UNIVERSITY OF GOTHENBURG

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SOLAR POWER PLANTS AND BIRD POPULATIONS IN THE AGRICULTURAL LANDSCAPE

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Abstract

Solar power is rapidly increasing in Sweden, with many solar parks constructed on agricultural land. At the same time, farmland bird species are suffering a steep long-term population decline. The effects of solar parks on local bird populations are not well known. Previous studies from Europe and other continents are suggesting opposing results. To estimate the effects of solar parks on bird populations in the agricultural landscape, a bird survey was conducted in Western Sweden during the breeding season of 2025. In total, 200 line transects were carried out, surveying 10 solar parks and 10 adjacent reference areas (agricultural fields), during two periods, to account for seasonal variability due to early and late migrants. Detection probability was shown to differ greatly between solar parks and reference areas, with lower detection probability in the solar parks. The effects of solar parks on population density and species diversity were examined using generalized linear mixed models (GLMM), while controlling random effects as well as testing for other potential explanatory variables. Solar parks were shown to increase population density, but not species diversity, compared to adjacent agricultural fields. Additionally, population density was shown to be positively influenced by low vegetation cover and higher wind. Species diversity increased with the later period and increased size of the area. The average density of threatened birds was not shown to differ between area types. Certain species or species groups seemingly preferred reference areas as they were not observed in the solar parks. An edge effect was found inside the solar parks, with higher diversity in the outer edges compared to the interior parts of the parks. The results suggest solar parks contain more individuals but potentially fewer species than surrounding agricultural fields. Further species-specific studies are desirable, to avoid additional pressure on threatened bird populations.

Summering

Solkraft är en snabbt växande energikälla i Sverige. En stor del av solenergin utvinns med hjälp av solkraftsparker placerade på jordbruksmark. Samtidigt är fåglar kopplade till jordbruksmark på stadig nedgång, med minskande populationsstorlekar sett över lång tid. Hur solkraftsparker i jordbrukslandskapet påverkar lokala fågelpopulationer är ännu okänt i dagsläget. Ett fåtal studier har tidigare publicerats kring ämnet, från olika världsdelar, med motsägande resultat. För att utreda eventuell påverkan från solkraftsparker på fåglar i jordbrukslandskapet genomfördes en fältstudie i Västsverige under häckningssäsongen 2025. Totalt genomfördes 200 linje-transekter i 10 solkraftsparker och 10 närliggande referensområden bestående av jordbruksmark. Fältarbetet var uppdelat i två perioder för att ta hänsyn till den senare ankomsten av långflyttande flyttfåglar. En stor skillnad i detektions-sannolikhet upptäcktes mellan de två typerna av områden. Sannolikheten att upptäcka en fågel var betydligt lägre inne i solkraftsparkerna. För att utvärdera effekterna av solkraftsparker på populationsdensitet och artdiversitet användes statistiska modeller (GLMM), vilka tillåter kontrollerandet av slumpmässiga skillnader inom och mellan de olika områdena, samt undersökandet av andra potentiella förklaringsvariabler. Modellerna visade att solkraftsparker har en ökande effekt på populationsdensitet men inte på artdiversitet. För hotade arter framkom ingen skillnad i genomsnittlig täthet. Vissa arter och artgrupper föredrog till synes referensområdena, då de inte återfanns i solkraftsparkerna. Inuti solkraftsparkerna förekom en kanteffekt, då fler arter var knutna till parkernas ytterkanter, jämfört med de inre partierna. Sammantaget förefaller solkraftsparker innehålla fler fåglar, men färre arter, än omkringliggande jordbruksmark. Framtida artspecifika studier är önskvärda för att minimera risken för negativa effekter på redan hotade fågelarter.

Introduction

Modern society is facing two fundamental challenges: climate change and loss of biodiversity. The global climate is getting warmer through the ongoing and increasing emission of greenhouse gases (IPCC 2023). These are a part of the planet's atmosphere and act as a trap for solar radiation, keeping heat in the atmosphere (EPA 2024). The emissions of greenhouse gases stem from both natural and anthropogenic sources. Natural sources include respiration and decomposition (EPA 2024), while man-made sources are the production and usage of unsustainable energy sources, land use and consumption patterns (IPCC 2023). Climate change is causing documented destruction, some irreversible, in a wide range of ecosystems, both terrestrial and aquatic, with subsequent mass mortality events and local species extinctions as a result (IPCC 2023). Some key drivers of the increased consumption of energy and resources are overpopulation, overconsumption and advancing technology (Princen 1999). For decades, a wide range of scientists have published alarming reports on the dangers of excessive consumption and population growth (Daily & Ehrlich 1992, Postel 1994, Princen 1999, Cassils 2014, Garg 2016). Yet, these factors keep accelerating. From the mid twentieth century until today the global human population has tripled in size, reaching 8 billion people in November 2022 (UN n.d.). During the last 100 years energy consumption increased 16-fold (Arrow et al. 2004). Global energy consumption is still steadily increasing, reaching record levels of 620 EJ in 2023. Fossil fuels are still the largest source of energy worldwide, over 80 percent of all energy consumed, leading to record levels of 40 Gt CO2 (Davenport & Wayth 2024). Technological advancements, although effectivizing energy use, propels the overall increase of energy consumption (Jin et al. 2018). Faced with these challenges the need for alternative energy sources that can sustain human life without the current unendurable toll on climate and biodiversity becomes indisputably evident. Potential alternative energy sources to fossil fuels are nuclear, biomass, wind, hydro & solar power (Chu & Majumdar 2012).

Renewable energy sources, such as wind and hydro power are often seen as sustainable due to minimal greenhouse gas emissions (Renöfält et al. 2010). However, the effects on biodiversity often suggest otherwise. Construction of energy facilities alter the natural structures of terrestrial and aquatic ecosystems contributing to habitat fragmentation and degradation (Kuvlesky et al. 2007). The infrastructure related to wind energy production (turbines, power lines, roads, etc.) also lead to collisions, displacement and barrier effects (Kuvlesky et al. 2007, Schuster et al. 2015). Off-shore wind farms cause additional adverse effects on fish and marine mammals through noise pollution, turbidity & sedimentation (Schuster et al. 2015). Infrastructure necessary for hydropower production significantly alters the limnic ecosystems, changing the pathways and velocity of flowing water, disrupting natural rivers, wetlands, floodplains and deltas (Renöfält et al. 2010). The power from the sun reaching the earth alone far exceeds the current energy consumption levels, while also being the cleanest of the renewable energies (Parida et al. 2011). The human endeavor of harnessing energy from the sun dates back to the mid-19th century but remained relatively underdeveloped until the oil and energy crises of the 1970´s (Fraas & Partain 2010). Photovoltaic (PV) Solar Power is currently one of the fastest growing industries and energy sources worldwide (Jäger-Waldau 2006) and in Europe (Waldau 2005, Wolniak & Skotnicka-Zasadzień 2022). Due to recent technological advancements the cost of solar panels has decreased contributing to the expansion of solar power instalments in Europe (Kougias et al. 2021), including Sweden (Lindahl et al. 2022).

Total energy consumption for Sweden is slowly increasing (Energimyndigheten n.d.). As of 2024, solar power is contributing 2,4 % of electricity produced in Sweden, following a drastic increase in installed accumulated effect during the last 10 years (from 140 MW in 2016 to 3973 MW in 2023) (Svensk Solenergi n.d.). Yet, information on effects on biodiversity from solar power plants remains scarce.

Humanity is dependent on functioning ecosystems, from clean air to breathe, soil for cultivating food to manufacturing building materials and producing medicines (Raven 2020). In addition to supplying invaluable natural resources, healthy ecosystems provide ecosystem services such as climate regulation, nutrient recycling, sediment retention, flood prevention and control of pollution and erosion (M.E.A. 2005). As pressure from human demands keeps increasing, it is estimated that 2.4 million, or 20% of the estimated total number of species, could risk extinction within the coming decades (Raven 2020). The major cause of species extinction is fragmentation, degradation and loss of habitats through landscape modification (Fischer & Lindenmayer 2007). Due to habitat fragmentation, a majority of all species are experiencing decreasing population sizes and distribution ranges with subsequent loss of genetic diversity (M.E.A. 2005). Drivers of the global landscape transformation are increase in human population size and consumption, urbanization, forestry and technological advancements in agriculture (IPBES 2019). In short, the natural resources and ecosystem services that allow our societies to survive and prosper are currently at risk. Land converted for the purpose of energy production further amplifies competitive pressures for land use. Therefore, it is essential to properly determine potential adverse effects on biodiversity before progressing with large-scale implementation of solar parks.

Birds fill numerous important roles in their respective ecosystems: seed dispersal, pollination, predation on insects, fish and vertebrates as well as consumption of carrion (Şekercioğlu et al. 2004). Predation limits insect and rodent populations, thus preventing excessive crop damages, while scavengers consuming carrion adds to nutrient recycling and sanitation. Additionally, monitoring birds can provide valuable information since bird abundance and diversity indicate changes to natural habitats and ecosystems (Pimm et al. 2006, Mekonen 2017).

The global bird populations are estimated to have decreased by a quarter since the year 1500 with 1,3% of bird species extinct (Şekercioğlu et al. 2004). However, long before a species is completely eradicated from earth, the ecological function of species in decline can have severe cascading impacts on ecosystems and their functions (Pimm et al. 2006). By the end of this century up to 14% percent of all mainland bird species are projected to have become extinct, and up to 25% functionally extinct. As a result of these declines in species diversity and population sizes many ecosystem-services will most probably be reduced (Şekercioğlu et al. 2004).

Heterogeneity in landscape composition and configuration are known to be positively related to richer biodiversity (Benton et al. 2003). Changes in land use, especially for cropland and pastures, tend to reduce structural diversity (Gaston et al. 2003) rendering the landscape less heterogeneous. One of EU´s long-term monitoring programs, focusing on natural bird populations, reveals a steep decline in population sizes (14% in total), with birds connected to farmland at the forefront, experiencing a 40% decrease between the years 1990-2024 (EEA 2024). However, the authors of the report acknowledge that the baseline for bird populations starting in 1990 most likely omits a large decrease up until that year when monitoring started. The intensification of agriculture during the last century has had severe negative consequences for bird species connected to farmland (Donald et al. 2001). Especially the loss of fallow- and grassland and the increase of energy crops like maize and rapeseed are identified as high impact negative factors (Bowler et al. 2019, Busch et al. 2020). These adverse effects affect different bird types differently, with habitat specialists, insectivores and seedeaters experiencing steeper population declines while diet generalists remained the least impacted (Bowler et al. 2019). As the vast majority of solar power plants in Sweden are constructed on agricultural land (Björnsson et al. 2022), the need for sufficient information on potential effects on birds is evident.

Solar power plants can affect local bird communities in a variety of different ways, from collisions with panels, powerlines, buildings and other infrastructure related to the power plants, to providing shelter, nesting opportunities, changed microclimates with moisture retention and shading, possibly benefiting the insect population and thus influencing insectivores and breeding birds (Yuzyk 2024).

