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Fireworks are important elements of celebrations globally, but little is known about their effects on wildlife. The synchronized and extraordinary use of fireworks on New Year’s Eve triggers strong flight responses in birds. We used weather radar and systematic bird counts to quantify how flight responses differed across habitats and corresponding bird communities, and determined the distance-dependence of this relationship. On average, approximately 1000 times as many birds were in flight on New Year’s Eve than on other nights. We found that fireworks-related disturbance decreased with distance, most strongly in the first five kilometers, but overall flight activity remained elevated tenfold at distances up to about 10 km. Communities of large-bodied species displayed a stronger response than communities of small-bodied species. Given the pervasive nature of this disturbance, the establishment of large fireworks-free zones or centralizing fireworks within urban centers could help to mitigate their effects on birds. Conservation action should prioritize avian communities with the most disturbance-prone, large-bodied bird species.

As human activity continues to encroach on ecosystems globally (Williams et al. 2020), animal behavior is impacted both directly through interactions with humans (e.g., hunting, recreation) and indirectly by anthropogenic environmental changes (e.g., urbanization, noise and light pollution). When human activity is predictable in time and space, animals can shift their activity patterns to reduce overlap with human activity (Wilson et al. 2020). Although certain species have a marked capacity to co-exist alongside humans (Lowry et al. 2013), unpredictable anthropogenic disturbances (such as an approaching human or aircraft, or a sudden noise) commonly lead to flight responses similar to those elicited by predation risk (Frid and Dill 2002; Francis and Barber 2013).

Displays of fireworks are important parts of global celebrations, such as New Year’s Eve (NYE), as well as country-specific events such as Independence Day in the US and Diwali in India. Despite the documentation of profound effects of fireworks on human safety, environmental quality (Singh et al. 2019), and domestic animals (Blackwell et al. 2013), fireworks-related impacts on wildlife remain understudied, with the exception of the use of pyrotechnics as a deterrent (McKee et al. 2016). However, given clearly documented anti-predator responses in wildlife to unpredictable sounds (Francis and Barber 2013; Shannon et al. 2016), fireworks likely pose a formidable source of disturbance to wildlife in general.

Previous research has shown that annual NYE celebrations cause birds to flee en masse from fireworks lit by civilians throughout the Netherlands (Shamoun-Baranes et al. 2011). Although accounting for only 3.8% of the total human population of the EU, the Netherlands is responsible for 22% of all fireworks imported into the EU; a testament to an especially strong fireworks tradition. NYE fireworks alone may not be lethal, but the disturbance they cause extends well into protected waterbodies and occurs during winter. However, to what extent birds across a range of environments are affected by, and whether they respond similarly to, annual NYE fireworks is largely unknown. Generally, sensitivity to disturbance varies between bird species and environmental conditions, and increases with body size; that is, as compared with larger-bodied species, smaller-bodied species are more tolerant of disturbance and initiate flight at shorter distances when approached by a predator (Blumstein 2006). Because sudden loud noises can trigger anti-predator responses (Francis and Barber 2013), it should be expected that sensitivity to fireworks would decline with decreasing body size.

The primary goal of our study was to quantify the flight response of birds to fireworks across different habitat types and their corresponding avian communities. We used operational weather surveillance radar to quantify high-resolution spatial distributions of the biomass of birds aloft at the time of fireworks. We then used systematic bird counts by citizen scientists across the Netherlands to identify bird communities (i.e., species compositions) in different habitats and spatially compared these to bird densities aloft. To analyze the distance-dependence of the flight response, we used distance to residential areas, where fireworks are typically set off, as a proxy for distance to fireworks. Finally, we performed a comparison across habitats to identify variations in responses.
between bird communities. Understanding how the response to a sudden massive disturbance affects wildlife in different habitats and at different distances from the disturbance source can inform policy and the development of mitigation measures.

