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Research article

Large-scale mapping of nocturnal bird migration to accelerate a nature-inclusive energy transition

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ABSTRACT

The energy transition intensifies spatial conflicts between energy infrastructure (EI) and migratory birds, fueling public resistance, litigation and permitting delays. These conflicts are often addressed only at the project level, after EI sites are chosen, leaving little room for proactive impact avoidance. We present a globally scalable method using existing weather radar infrastructure and open data to map nocturnal bird migration at high spatial resolution across large areas, demonstrating its application in the Netherlands. We find that around 50% of migration occurs at altitudes of EI. Contrary to assumed homogeneous distributions or discrete routes, our maps reveal that migration intensity varies over distances relevant for spatial planning. We demonstrate how such maps can inform selection of wind energy sites with considerable variation in migration and wind potential. Our method facilitates early-stage impact avoidance through strategic EI siting, targeted mitigation and faster permitting, offering a low-cost, scalable path toward a more nature-inclusive energy transition.

1. Introduction

The transition from fossil fuels to distributed sources of renewable energy intensifies the space-use conflict between energy infrastructure and natural systems. This conflict not only occurs on land (Scheidel and Sorman, 2012; Rehbein et al., 2020), at sea (Isaksson et al., 2023), but also extends into the air through the vertical footprint of energy infrastructure (Lambertucci et al., 2015; Pérez-García et al., 2022; Gauld et al., 2022). This manifests clearly through the increasing difficulty of siting and permitting of new projects, particularly for wind energy. Across Europe, over 80 GW of onshore wind projects were stuck in permitting in 2022 (WindEurope, 2022), and similar bottlenecks plague the United States (McKenna et al., 2025). Biodiversity concerns — especially the protection of birds and bats — are among the most common causes of opposition and litigation (Susskind et al., 2022; Klain et al., 2018; Chang et al., 2013). In Germany, nearly half of all wind farm legal disputes cite impacts on birds or bats, highlighting the growing influence of conservation conflicts on energy roll-out (McKenna et al., 2025).

Particularly vulnerable are the billions of migratory birds that, through annual journeys spanning up to thousands of kilometers, encounter energy infrastructure at a multitude of established and emerging sites. Above-ground infrastructure, such as wind turbines and power lines, impacts migratory birds directly through collisions and electrocutions and indirectly by acting as obstacles along their flyways (Bernardino et al., 2018; Marques et al., 2014). To mitigate these impacts, diverse regulatory frameworks are in place at international, national and regional levels, such as the EU Bird and Habitat Directives (Directives 2009/147 and 92/43/EEC) and the US Migratory Bird

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Treaty Act. Environmental impact assessments, essential components of the permitting process for energy infrastructure, therefore require quantification and mitigation of avian impacts (Drewitt and Langston, 2006). Preferred mitigation measures generally follow a sequential approach known as the ‘mitigation hierarchy’: avoiding impacts is the primary goal, followed by minimization strategies, restoration efforts, and finally, compensatory offsets (Arlidge et al., 2018). However, in the absence of adequate data on migratory bird movements, particularly at night, these mitigation measures are difficult to implement effectively. As a result, conflicts over bird impacts continue to escalate, contributing to permitting delays, public resistance, and the cancellation of entire projects (Susskind et al., 2022; Klain et al., 2018; Chang et al., 2013), ultimately slowing down the energy transition considerably (McKenna et al., 2025; WindEurope, 2022).

Within environmental impact assessments, avian impacts are generally studied project-by-project, before and occasionally after construction, providing information for small spatial extents and short study periods. These assessments are frequently conducted after spatial planning procedures and locations have already been selected (Gauld et al., 2022). Despite the attention to potential impacts on birds, the information they provide may be highly uncertain (Ferrer et al., 2012), exacerbated by fluctuations in migration dynamics (Kranstauber et al., 2022; Shamoun-Baranes et al., 2017). Finally, the fragmented nature of impact assessments likely results in an underestimation of cumulative impacts on bird populations (Schippers et al., 2020), which might lead to population declines and progressively stronger opposition against and restrictions imposed on future energy infrastructure projects. Although environmental impact assessments consider post-construction mitigation measures for some negative impacts on birds, these measures are often costly and only partially effective (Ferrer et al., 2020; Marques et al., 2014; May et al., 2020).

The pace and scale of the energy transition will thus benefit from a proactive, integral and high-level approach to impact assessments of energy infrastructure on birds (Gauld et al., 2022; Pérez-García et al., 2022; Kiesecker et al., 2010). Avoiding or minimizing impacts on migratory birds early in the site selection process could accelerate the energy transition and reduce costs throughout the life-cycle of energy infrastructure by reducing the need for further mitigation (e.g., mandatory turbine shutdowns) or compensation (e.g., habitat restoration or reclamation) measures (Kiesecker et al., 2010). Generally, this is done through impact sensitivity mapping (Allinson et al., 2020), followed by spatial planning that avoids impacts as much as possible. For birds, this often requires identifying migratory routes or corridors (Marques et al., 2014; Northrup and Wittemyer, 2013), areas with high-intensity migration. However, while the distribution of daytime migration is reasonably well known (e.g., Sierdsema et al., 2021; Gauld et al., 2022; Paquet et al., 2022), the vast majority of birds actually migrate at night (Horton et al., 2019), making them more difficult to study. To continuously measure bird movements, day and night, environmental impact assessments have increasingly adopted dedicated bird radars (van Erp et al., 2024). However, these radars are costly to operate and only capable of detecting birds up to several kilometers away, making them suitable for site-specific and project-level impact assessments, but not for the large-scale deployment needed to develop impact sensitivity maps. The resulting lack of large-scale geospatial information on the distribution of nocturnal migrants in the air therefore poses a challenge for developers, policy-makers and planners aiming and required to proactively reduce impacts of energy infrastructure on birds (Balotari-Chiebao et al., 2023; Boggie et al., 2023; Thomas et al., 2018; Allinson et al., 2020).

To alleviate some of the aforementioned inefficiencies in siting, permitting and environmental impact assessment procedures, the EU has recently introduced ‘renewable acceleration areas’ in the revised Renewable Energy Directive (EU Directive 2023/2413). These areas are designated zones where the deployment of certain types of renewable energy is expected to have minimal environmental impacts. The process of identifying renewable acceleration areas relies on large-scale environmental impact assessments in which impact sensitivity mapping is a crucial component (Allinson et al., 2020). Projects within these areas can then receive an exemption from carrying out project-level impact assessments, leading to shorter permitting procedures (Directorate-General for Energy, 2024). While the Renewable Energy Directive explicitly requires the identification of major migratory routes, the fundamental lack of large-scale information to identify these for nocturnal migrants remains.

