important breeding populations of several ground-nesting bird species, particularly waders (Gunnarsson *et al.* 2006, Jóhannesdóttir *et al.* 2014, Skarphéðinsson *et al.* 2016). Wader breeding densities are estimated to be, on average, between 123-276 birds/km^2, depending on the habitat type (Jóhannesdóttir *et al.* 2014). Although little is currently known about the effects of power lines on birds in the Icelandic landscape, there are some recorded cases of birds colliding with power lines, mostly involving large species such as Whooper Swan *Cygnus cygnus* and White-tailed Eagle *Haliaeetus albicilla* (Hilmarsson & Einarsson 2009, Schmalensee & Skarphéðinsson 2021), but also smaller birds such as European Golden Plover *Pluvialis apricaria* (hereafter Golden Plover), Dunlin *Calidris alpina*, Common Snipe *Gallinago gallinago* (hereafter Snipe) and Redwing *Turdus iliacus* (Snæþórsson *et al*. 2018). Here we aim to assess the effect of overhead power lines on the density of ground-nesting birds in the Icelandic lowlands and identify which properties of these structures may influence these patterns.

METHODS

Bird counts

This study was conducted in southwest Iceland between the 6th of May and the 20th of June 2019 by transect counts (Figure 1). Transects were not conducted in heavy rain or if wind was over 7 m/s due to low detectability of the study species (Hoodless *et al.* 2006). Transects were chosen by selecting patches of homogenous habitat along power lines in the Icelandic lowlands (Figure S1). To eliminate any observer effect on the distribution of birds, transects were walked either to (n = 40) or from (n = 45) the power lines and this was included as direction of transect in the analysis. To minimise potential confounding effects, each transect was at least 100 m away from all other anthropogenic structures or habitats (houses, roads, agricultural fields and forest plantations). Before initiating each transect survey, the observer waited for 5 minutes at the starting position, or until all birds had settled, and then the transect was walked at a steady pace. Transect length varied between 300-500 m, depending on the area of homogenous habitat available (see Table 1 for habitat types). Birds were counted along 84 transects which were perpendicular to power lines (Fig. 1), and evenly distributed between starting at pylons (n = 42) or at the lines in between two pylons (n = 43). All birds seen within 100 m in each direction of the transect were recorded where first seen (distance determined with a laser range finder), and distance from the power line recorded (determined from GPS). For each power line, we recorded the number of cables, material of pylons, height and voltage of the line (Supporting Information Table S1). All power line characteristics were strongly correlated to voltage of line, with the largest lines which transported 220 kV had three or more cables, metal pylons and a mean height of 25 m (±7.4 SE), while lines that transported lower voltages (132 kV or 66 kV) always had three cables, most had wood pylons and their mean height = 11 m (±2.7 SE) (Table S1).

Statistical analysis

Each transect was divided into intervals of 50 m, each corresponding to 1 hectare (Table 1). The recorded density of birds within these intervals (for each species separately and all the study species combined) was calculated and set as the response variable in a generalized linear mixed model (GLMM) with a Poisson distribution, with distance from power line (in 50 m intervals) as an explanatory variable using the R-package glmmTMB (Brooks *et al*. 2017). Most of the study species have large home ranges, and therefore the data contains multiple zeros, which have been accounted for in all models by adding a zero-inflation parameter (*ziformula=~1*) (Bolker 2016). Transect number nested within habitat was included as random factor to account for non-independence of intervals within the same transect and varying bird abundances between habitat types. Distance to water (extracted from GIS layers (Landmælingar Íslands 2022)) and slope of transects (calculated from the elevation difference between the beginning and end points of the transects) were included as fixed factors in the model to account for any effect of these landscape structure variables on breeding densities (Whittingham *et al*. 2002, Eglington *et al*. 2008). To explore the potential effects of structural difference of lines, voltage (in two categories: <u>high</u>, 220 kV and <u>low,</u> 132 kV and 66kV) was included as a fixed factor along with an interaction term. To account for the effect of the observer on the distribution of the birds along the transect, an additional interaction term between direction of transect and distance from power lines was included in the models. Five models were constructed with all possible combinations of aforementioned factors, along with a null model (Table 1, models A-E). These models were subsequently compared (for each species separately and all species combined), and the model with the lowest AIC value chosen, provided it gave a significantly better fit than a simpler model ($\Delta AIC<2$). All data analyses were performed in RStudio (RStudio Team 2016, R Core Team 2017) and package ggplot2 (Wickham 2016) used for graphs.