As the solar power industry experiences a drastic global expansion, studies are emerging on the potential impact on plant- and wildlife biodiversity. Depending on the structure and management of solar farms, indicator species such as herbs, bumblebees and butterflies were shown to increase in the UK (Parker & McQueen 2013, Montag et al. 2016). A UK study showed that solar farms with wildlife-focused management, like grazing, diverse seed planting and limiting herbicides, yielded positive effects for a wide range of organisms including birds (Montag et al. 2016). For several bat species however, the presence of a solar power plant seems to have adverse effects (Barré et al. 2024).

The majority of published studies regarding birds and solar power have been related to mortality rates from collisions (Yuzyk 2024). A quarter million birds were estimated to succumb annually from accidents with solar power plants in California alone (Smallwood 2022). Some studies on mortality also estimated species richness and abundance and found lower numbers inside the solar power plants compared to the surrounding areas (Devault et al. 2014, Visser et al. 2019). The effects on avifauna from solar power plants are likely dependent on the setting the park is constructed in and upon. Solar power plants on, or adjacent to wetlands likely produces adverse effects on waterbirds (Anderson et al. 2025).

While there have been publications warning against the dangers of solar farms to birds (Upton 2014), recent studies from Europe reveal solar power plants to have a positive effect on bird diversity and abundance (Peschel et al. 2019, Jarčuška et al. 2024, Golawski et al. 2025, Copping et al. 2025). However, the studies differ in methodology and scope, for example limiting the focus to small-scale solar parks (Golawski et al. 2025). While an overall increase in diversity was observed in Germany, notably for skylark (Alauda arvensis) and stonechat (Saxicola rubicola), the authors also recognized a risk for open and cavity breeders to decline (Peschel et al. 2019). In Poland, the presence of solar farms correlated with an overall higher diversity and population density, notably for corn bunting and whinchat while skylark abundance decreased in comparison to control plots (Golawski et al. 2025). In UK, the difference in management methods severely impacted the level of biodiversity in solar power plants, with most species clearly preferring a “mixed-habitat” solar park including natural structural elements (hedges and wood), infrequent cutting and wildflowers as opposed to both “simple-habitat” solar parks with low vegetation, as well as control plots in arable land (Copping et al. 2025). In two of the studies (Jarčuška 2024, Golawski 2025) the observers were positioned along the perimeter fences while counting birds inside the parks, possibly obtaining biased results due to edge effects affecting diversity (Harris 1988). Further research on bird populations at solar power plants is required regarding population abundance and species composition, in particular on the regional scale since effects might differ between different regions (Yuzyk 2024).

To the best of my knowledge, no scientific studies regarding the effect of solar power plants on bird populations have been conducted in Sweden to this date.

To separate the potential effects of solar power plants on local bird populations, other explanatory variables must be accounted for. Variables known to affect bird diversity and population density in the agricultural landscape include food availability, nesting opportunity, predator-prey dynamics, vegetation coverage and height, anthropogenic structures like fences and drainage, as well as past and present land-use type.

Vegetation structure affects birds in numerous ways, through habitat selection for nesting and foraging (Bradbury et al. 2005). Differences in vegetation structure provide specific habitat conditions that are suitable for different grassland bird species (Fischer & Davis 2010). Increased vegetation height has been shown to be correlated with higher density of smaller passerines like Meadow pipit (Anthus pratensis) but lower density of waders like Lapwing (Vanellus vanellus) (Milsom et al. 2000). Low vegetation coverage leads to higher population density in granivorous birds, while grazing species is more abundant in areas with higher vegetation coverage (Moorcroft et al. 2002). A study on Songthrush (Turdus philomelos) proposed that nesting site preference likely consists of a compromise between concealment and view of the surrounding environment (Götmark et al. 1995).

Predators, whether avian or mammalian, may take advantage of different physical elements of a habitat such as coverage or scouting positions. Many avian predators use elevated spaces to scout for potential prey. Hunting success is closely linked to prey visibility; therefore, perches located close to, or high above a prey habitat provide an important resource for avian predators (Andersson et al. 2009). Mammalian predators such as red fox (Vulpes vulpes) prefer to hunt in areas with dense vegetation during the daytime (Schwemmer et al. 2021). Like the perching spot for avian predators, the mammalian predators may use high vegetation or bushes as hide-out and ambush points. The agricultural practice of water drainage affects soil-moisture and the access to open water bodies, which may have negative effects on invertebrate fauna as well as water-dependent flora. Subsequently, birds are affected through loss of feeding and nestingopportunities. Wet habitats may provide feeding resources such as water-dependent invertebrates, feeding sites with moist soil and sparsely vegetated zones in the junction between water and land, as well as nesting sites and building material from aquatic plants (Bradbury & Kirby 2006). Types of drainage systems are affecting birds in the agricultural landscape, with typical birds such as skylark and meadow pipit both displaying higher abundance in fields with open-ditch surface drainage compared to subsurface drainage (Marja et al. 2013). Fences are a common part of most anthropogenically altered terrestrial biotopes and as such they are present in the agricultural landscape. Differing in size and permeability to cater to different human needs, they may subsequently affect birds in numerous ways and to different degrees (McInturff et al. 2020). The occurrence of fences may serve as a perching point or a prey refuge, hindering mammalian predators' access to nesting areas. Fences can, however, have a mortality effect due to collision, highlighted for certain species and stages of overgrowth (McInturff et al. 2020).

Here, building on a comparison with reference areas, I aim to investigate whether solar power plants have any effects on population density or species diversity for birds in the agricultural landscape. Furthermore, I will examine whether the additional explanatory variables described above predict population density and species diversity.

Material and methods

Study areas

Each of the 10 surveyed sites consisted of a solar park area and an adjoining reference area. Five transect lines were randomly placed inside each survey area (solar or reference area), equaling ten transects per site. To account for possible edge effects on species diversity (Harris 1988) in the solar park areas, two types of lines were identified: an inner type of line, between the rows of panels, as well as an outer type of line, along the outer perimeter of panel rows (but still within the area / inside the fence). Out of the five lines for each solar area, two were placed along the outer edge and three inside the rows. For the reference area the placements of inner or outer transect lines were decided by the state of the agricultural field. In Sweden, public access to agricultural fields varies depending on whether crops are actively growing in the field or not. For fields without active crops the method of randomized line transects was to start from the middle of the field and randomize a number between 0 and 360, which could then be interpreted as compass degrees, dictating the direction of the transect line. For fields consisting of active crops needed to be surveyed from the side lines, usually consisting of small strips of vegetation left between agricultural plots. In the case of active agricultural fields, the possible side lines were given an identification number, of which the order of surveying could be randomized.

Ten solar park owners granted access to their properties for bird surveying. All parks are located in western Sweden, spread out in three regions: Bohuslän, Västergötland and Halland. Out of the ten parks surveyed, one was in Bohuslän, two in Västergötland and seven in Halland. For all solar parks, a designated reference area consisting of agricultural fields was selected. The chosen reference areas were in close vicinity (200 - 1000 meters) to the solar parks with the aim of keeping environmental factors at a similar level, while not too close, to avoid non-independent observations.

Bird survey

Bird observations were made by the method of line transects (Buckland et al. 1993). The surveyor walks along a chosen straight line and counts all objects on one or both sides of the line. Every bird observed is noted by species and perpendicular distance to the walked transect line. Distance was measured primarily with a distance laser meter. Birds passing the area in flight was not registered, apart from skylarks, who usually display a behavior of flying and singing over their territories (Hedenström 1995). Birds of prey were counted as line transect observations only if they were assessed to be actively searching for prey inside the transect area, by either perching or circling repeatedly. The transect lines dimensions: length and width were also noted. Using the transect lines length and width, a corridor of surveyed area is calculated and used for population density estimations (Buckland et al. 1993). An outer limit (truncation distance) is set for the transect line width, where beyond, no effort is made to observe objects. Only the objects located at the center of the corridor (on the walked line) can be assumed to have a detection probability of 1 (100 %). Objects at a further perpendicular distance ought to be less likely to be detected. Hence, the detection probability is assumed to decrease from the middle of the corridor towards the edges of the line's width. To estimate the detection probability, a detection function was used with the distance package in R (Miller et al. 2019). The detection function assumes one general transect width (truncation) for the dataset. While this was true for the transects surveyed in reference areas, the transect widths in solar parks were not consistent, due to the physical structural variability of solar panels. The agricultural fields of the reference areas are wide open spaces with none or few objects blocking visibility, allowing a truncation distance to be set to 50 meters in one or both directions from the center of the transect line. Within solar parks the dimensions of solar panels and the placements of solar panels dictate visibility. The different solar parks varied in solar panel height and panel row spacing width, allowing truncation distances from just 15 meters up to 50. To account for the varied truncation values in the solar parks the maximum truncation was set to 50 but the line specific truncation was added as a covariate in a multi covariate distance sampling model, using the MCDS function (Marques et al. 2007) in the distance package (Miller et al. 2019).

Explanatory variables

To properly estimate if any detected differences in the main variables could be explained by area type, other potential explanatory variables (covariates) had to be considered. Potential covariates consisted of abiotic, biotic and temporal factors. Abiotic factors included: fences, drainage and predator refuges. Biotic factors included: vegetation coverage, vegetation height and predators. Temporal factors included: season and time of day.

Abiotic factors like fences and drainage were noted on a binary scale (0 or 1), as present or absent in each survey area. Biotic factors like vegetation coverage and height were noted on scales from low to high (1-3). Vegetation coverage ranged from open surfaces (gravel or soil) to total vegetation coverage. Vegetation height ranged from low (short as a golf course), medium (below knee height), to high (knee height and above). Predators were noted by number of individuals and species present in, or near, the survey area.

Predator refuges, environmental structures that may act as hide-outs or perches for predators, consists of both man-made objects such as buildings, electrical boxes, fences, poles for cameras, lamps or signs, as well as naturally occurring elements in the habitat such as bushes, trees, ditches and tall vegetation. The occurrence of predator refuges was noted on a scale from low to high (1-3) based on estimated amount and proximity of structures possible for a predator to hide at, or perch on, while searching for prey.

Temporal factors, such as season and time of day, affect the number of individuals, species and behavior of birds (Bibby et al. 1998). Breeding birds in Europe mainly breed during the same season (April - June in Northern Europe, like the UK) to coincide feeding of the chicks with the season of the greatest abundance of food, whether it be insects, seeds, or prey animals such as other birds (Lack 1950). However, within the breeding season there are variations in migration and nesting time between early and late breeders (Lack 1950). All surveys were split into two periods for early or late migrants, with period 1 (early to late April) and period 2 (early May to early June). For many bird species the peak activity hours per day occur in the morning and in the evening, with the morning being the highest peak (Bibby et al. 1998). Within the timeframe of the peak the activity may also differ slightly (Bibby et al. 1998). Hence, the order of which area type (solar or reference), that was surveyed first within each site, was randomized. All line transects were carried out between 05:00 and 10:00 to match the peak bird activity each day.

