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Factors associated with returns of snowy owls to airports following translocation

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Abstract

Human-dominated environments often include ecological traps for wildlife, such as airports that may be perceived as suitable habitat by grassland birds but reduce fitness because of collisions with aircraft. Birds of prey are often attracted to airports where collisions with aircraft (i.e., bird strikes) are usually fatal for the birds and are a significant threat to flight safety. The snowy owl (*Bubo scandiacus*) is known for its nomadism, exhibiting unpredictable and highly variable movements during the nonbreeding season, including being a common visitor to airports, which often have high small-mammal populations and mimic flat, open habitats used naturally by owls. Since 2009, the Federal Aviation Administration reported an average of 22 snowy owl deaths annually due to aircraft collisions throughout 55 North American airports. To aid in active management of owls at airports, we assessed relocation data of 42 telemetry-tracked snowy owls from 2000–2020 in the United States and Canada. Owls that returned to the airport after relocation (33%) frequently crisscrossed and perched near runways where they were at risk of strikes. Adult females and immature males were more likely to return than the other sex and age classes, and returns were less likely to occur as the distance between the release site and the airport increased. Owls relocated in open habitats with a greater proportion of wetland and cropland (including

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grasslands and pasture) land cover classes were also less likely to return. We conclude that inclusion of multiple factors to limit return rates of relocated snowy owls from airport facilities can unspring the ecological trap presented by airports to these owls.

KEYWORDS
airport risk, birdstrike, *Bubo scandiacus*, human-wildlife conflict, movement, raptors, snowy owl, telemetry, translocation

Human-wildlife conflict is a major conservation challenge and is expected to increase with climate change, habitat loss, and global human population growth (Nyhus 2016, Ravenelle and Nyhus 2017). Rapid environmental change and human-altered landscapes can threaten wildlife populations by shifting evolutionary and ecological dynamics (Stockwell et al. 2003, Cheptou et al. 2008, Schaub et al. 2010). For example, a sudden (relative to evolutionary timescales) change to the environment as a result of natural or human-induced alterations to the landscape may cause animals to misidentify suitable habitat and potentially suffer reduced fitness because previously reliable cues have become maladaptive (i.e., ecological trap; Kokko and Sutherland 2001, Kristan 2003, Gilroy and Sutherland 2007, Fletcher et al. 2012). Understanding how to mitigate or unspring ecological traps is important for long-term conservation of species cohabitating with humans in the developed world.

Airports are one of the many hazards wildlife face in human-altered landscapes. Collisions between wildlife and aircraft are notorious for causing extensive losses to the aviation industry with regard to damage and delays per annum, and pose a major threat to human safety (Allan 2000, Sodhi 2002). The effect of airfields on wildlife may be disproportionately high because airfields provide open, undeveloped land similar to early successional vegetation communities that are perceived as suitable habitat by many species. The United States Federal Aviation Administration (FAA) reported >231,320 wildlife collisions from 1990 to 2019, 96% of which involved birds, and 28% of which were raptors (Cleary and Dolbeer 2005, Blackwell and Wright 2006, Dolbeer et al. 2021). Raptors are one of the most frequently struck taxa in North America, probably because of their large size and low altitude soaring flight (e.g., typically ≤152 m above ground level; Dolbeer 2006). Mitigation for human-wildlife conflict at airports includes lethal and nonlethal control methods (i.e., landscape management or translocation of the bird; DeVault et al. 2013); however, few studies have assessed the efficacy of nonlethal control and more specifically, the intentional translocations of raptors (DeVault et al. 2013, Schafer and Washburn 2016, Pullins et al. 2018).

Snowy owls (*Bubo scandiacus*) are large and highly visible, and sometimes settle at airports during winter. Airports may mimic the flat, open landscapes of the Arctic tundra, and contain large populations of small mammals that may support multiple overwintering owls and other raptors (Baker and Brooks 1981). The presence and abundance of owls at airports vary regionally and annually, with some airports counting upwards of 23 owls at one time and 120 owls relocated from a single site in irruptive years (e.g., 2013–2014 winter; N. E. Smith, Massachusetts Audubon, personal communication). With their large body size (~2 kg, 1.5 m wingspan) and low-to-the-ground hunting behavior (Boxall and Lein 1982, Kerlinger and Lein 1988), snowy owl movements occur in the same airspace as aircraft take-offs and landings, an important phase of flight where pilots have little room to maneuver if they strike a bird. In a study characterizing owl strikes over a 20-year period in the United States, Linnell and Washburn (2018) reported that snowy owls accounted for 24% of 134 owl strikes that caused damage to aircraft, costing on average $209,536 (U.S. dollars [USD]) per reported strike.

