Received: 29 April 2022 | Revised: 13 September 2022 | Accepted: 24 October 2022

DOI: 10.1111/conl.12927

Conservation Letters
A journal of the Society for Conservation Biology
Open Access
WILEY

LETTER

Wild goose chase: Geese flee high and far, and with aftereffects from New Year's fireworks

Andrea Kölzsch[1,2,3] | **Thomas K. Lameris**[4,5] | **Gerhard J. D. M. Müskens**[6] | **Kees H. T. Schreven**[4] | **Nelleke H. Buitendijk**[4] | **Helmut Kruckenberg**[3] | **Sander Moonen**[6,7] | **Thomas Heinicke**[8] | **Lei Cao**[9] | **Jesper Madsen**[10] | **Martin Wikelski**[1,2] | **Bart A. Nolet**[4,11]

[1]Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany

[2]Department of Biology, University of Konstanz, Konstanz, Germany

[3]Institute for Wetlands and Waterfowl Research (IWWR) e.V., Verden, Germany

[4]Department of Animal Ecology, Netherlands Institute of Ecology (NIOO-KNAW), Wageningen, The Netherlands

[5]NIOZ Royal Netherlands Institute for Sea Research and Utrecht University, Den Burg, The Netherlands

[6]Team Animal Ecology, Wageningen Environmental Research, Wageningen, The Netherlands

[7]Institute of Avian Research, Wilhelmshaven, Germany

[8]International Bean Goose project, Samtens, Germany

[9]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China

[10]Department of Ecoscience, Aarhus University, Rønde, Denmark

[11]Department of Theoretical and Computational Ecology, Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam, The Netherlands

Correspondence
Andrea Kölzsch, Department of Migration, Max Planck Institute of Animal Behavior, Am Obstberg 1, 78315 Radolfzell, Germany.
Email: akoelzsch@ab.mpg.de

Funding information
National Geography Society, Grant/Award Number: GEFNE141-15; Svalbard Environmental Protection Fund, Grant/Award Number: 17/88; Dutch Research Council, Grant/Award Number: ALWPP.2016.024; Federal German Ministry of Education and Research, Grant/Award Number: FKZ50JR1306; Province of Fryslân, Grant/Award Number: 01443719; Lower Saxony Ministry for Food, Agriculture and Consumer Protection, Grant/Award

Abstract

In the present Anthropocene, wild animals are globally affected by human activity. Consumer fireworks during New Year (NY) are widely distributed in W-Europe and cause strong disturbances that are known to incur stress responses in animals. We analyzed GPS tracks of 347 wild migratory geese of four species during eight NYs quantifying the effects of fireworks on individuals. We show that, in parallel with particulate matter increases, during the night of NY geese flew on average 5–16 km further and 40–150 m higher, and more often shifted to new roost sites than on previous nights. This was also true during the 2020–2021 fireworks ban, despite fireworks activity being reduced. Likely to compensate for extra flight costs, most geese moved less and increased their feeding activity in the following days. Our findings indicate negative effects of NY fireworks on wild birds beyond the previously demonstrated immediate response.

Number: 406-04032/1-1502/1;
Naturschutzfonds Brandenburg,
Grant/Award Number: 1262

KEYWORDS
anthropause, Arctic breeding geese, compensatory feeding, GPS tracking, human disturbance, New Year fireworks, roost behavior

1 | INTRODUCTION

In the present Anthropocene, wild animals are globally affected by human activity (Tucker et al., 2018). Even if no harm is intended, animals can perceive human presence or actions as predation risk (Frid & Dill, 2002; Gill, 2007) and react accordingly in their "landscape of fear" (Laundré et al., 2001). As a result, animals often avoid areas with local and frequent, yet unpredictable disturbances (van der Kolk et al., 2021). If disturbances are large in magnitude (Commander & White, 2020) or occur at a landscape scale (Shilton et al., 2008), they may have large-scale demographic consequences (Gill, 2007). To mitigate such disturbance effects, global and local conservation directives (e.g., EU Birds Directive) have to be enforced with the help of detailed insights in short- and long-term effects.

Fireworks explosions with colorful lighting and loud acoustic effects for entertainment (Kukulski et al., 2018) are known to have strong immediate effects on animals, causing fear and anxiety in pets (Gähwiler et al., 2020) and stress responses in wild birds (Shamoun-Baranes et al., 2011; Stickroth, 2015; Bosch & Lurz, 2019). During New Year (NY; the night from December 31 to January 1), fireworks are lit in cities and in the countryside across large areas of the Western world (Sijimol & Mohan, 2014). In W-Europe, the main fireworks activity is not by organized, local fireworks displays, but by widespread, unconstrained lighting of huge quantities of consumer fireworks by the public on streets, backyards, and fields (ten Brink et al., 2019). An especially large response to those fireworks has been measured in the Netherlands, where waterfowl take flight en masse from night-time roosting sites for at least 45 min following NY's midnight (Shamoun-Baranes et al., 2011).

However, possible longer term behavioral effects and potential fitness consequences of such large-scale disturbances on birds have not been quantified. When animals experience higher energetic costs due to disturbance, they will need to forage more to compensate (Nolet et al., 2016). In order to gain a better understanding of such longer term effects, measurements at the individual level are needed. Fox et al. (2018) tracked five individual white-fronted geese and showed a modest flight response to a single evening, organized fireworks display, with birds returning to their roosts within 45 min. However, this local event is probably incomparable to the large-scale effects of NY fireworks that can hardly be escaped due to their omnipresence.