Weather conditions may affect both bird activity as well as the surveyor's ability to observe birds during a survey (Bibby et al. 1998). In bad weather conditions such as hard winds, cold temperature or precipitation, the bird activity usually decreases, making observations less likely. Certain weather conditions such as rain, fog or mist may cause limited visibility, or audibility, for the surveyor (Bibby et al. 1998). The weather conditions of rain, cold temperature, wind and fog were recorded for each survey as potential covariates. The factors of rain and cold temperature (below freezing) were noted as either present or absent (0 or 1). The factors of wind and sight (fog) were noted on a scale from low to high (1-3). The scale of wind ranged from low (0-3 m/s), medium (3-7 m/s), to high (7+ m/s). For the factor of sight, the scale ranged from low (clear weather), medium (mist), to high (fog).

Statistical analysis

Observed bird counts were adjusted with detection probability using the "ds" function from the package distance (Miller et al. 2019) in R studios (R version 4.5.1, 2025-06-13).

Based on the counts corrected by detection probability, population density and species diversity were calculated. For species diversity, two diversity-indices were tested, Shannon-Weiner diversity (H') and Simpson's diversity (1-D). Species diversity consists of both species richness (the number of species) and species evenness (relative distribution of species). Shannon's index is more influenced by richness while Simpson's is more influenced by evenness (Dejong 1975).

To analyse the main response variables of population density and species diversity, generalized linear mixed models (GLMM) where used, to manage non-normal data with random effects (Bolker et al. 2009). The GLMM structure, regarding distribution families and link functions, were adapted to fit the specific ranges and formats of data. All tests included the main predictor area type (fixed effects variable) and the sampling sites (random effects variable).

For population density and Shannon's diversity, the GLMM's used consisted of Tweedie distributions with log link function, to analyse the positive continuous data, containing zeroes (Shono 2008). Covariates (fixed effects) tested included period, area size, wind, sight, rain, cold, fences, drainage, vegetation height, vegetation coverage, predator refuges and presence of predators.

For the Simpsons diversity index, with index values ranging between zero and one, a hurdle GLMM was used to account for the zero- and one-inflated data (Panaccio et al. 2021). The hurdles model three different equations, the first hurdle (binomial, logit link) models the probability of index values being exactly zero, the second hurdle (binomial, logit link) models the probability of values being exactly one (if not zero), the third hurdle (beta, logit link) models the mean of variables spread between, but not exact, zero and one. Due to the complex structure and reduction of sample size by each hurdle level, the number of covariates was decreased to include only the essentials: area type (fixed effect) and site (random effect). All models were fitted using function glmmTMB in package glmmTMB (Brooks et al. 2017) in R studios (R version 4.5.1, 2025-06-13). All fitted models were evaluated using the simulateresiduals function in DHARMa package (Hartig, 2025). For tests including additional covariates beyond area type and site, non-significant covariates were removed stepwise with goodness of fit by LRT (Likelihood Ratio Tests) comparing AIC (Akaike Information Criterion) to make sure the removal did not significantly reduce model fit.

A threatened species lists were compiled by reviewing the national red list (SLU Artdatabanken, 2020) for red listing categories deemed threatened (NT, VU, EN, CR). Additionally, the annual bird population report (Green et al. 2024) was reviewed for farmland species with long-term population decline.

Results

Descriptive raw data

Out of the 200 surveyed transect lines, 137 transects (≈ 70%) contained bird observations while 63 transects (≈ 30%) were empty. Out of the 137 transects with birds present, 601 individual observations were made, of 41 different species. The total amount of surveyed transect area was 143 hectares. The results from the two area types differed in observed amounts of individual observations, number of species and transect area surveyed (table 1). The total amount of bird observations (601) where unevenly split between the two area types, with reference areas containing a large majority (432, ≈70%) compared to solar parks (169, ≈30%). The number of species (41 in total) differed between the area types, with reference areas containing 36 species, and solar areas containing 24 species. The total amount of surveyed transect area was 142.95 hectares, with the reference areas accounting for 102 hectares and the solar park areas for 40.95 hectares.

Table 1. Raw data overview, depicting the observed number of individuals, species and transect area surveyed per area type: SOL (solar parks) and REF (reference areas).

Observed data	SOL	REF	TOTAL
Number of individuals	169	432	601
Number of species	24	36	41
Surveyed area (hectares)	40.95	102	142.95

Threatened species

A total number of 320 observed individuals of 16 species, noted as red listed (SLU Artdatabanken, 2020) or declining (Green et al. 2024), were observed during the study. The individuals were spread unevenly by area type, with 249 (≈78 %) in reference areas and 71 (≈22 %) in solar parks (figure 1, 2). The average density of threatened birds was not shown to differ between reference areas (2.6 ± SD 3.8) and solar parks (1.8 ± SD 0.8) (figure 3). Out of the 16 species, 5 were found only in reference areas, 2 only in solar parks and the remaining 9 species occurred in both area types (figure 4, table 2).

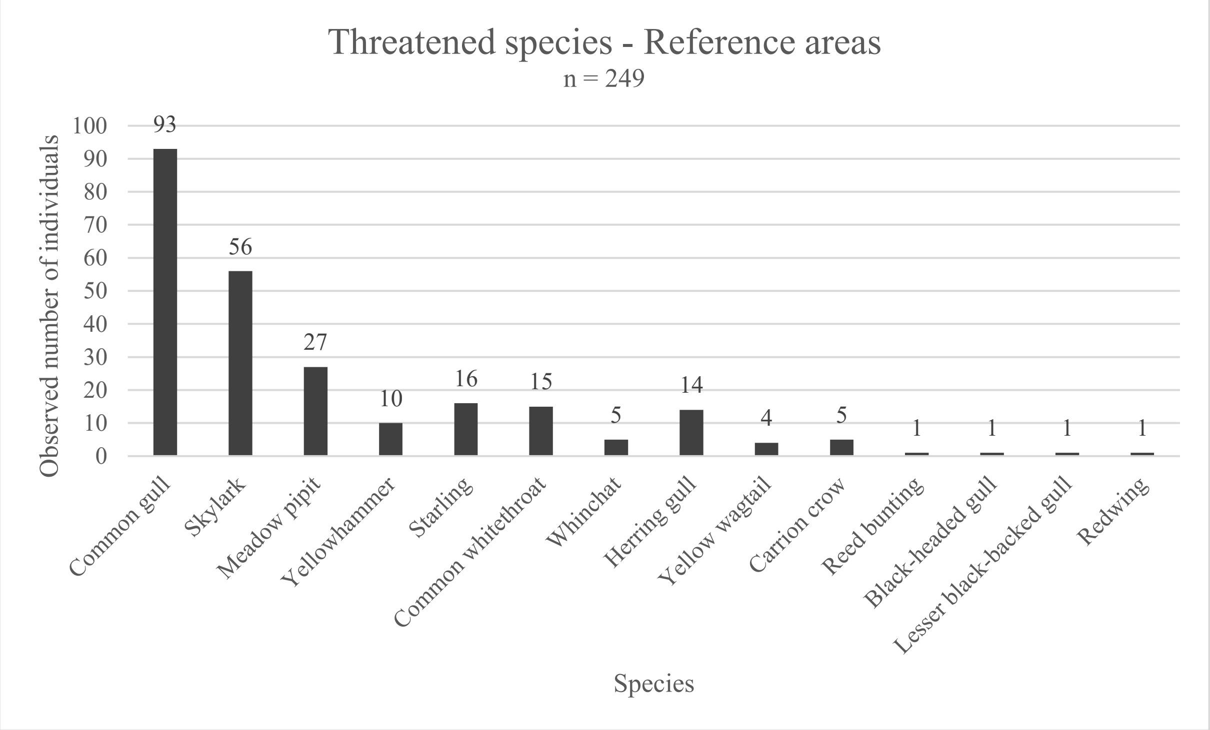

Figure 1. Threatened (red listed) or declining (farmland species with long term population decline) species in reference areas.

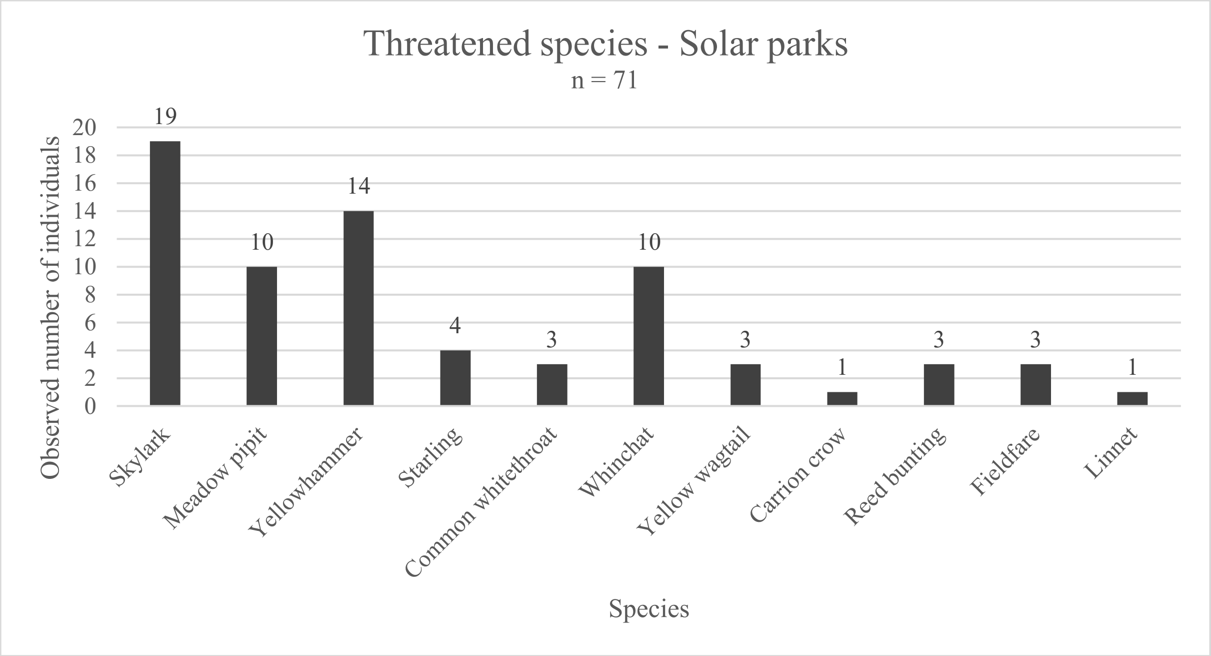

Figure 2. Threatened (red listed) or declining (farmland species with long term population decline) species in solar park areas.