To help mitigate collisions with aircraft and reduce the abundance of owls on the airfield, federal wildlife agencies, private industry, and volunteers capture and relocate owls from airports. But little is known about the success of relocations, and specifically what minimizes the probability of owls returning to an airport. Relocation sites are usually selected based on a coarse, subjective visual habitat assessment of what owls are thought to prefer (e.g., agricultural lands, open landscapes) and accessibility (e.g., distance from capture site), but there are currently very few empirical data on how to choose relocation sites to minimize snowy owl return rates. Relocation sites are often predetermined, limited, and sometimes highly constrained by state and provincial wildlife management agencies. Site characteristics such as direction or distance from the airport or suitability of the land cover and habitat structure at the relocation site may affect return rates. In a recent study, McCabe et al. (2021*a*) revealed that range-residency (i.e., owls that exhibited bounded overwintering home ranges) was strongly associated with the proportion of croplands in the landscape, suggesting that some types of agricultural lands may provide enough prey (Heisler et al. 2013) compared to other land cover types, to support overwintering owls and reduce the need to continuously move in search of prey in human-dominated landscapes.

We examined reports of snowy owl airstrikes in the United States and Canada using data from the Federal Aviation Administration's National Wildlife Strike Database (FAA NWSD) and translocation success from telemetry-tracked owls. First, we investigated when and where strikes occur. Second, we assessed factors associated with return rates of translocated owls. If it is energetically costly for owls to travel long distances, we predicted that those relocated farther from airports would be less likely to return than those relocated nearby. Because snowy owls migrate in a general north to south corridor in central and eastern North America (Brown et al. 2021), we expected owls relocated in east and west directions to be less likely to return than those relocated north or south of the airport. If owls prefer to settle in open, natural, or agricultural landscapes, we predicted that owls released at sites with more contiguous open land cover would be less likely to return to airports than those released in more urban or forested landscapes. We also predicted that adults and females (i.e., the socially dominant age and sex classes) would be more likely to return because they may have already established use areas at airports. Our overarching goal was to provide recommendations to wildlife managers that will reduce return rates of snowy owls translocated away from airport facilities.

STUDY AREA

We conducted this study using data from owls trapped opportunistically at 13 airport facilities and relocated across 10 states and provinces in the United States and Canada during winter (Nov–Mar) from 2000–2020. Airports in our study were as far west as the Central Wisconsin Airport (44.784°, −89.673°), near Mosinee, Wisconsin, USA, and as far east as the Brunswick Executive Airport (43.898°, −69.934°) near Portland, Maine, USA, on the Atlantic Coast (Figure 1). The most northern airport in our study was the Montréal-Pierre Elliott Trudeau International Airport (45.465°, −73.745°), in Montréal, Québec, Canada and the most southern was the Martin State Airport (39.328°, −76.423°) in Middle River, Maryland, USA. Snowy owls were trapped on airport grounds ranging from the largest (2,082 ha) at Montréal-Pierre Elliott Trudeau International Airport to the smallest (182 ha) at Erie International Airport in Pennsylvania, USA. The mean proportions of land cover classes calculated in each 15-km buffer (i.e., 706 km^2) surrounding the 13 airports included urban (0.35 ± 0.06 [SE]), forest (0.18 ± 0.04), cropland (0.18 ± 0.05), freshwater (0.11 ± 0.04), marine (0.09 ± 0.04), wetland (0.06 ± 0.01), barren (0.03 ± 0.02), and natural shrubland-grassland (0.01 ± 0.002).

METHODS

Owl relocations

We trapped snowy owls ($n = 42$) at airport facilities ($n = 13$) in the United States and Canada from November to March in 2000–2020 using lure animals in bal-chatri traps, bow nets, or Swedish goshawk traps (Bloom et al. 2007). Owls were trapped, banded, and fitted with transmitters by raptor banders participating in Project SNOWstorm, the