Here, we used tracking data from four Arctic, migratory goose species wintering in W-Europe to quantify the effects of NY fireworks on their behavior. All species spend their nights on small lakes or coastal sites and are sensitive to disturbance there, leading to flight responses (Nolet et al., 2016). In parallel with estimated fireworks intensities, we studied changes in nightly flight distance and roost site use, energetic costs, and foraging behavior in the 12 days/nights before NY, during NY, and the 12 days/nights after NY. We compared results from NY 2014 to 2020 with NY 2021, during the COVID-19 pandemic, when fireworks were banned in most countries covered by this investigation, expecting no disturbance response in the latter.

2 | METHODS

2.1 | GPS tracking data

We analyzed GPS data from December 19 to January 12 of 8 years (2014–2021), from a total of 347 individual geese of four different species (greater white-fronted goose *Anser albifrons*, bean goose *Anser fabalis*, barnacle goose *Branta leucopsis*, pink-footed goose *Anser brachyrhynchus*), equipped with backpack or neckband GPS transmitters (Kölzsch et al., 2022). We only included data from migratory adults, and when these had carried a transmitter for >2 weeks to minimize tag effects (Lameris et al., 2018; Clausen et al., 2020). Data resolution varied due to different fix rates (between 5 and 30 min; Table S1) and by weather conditions often leading to low battery charges. The median interval between positions was 30.0 min during the day (95% confidence interval [CI]: 10.0–1080.2 min) and 30.4 min at night (95% CI: 10.0–539.8 min).

2.2 | Night movement

All GPS positions were split into night and day positions, delineated by sunrise and sunset +30 min (as geese tend to stay at foraging sites until 30 min after sunset; Supporting Information). For each night and individual, we calculated the proportion of locations in flight (GPS ground speed above 10 m/s), the maximum pairwise distance (Vincenty approximation), and the maximum altitude (height above mean sea level; outliers removed, Supporting Information).

2.3 | Night roosting and roost switches

Geese usually spend the night on one safe roosting site with little disturbance, and tend to return to the same site for nights in a row (Giroux, 1991). However, when disturbed they fly up and may switch roost site between nights or even within a night. We extracted all roosts per full night (December 19/20 to January 11/12) and individual from the night GPS positions (Kölzsch, 2022). Roosts were defined as all sites at night where a goose stayed at least 2 h within a radius of 1 km, not moving faster than 1 m/s (GPS ground speed). We then calculated how many roosts were detected per night and for how long each individual stayed in the roost(s) of each night.

To explore successive roost use and switching between nights, we extracted the minimum pairwise distance between roosts of successive nights, the number of successive days in the future during which the last roost of each night was used, and the number of geese that switched roosts (i.e., >2 km away) and returned to it within our time frame. Note that the latter values are affected by the relatively short duration of our time frame, but comparisons between NY and nights before and shortly after NY are still meaningful.

2.4 | Fireworks intensity at roosts

To link fireworks intensity with goose movement and explore if the birds moved away from it during and after NY, we quantified the spatial–temporal variation of estimated fireworks use. The most direct approximation of intensity of consumer fireworks lit by the public is particulate matter in the air PM10 (Khaparde et al., 2012; ten Brink et al., 2019). We annotated each roost with the maximum PM10 measurement of the respective night within a circle of 10 km around the central roost position (accessed from https://sensor.community).

As the availability of PM10 measurements was limited and the spatial distribution of PM10 is strongly influenced by wind and rain, we additionally tested for an effect of human population density. Each roost was annotated with the maximum adjusted human population density within a circle of 10 km around its central position (data resolution 1 km; downloaded from the NASA SEDAC [Center for International Earth Science Information Network [CIESIN], Columbia University, 2018]). Relations between the two measurements were tested with linear mixed models (random factor "year," see below) for all roosts used during NY.

2.5 | Testing the effect of NY

To test for effects of NY fireworks (or NY in short) on goose behavior, all movement, roost, firework intensity, and foraging measurements (see below) were grouped into "before NY" (all nights before NY), "during NY" (night of December 31 to January 1), and "after NY" (all nights after NY). Using linear mixed models (lmer in R package lme4) with random factors "individual" and "year," we compared them per species between the three time periods (before, during, and after NY). Using the model estimates, we calculated relative changes of the movement properties by dividing the NY effect size estimate by the before NY model intercept.

2.6 | Flight energetics and costs

To judge how the additional flight movement during NY potentially impacted the geese' energy budget, we related the cost per distance flown to each species' daily energy expenditure. Flight costs were calculated from chemical power (Table S2; Pennycuick et al., 2011), based on literature values and estimates of body mass, basal metabolic rate (BMR), ground speed, wing span, and wing area (Cramp et al., 1996; Baveco et al., 2011). On days without extra flights, daily energy expenditure was estimated as a multiple (factor 1.9) of BMR (Stahl et al., 2001; Baveco et al., 2011). Finally, we calculated the proportional increase of daily energy intake (approximated by daily energy expenditure) required to compensate for the extra flight costs of NY (model average) for each species.

2.7 | Compensation by more foraging

We explored whether goose foraging behavior changed as a reaction to the disturbance of NY by characterizing the use of feeding sites. To identify feeding sites, we extracted all sites during daytime (Kölzsch, 2022), where a goose stayed for at least 2 h within a radius of 1 km with GPS ground speeds below 1 m/s (no outliers allowed). For each individual and year, we calculated the cumulative daily duration at feeding sites, the number of distinct daily feeding sites, and the pairwise distance between all feeding sites of the same day.

