

THESIS

EFFECTS OF A NON-LETHAL CHEMICAL REPELLENT ON AIRPORT BIRD  
COMMUNITIES

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Kathleen Urchek

Department of Fish, Wildlife, and Conservation Biology

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Master's Committee:

Advisor: Liba Pejchar

Scott Werner  
William Kendall  
Alan Bright

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## ABSTRACT

### EFFECTS OF A NON-LETHAL CHEMICAL REPELLENT ON AIRPORT BIRD COMMUNITIES

Human-wildlife conflicts are likely to occur wherever the interests and activities of humans and wildlife overlap. Airport environments are a prime example of where such conflict is pervasive because wildlife can view airports as habitat, yet the presence of wildlife increases the risk of collision. As humans increase our reliance on air travel and development encroaches on natural areas, conflicts between humans and wildlife will continue to be prevalent in airport settings, thus creating the need for effective management tools. To assess the effectiveness of one such tool, we evaluated the effect of a non-lethal chemical repellent on bird abundance, species richness, movement, and behavior in airport settings. Following a Before After Control Impact Paired study design we compared the changes among each variable from a period of pre-treatment to a period of active treatment, in both treated and control sites. Using Poisson and zero-inflated mixed effects models we found that the repellent is likely effective in shifting birds from treated to untreated areas within airports, and that the abundance of two common species, Bobolinks and European Starlings, declined following treatment. We also found that the repellent does not change the frequency in which birds move out of treated plots and intersect with runways, but may be altering the within-plot behavior of Eastern Meadowlarks, Red-winged Blackbirds, and Sandhill Cranes. Our mixed findings highlight the need for continued study of the mechanisms behind avian response to chemical repellents in airport settings. Although a diverse set of approaches will always be needed to alleviate the many human-wildlife conflicts associated with airports, here we show that, to promote co-existence with wildlife, this chemical repellent can be a part of that toolset.

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## INTRODUCTION

The conflict between humans and wildlife is perhaps one of the oldest conservation challenges that we still face today (Lee-Thorp et al. 2000, Balmford et al. 2001, Berger and McGraw 2007, Baruch-Mordo et al. 2010). Humans compete with other animals for space and resources, and can act as either predators or prey (Graham et al. 2005, Okello 2006, Gordon 2009). These inter-specific interactions have led to the extinction of some species, major changes to ecosystem structure and function, detrimental effects on livelihoods, and the loss of human life (Nyhus 2016). Mitigating these conflicts, and resolving them where possible, is critical to the survival and conservation of many species, as well as the vitality of human communities. Although some tools (e.g., adaptive management) have been developed, future research to alleviate conflict is still needed in many socio-ecological contexts (Madden 2004, Nyhus 2016). For example, wildlife collisions related to transportation are one of the most universal and persistent forms of human-wildlife conflict (Nyhus 2016). The ongoing challenges that airports experience with wildlife provide an optimal opportunity to advance the science and practice of managing human-wildlife conflict and co-existence.

Wildlife, particularly birds, have posed a serious risk to aircraft and human safety since the beginning of aviation. Between 1988 to 2020 aircraft strikes with wildlife caused the deaths of 292 people and the destruction of over 271 aircraft (Dolbeer et al. 2021). Airstrikes not only result in the loss of human life, but the damage caused by wildlife collisions is also associated with significant economic losses. Direct costs include damaged aircraft, and some examples of indirect costs are loss of revenue, flight cancellations, and re-scheduling flights. The combination of these costs is estimated to result in an average of \$196 million in losses to the aviation industry each year (Dolbeer et al. 2021).