Weather radars operate globally across continental networks (e.g., NEXRAD in the US, OPERA in Europe and CINRAD in China) and continuously monitor vast airspace upwards of 70–100 km from hundreds of sites (Saltikoff et al., 2019). While fulfilling their primary weather surveillance purpose, they can also provide information on migratory bird movements, generally once every 5 min. Contrary to short-term deployments of dedicated bird radars, many weather radars have operated for decades, offering unique opportunities to map long-term migration patterns when suitable archives exist. Importantly, this data is increasingly archived as open data (Ansari et al., 2018; Desmet et al., 2025). While weather radars cannot resolve individuals or identify species, they can be used to quantify abundance of birds in the air across large areas with a fine spatial resolution of 250–500 m horizontally and 50–100 m vertically. They are therefore uniquely positioned to provide large-scale, spatially continuous information on vertical (Dokter et al., 2011; Kemp et al., 2013) and horizontal bird distributions during nocturnal migration at regional to continental scales (Nilsson et al., 2019; Van Doren and Horton, 2018).

When aggregated to long-term averages across multiple migration seasons, biological data extracted from weather radars can serve as a ‘climatology’ of bird migration suitable for use in spatial planning, environmental impact assessments and the implementation of mitigation measures across local to national scales. To provide information on these long-term spatial distributions of nocturnally migrating birds for use by policy makers, spatial planners and developers, we introduce a scalable method for the quantification of vertical and horizontal distributions from the long-term archives of weather radar data. We focus on nights of intense migration and, within those nights, on the periods when the maximum number of birds are generally in flight. We illustrate the method using open data from two Dutch weather radars, aggregating their data over six years and spring and autumn migration seasons. We first quantify the degree of overlap of bird migration with operational heights of energy infrastructure at 50-m vertical resolution, crucial for an assessment of collision risk. We then map horizontal distributions at 500-m resolution and illustrate how these maps can inform site selection by comparing migration intensity and wind power potential across candidate development sites identified by local and regional governments. Our approach illustrates how this geospatial information can support an acceleration of the energy transition through nature-inclusive spatial planning. In addition, it provides a framework for optimizing the cost-effectiveness of mitigation measures for emerging and existing energy infrastructure based on quantitative migration data.

2. Methodology

2.1. Workflow design

Although weather surveillance radars are used around the world (Saltikoff et al., 2019), their data is often not directly accessible or usable for ecological research (Shamoun-Baranes et al., 2022). The United States’ NEXRAD radar archive is the gold standard in open data sharing for weather radar networks, by making a wealth of ecologically-relevant radar data available online since 2015 (Ansari et al., 2018). Improved access to this data, combined with methodological advances (Dokter et al., 2019; Lin et al., 2019; Kranstauber et al., 2020), has led to an acceleration of the field of 'radar aeroecology' — the study of flying animals using radar — and unlocked long-term, continent-wide ecological insights from weather radars (e.g. Rosenberg et al., 2019; Van Doren and Horton, 2018).

In many countries outside the US, only a subset of weather radar measurements (known as 'products', see *Processing radar data into spatial maps*) or merely derivatives thereof are archived publicly (Shamoun-Baranes et al., 2022). This has two major disadvantages. First, ecologically-relevant weather radar data might have to be separately requested from meteorological agencies, and, depending on the volume of data requested, a data management infrastructure might be necessary. Secondly, given substantially less standardization between individual radars and countries, it is more difficult to benefit from methodological advances such as in Lin et al. (2019) for fully automated classification of radar data — necessary to separate biological from meteorological signals. As a consequence, manual screening of data often remains necessary.

To overcome these disadvantages, we have designed a workflow aimed at minimizing data requirements and screening efforts needed to create the altitude profiles and distribution maps of birds. First, we focus on the identification of pulses of migration to reduce the data requirements. When, for example, 10% of nights already encompasses over 50% of all seasonal migration, as is the case in the US (Horton et al., 2021), including the other 90% of the nights would yield progressively less information of the largest movements of nocturnal migrants at a substantial computational, storage and processing cost. Through existing open data archives of vertical profiles of bird movements, such as the Aloft repository for European weather radars (Desmet et al., 2025, at https://aloftdata.eu), it is possible to identify these pulses of migration and limit data requests and processing to the minimum nights needed to capture 50% of migration dynamics. Secondly, following a similar methodology to take-off distribution mapping (Buler et al., 2017), we limit our data aggregation to a single scan of the atmosphere for each night a pulse of migration occurs. For a night of 8 h, this reduces manual screening efforts from 96 scans (one scan every 5 min) to just a single scan. By taking this data minimization approach and making use of the existing archives of vertical profiles of birds, we have designed a simple, generalizable workflow that can provide critical information on bird distributions across countries with widely differing weather radars and data sharing policies.

In case data requests for polar volume data needed for high-resolution spatial mapping and storage have to be minimized, it is recommended to first identify these pulses of migration from existing vertical profiles (e.g. Desmet et al., 2025) and narrow down the data selection period. All subsequent steps can then be followed as described. However, given that Dutch weather radar data is publicly available, data minimization was not necessary for the purpose of this study.

2.2. Radar data

Weather radars have established an essential role in the quantification of mass movements of aerial organisms, in particular that of birds (Shamoun-Baranes et al., 2022). We used data from 2 operational C-band (5-cm wavelength) weather radars operated by the Royal Netherlands Meteorological Institute (KNMI), at Den Helder (52.95° N, 4.79° E, 55 m above sea level (asl)) and Herwijnen (51.84° N, 5.14° E, 25 m asl). Each radar scans the lower atmosphere once every 5 min across 360° azimuthal directions (1° resolution) and at 16 elevations. We use the 13 elevation scans between 0.3° and 25° that provide high-resolution reflectivity and velocity data. The resolution of radar measurement volumes (range gates) varies per elevation but ranges between $90\,\mathrm{m} \times 1°$ and $399\,\mathrm{m} \times 1°$. Primarily intended for meteorological use, weather radars can detect rain upwards of $250\,\mathrm{km}$ from the radar. With increasing distance from the radar, the lowest radar beam increasingly overshoots the altitudes at which birds migrate, so their typical detection range during intense migration is lower than that of rain (around 100–125 km for birds on Dutch radars). This measurement range and resolution of operational weather radars enables fine-scale mapping of birds across large parts of the Netherlands (Hoekstra et al., 2024). Within the range gates, radar reflectivity η (cm^2 km^{-3}) is proportional to the density of scatterers in a volume of air and is commonly converted to bird densities assuming a standard radar cross-section of 11 cm^2, which represents the radiated body surface per bird on C-band radars averaged across all detected individuals in a year (Dokter et al., 2011).

We used radar data collected between spring 2017 and autumn 2022, starting from the moment both radars were upgraded with dual-polarization capabilities allowing for an improved separation of meteorological and biological scatterers (Stepanian et al., 2016; Kilambi et al., 2018). We only extracted data from the migration seasons, between February 15 and May 31 for spring and August 15 and November 30 for autumn migration. Data from Dutch radars can be accessed freely via the KNMI Data Platform at https://dataplatform.knmi.nl.