Methods

Weather surveillance radar

Weather radars are well-established tools for quantifying the number of birds in flight (Chilson et al. 2017; Bauer et al. 2019). We used data from two operational C-band weather surveillance radar installations in the Netherlands, one at Herwijnen (51.84°N, 5.14°E) and the other at Den Helder (52.95°N, 4.79°E), to maximize spatial coverage of diverse habitats across urban–rural landscape gradients. Radar data were processed with bioRad (Dokter et al. 2019) to calculate bird densities in 50-m altitude bins. To prevent rain from masking bird movements, we selected NYE of 1 Jan 2018, which featured mostly rain-free weather around midnight. According to an earlier multiyear study, the mass takeoff starts 5 minutes after midnight on NYE each year and birds fly to altitudes as high as 500–600 m (Shamoun-Baranes et al. 2011). To ensure birds were close to the takeoff habitat, we selected the radar scan during mass takeoff between 00:05 and 00:10 CET (Central European Time) for our analysis. To compare this NYE disturbance with flight activity on nights other than NYE, we selected rain-free radar scans for the same time between December 15–25 and January 5–15 (hereafter, “regular” nights), excluding the 10 days surrounding NYE because small-scale fireworks are occasionally set off during these days.

We removed remaining sources of non-biological radar signals from the radar volumes following the methods described in Appendix S1: Panel S1. We then calculated the vertically integrated reflectivity (VIR: the integrated reflectivity in a given column of airspace, expressed in square centimeters per square kilometer) and corrected it for radar range-bias (Kranstauber et al. 2020). Because this correction relies on the assumption that the altitudinal distribution of birds calculated between 5 and 25 km is representative of and can be extrapolated to the entire radar domain, the maximum horizontal extent of our analysis extended up to 66 km from the radar sites, the distance at which the lowest radar beam begins to “overshoot” the main altitudinal range of birds (<600 m). Implementation of these steps ensures that VIR essentially represents aerial biomass. In the middle of winter, the contribution of insects and bats to VIR is negligible, and therefore during NYE it can be assumed that VIR predominantly represents avian biomass over a given area. To link the spatial distribution of birds in the air to terrestrial habitats, we calculated and projected VIR on a 500-m × 500-m resolution plan-position indicator (PPI) grid. For each grid cell, we also calculated the distance to the radar to capture remaining range effects during modeling.

Bird counts

Data on millions of wintering birds are systematically collected by many hundreds of trained volunteers as part of national monitoring schemes. We combined dedicated waterbird counts and point transect counts, in which non-waterbirds were monitored, to provide the most comprehensive and systematic count of birds wintering in the Netherlands (Appendix S1: Panel S2). Because radar-measured reflectivity is a function of bird body size, we calculated a “pseudo” radar cross-section (RCS) for all species by converting mean body mass $m_{\text{bm}}$ (extracted from Storchová and Hořák 2018) as follows:

$$\text{RCS} = \frac{m_{\text{bm}}^{2/3}}{\pi} \quad (\text{Equation 1}).$$

This allowed conversion of a bird’s mass into a measure approximately proportional to the size of a bird as measured by the signal returned to the radar (ie irradiated body area), leading to a similar scaling from body mass to RCS (in square centimeters) as described by Horton et al. (2019).

We overlaid the spatial coverage of all counts on the radar PPI grid (Appendix S1: Panel S2). For each PPI cell, the total count RCS was calculated by multiplying the RCS (Appendix S1: Table S1) with the number of counted individuals per species and then summing these values. To correct RCS estimates for the size of count areas, we divided total count RCS by the number of 500-m × 500-m PPI pixels covered by each count. Finally, we summed the total count RCS from the transect and waterbird counts, leading to a total RCS representative of birds on the ground and the potential radar-measured VIR if all birds were to take flight. In addition, to quantify bird communities across habitats, we aggregated species into taxonomic groups with different body size classes (Appendix S1: Table S1) and calculated the proportion of birds that belong to these classes for each count.

Distance to fireworks and habitat types

We used the 2018 version of the CORINE Land Cover (CLC) dataset, which contains land-use classifications at 100-m × 100-m resolution. We calculated the distance to the nearest residential area for every PPI pixel and used this as a proxy for the distance to fireworks, given that fireworks are typically set off by civilians from directly outside their homes. To derive biologically distinct habitats, which correspond to different bird communities, we reclassified the initial 45 classes into six functional classes: urban, agricultural, semi-open, forests, wetlands, and waterbodies (Appendix S1: Table S2). We resampled these six classes to the PPI grid by calculating proportions of these six habitat types for each 500-m × 500-m PPI pixel.
Analysis