RESULTS

In total, 1067 birds of 21 different species were recorded on the 84 transect surveys (Supporting Information Table S2). The vast majority (~91%) belonged to eight species which were used in the subsequent analysis: Dunlin, Black-tailed Godwit *Limosa limosa* (hereafter Godwit), Golden Plover, Meadow Pipit *Anthus pratensis*, Common Redshank *Tringa totanus* (hereafter Redshank), Redwing, Snipe and Eurasian Whimbrel *Numenius phaeopus* (hereafter Whimbrel). For all eight species combined, the areas closest to the power lines (0-50 m) supported densities of ~112 birds/km^2 (±13 SE) which increased by approximately 58% to ~177 birds/km^2 (±24 SE), between 450-500 m away from the power lines (Fig. 2). Estimates from the model for all species combined showed, on average, a 4% increase per 50 m increment from the power lines. At the species level, Redshank and Whimbrel density increased significantly with distance from power lines (18% and 10% per 50 m, respectively; Fig. 2, Table 2), but no other significant effects of distance from power lines or voltage were found for other species (Table 2).

DISCUSSION

The combined breeding density of the eight study species was lowest close to power lines and increased with distance, with two species (Whimbrel and Redshank) showing significant increases and the remaining species showing no changes. Power lines are expected to increase in frequency in Iceland, and the world, in future years and with bird density being on average ~58% higher at the end of transects (450-500 m) compared to the first 50 m surrounding the lines, the repercussions of long power lines, which can be thousands of kilometres and run through semi-natural habitats, may be considerable. Considering this depressed density of several ground-nesting bird species in the vicinity of overhead power lines, underground power lines may be more beneficial, even though this may cause a temporary disturbance to the ground.

Previous research on waders has shown that they are often found in lower densities close to anthropogenic structures (Pearce-Higgins *et al.* 2012, Fernández-Bellon *et al.* 2018, Żmihorski *et al.* 2018). Overhead power lines differ from some of these structures as they do not introduce a physical barrier to the landscape, nor do they notably increase human traffic. It is possible that lower bird density in the proximity of power lines may be due to increased collision risk, but this is difficult to establish directly as carcasses are likely to be removed by scavengers (Ponce *et al.* 2010). Another possibility is that predation risk increases close power lines, if they are used as perches by avian predators (DeGregorio *et al.* 2014). Common Ravens *Corvus corax*, which are known nest predators in Iceland (Laidlaw *et al.* 2020) were seen on pylons during the course of this study. This could cause an increase in actual or perceived predation rate close to the power lines which may affect the distribution of ground-nesting birds. Power lines may also cause disturbance due to noise, ultraviolet discharge or electromagnetic fields, which could potentially cause birds to avoid nesting close to power lines. Any noise originating from the power lines was not noticeable to the observer during the survey, but it is possible that birds sense low frequency sounds or electromagnetic currents stemming from the power lines, as well as detecting light frequencies (UV light) not noticeable to humans (Engels *et al.* 2014, Tyler *et al.* 2014, Plumb *et al.* 2019). The reason why significant reductions in density close to power lines were apparent for Whimbrels and Redshanks but no other species is not clear, especially as previous studies have found breeding waders of several species in lower densities surrounding novel structures such as trees (Pálsdóttir *et al. in review*, Żmihorski *et al.* 2018) and anthropogenic structures (Wallander *et al.* 2006, Pearce-Higgins *et al.* 2009). It is possible that sample sizes were too low to detect effects in some species or that the distances over which it was possible to conduct transects within the same habitat was not long enough to detect effects. Breeding waders often occur at relatively low densities and, for some species, the small numbers of birds recorded on these transects (e.g. Golden Plovers for which a total of 44 birds, or ~1 bird per two transects, were recorded) is likely to have limited the power to detect effects of power lines. Increasing the number of transects would perhaps make these patterns clearer but the availability of suitable sampling sites was limited, as many power lines occur close to urban areas or parallel to roads and were thus not included in the study. For Golden Plover and Godwit, densities in the furthest distance band from the power lines were higher than all other bands (Fig. 2), which might suggest that effects could occur over larger distances than

500 m, but this remains to be assessed. It does not appear that effects of power lines vary depending on species' differences in nesting strategies, as Whimbrels nest in the open in areas with short vegetation (similar to Golden Plovers), while Redshanks conceal their nests (similar to Godwits and Snipe) in more vegetated areas (Jóhannesdóttir *et al*. 2014, Laidlaw *et al*. 2020).