Just as this conflict threatens the lives and livelihoods of people, it also threatens the safety of wildlife. Vegetative cover at airports typically consists of turf grass and other herbaceous plants; in the contiguous U.S. alone, it is estimated that airports create 3306 km<sup>2</sup> of grasslands (DeVault et al. 2012, DeVault et al. 2013). Because airports are often embedded in otherwise urbanized landscapes, these green

spaces serve as locations for wildlife to seek shelter, water, and food in an environment that is comparatively free from human activity (DeVault et al. 2013). For example, grasses provide shelter for prey that in turn attract raptors, killdeer (*Charadrius vociferous*) are often found nesting in airport grasslands, deer and coyotes regularly use airfields to forage, and water stored on airfields often attracts waterfowl (DeVault et al. 2013). Some of the species drawn to these sites are also classified as threatened or endangered. Osborne and Peterson (1984) found the then-endangered upland sandpiper (*Bartramia longicauda*) preferred airport habitats compared to all other environments, citing it as optimal breeding ground for the species. From 1988 to 2019 a total of 231,320 animals and 701 different species have been reported as struck by aircraft in the U.S., including 222,753 birds, 3,302 bats, 4,774 mammals, and 491 reptiles (Dolbeer et al. 2021).

Reducing the risk to human and wildlife safety is a complex issue requiring advancements in the aviation industry and the proper management of wildlife in airport environments. Research and mitigation efforts have largely focused on birds, since avian species are most often involved in airstrikes (i.e., in 2019 birds were the cause of 94% of reported strikes) (Dolbeer et al. 2021). Management plans require context-dependent approaches and an array of strategies to properly address an individual airport's conflicts with wildlife (DeVault et al. 2013). Thus, on-the-ground wildlife mitigation activities remain an important part of reducing human-wildlife conflicts in airports. Currently, the primary management tools used to minimize wildlife use of airports include visual deterrents, tactile, auditory and chemical repellents, wildlife translocation, and the management of populations, food resources, airport stormwater, and turfgrass (DeVault et al. 2013). Each management tool has its own drawbacks and benefits, but perhaps one of the most misunderstood, yet promising, practices is the use of chemical repellents to modify wildlife habitat use and behavior.

Chemical repellents combine animal learning with individual perceptions of stimulus to produce avoidance behaviors. They have long been used to deter wildlife from interfering with human activities, and are often favored because of their non-lethal nature (Werner and Avery 2017). The success of a

repellent requires many factors, often with consideration of the individual circumstances that are present where the repellent will be used. These factors include understanding how animals learn, understanding the sensory perceptions of the targeted animal, understanding that learning occurs on an individual basis and training may need to continue if population turnover is rapid, and acknowledging that repellents may be more tolerated by wildlife if alternative food resources are not available (DeVault et al. 2013). Because these aspects of chemical repellents are often not considered or well understood when put into use, repellents can be subject to undue criticism and deemed to “fail” (DeVault et al. 2013). However, when chemical repellents are used correctly and in an appropriate context they can be excellent non-lethal wildlife management tools (DeLiberto and Werner 2016).

Anthraquinone is a chemical compound that has been tested as an avian repellent since the 1940's, and was first patented for that purpose in 1944 (Heckmanns and Meisenheimer 1944, DeLiberto and Werner 2016). Anthraquinone is a naturally occurring compound that is most often found in plants, and when consumed causes non-lethal post-ingestive distress (DeLiberto and Werner 2016). Research has shown that the pairing of an ultra-violet cue with anthraquinone-based repellents creates an effective combination of cue and consequence that causes feeding avoidance in a number of avian, and some mammal, species (Werner et al. 2014, DeLiberto and Werner 2016). Anthraquinone-based repellents have largely been tested in agricultural settings, and used as foliar applications or as seed treatments (DeLiberto and Werner 2016). Another use of anthraquinone-based repellents is the foliar application to turf grass, which has been shown to be effective at repelling Canada geese (*Branta canadensis*) and other avian species (DeLiberto and Werner 2016).