2.8 | Disturbances during NY fireworks ban

During the first full winter of the COVID-19 pandemic, 2020–2021, the sale and/or ignition of fireworks were banned in all W-European countries where our tagged geese were present, with the exception of Denmark (Bundesministerium des Innern und für Heimat, 2020; Rijksoverheid, 2020). Using this anthropause (Rutz et al., 2020) as a likely control case, we calculated and tested the NY effect on a selection of variables, namely, flight

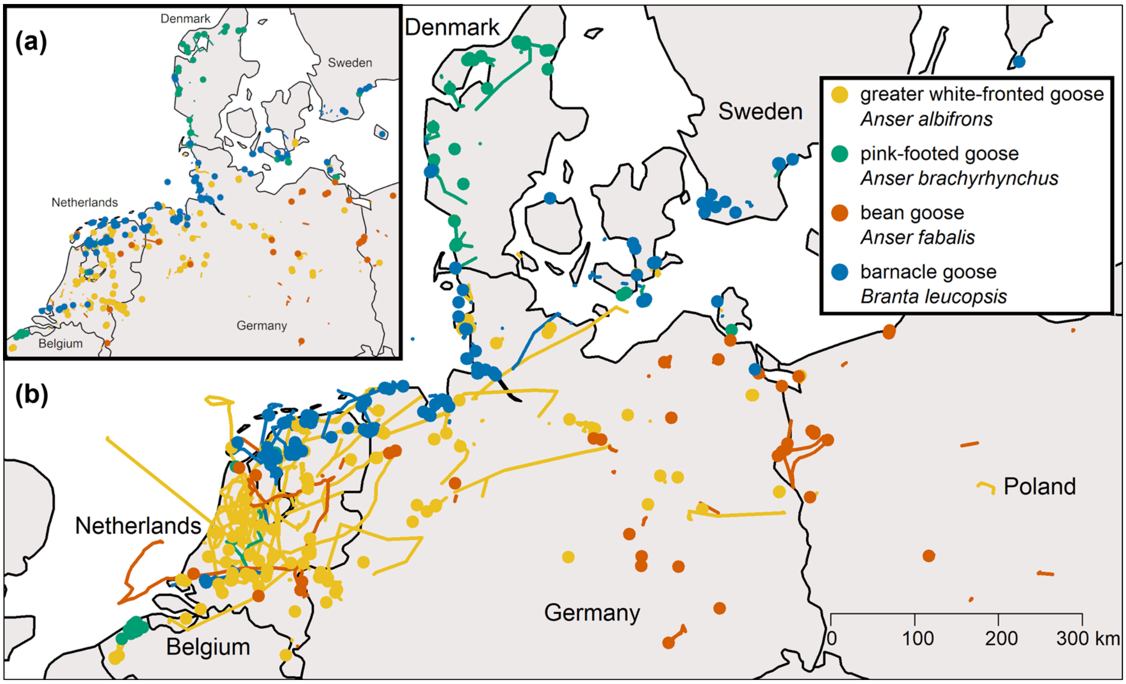

FIGURE 1 Roost sites (dots) and night tracks (lines) of the tagged geese of four species (see color legend) of all eight analyzed years (a) during the night of December 22/23 (as a "normal" night) and (b) during New Year (NY)

activity, maximum distance, and altitude for that year only, and compared findings with those of the complete dataset.

3 | RESULTS

The compiled GPS dataset consisted of 702 tracks of a 25-night period around NY, including 170,165 night positions (Table S1). All individuals spent their winter in W-Europe, mostly concentrated in the Netherlands, Northern Germany, and Denmark (Figure 1).

3.1 | Night movement

The immediate response of most geese to NY fireworks was high and far flying behavior. In comparison to previous nights, for greater white-fronted, bean, and barnacle geese, our data showed an added 1%–11% (minimum–maximum species value) of GPS locations with flight behavior during NY, amounting to a 29%–92% relative increase of flight behavior (Figure 2a; Table 1). These geese increased their movement distances during NY by 5–16 km on average (relative increase by 139%–443%; Figure 2b; Table 1), with extremes of up to 500 km (Figure 1). Interestingly, pink-footed geese did not show significant increases in flight behavior and distance moved. However, maximum flight heights increased for all four species during NY: they flew on average 40–150 m higher than in previous nights (relative increase of 54%–246%; Figure 2c; Table 1), amounting to about 100–220 m flight height, with extremes of 700 m, which is similar to radar measurements of waterfowl flight during NY (Shamoun-Baranes et al., 2011).

3.2 | Night roosting and roost switches

Before NY, geese roosted about 10–14 h per night, but during NY pink-footed geese and barnacle geese decreased their average cumulative roost duration by 0.2 and 1.9 h, respectively (Figure 3a; Table 1), while the cumulative roost duration did not change for greater white-fronted geese and bean geese during NY. Even so, the number of used roosts per night did increase significantly for all species from 1.1–1.2 roosts per night to 1.2–1.6 (Figure 3b; Table 1).

Before NY, roosts were used for 2.4–4.1 successive days. This revisitation decreased due to NY by 0.2–1.5 days (Figure 3c; Table 1). Nightly averages of minimum distances between roosts of successive nights were 9.5–23.7 km, but increased significantly between NY and the night of January 1 by 1.7–11.2 km (Figure S1a; Table 1). Interestingly, already roosts of December 30/31 and NY were further apart than before for bean geese. Before NY, geese revisited previously used roosts at average rates of 0.29–0.39, which decreased by 0.09 and 0.19 for roosts used on NY for greater white-fronted geese and barnacle geese (Figure S1b; Table 1). Similar to above, strong