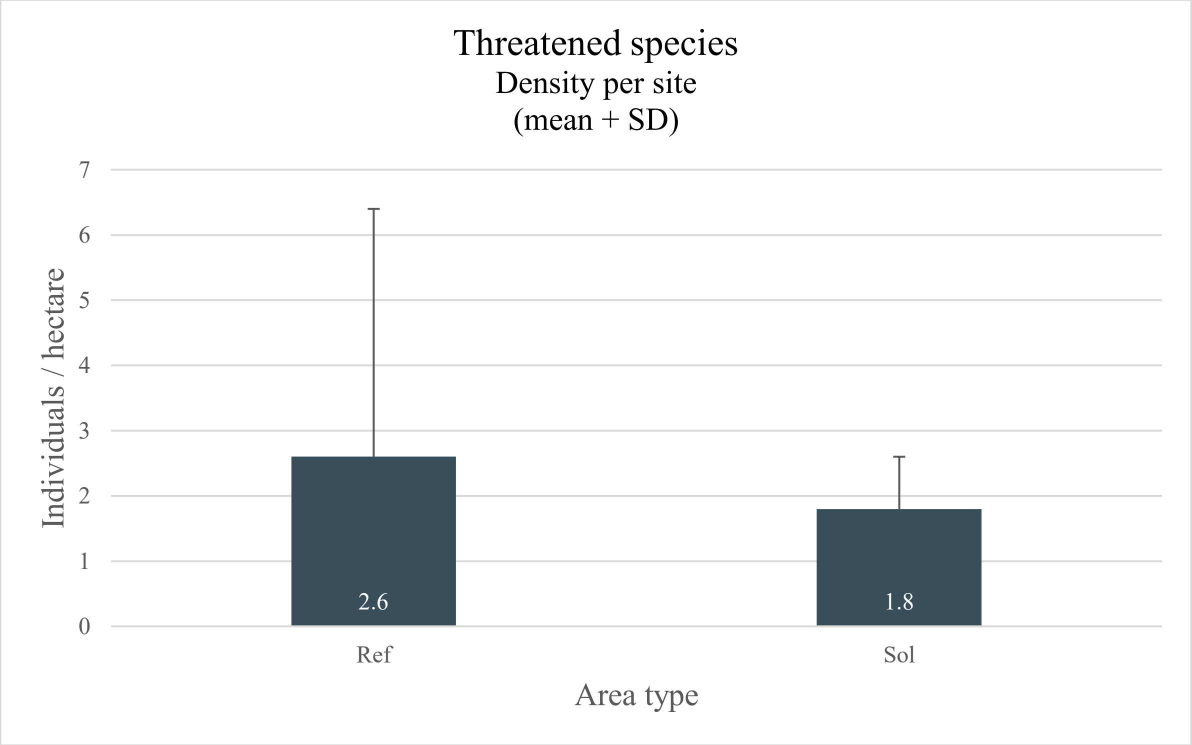

Figure 3. Mean number of densities of threatened species per site, by area type. Vertical axis shows average number of individuals per hectare. Horizontal axis shows area type.

Table 2. Declining and threatened species observed in the study. Each species is presented with English and scientific name, area type presence, red list category and/or noted as a farmland species with long- term population decline.

English name	**Scientific name**	**Red list (2020)**	**Farmland species in long-term decline**	**Area type**
Black-headed gull	*Chroicocephalus ridibundus*	NT		Reference
Carrion crow	*Corvus corone*	NT		Both
Common gull	*Larus canus*	NT		Reference
Common whitethroat	*Curruca curruca*	NT		Both
Fieldfare	*Turdus pilaris*	NT		Solar
Herring gull	*Larus argentatus*	VU		Reference
Lesser black-backed gull	*Larus fuscus*	NE (NT 2015)		Reference
Linnet	*Linaria cannabina*		X	Solar
Meadow pipit	*Anthus pratensis*		X	Both
Redwing	*Turdus iliacus*	NT		Reference
Reed Bunting	*Emberiza schoeniclus*	NT		Both
Skylark	*Alauda arvensis*		X	Both
Starling	*Sturnus vulgaris*	VU	X	Both
Whinchat	*Saxicola rubetra*	NT	X	Both
Yellow wagtail	*Motacilla flava*		X	Both
Yellowhammer	*Emberiza citrinella*	NT	X	Both

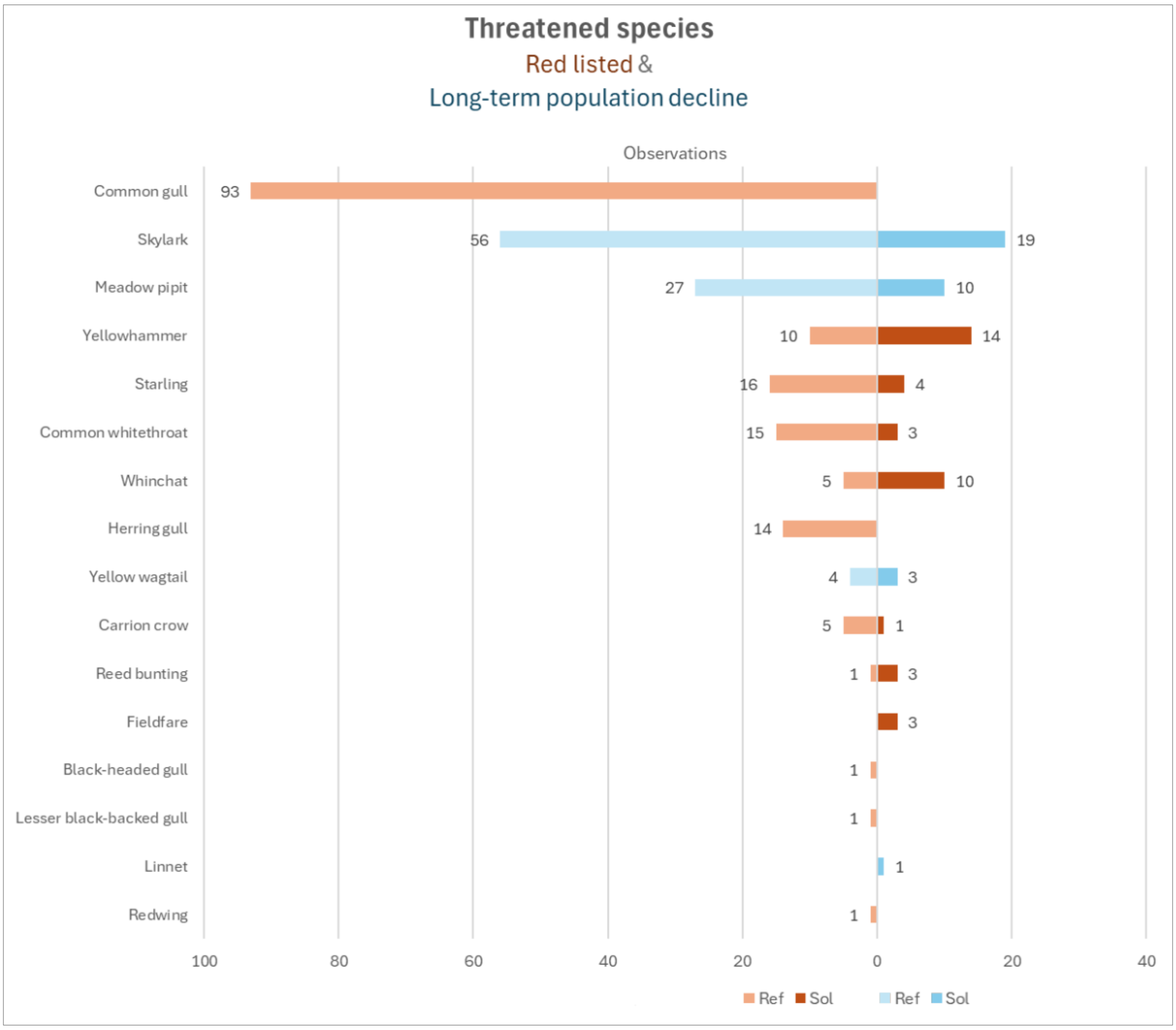

Figure 4. Distribution of threatened species by area type. Horizontal axis shows species, vertical axis shows number of individuals observed. Pink bars (reference areas) and red bars (solar parks) show red-listed species, while light blue bars (reference areas) and dark blue bars (solar parks) show species listed as typical farmland birds with a long-term population decline (Green et al. 2024).

Detection probability

The probability of detecting birds differed greatly between area types, with solar parks having a 0.27 (0.03 SE) detection probability (figure 5, table 3) and reference areas having a 0.99 (4e-8 SE) detection probability (figure 6, table 4). The results indicate that the observed number of individuals only accounts for a small proportion of the estimated actual population present in the solar areas, while in the reference areas the observed number is almost identical to the estimated population. For solar parks, the corrected count of individuals was 624 (compared to 169 observed). For reference areas, the corrected count was 433 (compared to 432 observed).

Solar parks

Table 3. Detection probability for solar parks. Average probability of detection is 0.27, giving an estimated population size of 624 individuals.

Area type	No. of obs.	Distance range (m)	Model
Solar	169	0-50	Hazard-rate
	Estimate	SE	CV
Average prob.	0.27	0.03	0.12
N in covered region	624.47	86.39	0.14

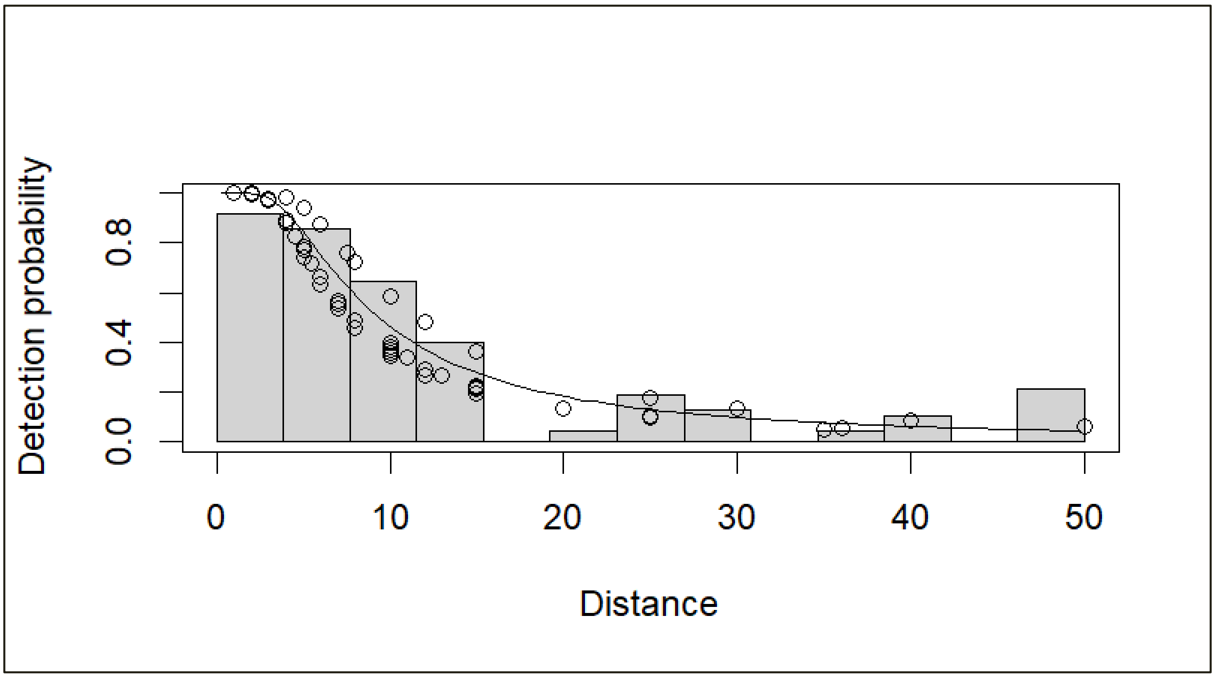

Figure 5. Histogram shows probability in solar park areas. The black line shows the detection probability with a maximum of 1 (100%). The horizontal axis shows detection probability expressed as frequency density, the vertical axis shows perpendicular distance to the transect line centre. Bars on the histogram visualize the frequency density, the number of observations at a binned distance. The probability of detecting a bird decreases with increased perpendicular distance from the centre of the transect line. The average probability of detection was 0.27, indicating that observed number of individuals only accounted for a small portion (27%) of estimated population numbers present.