Some researchers have argued that this tool could be useful in airport environments, but only limited testing with anthraquinone-based repellents has occurred on airfields (Dolbeer et al. 1998, Blackwell et al. 1999). Ballinger et al. (1999) found that spraying Flight Control, an anthraquinone-based repellent, at Ronald Reagan National Airport might have repelled birds in treated areas, but the results could not be isolated from other harassment techniques being conducted at the same time. Trials were

also conducted at Portland International Airport, and the findings indicated significant initial repellency for Canada geese that slowly diminished over the subsequent three weeks of the study (Gordon and Lyman 2000). USDA's Wildlife Services (WS) conducted trials of Flight Control Max (9,10, anthraquinone) at nine different cooperating airports throughout the U.S. in 2021. The trials were intended to be an informal test of how Flight Control Max (FCM) could be used at airports. Based on observations, this chemical repellent seemed potentially effective at deterring Canada Geese, Sandhill Cranes (*Antigone canadensis*), and some species of waterfowl and songbirds. It did not appear to be effective at repelling Killdeer or migrating Mourning Doves (*Zenaida macroura*) (WS Unpublished data).

Our objective was to build on these preliminary observations to more systematically evaluate the potential use of anthraquinone to reduce human-wildlife conflict on airports. Specifically, we compared bird abundance, species richness, movement frequency and direction, and behavior before and after the application of the chemical repellent on treatment and control plots at six Wisconsin airports over a two-year period. We predicted that, within a treated airport, bird abundance would generally decrease in treated plots and possibly increase in untreated plots, that species richness would decline in treated areas, that movements would increase in treated areas, and that time spent foraging would decrease in treated areas. This study could help increase understanding of the use of chemical repellents to reduce human-wildlife conflict at airports, as well as providing new insight into bird use and behavior in these human-dominated landscapes.

## METHODS

### *Study Area*

This study took place in Monroe and Juneau counties in Wisconsin (U.S.A). Juneau county has a population of 26,718 people and an area of approximately 1987 square kilometers, and Monroe county has a population of 46,274 and an area of 2,334 square kilometers (U.S. Census Bureau). Wisconsin is home to 90 general aviation (GA) airports, of which seven public use airports are located within Monroe and Juneau counties (State of Wisconsin Department of Transportation). This study occurred on six of those public use airports; Volk Field is a military airbase, Sparta - Fort McCoy is a joint civil/military airport, and Mauston - New Lisbon, Necedah, Elroy, and Three Castles Airpark are all general aviation (GA) airports. All six airports varied in size, runway surface type, level of anthropogenic activity within the airport, and surrounding habitat (Table S1), but overall, they are typical of most airports in this area. Each of these airports have reported human-wildlife conflict on their airfields, and airport managers have cited deer (*Odocoileus virginianus*), Wild Turkeys (*Meleagris gallopavo*), Sandhill Cranes and passerines as some of the more problematic species (personal communication). Wildlife are managed in various ways at all six airports; for example, Volk Field utilizes Bird/wildlife Airstrike Hazard (BASH), a Department of Defense program created to minimize wildlife hazards to aircraft through data collection and policy development (Airforce Safety Center, n.d.), Mauston - New Lisbon uses an automobile to scare wildlife off the runway, and Necedah takes little to no action to remove wildlife from the airfield. Two airports also have permits that allow limited lethal take of Sandhill Cranes. Beyond the airports, these counties are characterized by wetland, agriculture, and forest land use types, and are also home to Necedah Wildlife Refuge, which encompasses more than 17,401 hectares and provides habitat for more than 230 bird species, including Whooping Cranes (*Grus americana*) and Sandhill Cranes (U.S. Fish and Wildlife Service). Both crane species nest and rear young at this site, flocks utilize the habitat for foraging and roosting, and in the fall the refuge serves as a staging area for migrating cranes.