We combined PPIs of VIR and predictor variables for both radar sites to create a single PPI encompassing the combined area, up to a distance of 66 km from each radar installation. To avoid potential contamination by fireworks aloft in the radar measurements, we filtered out pixels where the proportion of urban area was >10%. To avoid areas with large-bodied species dominating the model fit, we log_{10}-transformed VIR (with a minimum value of -1), thereby giving more weight to areas with fewer or smaller birds. We used a boosted generalized additive model (BGAM; Hofner et al. 2014) to model VIR using total RCS, the non-urban habitat proportions, distance to fireworks, and distance from the nearest radar installation as predictors. BGAMs are suitable when nonlinear relationships are expected and predictor variables are correlated (Maloney et al. 2012). Component-wise gradient boosting was used for variable selection and parameter estimation (Hofner et al. 2014). All predictors were included using smooth base-learners (penalized B-splines, four degrees of freedom). We used tenfold cross-validation to determine the optimal number of boosting iterations that maximize model performance but limited the number of boosts to 10,000 to reduce computation time, given that model performance improved only minimally with additional boosts. To account for remaining spatial autocorrelation in residuals, we included an autocovariance (distance weighted mean) term of residuals in a two-step fitting procedure described by Crase et al. (2012).

We calculated variable importance, which was defined as a measure of the number of times a predictor was used in the model weighted by its improvement to model fit (Hastie et al. 2019). To explore the relative importance of biologically relevant variables, we removed the residual autocovariance term and distance to the radar and rescaled variable importance for remaining variables to once again sum to 100%. To interpret directionality and shape of effects of individual predictors on model outcome, we used partial dependence plots of marginal effects (Friedman 2001), which were calculated by integrating the effects of all predictors while varying the variable of interest across a relevant range of values. To quantify model uncertainty, we estimated confidence intervals of variable importance and marginal effects using a 1000-fold bootstrapping approach.

Results

Spatial distribution of disturbance response

The synchronized ignition of fireworks across the Netherlands caused widespread flight initiation of birds (Video S1). Within our study area, the radars measured a total VIR of $3.3 \times 10^7$ cm$^2$. Based on the mean RCS of the 2.3 million birds in our ground-based counts of 86 cm$^2$ (the RCS of an 800-g bird), this corresponded to an instantaneous flight response to fireworks by 384,000 birds across our study area. However, biomass aloft (VIR; Figure 1a) and total RCS (reflecting birds on the ground; Figure 1b) were not evenly distributed in space and displayed limited similarity. In the Netherlands, the predominant habitat type is agricultural, with forests and rivers mostly in the domain of the southern radar installation, semi-open habitat (heathlands, coastal dunes) near the forested areas and coastal regions, and wetlands and inland lakes in the north (Figure 1c). In our study area, 62% of all birds on the ground were within
2.5 km of fireworks and only 11% of birds could be found at distances >5 km from fireworks, mainly consisting of shorebirds in the Wadden Sea area (Appendix S1: Figures S1 and S3).

On average, the number of birds exhibiting an instantaneous flight response to fireworks on NYE exceeded the number of birds in flight during regular nights by a factor of approximately 1000 (Figure 2a). However, across our study area grid, relative increases of 4–5 orders of magnitude were common. Disturbance decreased with distance to fireworks, especially within the first 5 km, but overall the average flight response on NYE remained elevated as compared to that on regular nights by at least a factor of ten. The number of birds in flight on NYE was similar to that on regular nights only at distances at or beyond ~10 km from fireworks (eg over the Wadden Sea).

Factors influencing flight response to fireworks

The BGAM explained 75% of the deviance in VIR. Residual spatial autocorrelation was effectively eliminated (Moran’s I ranged between −0.02 and +0.03). Although it would be expected that total RCS is the most important predictor if all birds were to take flight, in fact the proportion of agricultural area ranked highest among biological variables, with a mean relative influence of 58%. In the final model, habitat predictors (Figure 3) cumulatively accounted for 72% of variable importance, whereas distance to fireworks and total RCS (Figure 2b) accounted for 15% and 13% of variable importance, respectively.

We calculated marginal effects of all predictors on the flight response in VIR and separated those into total RCS and distance to fireworks (Figure 2b), and habitat effects (Figure 3a). VIR increased with total RCS up to 30,000 cm², after which VIR remained stable. The effect of distance to fireworks peaked at 1500 m, then declined and reached a first minimum just beyond 5 km. At longer distances, the effect of distance to fireworks increased again, reaching a second peak at 9 km, but at these distances uncertainty was markedly higher and the number of datapoints was limited (3% of total).