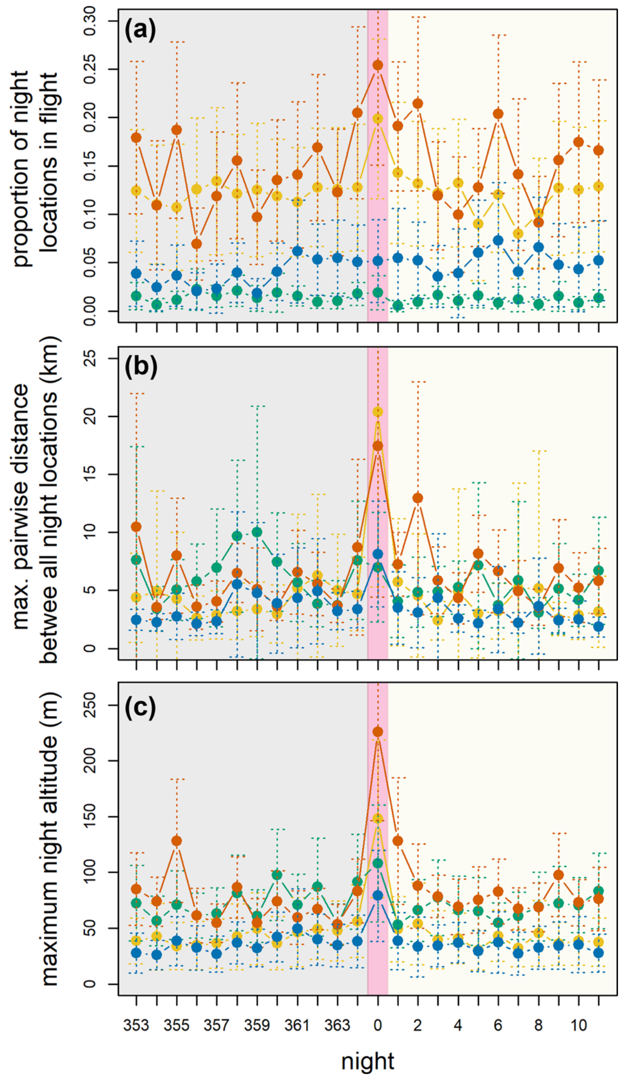

FIGURE 2 Averages of night movement per species. The underlying colors indicate the nights before NY (gray), NY (rose), and the nights after NY (beige). The nightly averages (dots) of the four species (colors as in Figure 1, i.e., orange: greater white-fronted goose, green: pink-footed goose, red: bean goose, blue: barnacle goose) are augmented with half standard errors (vertical dotted lines). Night = 0 indicates NY (i.e., night of December 31/January 1) and night = 364 the night of December 30/31, also in leap years

decreases of use duration and revisitation were already notable between December 30 and NY (Figures 2c and S1b).

3.3 | Fireworks intensity at roosts

During NY, maximum PM10 was significantly related to human population density at roosts (n = 95, effect size: 0.21, p = 0.005). Depending on the regions in which the species wintered, before NY, maximum PM10 values and maximum human population densities around the roosts ranged between 49.4 and 196.1 $\mu g/m^3$ and 525 and 1235 people/km^2, respectively (Table 1). For all species and regions, PM10 at used roosts rose drastically during NY, with relative increases of 324%–655% (Figure 4a; Table 1). This increase remained after NY for bean geese and barnacle geese (Table 1). Greater white-fronted, bean, and barnacle geese selected roosts with less surrounding maximum human population densities during and after NY, namely, decreased by 217–295 people/km^2 and 32–224 people/km^2, respectively (Figure 4b; Table 1). Only pink-footed geese used roosts of similar surrounding human population density during NY.

3.4 | Flight energetics and costs

Energetic costs due to additional flights during NY were estimated to increase the daily energy expenditure of geese by 1%–10% (Tables 1 and S2). Costs were especially high for geese that flew longer distances during NY (greater white-fronted geese) and those that are heavy and have high flight costs (bean geese).

3.5 | Compensation by more foraging?

Cumulative foraging durations increased by 0.1–0.5 h during and after NY (Table 1; Figure 5a). The consequent relative increase of 2%–10% daily foraging duration lasted (at least) until the end of our observation period (11 days), indicating a longer term effect. The number of and distance between feeding sites per day did not differ before, during, and after NY (Table 1; Figures 5b and S2).

3.6 | Disturbances during NY fireworks ban

The analyses of goose tracks during the fireworks ban of 2020–2021 show that the geese still reacted with increased flight activity, distance, and altitude during NY (Table S3; Figure S3). Greater white-fronted geese and bean geese showed high increases, whereas pink-footed geese and barnacle geese showed lower responses to NY during the 2020–2021 ban than during the previous NYs, with no increase in flight height.

4 | DISCUSSION

Adding to previous insights into the immediate effect of fireworks on wild animals (Shamoun-Baranes et al., 2011; Fox et al., 2018), we have demonstrated that NY fireworks

TABLE 1 Linear mixed model results of night movements, roost properties, firework intensity estimates, and foraging properties for the four species