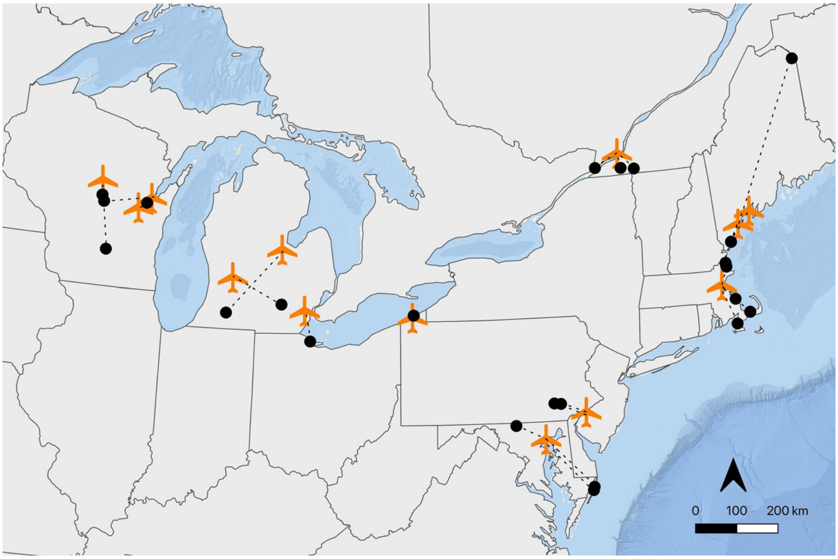

FIGURE 1 Airports (orange plane symbol; *n* = 13) in the United States and Canada where snowy owls (*n* = 42) were trapped and relocated (black dots) during winter (Nov–Mar), 2000–2020. Dashed lines connect the release site with the airport the owl was captured at.

Massachusetts Audubon Society's Snowy Owl Project, and Falcon Environmental staff. All participating banders possessed current valid permits with the necessary auxiliary marking authorizations from the United States Bird Banding Laboratory and the Canadian Bird Banding Office. We used plumage characteristics and molt patterns to assess sex and age for each individual (Pyle 1997, Seidensticker et al. 2011, Solheim 2012), and classified immatures as being <12 months old and adults as ≥12 months old.

We equipped owls with either 30-g satellite transmitters (Microwave Telemetry, MD, USA) or 40-g global positioning system–global system for mobile communications (GPS–GSM) transmitters (Cellular Tracking Technologies, Rio Grande, NJ, USA), fitted with a backpack harness of 10-mm tubular Teflon (Steenhof et al. 2006), which weighed <3% of the owl's body mass ($\bar{x}$ = 1,960 ± 52 g). The GPS–GSM transmitters recorded 1 GPS location at 30–60-minute intervals during winter, and downloaded the data via the GSM networks, whereas satellite transmitters relied on the Advanced Research and Global Observation Satellite (ARGOS) system and transmitted locations following fixed schedules (Therrien et al. 2014, Heggøy et al. 2017). We translocated tagged snowy owls from airport facilities to various release sites surrounding the airport. We selected sites by general habitat characteristics (e.g., open landscapes, away from major highways and roads) at variable distances. Relocations occurred as early as 25 November and as late as 16 March, and 69% of the relocations occurred in the middle of winter (Jan–Feb).

We analyzed the movements of relocated owls affixed with transmitters from the time the owl was released and for the remainder of the overwintering period or until an individual began moving northward systematically with no reverse migration or stopovers >3 days. First, we calculated the proportion of owls that returned to the same airport after their first translocation. We excluded multiple translocation events (i.e., second or third translocation) for the same owl during the same winter and did not include analyses related to other airport visits during the same winter period. Among those owls that returned to the same airport after their first translocation, we calculated the number of days it took to travel between the release site and the airport. We recorded the date and coordinates for each relocation (i.e., individual owls) and measured straight-line distances and azimuth (degrees) from airports to release sites in ArcGIS 10.5.1 (Esri, Redlands, CA, USA) using the distance to nearest hub tool and the measure azimuth tool.

We quantified land cover composition at release sites by creating a 15-km buffer around release sites ($n = 42$); the buffer was a circle centered around the release site and represented the secondary bird hazard zone used by Civil Aviation Authorities of both Canada and the United States in regards to the identification of hazardous land uses and their relative attractiveness to bird species that are hazardous to aircrafts (Transport Canada 2007). We then overlayed buffers with 30-m resolution land cover data for North America (2010 for Canada and 2011 for USA) from the North American Land Change Monitoring System (NALCMS; Homer et al. 2017) in ArcGIS 10.5.1. We calculated the proportion of cover in each 15-km buffer (i.e., 706 km^2), and grouped land cover types as follows (NALCMS definitions in parentheses): 1) forest including evergreen, deciduous, and mixed forest (forests generally taller than 3 m and >20% of total vegetation cover); 2) natural shrubland-grassland (areas dominated by woody perennial plants with persistent woody stems <3 m tall, or dominated by graminoid or herbaceous vegetation and generally accounting for >80% of total vegetation cover); 3) wetland (areas dominated by perennial herbaceous and woody wetland vegetation including marshes, swamps, bogs); 4) cropland (areas dominated by managed crops including perennial grasses for grazing and areas used for the production of annual crops including hayfields; crop vegetation accounts for >20% of total vegetation); 5) barren lands (areas characterized by bare rock, gravel, sand, silt, or clay with little or no green vegetation present); 6) urban (areas that contain ≥30% of constructed materials for human activities including cities, towns, transportation); 7) freshwater (areas of open water, generally with <25% cover of non-water cover types): and 8) marine (including coastlines).