Reference areas

Table 4. Detection probability for reference areas. Average probability of detection is 0.99, giving an estimated population size of 433 (432.73) individuals.

Area type	No. of obs.	Distance range (m)	Model
Solar	432	0-50	Hazard-rate
	Estimate	SE	CV
Average prob.	0.99	<0.01	<0.01
N in covered region	432.73	<0.01	<0.01

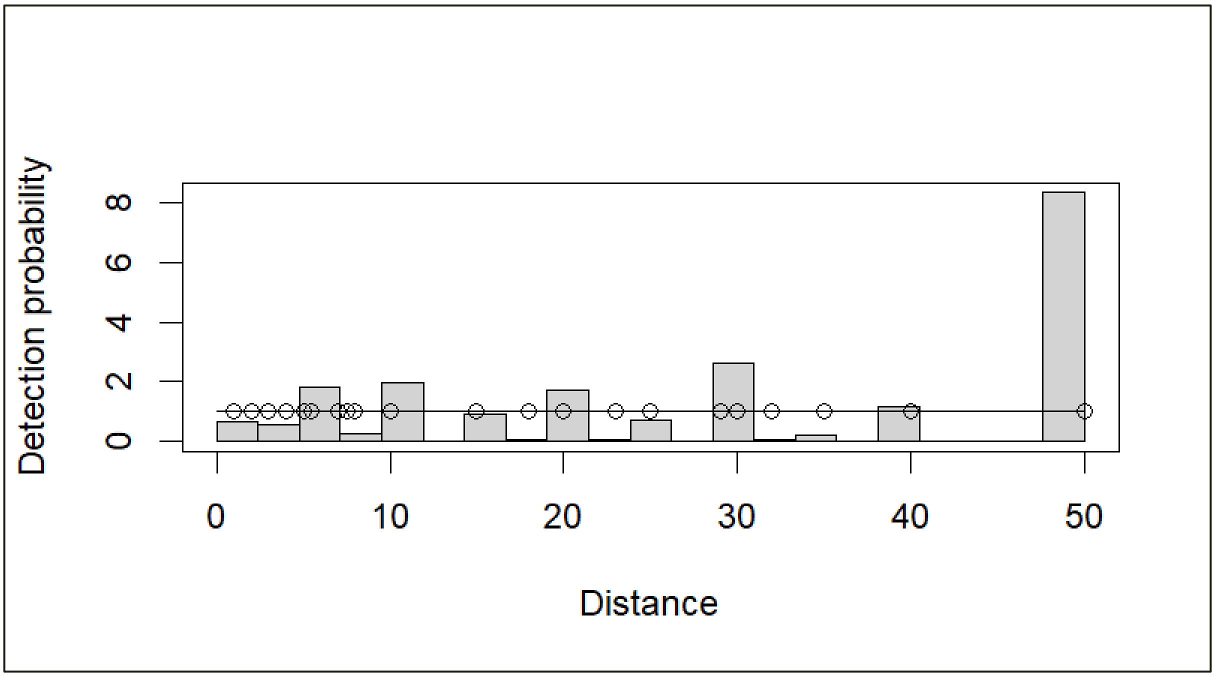

Figure 6. Histogram shows the detection probability in reference areas. The black line shows the detection probability with a maximum of 1 (100%). The horizontal axis shows detection probability expressed as frequency density, the vertical axis shows perpendicular distance to the transect line centre. Bars on the histogram visualize the frequency density, the number of observations at a binned distance. The probability of detecting a bird does not decrease as expected, with increased perpendicular distance from the centre of the transect line, due to many observations at high distances. The average probability of detection was 0.99, indicating that the observed number of individuals is nearly equal (99%) to the estimated population numbers.

Population density

Solar parks showed an increase (1.92 ± SE 0.21, on log scale) in population density compared to reference areas. After removing non-significant covariates, the final model included random effects of site and fixed effects of wind and vegetation coverage (table 5).

Table 5. Generalized linear mixed model (Tweedie distribution, log link) examining population density differences between solar parks and reference areas, with sites as random effect, while accounting for the covariates of wind and vegetation cover.

Variable	Coefficient	SE	Z-value	P-value	Significance
Intercept	1.93	0.27	7.12	<0.01	***
Area type Sol	1.92	0.21	8.99	<0.01	***
Wind	0.58	0.22	2.58	0.01	**
Veg. cover	-1.99	0.35	-5.62	<0.01	***
Random					
Site	Var: 0.17	SD: <0.01	n = 10		
No. of obs:	200				

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

Species diversity

Shannon diversity

Shannon-Weiner's diversity index (H') did not show a clear difference in diversity between area types. The results hinted towards a trend of solar parks decreasing diversity (-0.44 ± SE 0.23, on log scale) compared to reference areas, although this effect was only marginally significant (p = 0.06). Shannon's diversity, regardless of area type, was shown to be positively correlated with both size of the area and later period. A large increase in diversity was observed between the first and second period (P = 0.04), while the effect of increased area size was relatively small per hectare, but clearly significant (P = 0.01).

Table 6. Generalized linear mixed model (Tweedie distribution, log link) examining Shannon diversity difference between solar parks and reference areas, with sites as random effect, while accounting for the covariates of period and area size.

Variable	Coefficient	SE	Z-value	P-value	Significance
Intercept	-1.68	0.25	-6.81	<0.01	***
Area type Sol	-0.44	0.23	-1.91	0.06	.
Period	0.32	0.16	2.01	0.04	*
Size (ha)	0.06	0.03	2.53	0.01	*
Random					
Site	Var: <0.01	SD: <0.01	n = 10		
No. of obs:	200				

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

Simpson diversity

For Simpson's diversity (1-D), the probability of transects with a diversity value of zero increased in solar parks (1.01 ± SE 0.32, on log scale) compared to reference areas. No other patterns were confidently discernible (table 7).

Simpson's diversity was computed with a three-parts hurdle GLMM. Since the index, ranging from 0-1, contained large amounts of exact zeros and ones, a regular beta distribution GLMM could not be used. The hurdles allowed the full range of values to be statistically evaluated (Min & Agresti, 2005). The first hurdle was a binomial GLMM, calculating the probability of getting an index value of exactly zero, meaning no diversity. The second hurdle, a binomial GLMM as well, calculated the probability of exact ones (perfect diversity), given it was not exact zeros. The third hurdle was a beta GLMM that calculated the means of the remaining values, not being either zero or one. For each hurdle, the sample size decreases, due to the high amounts of exact zeros and ones. The first hurdle could use all 200 transects, the second hurdle 137 and for the third hurdle only 61 transects remained. Therefore, the results of the latter may be interpreted with caution due to the small sample size. Simpson's diversity was calculated with the factors of area type (fixed effect) and site (random effect). Adding more covariates might render unreliable results due to the complex nature of the model and the reduction of sample sizes.

Table 7. Hurdle GLMM's examining Simpson diversity per area type with site as random factor.

Hurdle 1	No. of obs.	Dist. family	Link function		
(Prob. of 0)	200	Binomial	logit		
Covariate	Coefficient	SE	Z-value	P-value	Significance
Intercept	-1.33	0.26	-5.23	<0.01	***
Area type Sol	1.01	0.32	3.15	<0.01	**
Random					
Site	Var: 0.03	SD: 0.18	n = 10		
Hurdle 2	No. of obs.	Dist. family	Link function		
(Prob. of 1)	137	Binomial	logit		
Covariate	Coefficient	SE	Z-value	P-value	Significance
Intercept	0.20	0.26	0.77	0.44	
Area type Sol	0.11	0.36	0.32	0.74	
Random					
Site	Var: 0.12	SD: 0.36	n = 10		
Hurdle 3	No. of obs.	Dist. family	Link function		

(Mean)	61	Beta	logit		
Covariate	Coefficient	SE	Z-value	P-value	Significance
Intercept	-0.08	0.09	-0.85	0.40	
Area type Sol	0.08	0.15	0.49	0.62	
Random					
Site	Var: <0.01	SD: <0.01	n = 10		

Species evenness

Two indices for species evenness (Pielou's J' and Simpson's evenness) were used, but no reliable results could be calculated due to the small sample size and complexity of the models.

For the species evenness indices, only a smaller portion (61 transects) of the original sample (200) could be used for calculations of evenness, since evenness is not defined when species richness <2. Due to the distribution of values found in the remaining data, with heavy skews towards evenness values of 1, hurdle GLMM's was used. The first hurdles (binomial distribution, logit link) modelled probability of exact ones, and the second hurdles modelled the mean of remaining values (not being exact zeros or ones). However, each hurdle in a GLMM decreases the sample size for the next. Due to the very limited starting sample size and further reductions, the results (showing no difference or effects of any variable for either evenness index) could not be reliably interpreted and therefore are not shown.

Edge effects on diversity inside solar parks

To account for potential edge effects on diversity in solar parks, two types of transect lines were placed inside each solar park area. A separate dataset containing only the solar park data (100 transects) was used to calculate a diversity index (Shannon's H') by transect line type (In, Out).

Shannon diversity and edge effects

Inside the solar parks, the transect lines in the inner parts of the parks showed a strong decrease (-2.4 ± SE 0.34, on log scale) in Shannon diversity compared to the outer transects (table 8). A small variance was found due to the random variable of site (0.03, SD = 0.17, on log scale), inferring that most of the effects are explained by the fixed variable of line type.

Table 8. GLMM (Tweedie distribution, log link) comparing Shannon's H' correlation with transect line placement inside a solar park, while accounting for the random variable of sites. The intercept refers to the first level of the main predictor "Line type: In", meaning the inner transects.