### *Study Design and Site Selection*

To assess the effectiveness of the chemical repellent this study followed a Before After Control Impact Paired Series (BACIP) design adapted from Stewart-Oaten et al. (1986) and Bence et al. (1996). Like most BACIP assessments, this study was quasi-experimental because variability in the willingness of airports to apply a chemical repellent, airport regulations, and terrain did not allow us to randomly assign treatment to the airports or to the plots within airports. In this regard, three airports were treated with the chemical repellent (serving as “Impact” airports), and three airports were left untreated (“Control” airports) (Figure 1a). All airports were divided into six plots – in treated airports three of these plots were sprayed with the chemical, in untreated airports no plots were sprayed. This design allowed us to examine the effect of the repellent, while controlling for unrelated environmental factors that could affect bird communities on airports in the region. Hereafter, plot types are referred to as “sprayed” (chemically treated plots within a treated airport), “unsprayed” (chemically untreated plots within a treated airport) and “control” (chemically untreated plots within an untreated airport). Sprayed and unsprayed plots were paired and each pair was adjacent to each other, resulting in three pairs of plots throughout the airfield (Figure 1b). The sum of all plot sizes ranged from roughly 8-33 hectares in one airport, depending on airfield size and frequency of wildlife activity, and no more than a total of 16.19 hectares was sprayed at each treated airport. Plots were concentrated in areas with the highest density of conflict-causing wildlife, which was determined in coordination with airport biologists and staff. The plots at Volk field remained consistent with those used in the WS 2021 trial. Chemical spraying of the airfields was conducted by Sparta Co-op Services and, to maintain consistent repellent application, occurred every 2-4 weeks between May-September for a total of 5 times per year over a 2-year period (2022-2023).

### *Bird surveys*

To assess bird species presence and relative abundance, observations were conducted at each plot before the application of the chemical repellent, and after application began. One or two airports were

surveyed each day, and plots within the airport were surveyed three times a day – once in the morning (06:00 – 10:00), midday (10:00 – 14:00) and afternoon (14:00 – 18:00). A single survey point was selected adjacent to each plot (approximately 150m away) to allow for a clear view of the entire plot, and a consistent route was driven to each point. Surveys were conducted with binoculars from the vehicle to minimize disturbance and meet airport regulations. No surveys were conducted in rain, fog, or high winds. The species and number of individuals initially present in each plot were recorded over a 10-min period. To precisely capture the specific use of a plot, any bird or group of birds that entered a plot while the survey was underway, or that flew over and did not land in the plot, was excluded. All individuals observed were identified to species; if this was not possible, more coarse taxonomic levels (e.g., “blackbird sp.,” “sparrow sp.” etc.) were recorded. The date, temperature, proportion of cloud cover, wind speed, and start and end times of surveys were also recorded.

### *Behavior and Movement*

The general behaviors of each individual bird or group of birds observed during the surveys were recorded (e.g., foraging, loafing, locomotion, etc.) in both field seasons; however more systematic behavior observations occurred in 2023. In 2023, the most abundant bird species observed in 2022 served as the target species for 2023 behavioral surveys (Table S2). After completing the bird survey for a plot, an individual of a target species, if present, was randomly chosen for behavior observations. The focal individual was observed for 5 minutes, and the type and duration of each behavior, including locomotion, foraging, resting, comfort, social and alert/vigilant (Table S3) was recorded. This process was repeated for each target species present in the plot, and for each plot on the airfield. No more than one sample was taken per time shift (morning, midday, afternoon) for a total of no more than 3 sampling periods per day. A digital voice recorder was used to record behavioral observations.

To gain insights into the strike risks associated with the use of this repellent, movement data was collected in 2023. During the bird surveys, any bird that flew out of the plot boundary was noted.

Specifically, the species, number of individuals, cardinal direction of flight, and whether or not the bird flight path intersected with a runway was recorded. If an individual's starting point was located on the runway this was also recorded, so as to isolate these movements from "true" runway intersects.