Statistical analyses

We analyzed strike data from the FAA NWSD (https://wildlife.faa.gov/home; accessed 28 June 2019), which reports civil aircraft collisions with wildlife. Participation in the FAA NWSD is voluntary and the database represents strikes reported from airlines, airports, pilots, and other sources. We used all reported strikes of snowy owls in the United States and Canada during winter (April included only for strike analysis) from 2009–2020, including date and time of the incident, and the airport where the strike occurred. To determine if strikes occurred consistently throughout winter, we used a χ^2 test to assess the relationship between the number of FAA NWSD reported strikes across winter months.

We modeled return rates of telemetry-tracked snowy owls using a binomial (1 representing owls that returned to the same airport after translocation within the same winter period and 0 representing owls that did not return) generalized linear mixed model using the lme4 package (Bates et al. 2015, R Core Team 2020). We tested the relation between the return rate as a binary variable and fixed factors in 3 separate analyses: individual owl characteristics (i.e., age and sex), management strategies (i.e., relocation distance and direction [the sine and cosine functions of the direction of the release site from the airport measured in degrees; Batschelet 1981]), and release site land cover composition. For the third analysis, we excluded rare land cover classes with proportions <0.05 (i.e., forest, natural shrubland-grassland, and barren lands). Of the 42 relocated owls, 9 were released at the same site and multiple owls were captured at some of the 13 airports so we included release site and airport as random effects in all models. We used Akaike's Information Criterion values, adjusted for small sample size (AIC_c; Burnham and Anderson 2002), to select the best fit model (i.e., lower $\Delta\mathrm{AIC}_c$ scores) in each analysis (Appendix A). We compared relocation distance for owls that returned versus owls that did not return to the airport using a Mann-Whitney U test. Values reported in the results are mean ± standard error, and we considered statistical test results when data indicated strong evidence of a relationship.

RESULTS

From 2009–2020, FAA NWSD reported 267 aircraft collisions with snowy owls during winter from 55 airports in the United States and Canada. Of the 55 airports, 5 accounted for 58% of the snowy owl strikes reported over the study period: General Edward Lawrence Logan International (MA, USA), Chicago O'Hare International (IL, USA),

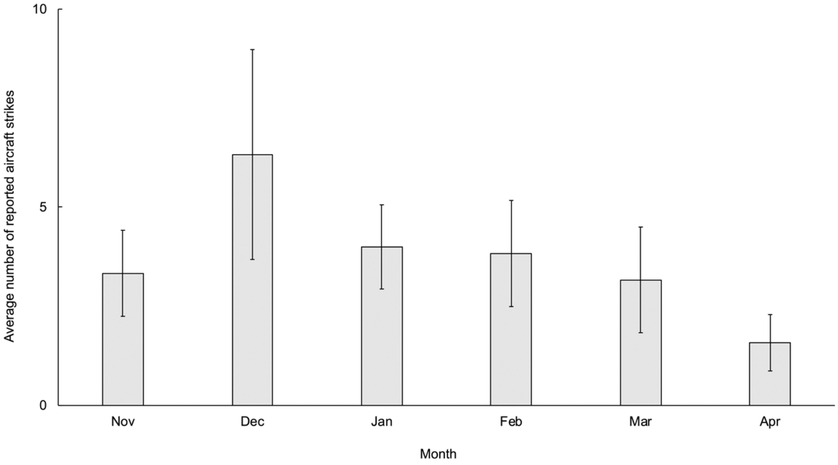

FIGURE 2 Monthly average (± SE) of reported snowy owl aircraft collisions (*n* = 267) from the Federal Aviation Administration National Wildlife Strike Database per year across airports (*n* = 55) in the United States and Canada, 2009–2020.

Detroit Metro Wayne County (MI), John F. Kennedy International (NY, USA), and Newark Liberty International (NJ, USA). Number of strikes reported varied among months (χ^2_5 = 38.6, $P < 0.001$), with the greatest number of strikes occurring in December (Figure 2). Although 61% of the strikes did not have a time of day associated with the incident, 24% occurred during the day between 0700–1900, and 15% occurred at night between 1900–0700.

The 42 relocated snowy owls included 21 adults (6 males, 15 females) and 21 immatures (9 males, 12 females) from 13 airports. After the first translocation, 33% of the 42 owls returned to the airport at which they were trapped during the same winter, taking between a few hours to >2 months to return ($\bar{x}$ = 16.9 ± 5.7 days; *n* = 14). Of the 14 snowy owls that returned after relocation, 7 were adults (1 male, 6 females) and 7 were immatures (6 males, 1 female). Two owls were subsequently killed by an aircraft collision or jet blast after returning to the airport that winter. An adult female frequently crossed runways in the southwest section of General Edward Lawrence Logan International airport before being killed by a jet blast 19 days after returning, when it strayed on to one of the main runways (Figure 3A). Similarly, an immature male flew regularly from nearby roads, across runways, to the eastern section of Philadelphia International airport (PA, USA) and was struck near a main runway between 1800–2000, 15 days after returning (Figure 3B).