There was a clear positive relationship between proportion of agricultural area and VIR, as a modest increase in agricultural area from 0% to 20% prompts a strong increase in VIR; above 20% agricultural area coverage, the effect on VIR remained stable. For waterbodies and wetlands, VIR increased with increasing habitat extent, particularly in the range of ~80–100% coverage. In contrast, there was a negative relationship between proportion of forest and semi-open habitat and VIR, and particularly so for semi-open habitat, where at full coverage the flight response was the lowest of all compared habitats.

Bird community composition differed substantially among habitat types, as can be seen in Figure 3b, in which proportions of several characteristic bird groups with differing body sizes across habitat types are shown. Larger-bodied taxa such as geese and ducks were dominant in agricultural areas and waterbodies, whereas smaller-bodied taxa such as tits and finches were most abundant in forests.

Discussion

We analyzed the instantaneous flight response of birds across habitats and distances to the synchronized discharging of
Fireworks disturbance across bird communities

Fireworks throughout the Netherlands on NYE. Habitat predictors accounted for most of the variation in flight response in our model. Bird response to fireworks increased with greater spatial coverage of agricultural areas, waterbodies, and wetlands, but decreased with greater spatial coverage of forests and semi-open habitats. Numbers of birds aloft decreased most strongly in the first 5 km from fireworks but remained higher than on regular nights even at distances of up to 10 km.

Linking ground-based bird counts to interpret radar measurements

Given that larger, heavier birds are more reflective via radar, their numbers contributed more to VIR than did lighter, smaller birds (Chilson et al. 2017). Quantifying the differential response to fireworks across habitats and bird communities (Figure 3) therefore requires accounting for this disparity, which was achieved through the inclusion of total RCS derived from systematic ground-based bird counts. Despite the direct physical relationship between RCS and VIR, our model demonstrated that the variable importance of total RCS is limited (accounting for only 13% of variation). If all birds were to respond similarly to fireworks by taking flight, total RCS should be an important predictor of flight response, as it is proportional to VIR. Instead, most of the variation in VIR was explained by habitat (Figure 3), emphasizing substantial differences in flight response across different habitats and bird communities.

Differential responses to fireworks across bird communities

Abrupt loud noise, such as the sound of exploding fireworks, can trigger escape responses in birds (Shamoun-Baranes et al. 2011; Francis and Barber 2013; Stickroth 2015; Krijgsveld et al. 2022). After controlling for the effect of the number and size of birds on the ground on the potential radar-measured signal (total RCS), our results indicated that bird response to fireworks increased with increasing cover of open habitats and decreased with increasing cover of semi-open or forest habitats. In winter in the Netherlands, open habitats such as agricultural areas, waterbodies, and wetlands are inhabited predominantly by large-bodied birds such as geese, ducks, and gulls, whereas forests are inhabited mainly by small passerines such as tits and finches (Figure 3). The patterns of flight response we observed aligned with those reported by Blumstein (2006), who found that larger birds generally initiated flight from disturbances at greater distances than did smaller birds. In urban environments, birds flee from a disturbance earlier with increasing distance to the nearest refuge (Morelli et al. 2022). Although we excluded urban environments from our analysis, this relationship could suggest the
larger-bodied species inhabiting open areas also take flight earlier because the distance to the nearest refuge from fireworks is likely much greater for them than it is for smaller-bodied species, which generally inhabit less exposed habitats like forests. In addition, the sound and light produced by fireworks is able to propagate further in open habitats than in other environments, such as forests (Fricke 1984), leading to more potential for widespread disturbance of birds inhabiting agricultural areas, wetlands, and waterbodies. While 58% of variation in flight response is explained by agricultural habitat, movements between counting sites and roosting sites around waterbodies, and in wetlands and forests, where birds take flight during NYE, may result in a degree of bias in RCS estimates of birds on the ground and consequently in the effect of habitat type.

**Distance-dependence of disturbance**

With virtually unhindered propagation of sound and light through the flat and mostly open agricultural landscapes of the Netherlands, the effect of fireworks on bird flight response only disappears completely at about 10 km from fireworks sources. Although the observed increase in bird density and modeled flight response (Figure 2) at around 9 km from fireworks was likely driven primarily by limited datapoints and nocturnal tidal-influenced shorebird movements in the Wadden Sea, a substantial residual effect of fireworks at this distance cannot be excluded.