Variable	Coefficient	SE	Z-value	P-value	Significance
Intercept	-2.4	0.34	-7.00	<0.01	***
Line type: Out	1.31	0.39	3.35	<0.01	***
Random					
Site	Var: 0.03	SD: 0.17	n = 10		
No. of obs:	100				

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

Discussion

The large difference in detection probability found between solar parks and reference areas resulted in a significant increase in the estimated population density for the solar parks compared to the observed number of individuals. This variation in detectability might be explained by the environmental differences between the two area types. In solar parks, much of the field of view is obscured by solar panels, while the reference areas, with wide-open spaces, allow for observations at great distances.

The addition of solar parks to the agricultural landscape has been proposed to positively impact the local bird populations through increased landscape heterogeneity (Golawski et al. 2025). The loss of landscape heterogeneity from intensified agricultural practices is recognized as a major driver of biodiversity loss in agricultural habitats (Benton et al. 2003). Restored habitat heterogeneity is believed to potentially increase species richness and abundance alike (Denac & Kmecl 2021). The result of higher density in solar parks supports findings from some previous studies (Copping et al 2025), while other studies found lower densities in solar parks (Devault et al. 2014, Visser et al. 2019). These opposing results might stem from methodical or geographical differences. The studies showing lower population densities in solar parks compared the effects to reference areas consisting of grasslands (not agricultural land) and was conducted in South Africa (Visser et al. 2019) and in the USA (Devault et al. 2014). One of them was carried out exclusively inside airport property (Devault et al. 2014). Studies showing an increase of bird population densities in solar power parks overall (Copping et al. 2025), on species group level (Jarčuška et al. 2024) or species level (Golawski et al. 2025) were all conducted in Europe. Certain studies (Golawski et al. 2025, Jarčuška et al. 2024) restricted their investigations to parks within specific ranges of size (5.3 ha maximum) or age (at least 8 years between construction and survey). I also found that vegetation cover and wind influenced density, regardless of area type. Bird density was greater at lower levels of vegetation cover and higher levels of wind. The correlation of higher bird densities with low vegetation cover was partially expected, but mainly for granivorous birds (Moorcroft et al. 2002). During the surveying of reference areas, certain transects were placed on fields that happened to host large flocks of geese and gulls. These flocks were present on fields where the soil had seemingly recently been turned over for the sowing of seeds. It is possible that this provided attractive conditions for foraging of seeds or fresh vegetation of new crops. However, during this study, I did not sort species by functional groups and thus have not tested whether that might explain the result. The positive effect of wind was rather unexpected, since stronger winds are usually assumed to reduce both bird activity and the surveyor's ability to hear and observe birds (Bibby et al. 1998). It is possible that certain species, like Skylarks (*Aluda arvensis*), might benefit from moderate wind, if it allows for energy conservation during song flight.

The observed number of species (richness) was higher in reference areas than solar areas, supporting certain previous findings (Devault et al. 2014, Visser et al. 2019) while contrasting with others (Jarčuška et al. 2024, Copping et al. 2025). When reviewing the observed distribution of species, a pattern of absence of larger birds in solar parks was seemingly prevalent. All observed species of geese, gulls or cranes were observed exclusively in reference areas (APPENDIX II), indicating avoidance of solar parks, potentially due to their larger body size. This pattern supports observations from a North American study, in which larger birds (> 1.125 kg) were found to be significantly less abundant in solar parks, compared to adjacent reference areas (Devault et al. 2014). For threatened species, the observed number of species was higher in reference areas, but after accounting for the surveyed area, the density of threatened species did not differ significantly between area types. However, due to the large variation in the reference areas (SD = 3.8), the results ought to be interpreted with caution.

Solar parks showed a higher probability of having a Simpson's diversity index value of zero, compared to reference areas (hurdle 1). An index value of zero comes from empty transects, with no species present and therefore, no diversity. No effects were found for the probability of index values of one (hurdle 2), nor for the mean diversity (hurdle 3). Due to the hurdle structure, sample size decreased by each hurdle and any results found in the latter two hurdles ought to be interpreted with caution. Whether the results indicate any difference in species diversity by area type is debatable. The only effect found in the model examined empty transects but not the overall species composition. Conclusively, the choice of testing Simpson's diversity index was not ideal in this study, due to the data containing a high number of transects with extreme index values (zero or one).

Shannon diversity did not show a significant difference between solar parks and reference areas, but a trend towards lower diversity in solar parks was marginally significant ($P = 0.056$). A trend of lower species diversity in solar parks would support the findings of some previous studies (Devault et al. 2014, Visser et al. 2019), albeit not from Europe. Whether the reference areas were in fact more diverse, or simply equal to solar parks, the results contrast several recent studies from Europe showing higher diversity in solar parks (Peschel et al. 2019, Copping et al. 2025, Jarčuška et al. 2024, Golawski et al. 2025). The contrasting results might be related to differences in method, scope or region. Some previous studies (Golawski et al. 2025, Jarčuška et al. 2024) surveyed solar parks from outside the fences and reflected on potentially omitting birds in the interior (Golawski et al. 2025). The explanatory variables of period and area size used in this study affected Shannon diversity, regardless of area type. The later period was associated with higher diversity, likely due to the arrival of long-distance migratory birds. Diversity increased with larger area size, as is expected by the species-area relationship (Conor & McCoy 2023).

The species diversity varied inside the solar parks depending on the transect line placement. The outer transects, placed between the outer row of solar panels and the perimeter (fence) of the solar park, showed a higher Shannon diversity than inner transects, placed in between rows of solar panels. This result suggests the presence of an edge effect, where more species are using the spaces in the outer parts of the solar parks than the inner. However, I did not test for difference in detection probability between the different line types inside the solar parks, only between solar parks and reference areas. It is possible that the lower diversity found in the inner parts could be at least partially explained by missed observations due to a lower detection probability. Potentially, missed observations could also lead to underestimation of species richness if any species were present, but never observed, in the solar parks. However, this risk seems negligible since many of the species only observed in reference areas are large birds (geese and gulls) who ought to be easily observed (by sight or sound) even with the limited visibility within solar parks.

Interestingly, no effects were found on either species diversity or population density by the explanatory variables of vegetation height, fences, drainage, predators, predator refuges, rain, fog or cold temperatures. Vegetation structure, represented in this study as vegetation height and vegetation coverage, is expected to influence the local bird communities. However, if vegetation height and cover increased in a parallel pattern, the software used might struggle to interpret the two effects separately. While no general effect of drainage was found, it is possible that the different types of drainage (over or underground) could influence the bird populations if examined separately. Fences were observed exclusively around solar parks. Hence, the effect of fences was only tested on the solar park data, with no effect found, potentially due to the decreased sample size. Predators were present in both area types. However, the total number of observed predators was small, and no effect was detected, possibly from the limited sample size. Interestingly, red foxes (Vulpes vulpes) were observed in numerous solar parks with fences, inferring that the fences' expected protective effect against mammalian predators was small or absent. Likely, the subjective scaled estimation of predator refuges did not capture the relevant refuge variations. Examining the distance to the nearest large forest patch, instead of counting singular trees and bushes, might be a more appropriate scale for evaluating predator refuges. The weather variables of rain or fog were never observed during the survey. Cold temperature, with frozen ground was noted on only one occasion.

The perpendicular distance between observed birds and the transect line centre was primarily measured with a laser meter. In some instances, with strong sun, however, the visibility of the laser was severely reduced at longer distances. When the laser meter did not work due to the intense light, I would walk to the location of the first sighting of an individual bird, with an estimated distance of 1 meter between each foot placement. The accuracy of this secondary method is unknown and could potentially yield slightly misleading distance estimations. As a result, the detection probability of some far away observations could be bias due to uncertain distance measurements. However, due to the random occurrence of transects that required the alternative measurement method, I estimate the overall effect to be minimal.

While I have some experience of bird observation, my knowledge is at the level of an enthusiast and not a professional bird surveyor. It is possible that a professional bird surveyor might get slightly different results.

Conclusion

When reviewing the current knowledge on bird populations and solar parks (including this study), the contrasting conclusions on the potential effects might be at least partially explained by methodical differences. Defining a clear, easily replicable method would be desirable to allow for more direct comparisons of regional variations of solar park effects on local bird populations. The topic of effects of solar parks on bird communities is still at an early stage with few published studies. Most of the studies this far have looked at diversity from an over-arching perspective, comparing the average diversity between area types. More studies on the species-specific level, especially threatened species, are needed to establish which species prefer or avoid solar parks and why that might be. Establishing the environmental factors that attract certain species to solar parks could be used for advising future solar park development in terms of maintaining or increasing biodiversity. Likewise, knowledge of which species avoid solar parks could be used for influencing the placement of future constructions to minimize negative impacts.

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References

Alex McInturff, Wenjing Xu, Christine E Wilkinson, Nandintsetseg Dejid, Justin S Brashares, Fence Ecology: Frameworks for Understanding the Ecological Effects of Fences, BioScience, Volume 70, Issue 11, November 2020, Pages 971–985, https://doi.org/10.1093/biosci/biaa103

Anderson, C. M., Hopkins, A. P., & Anderson, J. T. (2025). Assessing the Impact of Solar Farms on Waterbirds: A Literature Review of Ecological Interactions and Habitat Alteration. Conservation, 5(1), 4.

Andersson, M., Wallander, J., & Isaksson, D. (2009). Predator perches: a visual search perspective. Functional Ecology, 373-379. doi:10.HH/j.1365-2435.2008.01512.x

Benton, T. G., Vickery, J. A., & Wilson, J. D. (2003). Farmland biodiversity: is habitat heterogeneity the key? Trends in Ecology & Evolution, 18(4), 182 188. https://doi.org/10.1016/s0169-5347(03)00011-9

Bibby, C. J., Jones, M., & Marsden, S. (1998). Bird surveys (pp. 1-137). London: Expedition Advisory Centre.

Bibby, C. J. (2000). Bird census techniques. Elsevier. ISBN-13: 978-0-12-095831-3

Bowler, D. E., Heldbjerg, H., Fox, A. D., de Jong, M., & Böhning-Gaese, K. (2019). Long-term declines of European insectivorous bird populations and potential causes. Conservation Biology, 33(5), 1120-1130.

Björnsson, L. H., Morell, K., van Noord, M., & Pettersson, I. (2022). En kartläggning av solcellsparker i Sverige 2021.

Bradbury, R. B., Hill, R. A., Mason, D. C., Hinsley, S. A., Wilson, J. D., Balzter, H., ... & Bellamy, P. E. (2005). Modelling relationships between birds and vegetation structure using airborne LiDAR data: a review with case studies from agricultural and woodland environments. Ibis, 147(3), 443-452.

Bradbury, R. B., & Kirby, W. B. (2006). Farmland birds and resource protection in the UK: Cross-cutting solutions for multi-functional farming?. Biological Conservation, 129(4), 530-542. https://doi.org/10.1016/j.biocon.2005.11.020

Bolker, B. M., Brooks, M. E., Clark, C. J., Geange, S. W., Poulsen, J. R., Stevens, M. H. H., & White, J. S. S. (2009). Generalized linear mixed models: a practical guide for ecology and evolution. *Trends in ecology & evolution*, *24*(3), 127-135.