2.3. Identifying pulses of nocturnal migration

We used an established method to convert the volumetric weather radar measurements to vertical profiles of bird densities, using the vol2bird algorithm included in the bioRad R package (Dokter et al., 2019). These vertical profiles contain information about the density, ground speed and direction of birds every 5 min in the lowest 5 km of the atmosphere, usually in altitude bins of 200 m in height. The vol2bird algorithm filters unwanted radar reflections known as 'clutter' and makes use of the differences in radar signature between wind-borne sources of reflectivity, such as rain, and self-propelled sources such as birds. Additionally, we used a dual-polarization correlation coefficient ρ_{hv} threshold of 0.95, above which signals were classified as rain. To improve the vertical resolution at altitudes close to the surface, critical to identify the vertical overlap of flight altitudes of birds with energy infrastructure, we increased the altitude bin resolution to 50 m. We excluded the lowest altitude bin covering 0–50 m above sea level, because the radars located at 25 m (Herwijnen) and 55 m (Den Helder) overshoot a large part of this altitude range already and strong ground clutter reduces the ability to detect birds. As the vertical distributions of birds are strongly correlated and the vertical resolution has increased 4-fold, for simplicity we refer to the lowest 200 m of the atmosphere without continuously mentioning the lowest 50 m has been excluded.

We defined the night as the period between sunset and sunrise (when the geometric center of the sun crosses the horizon), and discarded the daytime observations. For every night in the time series of vertical profiles, we calculate the cumulative migration traffic (birds km^{-1}) from a temporal integration of the 5 min migration traffic rate (birds km^{-1} h^{-1}) across all vertical profiles within the respective night (using the `integrate_profile()` function in bioRad). For each season in every year, we then ranked the cumulative migration traffic in decreasing order and incrementally selected the top nights in terms of highest cumulative migration traffic until these contained at least 50% of the total nightly seasonal migration traffic. In other words, we selected the smallest combination of nights during which at least half of all seasonal nocturnal migration would occur. We refer to these selected nights as 'peak nights'.

2.4. Flight altitudes

For each season and year, we calculated the total bird density within each 50-m altitude bin by summing the 5 min measurements of bird densities across all peak nights. To determine an overarching seasonal altitude distribution, we averaged these total bird densities across the six years of data (i.e., spring 2017–2022 and autumn 2017–2022) and subsequently converted them to proportional flight altitude distributions for spring and autumn.

Although the vertical profiles are calculated up to 5 km in altitude, high-altitude migration is comparatively rare and only accounts for a small proportion of seasonal passage (Dokter et al., 2013; Kemp et al., 2013). For energy infrastructure, which is mostly situated close to the surface in the lowest 200–300 m of the atmosphere, the altitude range well above 1 km is therefore not as relevant. To provide the ecological context of the altitude distribution of migrating birds, but not add unnecessary detail at high altitudes, we present altitude distributions up to 1 km in detail and combine altitude bins above into a single > 1 km class.

2.5. Processing radar data into spatial maps

To map the spatial distribution of birds as measured by weather radars, it is essential to identify and remove non-biological clutter (e.g., from rain, wind turbines or electromagnetic interference). Since migrating birds produce a relatively weak signal compared to meteorological phenomena or ground-based interference, accidentally including clutter can lead to significant overestimation of bird numbers aloft. In the absence of machine learning methods for fully automated volumetric radar data classification, such as Lin et al. (2019), we have developed a semi-supervised workflow to process and manually screen radar data for clutter contamination.

For each of the peak nights, we selected the radar scan closest to the average moment of peak migration, 2.5 h after sunset (Kranstauber et al., 2022), aiming to represent the spatial distribution when most birds are simultaneously in the air and en route during migration. The volumetric radar measurements were then converted into vertically integrated, two-dimensional maps of bird densities, capturing the spatial distribution of birds across the Dutch landscape at a 500 × 500 m resolution. To create these maps, we used the `integrate_to_ppi()` bioRad function to correct for radar range-bias due to partial radar overshoot of the altitude layer with biological echoes (Kranstauber et al., 2020). Where the range-bias adjustment factor R was >10, we set pixels to NA. Prior to this conversion, we removed electromagnetic interference and corrected for aspect effects, i.e., the variation in birds' radar cross-section with body orientation.

2.5.1. Electromagnetic interference

Electromagnetic interference (Saltikoff et al., 2016), caused by e.g. long-range wireless networks, shows up as long linear elements of gradually increasing radar reflectivity (DBZH) with increasing range from the radar. We used this characteristic to identify contamination by fitting linear models to individual beams on the original polar grid, modeling beam DBZH as a function of range. Beams were then classified as contaminated with electromagnetic interference when the model coefficient of determination was >.75, the model slope was positive, and >75% of the beam range contained non-NA DBZH measurements (i.e. measurements above the radar noise level and not removed by a radar clutter filter). As this, when present, generally concerns only 1 to 3 (of 360 in total) adjacent beams, we removed this clutter through a simple nearest-neighbor interpolation on the original polar grid between the beams directly adjacent to the electromagnetic interference.

2.5.2. Aspect effect during intense migration

In some cases of strong migration, birds are moving very uniformly in the same direction and with the same headings, a phenomenon most apparent around the nightly peak in migration intensity considered in this study, 2.5 h after sunset. This can result in higher reflectivities in areas where birds are radiated side-on and lower where radiated head- or tail-on, due to the strong aspect dependence of the radar cross-section (Stepanian et al., 2016). To correct for this aspect effect, which typically results in symmetrical reflectivity 'lobes' on either side of the radar, perpendicular to the migration heading, we fitted a sine wave with a fixed period of 180° to the reflectivity (DBZH) values across all 360 azimuths. We did this for all elevations, but only in the range of 5–35 km from the radar and between 200 m and 5000 m, similar to the vol2bird algorithm (Dokter et al., 2011). This spatial domain was chosen to avoid excessively large sampling volumes, ground clutter interference, and altitudes above 5 km, where migratory activity is typically negligible. After fitting, we then subtracted the sine component, capturing what reflectivity could be explained through the aspect effect, from reflectivity values across all elevation scans and the full range (0–100 km). This correction reduces the azimuthal aspect bias by down-weighting reflectivity from side-on views and up-weighting it for head/tail-on views, crucially maintaining the same mean reflectivity as uncorrected measurements. This preserves comparability with standard vertically integrated density (VID, the density of birds in a column of airspace, expressed in birds km^{-2}) calculations from the vertical profiles, which inherently average out variations in radar cross-sections across viewing angles. This correction for aspect effects assumes a uniform migratory direction and therefore has only been applied for the Herwijnen radar. We did not apply this correction to the Den Helder radar data, as the coastal setting with its large surrounding water bodies induces more variable migratory directions that violate the necessary assumption of directional uniformity.

2.5.3. Radar clutter removal

Next, we visually screened scans for clutter from precipitation or anomalous propagation and excluded these from further analysis. To identify rain-contaminated scans, we calculated the depolarization ratio (DPR; Kilambi et al., 2018) using the correlation coefficient and differential reflectivity moments as measured by dual-polarization radars (Stepanian et al., 2016). As suggested by Kilambi et al. (2018) and previously validated (Hoekstra et al., 2024), we used a typical threshold of DPR > -12 to separate biological from meteorological signals. While we used this primarily to quickly identify rain, we also used the threshold to remove rain in case small-scale rain was accidentally missed. Anomalous propagation arises when atmospheric conditions cause the radar beam to refract strongly toward the surface. This is readily identified through the presence of strong ground clutter at locations where, under normal conditions, no strong reflectivity from the ground can be expected. We only excluded scans with precipitation or anomalous propagation when this was present over our study area, the terrestrial parts of the Netherlands buffered by 5 km within 100 km from the radars. Through this screening procedure, we removed 198 clutter contaminated scans from all 343 radar scans of peak nights; 116 scans for spring and 82 for autumn migrations.