### *Data Analysis*

Bird abundance and species richness - To identify the relationship between the repellent and overall bird abundance and bird species richness, and to account for the nested study design, we developed a series of Poisson generalized linear mixed effects models with logarithmic links in program R using package 'lme4' (Bates et al. 2004, McDonald et al. 2000, R Core Team 2023). Following a common approach to BACI analyses, all models included treatment (sprayed/unsprayed/control), time (before/after) and the interaction between the two as fixed effects (McDonald et al. 2000). Due to the disparities in airport characteristics, all models also included plot (1-6 at each airport) and airport (e.g. "Elroy Municipal"), as random effects. The size of each plot was also included as an offset in all models to account for the variation in area that could be associated with variation in bird counts. In summation, the models followed the format:

$$\text{Overall Bird Abundance or Bird Richness} \sim \text{Treatment} + \text{Time} + \text{Treatment:Time} + \text{offset}(\log(\text{Area})) + (1|\text{Airport}) + (1|\text{Plot}), \text{family} = \text{poisson}(\text{link} = \text{"log"})$$

To account for the potential impact of variation associated with year, we included year (2022 or 2023) as a random effect in some models. The inclusion of this random effect in final models was determined using Akaike Information Criterion (AIC; Akaike 1973) (Table S4).

Common species abundance - Due to a large number of zero counts, the mixed effects model was adapted to a zero-inflated model with a Poisson distribution to analyze the relationship between time and treatment with the abundance of the most common bird species (Lambert 1992). Using the package 'glmmTMB' (Brooks et al. 2017), we used the same fixed and random effects as the previous models,

along with the inclusion of area as an offset, and we also compared the use of “year” as a random effect and once again ranked these models using Akaike Information Criterion. The models for these variables of interest were generally as follows:

$$\text{Species Abundance} \sim \text{Treatment} + \text{Time} + \text{Treatment:Time} + \text{offset}(\log(\text{Area})) + (1|\text{Airport}) + (1|\text{Plot}), \text{family} = \text{poisson}(\text{link} = \text{"log"}), \text{ziformula} = \sim 1$$

We repeated this model for all twelve of the most common species; if the model did not converge for a specific species descriptive statistics were reported (mean  $\pm$ SE).

Bird movement and behavior - To investigate the effect of treatment on bird movements, we created models both for the number of birds flying out of the plot (“movements”), and the number of birds whose flight path intersected with a runway (“runway intersects”). We again used a zero-inflated model with a Poisson distribution to analyze the relationship between time and treatment with bird movement. The model for movement and runway intersects were generally as follows:

$$\text{Movement or Runway Intersects} \sim \text{Treatment} + \text{Time} + \text{Treatment:Time} + \text{offset}(\log(\text{Area})) + (1|\text{Airport}) + (1|\text{Plot}), \text{family} = \text{poisson}(\text{link} = \text{"log"}), \text{ziformula} = \sim 1$$

Year was not used as an effect in the movement models due to the presence of only one year of data. Due to small sample sizes, bird behavior data were collated and reported using descriptive statistics; thus, bird behavior was the only response variable that was not analyzed using a model.

## RESULTS

We observed a total of 2154 birds comprised of 38 species in 2022, and 1859 individuals of 36 species in 2023. The most common bird species observed across the two-year study were Red-winged Blackbird (*Agelaius phoeniceus*) (n=865), Eastern Meadowlark (*Sturnella magna*) (n=488), American Crow (*Corvus brachyrhynchos*) (n=424), Brown-headed Cowbird (*Molothrus ater*) (n=392), American Robin (*Turdus migratorius*) (n=392), European Starling (*Sturnus vulgaris*) (n=258), Canada Goose (n = 162), Bobolink (*Dolichonyx oryzivorus*) (n=136), Mourning Dove (n=107), Sandhill Crane (n=99), Killdeer (*Charadrius vociferous*) (n=92), and Eastern Kingbird (*Tyrannus tyrannus*) (n=66; Table S5).

### *Overall bird abundance*

Relative to the “before” (pre-treatment) period in treated airports, there was a 29.5% decrease in average bird abundance in the sprayed plots, compared to a 7.5% increase in unsprayed. In untreated airports there was a 32.7% decrease in bird abundance in control plots (Table S6). We found that time had a significant negative effect on overall bird abundance ( $p < 0.01$ ), and that, compared to the other plot types, abundance in unsprayed plots increased significantly ( $p < 0.01$ ) from the before to the after period (Figure 2). We found no difference in the change in bird abundance between the sprayed and control plots.