For the intrinsic factors analysis, there was a significant sex-age class interaction (Table 1) that we explored further with a Tukey *post hoc* test. Immature males (0.54 ± 0.27) and adult females (0.38 ± 0.22) had a greater probability of returning to the airport, compared to adult males (0.04 ± 0.07) and immature females (0.01 ± 0.02), although some confidence intervals overlapped. For the management strategies analysis, the likelihood of return was associated with distance, with returns more likely to occur as the distance between the release site and the airport decreased (Table 1; Figure 4). For every 10-km increase in relocation distance, we expect a 9.7% decrease in the odds of an owl returning to the airport (odds ratio = 0.97, χ^2_1 = 3.92, $P = 0.04$). Relocation distance for owls that did not return to the airport ($\bar{x}$ = 95.7 ± 15.0 km; median = 64.8 km; *n* = 28) was greater (Mann-Whitney U = 117, $P = 0.03$) than relocation distance for returning owls ($\bar{x}$ = 52.0 ± 6.8 km; median = 52.1 km; *n* = 14). Finally, the landcover analysis revealed that returns were less likely to occur as the proportion of wetlands (odds ratio = 4.28e − 17, χ^2_1 = 6.82, $P = 0.009$) and croplands (odds ratio = 7.69e − 08, χ^2_1 = 4.51, $P = 0.03$) increased surrounding release sites (Table 1; Figure 5). Other landcover types in the top model had weak to no evidence of a relationship with return probability (Table 1).

FIGURE 3 Movements (red dots and black dashed lines) from telemetry-tracked snowy owls including an A) adult female at General Edward Lawrence Logan International (MA, USA) prior to being killed by a jet blast from a plane on the evening of 5–6 April 2016, and B) immature male at Philadelphia International Airport (PA, USA) prior to being struck by a plane and killed on the evening of 28 January 2014. Yellow star indicates last known location.

DISCUSSION

Snowy owls congregate at airports, yet such behavior can be detrimental to their survival with about 22 owls strikes reported annually by the FAA NWSD in North America despite relocation efforts at some airport facilities. The risks of owls on the airfield are apparent from the number of reported strikes over the last decade, and the tracking data prior to collision or jet blast of the 2 tagged owls in this study regularly crisscrossing and spending time near

TABLE 1 Parameter estimates and 95% confidence intervals from the 3 preferred generalized linear mixed models relating returns (i.e., 0 = no return; 1 = return) of snowy owls to airport facilities in the United States and Canada from 2000–2020 with various explanatory variables and including 2 random effects (airport and release site).

Explanatory variables	Estimate	95% CI	*P*-value
Intrinsic factors analysis			
Sex female	−4.686	−8.259–−1.113	0.010
Age adult	−3.271	−6.739–0.198	0.065
Sex × age	7.305	1.647–12.964	0.011
Management strategy analysis			
Distance	−0.027	−0.053–−0.0003	0.048
Landcover analysis			
Wetland	−37.69	−65.967–−9.411	0.009
Cropland	−16.38	−31.492–−1.270	0.034
Urban	−11.33	−29.509–6.844	0.222
Freshwater	9.59	−16.728–35.912	0.475
Marine	−10.33	−22.050–1.384	0.084

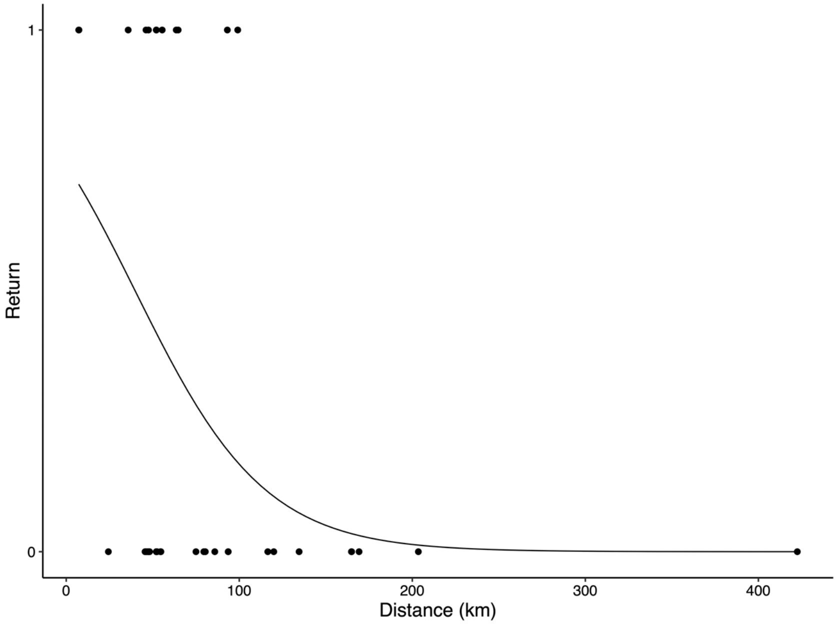

FIGURE 4 Airport returns (0 = no return, 1 = return) relative to the straight-line distance between the airport and release site of snowy owls captured and relocated from airports ($n = 13$) in the United States and Canada, 2000–2020. Regression line is the probability of return during the same winter from the generalized linear mixed model.