To remove sources of clutter, reflectivity from non-aerial biomass targets, we used a two-step approach to identify and remove both static and dynamic sources of clutter. Static clutter is consistent in presence and originates from, for example, buildings, roads or tall vegetation mostly very close to the radar. Dynamic clutter is more variable, e.g., because it is somewhat dependent on weather conditions, such as clutter from wind turbines. For both, if the vertically integrated reflectivity (VIR) exceeds the threshold value, we set the reflectivity in the corresponding pixel to NA. For sources of dynamic clutter, we found a VIR threshold of 2500 cm^2 reliably filters out this type of clutter. To identify static clutter, we used the vertical profiles to select the moments with the least bird migration. From those, we excluded the scans with clutter from rain or anomalous propagation. We then averaged the scans and calculated the average VIR during these migration-free moments. Pixels which had an average VIR > 250 cm^2 were classified as static clutter. For both types of clutter, we tracked the frequency of occurrence across all scans. We then buffered the areas for both types of clutter by 500 m and set the corresponding areas in the bird maps to NA. In addition, we calculated areas affected by beam blockage using a wradlib (Heistermann et al., 2013) procedure to calculate cumulative beam blockage fraction due to terrain topography using the 30 m SRTM data (NASA JPL, 2013). We then marked areas with a beam blockage fraction above 0.05. Remaining beam blockage, which could not be resolved at the horizontal and vertical resolution of the SRTM data, was easily identified as areas pointing radially outwards from the radar with consistently lower reflections (across individual as well as aggregated scans) and marked manually. Despite little topographic variation across the Netherlands in general, a landscape ridge on the northeastern side of the southernmost (Herwijnen) radar, blocked a large swath of that radar's beam, with underestimation of migrant numbers as a result. The remaining beam blockage was caused by man-made objects at the surface. Importantly, we designed our clutter filtering approach conservatively, erring on the side of identifying birds as clutter rather than missing actual clutter sources. Consequently, in bird-rich areas with very high densities of birds, such as the Wadden Sea and on the island of Texel, genuine bird signals were sometimes misclassified as clutter.

2.5.4. Mapping seasonal distributions

We aggregated seasonal average distributions of birds by first calculating seasonal means from individual years (e.g., autumn 2019, spring 2021) and then averaged these to seasonal averages across years for autumn and spring seasons. We used max-compositing to merge the maps from the two radars as it provided an artifact-free, smooth transition in bird densities in the overlap zone between the two radars. To avoid over-interpretation of small-scale pixel-level differences in the 'raw' maps (Fig. B.5), we applied a Gaussian smoothing kernel (s.d. = 4; window = 25 × 25 pixels = 12.5×12.5 km) to create the final maps of bird densities.

Assuming that bird densities scale proportionally with seasonal passage and areas with average bird densities also experience average seasonal passage, we converted the bird densities to seasonal passage P at each location i using:

$$P_i = \left(\frac{D_i}{\bar{D}}\right) P_{\text{total}}$$

where D_i is the bird density at location i, $\bar{D}$ is the mean density across all locations, and P_{total} is the average cumulative seasonal passage from both radars expressed in birds km^{-1}. This scaling ensures that locations with above average densities contribute proportionally more to the overall passage than locations where densities are below average.

2.6. Mapping migration intensity and wind power trade-offs

To assess the spatial trade-off between nocturnal bird migration intensity and wind energy potential, we overlaid the seasonal migration intensity maps with wind power density across North-Holland. Wind power density (W m^{-2}) extracted from the Global Wind Atlas (Davis et al., 2023) was based on long-term modeled wind averages at 100 m height above the surface at a fine 250 m resolution. For North-Holland and all candidate wind energy sites, we extracted average values of both variables and visualized their joint distribution using a bivariate distribution plot. A bivariate color scale was used to map spatial combinations of migration intensity and wind potential, highlighting trade-offs of current candidate sites from an ecological and energy production perspective.

2.7. Uncertainty analysis

To assess the stability of the spatial migration patterns across seasons, we performed a jackknife resampling procedure, computing the correlation between the seasonal average (e.g., from autumn 2017–2022) and leave-one-year-out means (e.g., autumn 2018–2022) of the raw maps. Across all radar-season combinations, pixel-wise Pearson correlation coefficients exceeded 0.94 (μ = 0.98; sd = 0.014), indicating the spatial structure was highly stable and not driven by extreme seasonal variation in spatial distributions.

Similarly, we used jackknife resampling to assess the stability of patterns sampled at two specific time points during a night: the average peak moment of migrant abundance (2.5 h after sunset) and 4 h after sunset. We computed pixel-wise Pearson correlation coefficients between seasonal averages of the two time points, iteratively leaving out individual years. Across all radar-season combinations, pixel-wise correlations averaged 0.76 (s.d. = 0.17), suggesting overall spatial patterns remain broadly similar later in the night. An exception was the Den Helder radar in spring, where the mean correlation dropped to 0.48 (s.d. = 0.07), likely due to the interplay of complex coastal topography and migration dynamics of birds crossing the North Sea, resulting in a somewhat delayed moment of peak abundance (Kranstauber et al., 2023).

3. Results and discussion

3.1. Nocturnal pulses of bird migration

Twice a year, billions of birds migrate between their breeding and wintering grounds (Hahn et al., 2009; Dokter et al., 2018) to track favorable environmental conditions. The vast majority of migration occurs at night (Horton et al., 2019) and is largely dependent on weather conditions like wind and precipitation (Shamoun-Baranes et al., 2017). As weather conditions can vary greatly, nocturnal bird migration generally occurs in 'pulses' of mass movements during favorable weather (Manola et al., 2020). Consequently, migration takes place over a relatively short period of time, confirmed by studies that found half of all seasonal passage occurring within only 10% of nights (Horton et al., 2021) and locally even within just 18–26 h (Bradarić et al., 2024b).

Here, we use weather radars to rank nightly migration activity across all years and seasons. In subsequent analyses, we use only the nights with the most activity, i.e., those that collectively capture at minimum 50% of the total seasonal migration. For consistency, we refer to these nights as 'peak nights'. We used the archive of open data from two Dutch radars covering approximately 80% of the Netherlands within 100 km from the radars. From 716,701 weather radar scans across 2536 radar days over a period of six years (2017–2022), we identified a total of 247 unique peak nights of bird migration: 138 in spring (February 15–May 31) and 109 in autumn (August 15–November 30). Across radars, on average 16 (range: 13–19) spring nights and 12 (range: 5–22) autumn nights captured 50% of all migration activity, clearly indicative of the pulsed nature of bird migration (see also Kranstauber et al., 2022).