	Greater white-fronted goose			Pink-footed goose			Bean goose			Barnacle goose		
	n	Before NY	NY effect	*n*	Before NY	NY effect	*n*	Before NY	NY effect	*n*	Before NY	NY effect
Proportion of night locations in flight	5581	0.10	+0.08***	1976	0.01	(+0.005)	1240	0.12	+0.11***	3749	0.07	+0.02**
Maximum night distance (km)	5581	3.66	+16.23***	1976	6.14	(+0.90)	1240	5.87	+11.59***	3749	3.44	+4.78***
Maximum night altitude (m)	5141	42.8	+105.5***	1976	69.5	+37.2***	673	70.9	+154.6***	3749	32.2	+43.1 ***
Cumulative nightly roost duration (h)	3740	9.5	(−0.2)	1893	13.8	+0.2**	1044	10.7	(−0.3)	3314	11.5	−1.9***
Number of roosts used per night	3740	1.1	+0.1***	1893	1.2	+0.2***	1044	1.1	+0.2*	3314	1.2	+0.4***
Minimum distance to next roost (km)	305	14.93	+11.18***	236	14.30	+3.26**	100	23.71	+9.47**	677	9.51	+1.66***
Number of successive days roost used	3528	2.4	−0.4*	1860	4.1	−0.2***	1002	3.5	−0.8***	3212	3.9	−1.5***
Roost revisit probability after switch	1560	0.32	−0.09***	561	0.37	(−0.14)	377	0.29	(−0.17)	1031	0.35	−0.19***
Particulate matter concentration PM10 around roost ($\mu g/m^3$)	998	91.9	+602.3*** <(+66.5)>	409	196.1	+1014.2*** <(−33.1)>	160	49.4	+223.7*** <+192.7***>	438	56.7	+183.7*** <+115.9**>
Maximum human population density around roost ($1/km^2$)	4224	1234.9	−217.1* <(−31.8)>	2375	722.3	(−15.3) <(+84.9)>	1317	525.4	−247.0*** <−91.2*>	4456	825.3	−295.2 *** <−224.4**>
Foraging duration on next day (h)	2934	4.8	+0.1*** <+0.3***>	1694	5.1	+0.4*** <+0.5***>	793	4.7	(+0.3) <(+0.2)>	2927	5.0	+0.1** <+0.2**>
Number of foraging sites per day	2934	1.0	(−0.0) <(+0.0)>	1694	1.1	(−0.0) <(+0.0)>	793	1.1	(−0.1) <(+0.0)>	2927	1.1	(−0.0) <(+0.0)>
Distance between foraging sites of the same day (km)	116	3.39	(−2.42) <(−1.00)>	119	3.45	(−0.83) <(−0.38)>	46	3.91	(−0.68) <(−0.16)>	284	2.67	(−0.41) <(−0.61)>

(Continues)

TABLE 1 (Continued)

	Greater white-fronted goose			Pink-footed goose			Bean goose			Barnacle goose		
	n	**Before NY**	**NY effect**	***n***	**Before NY**	**NY effect**	***n***	**Before NY**	**NY effect**	***n***	**Before NY**	**NY effect**
Cost per 1 km flight at ground speed = air speed (J/km)		7654			8437			10,513			4724	
Daily energy expenditure, DEE (J/day)		1,206,576			1,426,550			1,523,405			850,349	
Proportion of DEE for estimated NY extra flight cost		0.100			0.005			0.080			0.030	

Note: Provided are sample sizes, model intercepts (“before NY”), and NY effect sizes with significances given by ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$ and parentheses for nonsignificant effects. For the fireworks intensity estimates and foraging properties, the effect of “after NY” is added in angle brackets. At the end, see flight cost estimates.

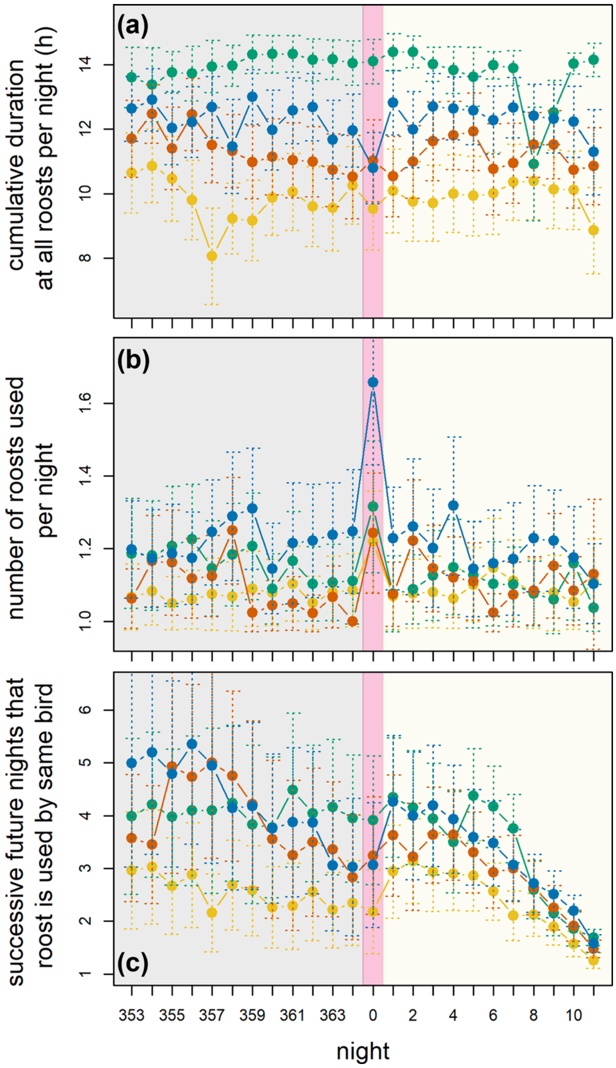

FIGURE 3 Nightly averages of roost properties per species. Note data truncation effect in panel (c). Colors and symbols as in Figures 1 and 2

are intensive disturbances lasting beyond the duration of the fireworks. The increased night movement of the geese during NY potentially depletes energy supplies that they need in order to survive the winter in W-Europe (Béchet et al., 2004), leading to two notable aftereffects: (1) long-lasting increased foraging and (2) roost shifts.