With the exception of military aircraft (van der Kolk et al. 2020), few documented sources of sudden anthropogenic disturbance (Livezey et al. 2016) are as pervasive as NYE fireworks. Given that distance to fireworks is an important predictor in our model, buffering protected areas with fireworks-free zones has clear potential for mitigation of wildlife disturbance from fireworks (see also Stickroth 2015; Krijgsveld et al. 2022). Although avian sensitivity to disturbance may change with landscape characteristics or season, the creation of fireworks-free zones should be prioritized around areas used by more disturbance-prone large-bodied species. In addition, buffers can probably be smaller in areas where light and sound propagation are reduced (eg forests; see Fricke 1984) and where small-bodied species predominate. When space for buffering is limited, or large congregations of birds or protected areas occur within or are adjacent to residential areas, centralizing fireworks in urban centers may be a more effective measure, as such an approach would reduce sound propagation and increase the distance between fireworks and bird communities. However, in countries as densely populated by both humans and wintering birds as the Netherlands, options for using fireworks without disturbing wildlife may be limited.

**Immediate and lasting effects of fireworks disturbance**

After the synchronized detonation of fireworks, birds remain aloft for 45 minutes to 1 hour (Video S1; Shamoun-Baranes et al. 2011). This disturbance causes an immediate increase in energy expenditure for flight (Pennycuick 2008), which would likely require greater time and energy to be spent foraging in subsequent days to compensate. Stress indicators, such as heart rate and body temperature, can remain elevated for several hours after the cessation of fireworks (Wascher et al. 2022). Furthermore, Kölsch et al. (2023) reported that geese disturbed by NYE fireworks increased their foraging time considerably, by up to 10% over at least 11 days following NYE (the end of their study period), indicating substantial compensation requirements. Moreover, geese were frequently displaced to new foraging and roosting sites, likely exacerbating the energetic impacts of fireworks disturbance because foraging intake rates at unfamiliar sites may be lower (Béchet et al. 2004). Reduced winter daylight for foraging and possible displacement to new sites may limit the ability of many other species to quickly compensate for depleted energy reserves as well.

While taking flight, as studied here, is likely the most energetically costly response to a disturbance, birds may also react by hiding (Francis and Barber 2013). Even in sheltered places, however, fireworks disrupt sleep patterns and induce stress in cavity-roosting birds (Bosch and Lurz 2019), which may also have long-term fitness consequences.

Although rare, several mass mortality events directly after fireworks disturbance have been documented, involving gregarious bird species such as the red-winged blackbird (Agelaius phoeniceus; eg in Beebe, Arkansas, during both NYE 2010 and 2011; https://perma.cc/9EBH-6MNL) and European starling (Sturnus vulgaris; eg in Rome, Italy, during NYE 2020; https://perma.cc/58LH-D9P). While confounding factors such as inclement weather conditions, flocking behavior, and disorientation likely played major roles in the mass mortality events, with hundreds to thousands of casualties, it is probable that the birds would not have panicked and taken flight in the absence of fireworks.

**Conclusion**

Not only a concern for public health and safety, fireworks also pose a formidable form of disturbance to wildlife. While a single disturbance event may not be directly lethal to wildlife, the sudden synchronized detonation of fireworks in the Netherlands on NYE causes a flight response in birds of unprecedented scale, with immediate and lasting energetic consequences. Because this particular disturbance activity is widespread and extends into protected areas, action should be taken to reduce the impacts of fireworks on birds and other wildlife. Conservation strategies should prioritize reduction of exposure to the most disturbance-prone large-bodied birds in open habitats, either by increasing the distance to fireworks through the creation of fireworks-free buffer zones or by centralizing fireworks strictly within urban centers. Ultimately, however, a drastic
reduction in the use of fireworks may be the only feasible option for substantially mitigating the impacts of this disturbance on birds.

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Data Availability Statement

Data are already published and publicly available, with those items properly cited below. Additional details on utilized datasets, novel code, and analysis are provided in Appendix S1: Panel S3.

References


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Supporting Information

Additional material can be found online at http://onlinelibrary.wiley.com/doi/10.1002/fee.2694/suppinfo