Most studies addressing the effect of power line presence on birds focus on collision risk, changes in predation pressure and secondary effects such as electromagnetic fields (Fernie & Reynolds 2005, D'Amico *et al*. 2018). Here we have identified reduced breeding densities of ground-nesting birds in the vicinity of power lines, however, the mechanisms driving these patterns are not yet known. Further studies quantifying demographic variation in relation to power-line presence (e.g. reductions in survival through collision risk and/or changes in breeding success as a consequence of predator use of pylons and overhead lines) may be informative, both in Iceland and other landscapes with power-lines and important ground-nesting bird populations. Additionally, as the human population grows, the amount of undisturbed land decreases (Torres *et al*. 2016) and opportunities to quantify the communities and abundances that can be supported in large patches of open habitats become rarer. It is imperative to utilize current opportunities to identify the effects of structures such as power lines, and consider any identified effects in future infrastructure planning, before areas becomes saturated with anthropogenic developments.

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DATA AVAILABILITY STATEMENT

We will archive the data in Dryad digital repository https://datadryad.org/).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Characteristics of the power lines

Table S2. Total number of birds of each species counted during the surveys

Table S3. AIC values of models constructed for all study species combined and separately for each species.

Table S4. Relative bird abundance per interval compared to the most distant interval

Figure S1. Habitat type of each transect sampled in this study

Tables and figure legends

Table 1: The model variables and structure used to explore effects of power lines on breeding birds in lowland Iceland

Variable	Unit	Definition
Bird density	Birds/ha	Total number of birds counted per interval (1 ha)
Interval	1-10	Distance bands of 50 m on transects from closest (1) to furthest away (10) from power lines. Measured with a GPS tracker.
Transect	Transect number	Transect identity
Direction	Towards or Away	If the transect was walked to or away from the power line
Voltage	Low/high	Voltage of the power line (Landsnet, 2019) categorized as high (220kV) or low (66 kV or 132 kV)
Habitat	Poor heathland/rich heathland/grassland/ semi-wetland/wetland	Classification of transect habitat type, from the Icelandic farmland database (Gísladóttir et al., 2014)
Distance to water	M	Distance from transects to water bodies extracted using ArcMap and hydrological data from the National Land survey of Iceland (Landmælingar Íslands, 2022)
Slope	Elevation difference/meter	Calculated from the elevation at each end of the transects, and length of transect

Model structure

Model A	Bird density ~ slope + distance to water + (1|Habitat/Transect)
Model B	Bird density ~ Interval + slope + distance to water + (1|Habitat/Transect)
Model C	Bird density ~ Interval*Direction + slope + distance to water + (1|Habitat/Transect)
Model D	Bird density ~ Interval*Voltage + slope + distance to water + (1|Habitat/Transect)
Model E	Bird density ~ Interval*Voltage + Direction + Interval:Direction + slope + distance to water + (1|Habitat/Transect)