3.2. Vertical overlap of bird migration with energy infrastructure

Assessing the impact of energy infrastructure on nocturnal migrants requires detailed knowledge of their flight altitudes relative to the vertical extent of this infrastructure. Here, we define this altitude range of overlap — where birds face collision risks (Marques et al., 2014) — as the lowest 200 m of the atmosphere, up to the top of the typical rotor-swept zone of current onshore wind turbines. Information on the degree of overlap is critical for risk assessment, modeling and mitigation of energy infrastructure impacts (Masden and Cook, 2016). We use established methods to quantify the vertical distributions of

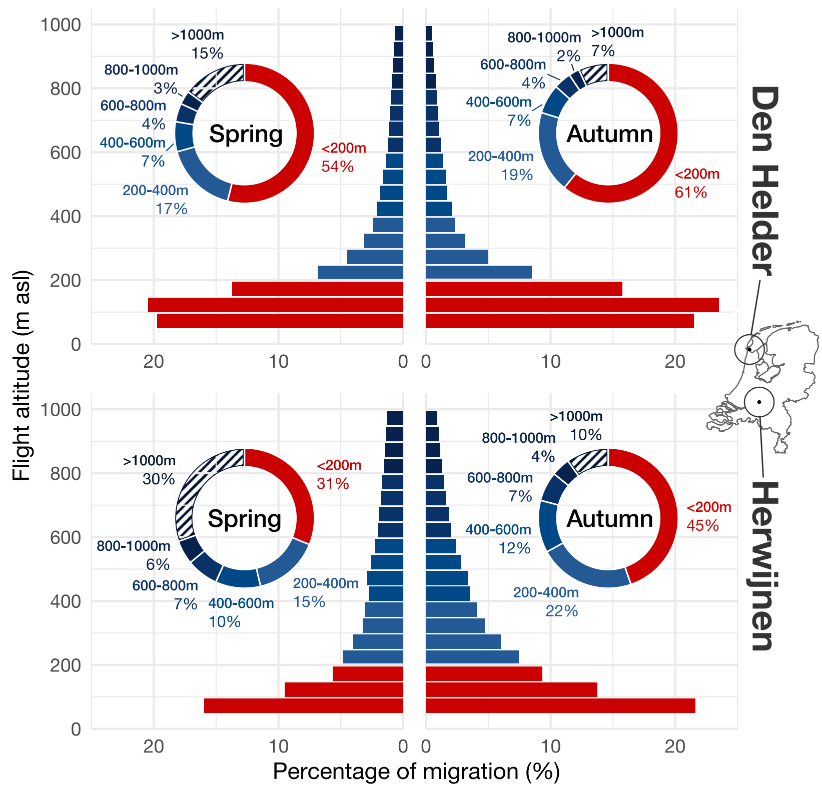

Fig. 1. Flight altitude distributions (in m above sea level (asl)) of nocturnal bird migration for both Dutch weather radars at a coastal Den Helder and inland site Herwijnen. Bar length denotes the proportion of migration within the respective altitude range (50 m vertical resolution). Donut charts aggregate this further to coarser 200-m classes and display the proportion of migration occurring above 1000 m (patterned). Red highlights indicate the altitude range of onshore energy infrastructure in the Netherlands, which is generally present in the lowest 200 m of the atmosphere. Donut chart proportions do not sum to 100% due to rounding. The small inset map of the Netherlands shows the locations of both radars (solid dots) and the surrounding areas up to 35 km (circles) from which altitude distributions are aggregated. Night-to-night altitude distributions can be found in Fig. A.4.

birds (Dokter et al., 2019) in 50-meter altitude bins in the lowest 50–1000 m of the atmosphere (Fig. 1).

Overall, we find that on average 48% of peak night migration overlaps with the vertical extent of energy infrastructure. In autumn, migration occurs lower than in spring, but the seasonal proportions of migration overlapping with onshore energy infrastructure differ only up to 14%. These results are consistent with previous findings in northwestern Europe for nocturnal migration, both onshore (Dokter et al., 2013; Bruderer et al., 2018) as well as offshore (Bradarić et al., 2024a). By contrast, migration in our study area appears to take place at lower altitudes than in the northern, eastern and coastal United States (Cohen et al., 2022; La Sorte et al., 2015; Curley et al., 2025), Colombia (Drucker et al., 2025) and Japan (Tago et al., 2020), while being more similar to reported heights in Australia (Shi et al., 2024). Taken together, these patterns highlight pronounced geographic differences in flight altitudes that should be considered when quantifying energy infrastructure impacts.

It is difficult to quantify how much migration occurs at the altitudes of most power lines, transmission towers, and below the rotor-swept zone of wind turbines, because the radars overshoot much of this altitude range. One possible way to address these data gaps at low altitudes is through extrapolation techniques (e.g. Nussbaumer et al., 2021; Curley et al., 2025), or locally through the incorporation of measurements by dedicated bird radars, which can be placed closer to the ground and have a lower minimum measurement altitude (Nilsson et al., 2018; van Erp et al., 2024). However, given that weather radars are capable of detecting the highest nocturnal migrants up to several kilometers altitude, but not those flying well below 50 m, the proportion of birds flying at energy infrastructure height is likely underestimated (Bruderer et al., 2018; Nussbaumer et al., 2021) and should be seen as a conservative estimate.

Some studies have highlighted adjusting the vertical dimensions of energy infrastructure to reduce impacts, for example, by increasing ground clearance of wind turbines above frequently used altitudes (Schaub et al., 2024; Johnston et al., 2014). This may benefit specific bird populations, but, with flight altitude distributions of nocturnal migrants in the Netherlands overlapping much of the airspace used by energy infrastructure, it is unlikely to sufficiently mitigate the impact on migrating birds. This challenge highlights the importance of strategic spatial planning to minimize the impact of infrastructure on migrating birds and to comply with environmental regulations.

3.3. Mapping migration intensity for energy infrastructure planning

Using measurements up to 100 km from the weather radars, we quantified spatially continuous patterns of nocturnal bird migration across 33,543 km^2 of onshore area at a spatial resolution of 500 × 500 m. We aggregated moments of peak migrant abundance to seasonal averages of peak night distributions of birds.

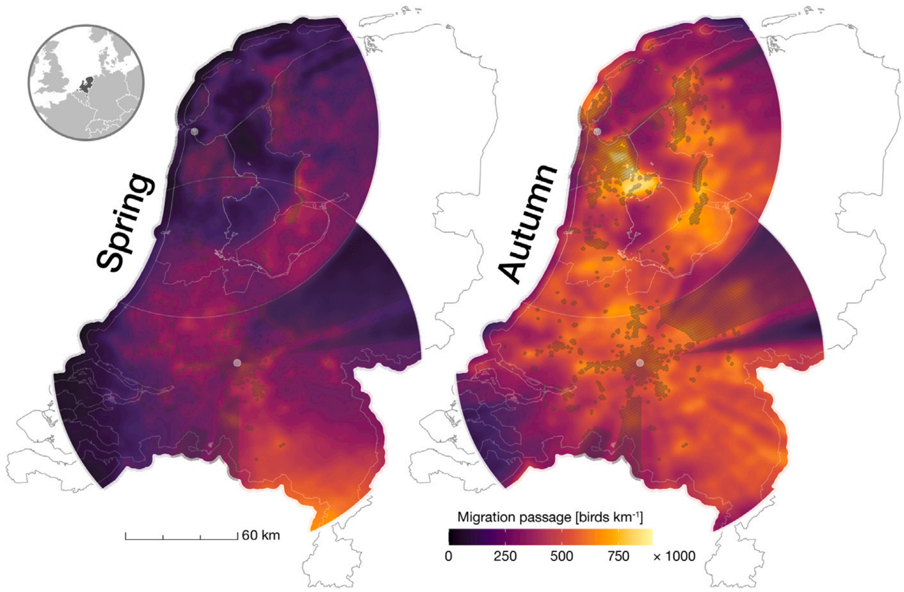

Fig. 2. Maps of nocturnal bird migration across the Netherlands in spring and autumn, with the 100 km radius circles of the weather radars enclosing the onshore study area. Colors represent seasonal migration passage, converted from the original bird densities. Shaded areas mark grid cells for which over 25% of the input data, prior to filtering, were impacted by ground clutter. Migration passage in these regions may be compromised in either direction: overestimated due to remaining clutter artifacts or underestimated where terrain features partially obstruct the radar's lower scanning angles.