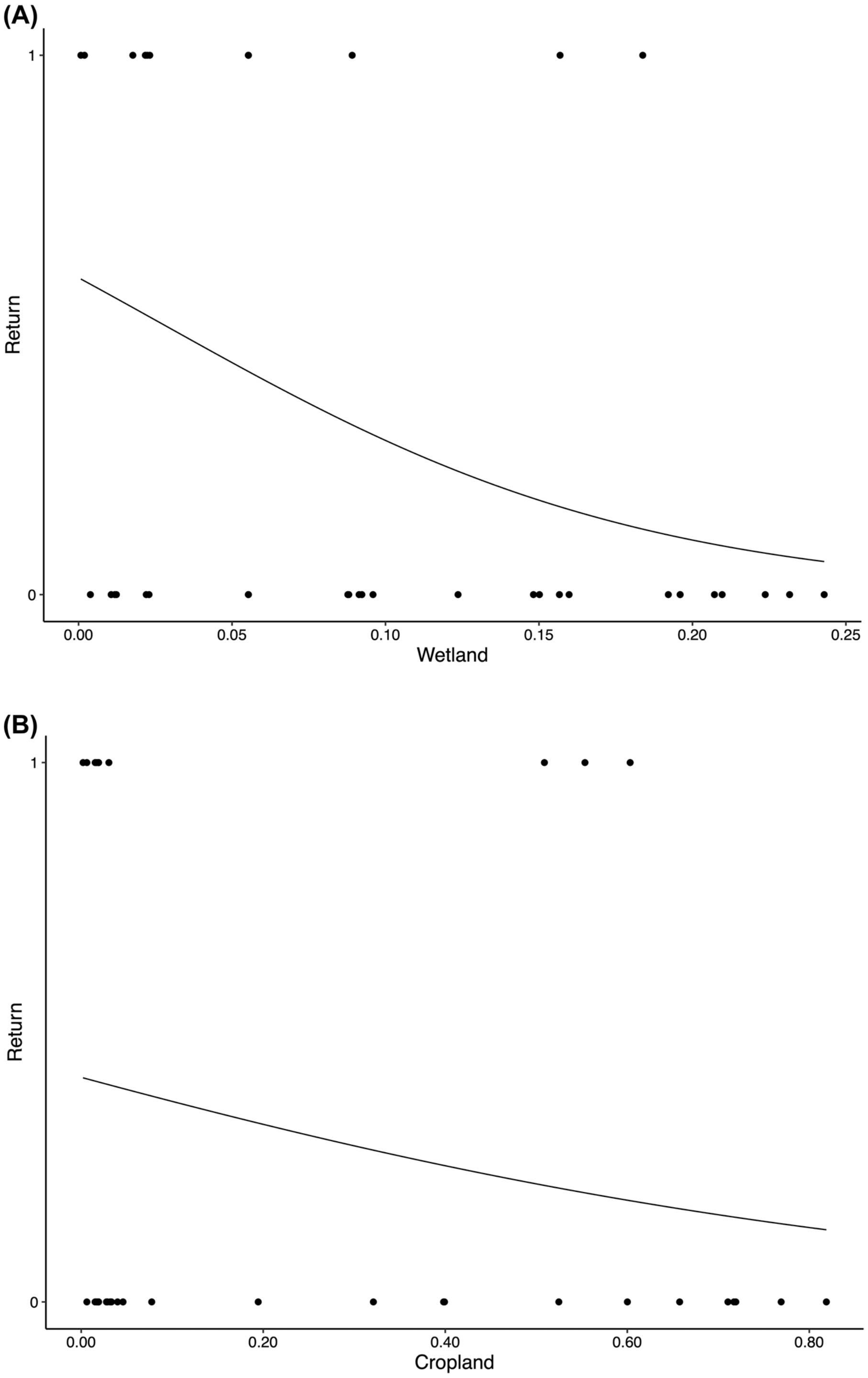

FIGURE 5 Airport returns (0 = no return, 1 = return) relative to land cover classes within release sites of relocated snowy owls from airports (*n* = 13) in the United States and Canada, 2000–2020. Regression line is the probability of return during the same winter in relation to the proportion of A) wetland and B) cropland within a release site from the generalized linear mixed model.

runways. Risks can be mitigated by a management strategy that minimizes returns by relocating owls to wintering habitats with a predictable prey availability such as coastal wetlands or several types of croplands and at distances >100 km from the airport. The NALCMS cropland land cover class definition includes a variety of land use types within the class (Homer et al. 2017), some of which may not be suitable for owl relocations (e.g., large monocultures). Therefore, future work should identify land use at a higher resolution and examine land cover types separated by areas of intensive cultivation, pastures, crop cover, and crop type to determine suitable cropland sites for translocated owls.