To compensate for the extra flight costs, the geese must forage more, notably on agricultural lands (Clausen et al., 2015; Pot et al., 2019) adding to a recently strong conflict with W-European farmers (Fox & Madsen, 2017). We found an increase of daily foraging in all analyzed days after NY, which might indicate that the short winter days prevent the geese to quickly compensate (Lameris et al., 2021). The long-lasting increased foraging might furthermore relate to yet additional costs of settlement in new roosting and

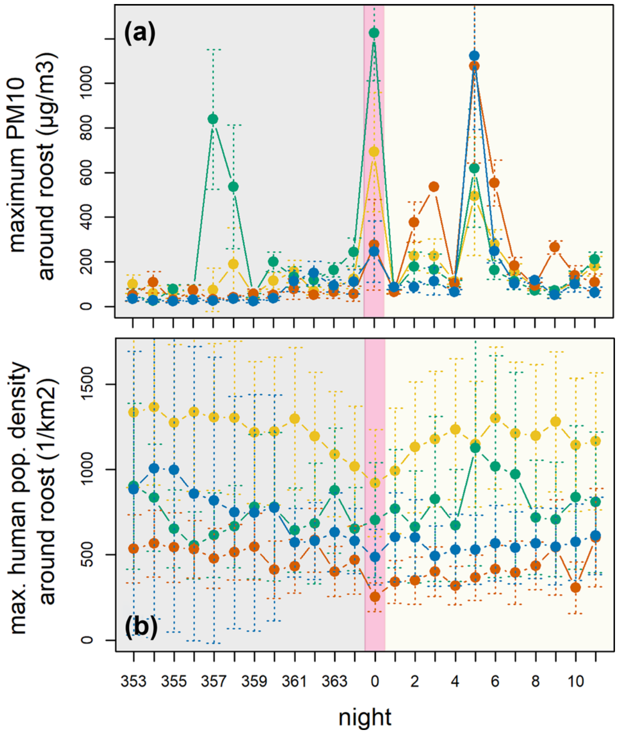

FIGURE 4 Nightly averages of fireworks intensity measures around the different species' roosts. Colors and symbols as in Figures 1 and 2

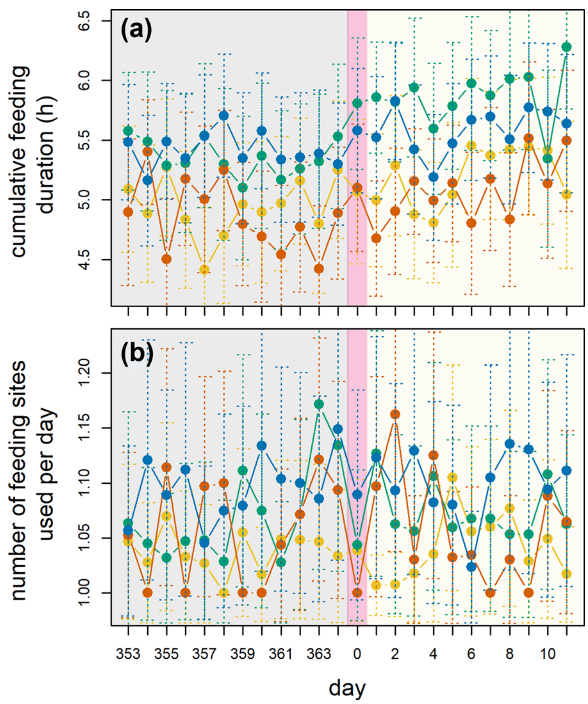

FIGURE 5 Daily averages of foraging site properties per species. Colors and symbols as in Figures 1 and 2

foraging areas during and after NY, as initial intake rates in unfamiliar sites are usually low (Béchet et al., 2004; Shamoun-Baranes et al., 2011). However, the geese seem to have been successful in avoiding human disturbance, as their new roosts were situated in less humanly populated areas.

All species responded to NY fireworks, yet some responses differed by species, most likely due to differing local conditions (Table S4): Pink-footed geese showed higher but not further flight movements during NY and, even though they experienced highest PM10 values during NY, they did not show a shift to less humanly populated areas for roosting after NY. The former might be due to often stagnant weather causing naturally higher PM10 concentration in coastal areas (ten Brink et al., 2019). The latter can be explained by a stronger stationarity due to heavy hunting outside the species' usually protected roosts (Clausen et al., 2019), which is also in line with their shorter movements during NY. Furthermore, the farther roost displacements of greater white-fronted geese might be caused by the immense fireworks activity in their most used wintering sites in the densely populated Netherlands (Shamoun-Baranes et al., 2011). PM10 values did not portray this activity, which might be caused by relatively strong winds in the Netherlands dispersing the particles.

Notably, cumulative roost duration decreased only for some species and not with a large effect size (0.2 and 1.9 h); still, the number of used roosts increased only somewhat (by 0.1 to 0.4), indicating that several individuals did not shift to new roosts during NY. Between 18.1% (barnacle geese) and 37.5% (pink-footed geese) of maximum nightly distances were below 2 km (Figure 2), indicating that some geese stayed at their roost all NY. In some examples, these roosts were surrounded by forest, likely with less disturbance. Thus, staying put might be an alternative strategy to NY disturbance. About half of those geese displaced their roost the next night, indicating a delayed response.

Different from passerines that were less disturbed during the fireworks ban of 2020–2021 than during previous NYs (Bosch & Lurz, 2021), disturbance effects were still visible in at least two of our four goose species. Migratory geese may be more reactive than other birds as they are hunted in part of their ranges, and the ban appeared not completely effective, as, for example, in the Netherlands fireworks activity was estimated about 30% of that of the years before (RIVM Team Samenmeten, 2021). We have noticed fireworks activity during NY 2020–2021 also in other countries, indicating that it is not easy to ban this usually unconstrained, public custom (ten Brink et al., 2019). In addition, fireworks are (illegally) often already lighted the night before NY, which explains our findings of differing roost use already following the night of December 30/31. Thus, NY fireworks activity in W-Europe is difficult to predict and animals cannot adapt their reactions to it (van der Kolk et al., 2021).