From 247 peak nights, we derived 145 validated migration measurements using a semi-automated filtering process that excluded rain and other 'clutter', yielding spatially unbiased estimates of 22% (range: 12%–36%) of spring and 24% (range: 12%–41%) of autumn migration. During these peak nights, the average reflectivity corresponded to bird densities of 17 ± 8 (mean ± s.d.) birds km^{-2} in spring and 35 ± 9 birds km^{-2} in autumn, assuming average-sized migrants with a radar cross-section of 11 cm^2. Converting these densities to spatially-explicit seasonal cumulative migration, this corresponds to an average seasonal passage of approximately 250,000 ± 120,000 birds km^{-1} in spring and 450,000 ± 120,000 birds km^{-1} in autumn (Fig. 2). Here, birds km^{-1} refers to the number of individuals that cross an imaginary 1 km transect oriented perpendicular to the direction of migration over the course of a season.

The maps show a clear difference in the general spatial distributions between the seasons, with the most prominent passage in spring in the southeast and a far more prominent passage in the northwest in autumn. Notably, the maps differ substantially from the wind energy impact sensitivity map for migrating birds in the Netherlands, which is based on visual surveys and expert knowledge (Sierdsema et al., 2021). This further emphasizes the importance of accounting for differences between daytime and nighttime movements within environmental impact assessments, as they can differ greatly.

Importantly, contrary to generally assumed homogeneous distributions of birds during nocturnal migration (Chilson et al., 2017), we find bird passage varying up to threefold across short distances of 10–20 km. Although this clearly indicates nocturnal migration is not necessarily uniformly distributed, our data reveal no evidence of consistent migration routes or corridors either, unlike patterns observed in several diurnal migrants (Gauld et al., 2022).

3.4. Case study: onshore wind energy in North-Holland

To meet its 2030 target of 35 TWh of renewable electricity from onshore wind and solar, the Netherlands has been divided into 30 energy regions tasked with planning energy developments in line with local needs. In each region, stakeholders contribute to regional energy strategies and identify candidate sites for renewable energy development. In the province of North-Holland — home to the Dutch capital, Amsterdam — this process designated 45 candidate wind energy sites.

Based on our maps, seasonal passage through North-Holland amounts to 230,000 ± 60,000 (mean ± s.d.) birds km^{-1} in spring and 540,000 ± 110,000 birds km^{-1} in autumn. The province shows the largest seasonal contrast in migration intensity of all Dutch provinces covered by radar measurements, with autumn passage 2.4 times higher compared to a 1.8-fold increase on average. Across candidate sites, autumn passage varies substantially (approximately 360,000–800,000 birds km^{-1}), while spring differences are smaller (170,000–330,000 birds km^{-1}; see supplementary Fig. C.6).

Because precise migration timing and route data are lacking for most nocturnally migrating species, it is difficult to target specific vulnerable species in energy infrastructure impact mitigation. As a result, efforts typically focus on minimizing impacts for the largest numbers of birds, assuming this will also benefit vulnerable species. In North-Holland, autumn distributions should therefore guide mitigation, as they involve by far the most birds. Targeting high-intensity migration areas and seasons can reduce collision mortality and barrier effects while minimizing societal costs.

When comparing long-term wind power potential (Fig. 3; Davis et al., 2023) and migration intensity, clear spatial trade-offs emerge. Twenty candidate sites overlap with areas of above-average migration intensity, and 15 of those simultaneously coincide with below-average wind potential. Such comparisons can help show trade-offs between different objectives (conservation and energy production) and identify areas with a desirable balance between the two. Ideally, from the perspective of bird conservation and energy, sites with high wind potential and low migration intensity should be prioritized, while those with high migration activity may require additional mitigation efforts.

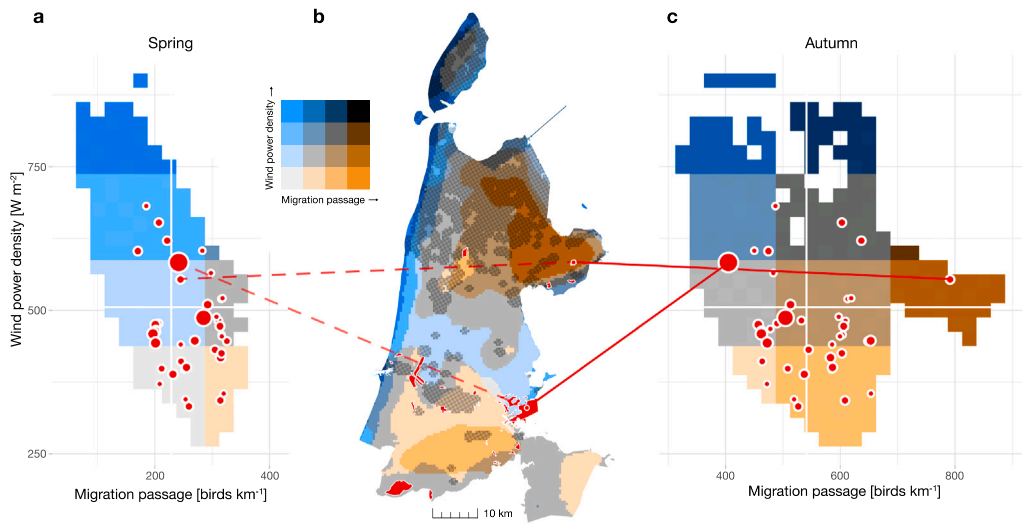

Fig. 3. **a, c** Observed combinations of migration passage and mean wind power density, a measure of wind power potential, in North-Holland. Red circles represent average values for candidate sites and their size reflects the relative candidate site area. The grid reflects binned values of migration and wind power density, with color shading indicating the type of combination: orange = high migration passage, blue = high wind power density, dark browns and blues = both high. White lines indicate averages for wind power density and seasonal migration passage. **b** Spatial distribution of autumn migration (orange hues) and wind energy (blue hues) in North-Holland. Candidate wind energy sites are shown in bright red. The highest and lowest autumn migration passage sites are linked to their positions in **a** and **c**, emphasizing large differences between sites in autumn, but not in spring. Shaded areas mark grid cells for which over 25% of the input data, prior to filtering, were impacted by ground clutter. Migration passage in these regions may be compromised in either direction: overestimated due to remaining clutter artifacts or underestimated where terrain features partially obstruct the radar's lower scanning angles.