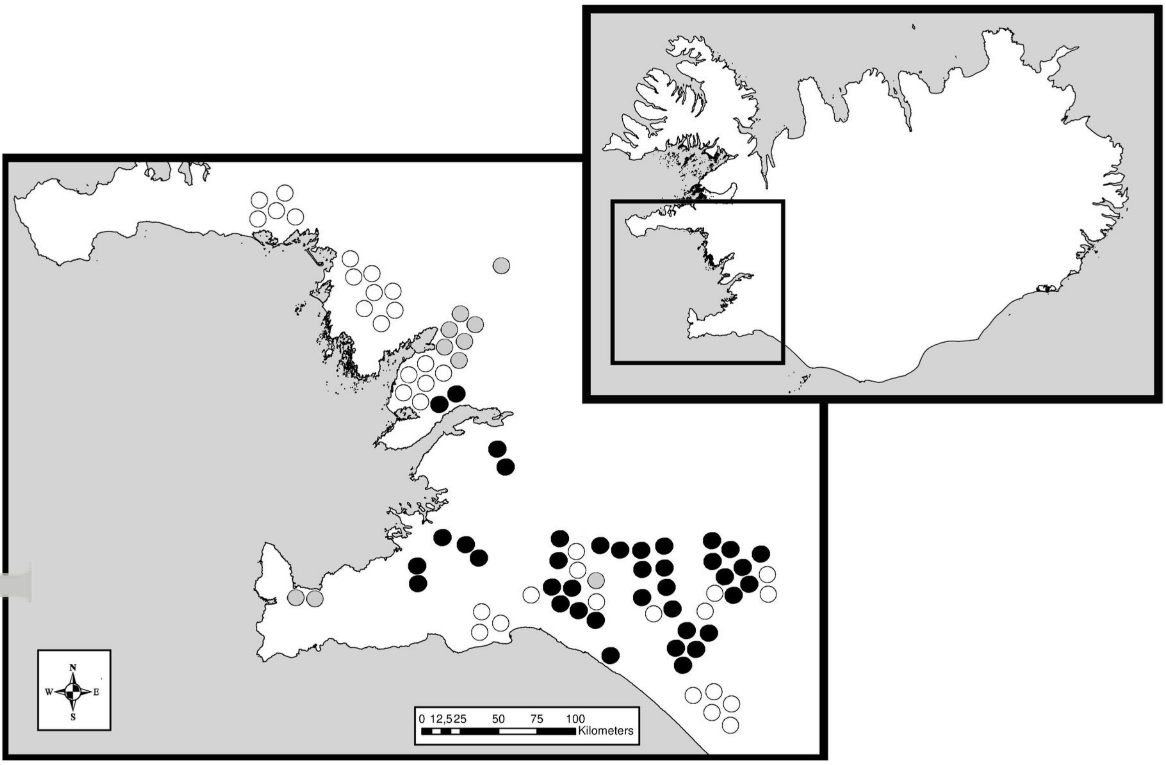
Table 2: The effects (±SE) of distance from power line (interval), voltage and their interaction term on numbers of birds of eight species separately and all eight combined. Estimates from the GLMM models (Table 1) with the lowest AIC values (see Supporting Information Table S3). Asterisks represent significance ($P < 0.05$ *; $P < 0.01$ **; $P < 0.001$ ***).

Species	Individuals counted (*n*)	Best model	(intercept)	Interval	Direction	Interval:Direction[i]	Distance to water	Slope
All species	974	B	0.13 (±0.20)	0.04 (±0.01)**			0.01 (±0.07)	-0.99 (±0.55)
European Golden plover	44	B	-4.57 (±0.83)	0.09 (±0.06)			0.67 (±0.23) **	0.99 (±1.92)
Common Redshank	46	B	-2.09 (±0.85)	0.17 (±0.06)**			-0.09 (±0.25)	-1.01 (±1.70)
Dunlin	47	A	-2.79 (±1.00)				-0.02 (±0.35)	3.20 (±2.43)
Redwing	49	C	-1.01 (±0.98)	-0.15 (±0.08)	-0.63 (±0.72)	-0.06 (±0.16)	0.30 (±0.23)	0.66 (±1.86)
Black-tailed Godwit	67	A	-2.32 (±0.98)				0.41 (±0.23)	1.08 (±1.30)
Eurasian Whimbrel	97	B	-1.83 (±0.51)	0.09 (±0.04)*			-0.05 (±0.18)	-2.54 (±1.48)
Common Snipe	159	A	-1.98 (±0.33)				0.04 (±0.17)	0.65 (±1.21)
Meadow Pipit	465	A	-0.32 (±0.17)				-0.11 (±0.10)	-1.80 (±0.77)*

[i]Reference direction: away from

Figure 1: Locations in southwest Iceland of the 84 transects surveyed perpendicular to power lines of 66 kV (white), 132 kV (grey) and 220 kV (black) voltage.