In conclusion, on top of the already demonstrated negative immediate impacts of fireworks on wild animals, pets, humans, and the environment (Shamoun-Baranes et al., 2011; Kukulski et al., 2018; Gähwiler et al., 2020), we show that NY fireworks also have aftereffects, lasting longer than the fireworks themselves, on wild geese. According to the EU Birds Directive (Directive 2009/147/EC, 2009), member states shall take steps to avoid deliberate disturbance of birds in protected areas. We believe people are not intentionally disturbing wild geese by lighting NY fireworks, but our results show that they disturb many of them away from their roosts.

ACKNOWLEDGMENTS

We thank all people that helped catching and tagging geese, in particular the Dutch Society of Goose Catchers, Kees Polderdijk, Petr Glazov, and Stefan Sand. For help with data download, we are grateful to a large group of volunteers. We thank the tag suppliers for logistic and technical support, especially Theo Gerrits (†) and Willem Bouten. Permits to catch and tag geese were obtained by the local and national authorities in all involved countries (see Supporting Information).

DATA AVAILABILITY STATEMENT

The used GPS tracks are uploaded to Movebank (www.movebank.org), available in the study "Goose flight around New Year in W-Europe 2014—2021" and published in the Movebank Data Repository (https://doi.org/10.5441/001/1.g51fs0jv; Kölzsch et al., 2022). The workflow "Roost and Foraging Site Extraction" with the main analysis functions is available on MoveApps and published in the Movebank Data Repository (https://doi.org/10.5441/001/1.5631hv19; Kölzsch, 2022).

REFERENCES

Baveco, J. M., Kuipers, H., & Nolet, B. A. (2011). A large-scale multi-species spatial depletion model for overwintering waterfowl. *Ecological Modelling*, *222*, 3773–3784.

Béchet, A., Giroux, J.-F., & Gauthier, G. (2004). The effects of disturbance on behaviour, habitat use and energy of spring staging snow geese. *Journal of Applied Ecology*, *41*, 689–700.

Bosch, S., & Lurz, P. (2019). Reactions of cavity-roosting passerine birds to fireworks (in German). *Ornithol Mitt*, *71*, 79–88.

Bosch, S., & Lurz, P. (2021). The COVID-19-lockdown leads to reduced disturbance of cavity-nesting birds during New Year's Eve fireworks (in German). *Vogelwarte*, *59*, 144–148.

Bundesministerium des Innern und für Heimat. (2020). *2020 kein Verkauf von Silvesterfeuerwerk*. https://www.bmi.bund.de/SharedDocs/pressemitteilungen/DE/2020/12/silvesterfeuerwerk.html

Center for International Earth Science Information Network (CIESIN), Columbia University. (2018). Gridded Population of the World, Version 4 (GPWv4)*: Population density adjusted to match 2015 revision UN WPP country totals, revision 11*. NASA Socioeconomic Data and Applications Center (SEDAC).

Clausen, K. K., Madsen, J., & Tombre, I. M. (2015). Carry-over or compensation? The impact of winter harshness and post-winter body condition on spring-fattening in a migratory goose species. *PLoS ONE*, *10*, e0132312.

Clausen, K. K., Schreven, K. H. T., & Madsen, J. (2020). Effects of capture and marking on the behaviour of moulting Pink-footed Geese Anser brachyrhynchus on Svalbard. *Wildfowl*, *70*, 13–29.

Clausen, P., Petersen, I. K., Bregnballe, T., & Nielsen, R. D. (2019). *Trækfuglebestande i de danske fuglebeskyttelsesområder, 2004 til 2017 (in Danish)*. Teknisk rapport. DCE Nationalt Center for Miljø og Energi, Aarhus Universitet.

Commander, C. J. C., & White, J. W. (2020). Not all disturbances are created equal: disturbance magnitude affects predator–prey populations more than disturbance frequency. *Oikos*, *129*, 1–12.

Cramp, S., Simmons, K. E. L., Ferguson-Lees, I. J., Nicholson, E. M., Olney, M. A., Voous, K. H., & Wattel, J. (1996). *The birds of the Western Palearctic*. Oxford University Press.

Directive 2009/147/EC. (2009). Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds. *Official Journal of the European Union*, *20*, 7–25.

Fox, A. D., & Madsen, J. (2017). Threatened species to super-abundance: The unexpected international implications of successful goose conservation. *Ambio*, *46*, 179–187.

Fox, A. D., Walsh, A. J., & Weegman, M. D. (2018). Effects of the Wexford Opera Festival firework display on roosting Greenland White-fronted Geese Anser albifrons flavirostris. *Irish Birds*, *11*, 96–99.

Frid, A., & Dill, L. (2002). Human-caused disturbance stimuli as a form of predation risk. *Conserv Ecol*, *6*, 11.

Gähwiler, S., Bremhorst, A., Tóth, K., & Riemer, S. (2020). Fear expressions of dogs during New Year fireworks: a video analysis. *Sci Rep*, *10*, 16035.

Gill, J. A. (2007). Approaches to measuring the effects of human disturbance on birds. *Ibis*, *149*, 9–14.

Giroux, J. - F. (1991). Roost fidelity of Pink-footed Geese Anser brachyrhynchus in north-east Scotland. *Bird Study*, *38*, 112–117.

Khaparde, V. V., Pipalatkar, P. P., Pustode, T., Rao, C. V. C., & Gajghate, D. G. (2012). Influence of burning of fireworks on particle size distribution of PM10 and associated Barium at Nagpur. *Environ Monit Assess*, *184*, 903–911.

Kölzsch, A. (2022). *Roost and foraging site extraction*. Movebank Data Repository, MoveApps Workflow.

Kölzsch, A., Lameris, T. K., Müskens, G. J. D. M., Schreven, K. H. T., Buitendijk, N. H., Kruckenberg, H., Moonen, S., Heinicke, T., Cao, L., Madsen, J., Wikelski, M., & Nolet, B. A. (2022). *Data from: Wild goose chase: geese flee high, far and with energetic losses from New Year's fireworks*. Movebank Data Repository.