Because our sample included some individuals that were previously trapped and banded at airports in earlier years (6 owls) prior to receiving a tracking device, learned behavior and fidelity to previous wintering sites may explain the higher return rate of adult females. Higher return rates of immature males may be attributed to their larger wintering areas (e.g., $\bar{x} = 190 \pm 55\ \text{km}^2$; McCabe et al. 2021*a*) compared to other age classes, which may be influenced by dominance and competitive exclusion in some parts of their winter range (Chang and Wiebe 2018). Furthermore, some factors, such as direction, may be airport-specific and impose constraints on local management strategies. For example, General Edward Lawrence Logan International is situated along the Atlantic Coast and is surrounded by the City of Boston and the Metro-Boston area, limiting the number of potential release sites at shorter distances and excluding release sites east of the airport (i.e., direction of the Atlantic Ocean).

In a study examining seasonal survival in telemetry-tracked and necropsied snowy owls, McCabe et al. (2021*b*) reported higher anthropogenic mortality compared to natural mortality for overwintering owls. In particular, airplane collisions made up approximately 10% of the anthropogenic causes of death, the second highest cause of death after automobile collisions. The increase in strike frequency during December may be related to the number of owls on the landscape, with many owls arriving south from the Arctic and assessing airports as a potential wintering site. For example, McCabe et al. (2021*b*) reported that yearling snowy owls had higher mortality rates than adults in early winter (Dec–Jan), especially in anthropogenically altered landscapes. This suggests that high-risk human infrastructure like airports and highways may not be recognized by inexperienced yearling owls when they arrive on the wintering grounds. Although the age or sex of owls was not documented in the FAA NWSD database, the relatively high number of owls killed in December may be the result of a greater number of yearling owls near runways. Therefore, more intensive trapping efforts during December might be effective in reducing the risk of strikes. Similar to our findings, Linnell and Washburn (2018) reported that the timing of snowy owl aircraft collisions occurred during both day and night. Thus, deterrence throughout the day and night can be an important management policy. We encourage airport personnel to report detailed data on snowy owl strikes to the FAA NWSD including estimated time of incident, cause of death (e.g., jet blast, collision), location of collision or jet blast, and photos of the owl to determine their sex or age.

The presence of snowy owls at airports can increase the risk of an owl being killed by a collision or jet blast, pose a threat to the safety of passengers and staff if a collision occurs (Cleary and Dolbeer 2005), and cause severe economic losses when strikes cause damage to the aircraft. The FAA NWSD reports the number of strikes, strikes causing damage, strikes having a negative effect on the flight, strikes involving >1 animal, and reported aircraft downtime and costs by identified wildlife species. For example, on 20 November 2020, a snowy owl was struck by a B-737 aircraft (Boeing, Chicago, IL, USA) at General Edward Lawrence Logan International airport during landing costing $24,000 USD in repairs. Linnell and Washburn (2018) reported an average cost of $113,292 USD per damaging strike event (between 1990–2014) to repair damages to aircraft caused by strikes involving barn owls (*Tyto alba*), short-eared owls (*Asio flammeus*), great horned owls (*Bubo virginianus*), and snowy owls. Reported strikes of snowy owls (U.S. only) cost on average $209,536 USD per reported strike ($n = 114$), the most costly of the owl species in their study. In February 2021, the FAA NWSD published the most up-to-date report on snowy owl aircraft collisions ($n = 323$) between 1990 and 2019, estimating $2,786,350 USD in reported economic losses (including 914 hr of aircraft downtime, repair costs, and other costs based on inflation-adjusted costs; Dolbeer et al. 2021).

The estimated costs associated with capturing and relocating snowy owls varies depending on the agency and the wildlife mitigation program of the airport. For example, snowy owl removal in Canada typically costs approximately $185 (Canadian dollars; including staff hourly wage, indirect fees, mileage) per relocation. Many private wildlife control agencies conduct active (e.g., bow nets) and passive (e.g., Swedish goshawk) trapping of snowy owls as part of their daily tasks and often use volunteers from local wildlife rehabilitation and veterinary facilities to assist with translocation events (e.g., Union québécoise de réhabilitation des oiseaux de proie [UQROP] used volunteers for 90% of relocations in Montréal over the last 3 years), reducing overall translocation costs. In other situations, volunteer raptor banders donate their time to trapping and cover costs related to relocating snowy owls. For instance, approximately 700 owls were captured and relocated by N. E. Smith, Massachusetts Audubon, from General Edward Lawrence Logan International airport between 1981 and 2020 (N. E. Smith, personal communication). The benefits of relocating snowy owls from airport facilities include low costs associated with translocations, and the potential to reduce strikes because the majority of birds do not return to the airport after relocation.