Brooks ME, Kristensen K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Maechler M, Bolker BM (2017). “glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling.” The R Journal, 9(2), 378–400. doi:10.32614/RJ-2017-066.

Buckland, S.T., Anderson, D.R., Burnham, K.P. and Laake, J.L. 1993. Distance Sampling: Estimating Abundance of Biological Populations. Chapman and Hall, London. Biometrics 50(3). DOI:10.2307/2532812

Busch M, Katzenberger J, Trautmann S, Gerlach B, Dröschmeister R, Sudfeldt C. Drivers of population change in common farmland birds in Germany. Bird Conservation International. 2020;30(3):335-354. doi:10.1017/S0959270919000480

Cassils, J.A. Overpopulation, Sustainable Development, and Security: Developing an Integrated Strategy. Population and Environment 25, 171–194 (2004). https://doi.org/10.1023/B:POEN.0000032321.00906.70

Chu, S., Majumdar, A. Opportunities and challenges for a sustainable energy future. Nature 488, 294–303 (2012). https://doi.org/10.1038/nature11475

Connor, E. F., & McCoy, E. D. (2023). Species–Area relationships. In Elsevier eBooks (pp. 361 377). https://doi.org/10.1016/b978-0-12-822562-2.00074-8

Copping, J. P., Waite, C. E., Balmford, A., Bradbury, R. B., Field, R. H., Morris, I., & Finch, T. (2025). Solar farm management influences breeding bird responses in an arable dominated landscape. Bird Study, 1–6. https://doi.org/10.1080/00063657.2025.2450392

Daily, G. C., & Ehrlich, P. R. (1992). Population, sustainability, and Earth's carrying capacity. BioScience, 42(10), 761–771. https://doi.org/10.2307/1311995

Davenport, J., & Wayth, N. (2024). Statistical review of world energy. Energy Institute. ISSN2976-7857. ISBN 978 1 78725 408 4

DeJong, T. M. (1975). A comparison of three diversity indices based on their components of richness and evenness. Oikos, 222-227.

Denac, K., & Kmecl, P. (2021). Land consolidation negatively affects farmland bird diversity and conservation value. Journal for Nature Conservation, 59, 125934.

DeVault, T. L., Seamans, T. W., Schmidt, J. A., Belant, J. L., Blackwell, B. F., Mooers, N., ... & Van Pelt, L. (2014). Bird use of solar photovoltaic installations at US airports: Implications for aviation safety. Landscape and Urban Planning, 122, 122-128.

Donald, P. F., Green, R. E., & Heath, M. F. (2001). Agricultural intensification and the collapse of Europe's farmland bird populations. Proceedings of the Royal Society B Biological Sciences, 268(1462), 25–29. https://doi.org/10.1098/rspb.2000.1325

Energimyndigheten (n.d.). Energianvändning i Sveriges energisystem. Visited 22/3 – 2025

EPA (2024). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 U.S. Environmental Protection Agency, EPA 430R-24004.

EEA (2024). Common bird index in Europe, Published 11 Sept 2024. Fraas, L. M., & Partain, L. D. (2010). Solar cells: A brief history and introduction, pp 1-15. in Solar cells and their applications, John Wiley & Sons.

Fischer, J., & Lindenmayer, D. B. (2007). Landscape modification and habitat fragmentation: a synthesis. Global Ecology and Biogeography, 16(3), 265–280.https://doi.org/10.1111/j.1466-8238.2007.00287.x

Fisher, R. J., & Davis, S. K. (2010). From Wiens to Robel: a review of grassland-bird habitat selection. The Journal of Wildlife Management, 74(2), 265-273. https://doi.org/10.2193/2009-020

Garg, S. (2016). Impact of overpopulation on land use pattern. In Advances in environmental engineering and green technologies book series (pp. 137–154). https://doi.org/10.4018/978-1-5225-1683-5.ch008

Gaston, K. J., Blackburn, T. M., & Goldewijk, K. K. (2003). Habitat conversion and global avian biodiversity loss. Proceedings of the Royal Society B Biological Sciences, 270(1521),1293–1300. https://doi.org/10.1098/rspb.2002.2303

Golawski, A., Mitrus, C., & Jankowiak, Ł. (2024). Increased bird diversity around small-scale solar energy plants in agricultural landscape. Agriculture Ecosystems & Environment, 379, 109361. https://doi.org/10.1016/j.agee.2024.109361

Green, M., Haas, F. & Lindström, Å. (2024). Monitoring population changes of birds in Sweden. Annual report for 2023. Department of Biology, Lund University.

Götmark, F., Blomqvist, D., Johansson, O. C., & Bergkvist, J. (1995). Nest Site Selection: A Trade-Off between Concealment and View of the Surroundings? *Journal of Avian Biology*, *26*(4), 305–312. https://doi.org/10.2307/3677045

Harris, L. D. (1988). Edge Effects and Conservation of Biotic Diversity. *Conservation Biology*, *2*(4), 330–332. http://www.jstor.org/stable/2386291

Hartig F (2025). *DHARMa*: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. R package version 0.4.7, https://github.com/florianhartig/dharma

Hedenström, A. (1995). Song Flight Performance in the Skylark Alauda arvensis. Journal of Avian Biology, 26(4), 337–342. https://doi.org/10.2307/3677050

IPBES (2019): Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio, H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M.Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.). IPBES secretariat, Bonn, Germany. 56 pages. https://doi.org/10.5281/zenodo.3553579

IPCC, 2023: Climate Change 2023: Synthesis Report. IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647.

Jagerwaldau, A. (2005). Photovoltaics and renewable energies in Europe. Renewable and Sustainable Energy Reviews, 11(7), 1414–1437. https://doi.org/10.1016/j.rser.2005.11.001

Jarčuška, B., Gálffyová, M., Schnürmacher, R., Baláž, M., Mišík, M., Repel, M., Fulín, M., Kerestúr, D., Lackovičová, Z., Mojžiš, M., Zámečník, M., Kaňuch, P., & Krištín, A. (2024). Solar parks can enhance bird diversity in agricultural landscape. Journal of Environmental Management, 351, 119902. https://doi.org/10.1016/j.jenvman.2023.119902

Jin, L., Duan, K., & Tang, X. (2018). What is the relationship between technological innovation and energy consumption? Empirical analysis based on provincial panel data from China. Sustainability, 10(1), 145. https://doi.org/10.3390/su10010145

Jäger-Waldau, A. (2006). European Photovoltaics in worldwide comparison. Journal of Non-Crystalline Solids, 352(9–20), 1922–1927. https://doi.org/10.1016/j.jnoncrysol.2005.10.074

Kenneth Arrow et al. (2004), "Are We Consuming Too Much?", Journal of Economic Perspectives, 18, pp. 147–72. (2017). In Sustainability (pp. 401–426). https://doi.org/10.4324/9781315241951-32

Kougias, I., Taylor, N., Kakoulaki, G., & Jäger-Waldau, A. (2021). The role of photovoltaics for the European Green Deal and the recovery plan. Renewable and Sustainable Energy Reviews, 144, 111017. https://doi.org/10.1016/j.rser.2021.111017

Kuvlesky, W. P., Brennan, L. A., Morrison, M. L., Boydston, K. K., Ballard, B. M., & Bryant, F.C. (2007). Wind energy Development and Wildlife Conservation: Challenges and opportunities. Journal of Wildlife Management, 71(8), 2487–2498. https://doi.org/10.2193/2007-248

Lack, D. (1950), THE BREEDING SEASONS OF EUROPEAN BIRDS.. Ibis, 92: 288-316. https://doi.org/10.1111/j.1474-919X.1950.tb01753.x

Lin, D., Wambersie, L., & Wackernagel, M. (2024). Estimating the date of earth overshoot day 2024. Nowcasting the World's Footprint & Biocapacity for 2024, 1-8. Global Footprint Network

Lindahl, J., Lingfors, D., Elmqvist, Å., & Mignon, I. (2021). Economic analysis of the early market of centralized photovoltaic parks in Sweden. Renewable Energy, 185, 1192 1208. https://doi.org/10.1016/j.renene.2021.12.081

Marja, R., Herzon, I., Rintala, J., Tiainen, J., & Seimola, T. (2013). Type of agricultural drainage modifies the value of fields for farmland birds. Agriculture, ecosystems & environment, 165, 184-189. https://doi.org/10.1016/j.agee.2012.11.008

Marques, T. A., Thomas, L., Fancy, S. G., & Buckland, S. T. (2007). Improving estimates of bird density using multiple-covariate distance sampling. *The Auk*, *124*(4), 1229-1243.

Mekonen, S. (2017). Birds as biodiversity and environmental indicator. Indicator, 7(21).

Millennium ecosystem assessment, M. E. A. (2005). Ecosystems and human well-being (Vol. 5, p. 563). Washington, DC: Island press.

Miller, D. L., Rexstad, E., Thomas, L., Marshall, L., & Laake, J. L. (2019). Distance Sampling in R. Journal of Statistical Software, 89(1), 1–28. DOI: 10.18637/jss.v089.i01

Milsom, T. P., Langton, S. D., Parkin, W. K., Peel, S., Bishop, J. D., Hart, J. D., & Moore, N. P. (2000). Habitat models of bird species' distribution: an aid to the management of coastal grazing marshes. Journal of Applied Ecology, 37(5), 706-727.

Min, Y., & Agresti, A. (2005). Random effect models for repeated measures of zero-inflated count data. Statistical modelling, 5(1), 1-19.

Montag, H., Parker, G., & Clarkson, T. (2016). The effects of solar farms on local biodiversity: a comparative study. Clarkson and Woods and Wychwood Biodiversity.

Møller, A. P. (2013). Long-term trends in wind speed, insect abundance and ecology of an insectivorous bird. *Ecosphere*, *4*(1), 1-11.

Panaccio, M., Ferrari, C., Bassano, B., Stanley, C. R., & von Hardenberg, A. (2021). Social network analysis of small social groups: Application of a hurdle GLMM approach in the Alpine marmot (Marmota marmota). *Ethology*, *127*(6), 453-464.

Parida, B., Iniyan, S., & Goic, R. (2011). A review of solar photovoltaic technologies. Renewable and Sustainable Energy Reviews, 15(3), 1625–1636. https://doi.org/10.1016/j.rser.2010.11.032

Parker, G. E., & McQueen, C. (2013). Can solar farms deliver significant benefits for biodiversity. Winchwood Biodiversity/Rowsell & McQueen.

Peschel, R., Peschel, T., Marchand, M., & Hauke, J. (2019). Solar parks-profits for biodiversity. Association of Energy Market Innovators.