Kukulski, B., Mleczko, D., & Wszołek, T. (2018). The impact of fireworks noise on the acoustic climate in urban areas. *Archives of Acoustics*, *43*(4), 697–705.

Lameris, T. K., Dokter, A. M., van der Jeugd, H. P., Bouten, W., Koster, J., Sand, S. H. H., Westerduin, C., & Nolet, B. A. (2021). Nocturnal foraging lifts time constraints in winter for migratory geese but hardly speeds up fueling. *Behav Ecol*, *32*, 539–552.

Lameris, T. K., Müskens, G. J. D. M., Kölzsch, A., Dokter, A. M., Van der Jeugd, H. P., & Nolet, B. A. (2018). Effects of harness-attached tracking devices on survival, migration, and reproduction in three species of migratory waterfowl. *Anim Biotelem*, *6*, 7.

Laundré, J. W., Hernández, L., & Altendorf, K. B. (2001). Wolves, elk, and bison: reestablishing the "landscape of fear" in Yellowstone National Park, U.S.A. *Can J Zool*, *79*, 1401–1409.

Nolet, B. A., Kölzsch, A., Elderenbosch, M., & Noordwijk, A. J. (2016). Scaring waterfowl as a management tool: how much more do geese forage after disturbance? *J Appl Ecol*, *53*, 1413–1421.

Pennycuick, C. J., Griffin, L. R., Colhoun, K., & Angwin, R. (2011). A trial of a non-statistical computer program for monitoring fuel reserves, response to wind and other details from GPS tracks of migrating geese. *J Ornith*, *152*, 87–99.

Pot, M. T., Koning, S., Westerduin, C., Boer, W. F., Shariati, M., & Lameris, T. K. (2019). Wintering geese trade-off energetic gains and costs when switching from agricultural to natural habitats. *Ardea*, *107*, 183–196.

Rijksoverheid. (2020). *Verboden vuurwerk vanaf 2020*. https://www.rijksoverheid.nl/onderwerpen/vuurwerk/verboden-vuurwerk-vanaf-2020

RIVM Team Samenmeten. (2021). *Oud, & Nieuw 2020–2021 (in Dutch) (Project overview)*. Bilthoven.

Rutz, C., Loretto, M. - C., Bates, A. E., Davidson, S. C., Duarte, C. M., Jetz, W., Johnson, M., Kato, A., Kays, R., Mueller, T., Primack, R. B., Ropert-Coudert, Y., Tucker, M. A., Wikelski, M., & Cagnacci, F. (2020). COVID-19 lockdown allows researchers to quantify the effects of human activity on wildlife. *Nature Ecology, & Evolution*, *4*, 1156–1159.

Shamoun-Baranes, J., Dokter, A. M., van Gasteren, H., van Loon, E. E., Leijnse, H., & Bouten, W. (2011). Birds flee en mass from New Year's Eve fireworks. *Behav Ecol*, *22*, 1173–1177.

Shilton, L. A., Latch, P. J., Mckeown, A., Pert, P., & Westcott, D. A. (2008). Landscape-scale redistribution of a highly mobile threatened species, *Pteropus conspicillatus* (Chiroptera, Pteropodidae), in response to Tropical Cyclone Larry. *Austral Ecol*, *33*, 549–561.

Sijimol, M. R., & Mohan, M. (2014). Environmental impacts of perchlorate with special reference to fireworks—A review. *Environ Monit Assess*, *186*, 7203–7210.

Stahl, J., Veeneklaas, R. M., Van der Graaf, A. J., Loonen, M., & Drent, R. H. (2001). Conversion factors for energetic expenditure of actively foraging brent and barnacle geese obtained by non-invasive heart rate telemetry. In J. Stahl (Ed.), *Limits to the co-occurrence of avian herbivores: how geese share scarce resources* (pp. 93–120). Groningen.

Stickroth, H. (2015). Effects of fireworks on birds – A critical overview (in German). *Ber. z. Vogelschutz*, *52*, 115–149.

ten Brink, H., Otjes, R., & Weijers, E. (2019). Extreme levels and chemistry of PM from the consumer fireworks in the Netherlands. *Atmospheric Environment*, *212*, 36–40.

Tucker, M. A., Böhning-Gaese, K., Fagan, W. F., Fryxell, J. M., Moorter, B. V., Alberts, S. C., Ali, A. H., Allen, A. M., Attias, N., Avgar, T., Bartlam-Brooks, H., Bayarbaatar, B., Belant, J. L., Bertassoni, A., Beyer, D., Bidner, L., Beest, F. M. v., Blake, S., Blaum, N., … Mueller, T. (2018). Moving in the Anthropocene:

Global reductions in terrestrial mammalian movements. *Science*, *359*, 466–469.

van der Kolk, H. - J., Ens, B. J., Oosterbeek, K., Jongejans, E., & van de Pol, M. (2021). The hidden cost of disturbance: Eurasian Oystercatchers (*Haematopus ostralegus*) avoid a disturbed roost site during the tourist season. *Ibis*, *164*, 437–450.

SUPPORTING INFORMATION

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

How to cite this article: Kölzsch, A., Lameris, T. K., Müskens, G. J. D. M., Schreven, K. H. T., Buitendijk, N. H., Kruckenberg, H., Moonen, S., Heinicke, T., Cao, L., Madsen, J., Wikelski, M., & Nolet, B. A. (2023). Wild goose chase: Geese flee high and far, and with aftereffects from New Year's fireworks. *Conservation Letters*, *16,* e12927. https://doi.org/10.1111/conl.12927