Figure 2: Mean bird densities per ha (±SE) at 50 m intervals with increasing distance from power lines for the eight most abundant species combined and individually. The horizontal lines represent model predictions, with the shaded interval as the standard error, and are shown for species with significant changes in density with distance from power lines (Table 2).



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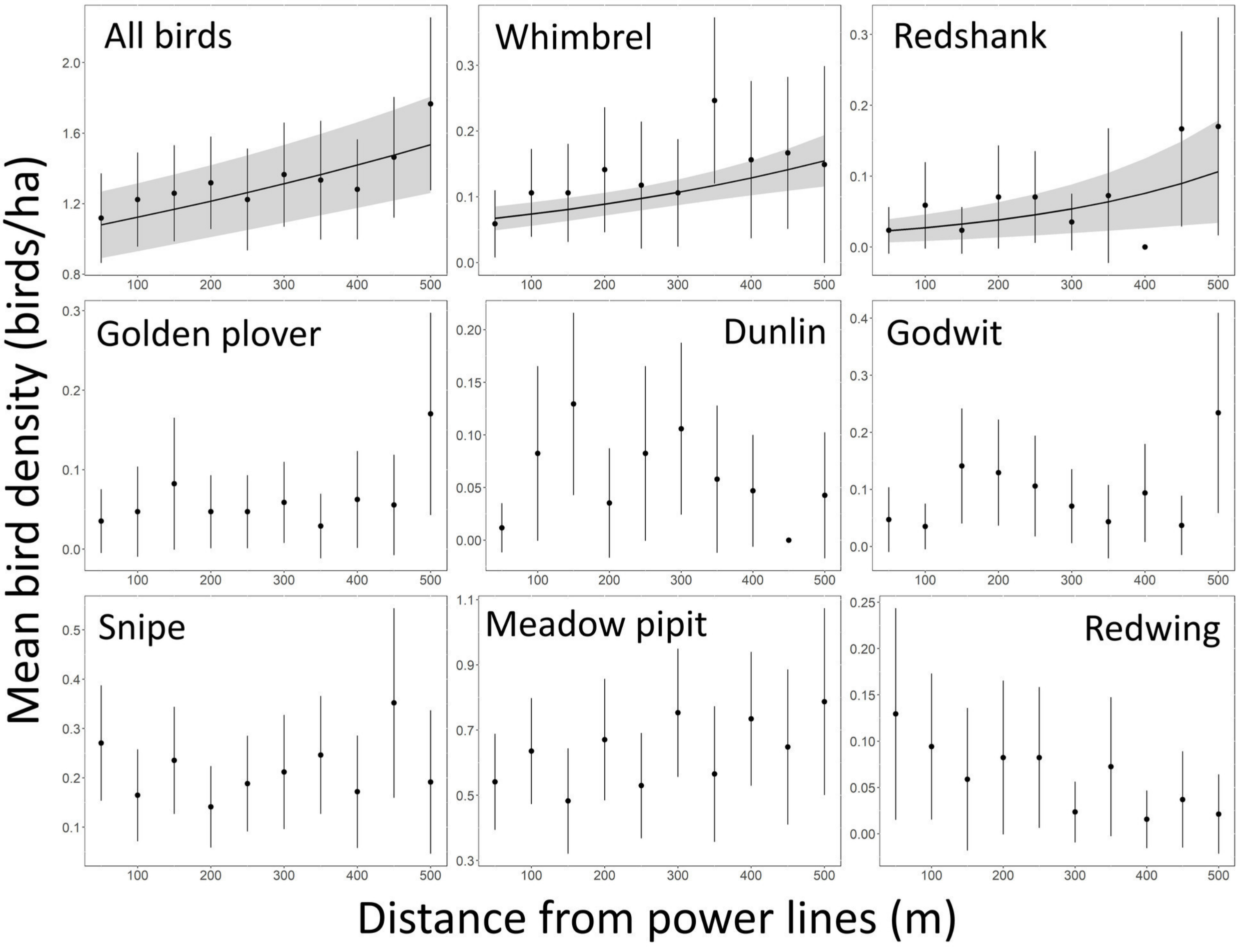

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