It is inevitable that some snowy owls will continue to congregate at airports in the southernmost part of their range, so translocation may be a better management tool with an important positive conservation outcome over lethal measures or non-mitigation. The suggested management techniques need further testing at small and large airports, and at airports spanning the breadth of North America. Further research should investigate additional factors influencing return rates, such as whether visual or audio cues of airplanes lure owls to airports. Further, a detailed analysis of return paths involving landscape searching patterns deserve to be explored to assess if owls use features like cities, roads, waterways to navigate when returning to the airport. In addition, we recommend building on previous work of translocation and management programs of other large raptors wintering at airports (Blackwell and Wright 2006, Pullins et al. 2018, Washburn et al. 2021), for developing translocation and mitigation protocols that are species-specific and cater to the logistics of the program or geographic region.

The effects of successful translocations, especially of tagged individuals, in subsequent years also warrants further study. Albeit anecdotal, an adult female relocated 66 km from the Montréal-Pierre Elliott Trudeau International (QC, Canada) in winter 2019–2020, returned to southern Québec in winters 2020–2021 and 2021–2022, but instead of returning to the airport, it wintered in the area where it was relocated to in winter 2019–2020. Because airplane collisions are the second leading cause of anthropogenic mortality of wintering owls (McCabe et al. 2021*b*) in North America, and snowy owls were recently listed as vulnerable because of decreasing global population trends (International Union for Conservation of Nature 2020, Partners in Flight 2021), we propose translocation as a practical, nonlethal, low cost conservation technique to deter this winter resident from repeated use of airports.

MANAGEMENT IMPLICATIONS

Relocation distances >100 km from airports are most effective at reducing return rates, when used in combination with selecting release sites in habitats presumed to have good prey conditions, such as open landscapes with a greater proportion of wetland and cropland (including pastures and grasslands) land cover classes. Croplands with good ground vegetation cover should be preferred (e.g., when natural grasslands-shrublands are not available) because they could host higher small-mammal density than bare lands in intensively managed crop fields. We encourage private industry and federal wildlife agencies capturing snowy owls at airports be trained to sex and age individual owls because the age coupled with the sex of an owl was important for relocation strategy, and we recommend translocating immature males and adult females farther than other owls. The relatively low costs associated with translocating snowy owls coupled with the 67% success rate, make translocations a viable and effective alternative method to lethal techniques.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All location data are available on Movebank (movebank.org, study names ‘Project SNOWstorm: Snowy Owl Movements’ and ‘Snowy Owl from Saskatchewan [Wiebe]’).

ETHICS STATEMENT

Research conducted in Canada followed the guidelines of the McGill University Animal Use Protocol (2015-7599, KHE, McGill University). Trapping and banding in the United States was in accordance with the relevant guidelines and regulations prescribed by the United States Geological Survey Bird Banding Lab and protocols were regularly reviewed by Project SNOWstorm cooperating veterinarians.

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APPENDIX A: MODEL SELECTION

(Table A1)

TABLE A1 Model selection results for generalized linear mixed models containing factors influencing airport returns (i.e., returned in same winter vs. did not return) of relocated snowy owls ($n = 42$) from airports ($n = 13$) in the United States and Canada from 2000–2020. Models are ranked by the difference in Akaike's Information Criterion adjusted for small sample size (ΔAIC_c) between the current and the top model adjusted for small sample size. All models include airport and release site as random factors.

Parameter	Rank	Log likelihood	ΔAIC_c	df
Intrinsic factors analysis				
Sex + age + sex × age	1	7.2	0.0	6
Sex	2	0.7	7.8	4
Age	3	0.0	9.2	4
Sex + age	4	1.0	9.8	5
Management strategy analysis				
Distance	1	3.5	0.0	4
Distance + sine direction + cosine direction	2	4.4	3.4	6
Sine direction	3	0.0	7.0	4
Cosine direction	3	0.0	7.0	4
Distance + cosine direction + sine direction + distance × cosine direction × sine direction	4	8.9	7.2	10
Landcover analysis				
Wetland + cropland + urban + freshwater + marine	1	10.1	0.0	8
Wetland	2	3.0	3.1	4
Freshwater	3	1.8	5.3	4
Urban	4	1.2	6.6	4
Cropland	5	0.9	7.2	4
Marine	6	0.0	9.0	4