These trade-offs underscore the value of integrating migration data into spatial planning to better align conservation and energy goals.

3.5. Policy implications for nature-inclusive energy infrastructure

Balancing renewable energy development with biodiversity conservation targets is increasingly important for a rapid, sustainable, and nature-inclusive energy transition (Kiesecker et al., 2019). This study provides scalable and actionable tools for mapping nocturnally migrating bird distributions at large scales and high spatial resolutions. The tools can be used to reduce the environmental impact of energy infrastructure, while optimizing the life-cycle efficiency and cost-effectiveness of mitigation measures. By identifying areas with high migration intensity — where mitigation needs and therefore costs are greatest — they help allocate limited conservation and project resources more strategically.

The migration maps developed in this study enable the quantitative inclusion of migratory bird impacts in nature-inclusive spatial planning procedures, for example, through multi-criteria optimization procedures or scenario development (Arnette and Zobel, 2012). Such methods can identify priority areas for migratory bird conservation within zones of high bird migration passage and, by extension, priority areas for energy infrastructure development where migration passage is low. Critically, these maps support the mitigation hierarchy's key principle that avoiding impacts entirely is more effective than reducing or offsetting them (Arlidge et al., 2018). By providing information on migratory birds early in the planning process, they help stakeholders anticipate risks and explore alternatives before sites are selected. This approach could also streamline regulatory processes by addressing avian impacts upfront, especially when integrated in frameworks like the EU's 'renewable acceleration areas' (EU Directive 2023/2413; Directorate-General for Energy, 2024).

Our findings also suggest the term 'migration routes', commonly used in planning and mitigation guidelines (Allinson et al., 2020) and regulations like the EU Renewable Energy Directive (EU Directive 2023/2413, article 15c), risks oversimplifying the spatial patterns of nocturnal bird migration. Rather than discrete pathways or entirely uniform movements, the aggregate pattern of nocturnal migrants' movement is on a spectrum with zones of higher and lower migration intensities. A narrow interpretation of 'routes', often based on visual surveys or tracking of a subset of species, risks underestimating impacts across the many species that collectively show a more diffuse migration pattern. Failing to address this reality, mitigation efforts might be insufficient, risking downstream legal challenges because of inadequate compliance with conservation regulations.

In cases where complete avoidance of all energy infrastructure impacts on migratory birds through spatial planning is unfeasible, geospatial maps and information about flight altitudes can inform strategies for the reduction of negative impacts. For instance, North Holland's heterogeneous pattern of bird migration suggests that directing costly collision minimization efforts toward areas of high migration passage can yield greater conservation benefits against lower societal costs than in areas of low migration passage. Projects in areas with high migration passage are also more likely to face stricter permitting, collision risk modeling or monitoring requirements, which increase costs over the project lifecycle. By contrast, siting energy infrastructure in low-passage areas may reduce the need for such measures, offering both ecological and economic advantages. These spatial trade-offs are similarly relevant for managing existing infrastructure, e.g., through repowering (Kitzing et al., 2020) or retrofitting mitigation measures (Marques et al., 2014). For energy infrastructure in areas of low migration passage, compensatory environmental offsets for residual impacts could be considered in areas with higher migration passage, enhancing conservation efforts where they are most effective.

For nocturnal migration, one increasingly popular and sometimes even required method of collision mitigation is turbine curtailment, the process of slowing down wind turbines during intense migration (Marques et al., 2014; Bradarić et al., 2024b). Due to the large scale at which birds synchronously take to the skies for their nocturnal migration, this mitigation measure has major consequences for grid stability if used widely (Bird et al., 2016). To avoid grid instability and ensure dispatch capacity is available, migration forecast models can predict when curtailment will be effective (Bradarić et al., 2024b; Kranstauber et al., 2022), so alternative energy sources can be dispatched for these moments. However, with increasing market penetration of wind energy, the ability to implement widespread wind curtailment could decrease, because the installed capacity of dispatchable power might be insufficient (Bird et al., 2016). Especially in these cases, information on bird distributions as provided by our maps, combined with spatial wind energy forecasts for the curtailment period, can dynamically guide decisions in which regions curtailment can be most effective, balancing conservation benefits with grid stability.

4. Conclusion

While our study is focused on a large part of the Netherlands, we propose a method with global potential that leverages the widespread network of weather radars (Saltikoff et al., 2019) to gather high-quality geospatial information on the distribution of otherwise invisibly migrating birds. Our approach to mapping vertical and horizontal distributions of birds provides critical information suitable across scales, ranging from project-level to national-level environmental impact assessments. Although our analysis focuses on onshore areas, the same approach can equally be extended to near-shore and offshore zones within radar coverage (see Curley et al., 2025), providing relevant information for offshore energy planning and mitigation as well. The large-scale and spatially continuous maps of seasonal bird migration presented here enable policy makers, spatial planners, and developers to proactively address conflicts between energy infrastructure and migratory birds across the avoidance, minimization, and compensatory steps of the mitigation hierarchy. These maps can therefore accelerate permitting procedures, reduce societal costs, and maximize conservation benefits of impact mitigation efforts, especially when current approaches do not yet utilize information on fine-scale spatial variations in bird distributions. As countries expand renewable energy infrastructure to meet climate targets, stakeholders need tools that identify where ecological impacts are most likely. Weather radars and their biological data products offer an underused but practical solution with tremendous potential for supporting a nature-inclusive energy transition around the world.

CRediT authorship contribution statement

Bart Hoekstra: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Bart Kranstauber:** Writing – review & editing, Software, Methodology, Conceptualization. **Maja Bradarić:** Writing – review & editing, Writing – original draft, Conceptualization. **Johannes De Groeve:** Software, Formal analysis, Data curation. **Stacy Shinneman:** Visualization, Project administration, Data curation. **Berend C. Wijers:** Software, Resources, Data curation. **Hidde Leijnse:** Writing – review & editing, Validation. **Hans van Gasteren:** Writing – review & editing, Validation. **Adriaan M. Dokter:** Writing – review & editing, Software, Conceptualization. **Emiel van Loon:** Writing – review & editing, Supervision, Conceptualization. **Judy Shamoun-Baranes:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Nightly flight altitude distributions

See Fig. A.4.

Appendix B. Unsmoothed bird density maps

See Fig. B.5.

Appendix C. Seasonal migration traffic across all candidate sites

See Fig. C.6.

Data availability

All code and processed data necessary to reproduce the key analyses and figures in this article are available at GitHub (https://github.com/barthoekstra/nl-birdmap/) and archived on Zenodo (https://doi.org/10.5281/zenodo.17185398). Due to the large volume of raw weather radar data, these files are not included in the repository, but are publicly available from the Royal Netherlands Meteorological Institute (KNMI) via the open data portal at https://dataplatform.knmi.nl/. These data can be accessed and downloaded using the open-source R package getRad: https://aloftdata.github.io/getRad/. A summary of required input files, their sources, and how they are structured is included in the GitHub repository. The data used from the Global Wind Atlas are available at https://globalwindatlas.info/en/area/Netherlands and the North-Holland shapefiles used for spatial planning analyses can be found at https://apps.vertigisstudio.eu/web/?app=194abc647f794375873dcd563932dd8e.