Pimm, S., Raven, P., Peterson, A., Şekercioğlu, Ç. H., & Ehrlich, P. R. (2006). Human impacts on the rates of recent, present, and future bird extinctions. Proceedings of the National Academy of Sciences, 103(29), 10941–10946. https://doi.org/10.1073/pnas.0604181103

Postel, S. (1994). Carrying capacity: Earth's bottom line. Challenge, 37(2), 4–12. https://doi.org/10.1080/05775132.1994.11471725

Princen, T. (1999). Consumption and environment: some conceptual issues. Ecological Economics, 31(3), 347–363. https://doi.org/10.1016/s0921-8009(99)00039-7

Raven, P. H. (2020). Chapter 2 - Biological extinction and climate change. In Wael K. Al Delaimy, Veerabhadran Ramanathan & Marcelo Sánchez Sorondo (Eds.), Health of People, Health of Planet and Our Responsibility (pp. 11-20). https://doi.org/10.1007/978-3-030-31125-4

Renöfält, B. M., Jansson, R., & Nilsson, C. (2010). Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems. Freshwater Biology, 55(1), 49-67.

Robbins, C. S. (1981). Bird activity levels related to weather. Studies in avian biology, 6(627), 301-310.

Schuster, E., Bulling, L. & Köppel, J. Consolidating the State of Knowledge: A Synoptical Review of Wind Energy's Wildlife Effects. Environmental Management 56, 300 331 (2015). https://doi.org/10.1007/s00267-015-0501-5

Schwemmer, P., Weiel, S. & Garthe, S. Spatio-temporal movement patterns and habitat choice of red foxes (Vulpes vulpes) and racoon dogs (Nyctereutes procyonoides) along the Wadden Sea coast. Eur J Wildl Res 67, 49 (2021). https://doi.org/10.1007/s10344021-01474-6

Şekercioğlu, Ç. H., Daily, G. C., & Ehrlich, P. R. (2004). Ecosystem consequences of bird declines. Proceedings of the National Academy of Sciences, 101(52), 18042–18047. https://doi.org/10.1073/pnas.0408049101

Shono, H. (2008). Application of the Tweedie distribution to zero-catch data in CPUE analysis. Fisheries Research, 93(1-2), 154-162.

Singh, J. S. (2002). The biodiversity crisis: a multifaceted review. Current Science, 638-647.

Smallwood, K. S. (2022). Utility-scale solar impacts to volant wildlife. Journal of Wildlife Management, 86(4). https://doi.org/10.1002/jwmg.22216

SLU Artdatabanken (2020). Redlisted species of Sweden 2020. SLU, Uppsala. ISBN: 978-91-87853-55-5

Svensk Solenergi (n.d.) Visited 22/3-2025. https://svensksolenergi.se/statistik/

Tinsley, E., Froidevaux, J. S. P., Zsebők, S., Szabadi, K. L., & Jones, G. (2023). Renewable energies and biodiversity: Impact of ground-mounted solar photovoltaic sites on bat activity. Journal of Applied Ecology, 60(9), 1752–1762. https://doi.org/10.1111/1365-2664.14474

UN (n.d.) Global issues - population. Visited 22/3 – 2025. https://www.un.org/en/global-issues/population

Upton, J. (2014). Solar Farms Threaten Birds. Scientific American, 27, 564.

Wolniak, R., & Skotnicka-Zasadzień, B. (2022). Development of photovoltaic energy in EU countries as an alternative to fossil fuels. Energies, 15(2), 662 https://doi.org/10.3390/en15020662

Yuzyk, A. V. (2024). Global insights on the impact of solar power plants on bird populations.

Appendix I – Popular science summary

Solar parks - friend or foe of farmland birds?

Imagine if you could switch to a clean, affordable and sustainable energy source and at the same time help save struggling wildlife, like birds. Perhaps this option is already available with the rise of solar power parks, or is it simply too good to be true?

All around the Swedish countryside, new solar parks are being built at a rapid pace, to supply us with clean energy straight from the sun. Similar trends are seen elsewhere in Europe and around the world. This trend of switching to sustainable energy is great for combatting the issue of climate change. A major driver of climate change is the energy use from unsustainable sources, like fossil fuels, which the majority of humanity still relies on. In Sweden, the amount of installed solar power has skyrocketed in the last 10 years, from under 140 MW in 2015 to 4000 MW in 2024 (Svensk Solenergi). Most of the new solar power comes from solar parks, large fields with rows of solar panels, usually being built on farmland.

Farmland is home to many creatures that have adapted to a landscape shaped by thousands of years of cultivation, mainly from small-scale farming practices. This long history created a vast mosaic landscape of small patches of fields, pastures and forests. With the invention of new agricultural machines, fertilizers and pesticides, the landscape has undergone radical transformation, leading to large homogenous plots to maximize output of a single product. These changes to the habitat, from varied to uniform, have been too rapid for most of the wildlife to adapt to.

Birds connected to farmlands are experiencing a long-term population decline. A long-term study measured a 40% population decrease in European farmland birds between 1990 and 2024 (EEA 2024). Habitat degradation or destruction is a key factor. Birds fill many important roles, like seed dispersal, nutrient recycling and predation on rodents and insects that can damage crop yields. Therefore, halting these decreasing trends would benefit the natural ecosystems and farmers alike.

Little is known on how the solar parks built on farmland affect the birds that call it their home. Few studies have been published on the topic, and the pattern of results is inconsistent. Some have argued it is positive, and some negative for the local bird populations. To avoid previous mistakes made with other sustainable energy sources that were implemented at large scale (hydro, wind), only to realize significant harm was caused to biodiversity, more data was needed.

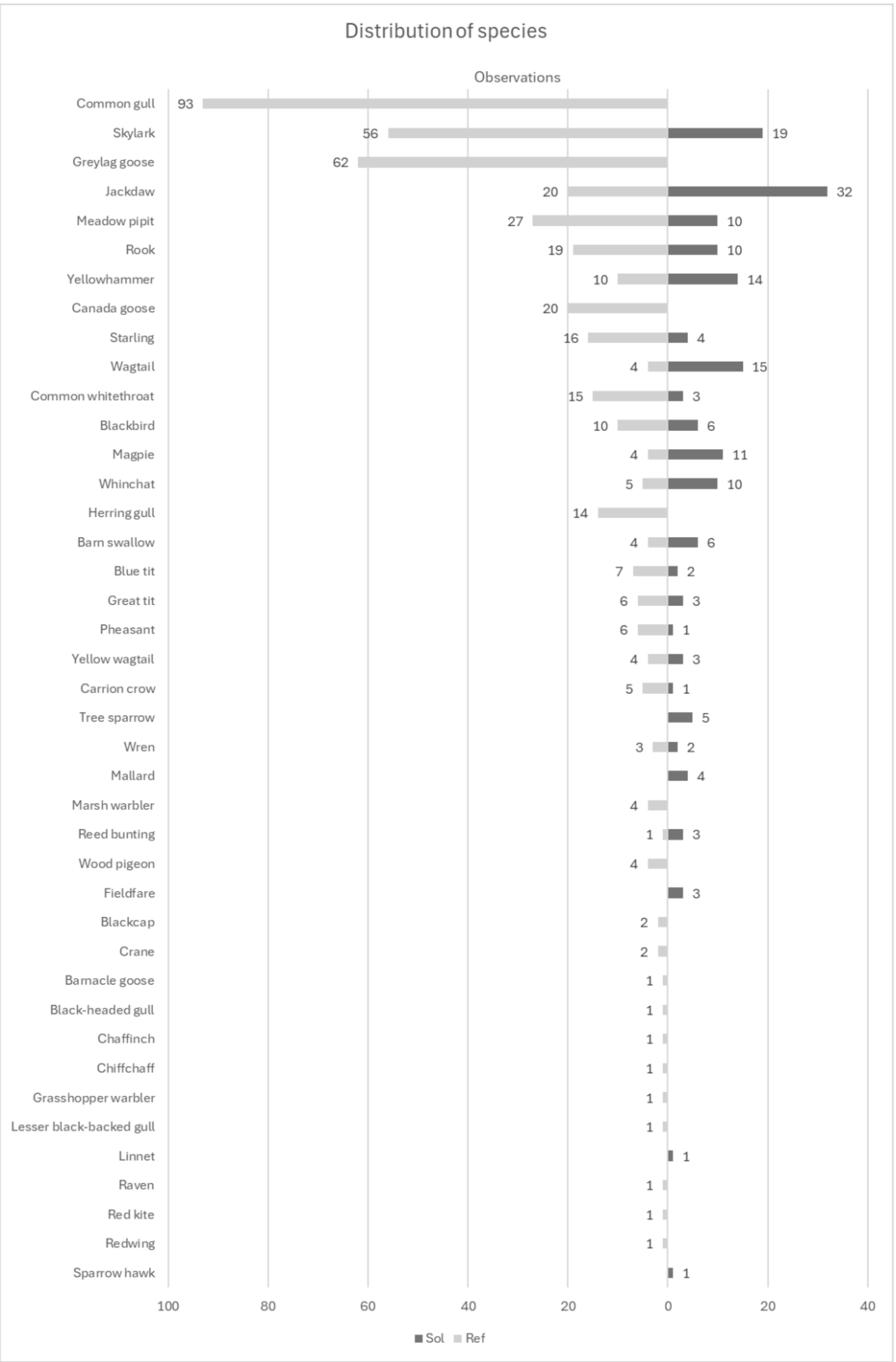
In this study I compared the bird populations between solar parks and ordinary agricultural fields to see if and how they might differ. I wanted to measure both population density - the number of birds, and the species diversity, the composition of bird species. To do this I needed bird survey data. 10 solar parks and 10 adjacent farmland fields (for comparison) were surveyed for birds during the breeding season of 2025. To see if any difference stemmed from the solar parks, other potential explanations had to be ruled out. After testing several explanatory variables such as vegetation structure, fences, predators, area size and others, and controlling for the variation between different sites some results were acquired.

The solar parks did show a higher population density, but not species diversity.

In other words, the parks seem to have more birds than the surrounding farmland fields. But whether the number of species using the parks was equal, or maybe lower, than the fields was not clear. Additionally, the diversity inside the parks varied between the outer and inner parts. There was a pattern of more species using the outer parts of the parks than the interior. Some larger species, like geese and gulls, were showing clear signs of avoiding the parks all together, while some smaller species, namely whinchat, seemed to prefer the parks over the fields.

With these results, some pieces were added to the puzzle about the relationships between solar parks and birds but more remains yet to be discovered. Specifically, we need to know more about which threatened birds prefer solar parks and which avoid them. When we find out which structural features in the parks attract certain species, we can plan the construction to maximize these benefits for the birds. Potentially the structure could be altered to fit more additional species' habitat preferences. Likewise, if threatened species avoid the parks, we need to know which species, so we can plan our development to avoid building on sites they need. Hopefully we can soon define a strategy to implement solar power at a large scale while benefiting biodiversity or at least minimizing potential adverse effects on the local wildlife.

Appendix II – Observed species



Distribution of observed species by area type. Total number of observed individuals was 601.