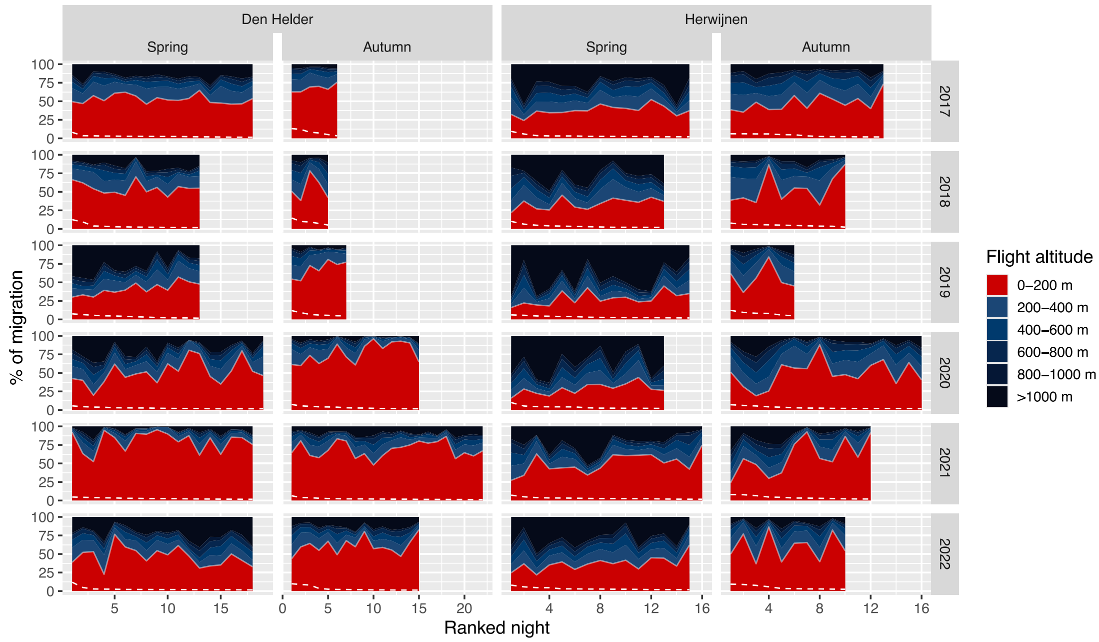

Fig. A.4. Nightly flight altitude distributions shown in 200-m classes from 0–1000 m, with an additional aggregate class for all migration above 1000 m. Nights are ranked by their contribution to seasonal migration, with lower ranks indicating higher nightly passage. Only nights cumulatively accounting for the first 50% of seasonal migration are shown, so the number of nights included varies greatly. The dashed white line shows the proportion of total seasonal migration occurring on each night.

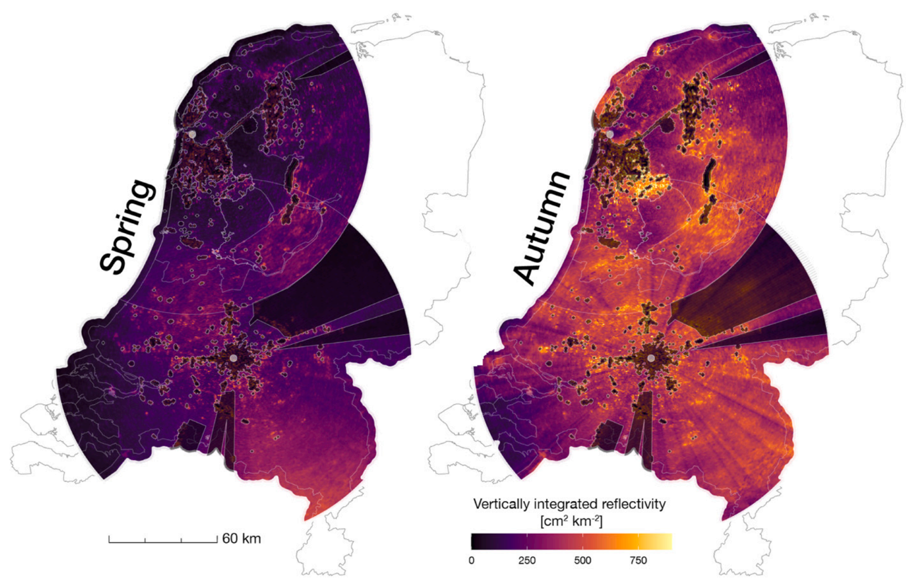

Fig. B.5. Maps of nocturnal bird migration across the Netherlands in spring and autumn, with the 100 km radius circles of the weather radars enclosing the onshore study area. Colors show vertically integrated reflectivity, the integrated reflectivity in a given column of airspace, expressed in cm^2 km^{-2}. Contrary to Fig. 2, bird densities have not been smoothed here. Shaded areas have been subject to clutter in >25% of measurements and might continue to be affected by remaining sources of ground clutter or by landscape topography partially shielding the lowest radar scans, resulting in an underestimation of bird densities aloft.

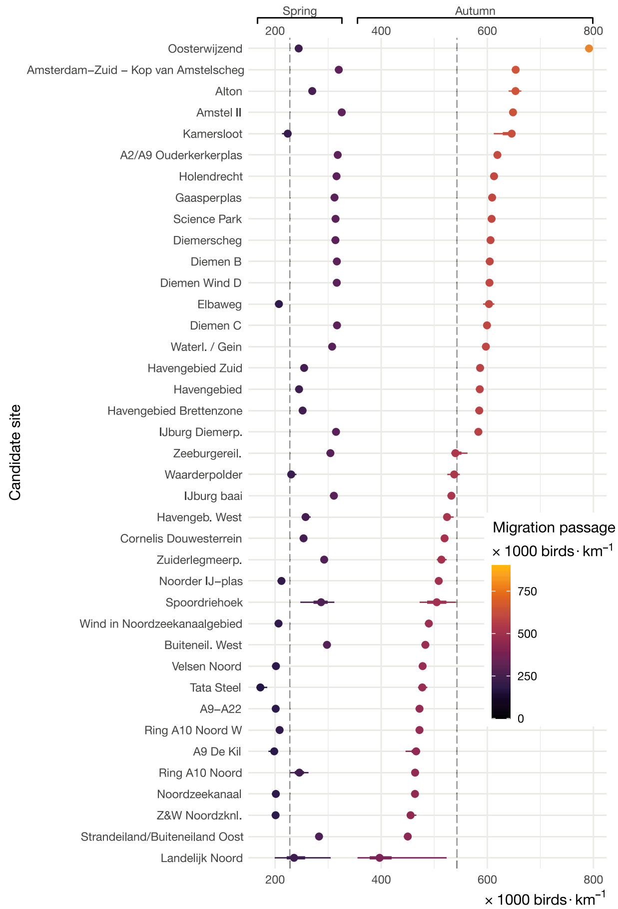

Fig. C.6. A comparison of seasonal migration passage across all candidate sites for wind energy. Migration passage is calculated for the 39 candidate sites in the province of North-Holland outside of clutter-affected areas. Circles represent means, with horizontal bars indicating the central 50% and full range of migration passage across all pixels covered by a candidate site.

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