### *Abundance of the most-common species*

Models for eight of the most common species did not converge (Table S7), however models for four common species, American Crow, Bobolink, European Starling and Sandhill Crane, all converged and produced realistic estimates. The average abundance of American Crows and Sandhill Cranes increased across all plot types, Bobolink abundance decreased in both the sprayed and unsprayed plots, and European Starling abundance decreased only in the sprayed plots (Table S6). Only Bobolink and European Starling abundance changed significantly before and after treatment (Table S8). Time had a

significant negative effect on Bobolink abundance ( $p < 0.01$ ), and we found that compared to sprayed plots, abundance of Bobolinks in unsprayed plots declined less from the before to the after period ( $p < 0.01$ ). The abundance of European Starlings in sprayed plots decreased significantly compared to both unsprayed plots ( $p = 0.047$ ) and control plots ( $p = 0.014$ ) (Figure 3).

### *Species Richness*

Average species richness declined across all plot types: 44.4% in sprayed areas, 16.8% in unsprayed, and 41.5% in control plots (Table S6). Time had a significant negative effect on bird species richness ( $p < 0.01$ ) and species richness declined less in unsprayed plots ( $p = 0.014$ ) compared to sprayed and control plots (Figure 4). There was no difference in the change in species richness from the before to the after period between the sprayed and control plots.

### *Movement and Behavior*

We found that there was no association between treatment and the frequency of bird movement, or the number of runway intersects. Average bird movements and runway intersects increased across all plot types (Table S6), and time had a significant positive effect on the number of movements ( $p = 0.048$ ), while time had no effect on the number of runway intersects (Table S9). Of the 11 most common species, three species (Eastern Meadowlark, Red-winged Blackbird, Sandhill Crane) had sufficient data to report behavioral responses using descriptive statistics (Table S10). In the treated airports in the after period, all three species spent less time foraging in the sprayed plots compared to the unsprayed plots. Eastern Meadowlarks spent more time moving and alert, while Cranes spent more time in comfort behaviors. In sprayed areas Red-winged Blackbirds spent most of their time moving (Figure 5).

## DISCUSSION

To protect the lives of both people and animals, exploring the efficacy of management tools to reduce human-wildlife conflict is essential in shared landscapes. We evaluated the effects of a promising new tool for co-existence, a non-lethal chemical repellent, on bird abundance, richness, movement, and behavior in airports. We found that the repellent may be associated with a shift in overall bird abundance from sprayed to unsprayed plots within treated airports. Among the most common bird species in the study area, most did not have sufficient samples for comparative analysis, but European Starling abundance decreased following treatment, and Bobolink abundance increased in unsprayed plots, relative to sprayed plots, suggesting a shift within airports. The repellent did not affect the frequency of bird movement out of plots, including those that intersected runways. Finally, several species (Eastern Meadowlark, Red-winged Blackbird, Sandhill Crane) appeared to reduce time spent foraging and increase time devoted to non-foraging behaviors following treatment with the chemical repellent. These findings suggest that chemical repellents hold promise for reducing bird abundance on airports without increasing risk of collision, but that responses are species-specific, and a greater understanding of the mechanisms driving shifts in abundance and behavior are needed.

For both bird abundance and species richness, we found that the change in unsprayed plots differed from the sprayed areas (Figures 2,4), suggesting an indirect treatment effect wherein birds are likely moving from sprayed to unsprayed areas within the same airport. This finding is consistent with optimal foraging theory (Pyke 2010) and previous studies, where birds were deterred from treated plots but still remained in the general area (Dolbeer et al. 1998, Ballinger et al. 1999, Blackwell et al. 1999). It is likely that birds will not move farther than needed to avoid the repellent and seek food resources. Since many of the unsprayed plots were directly adjacent to sprayed areas, it follows that some individuals will be displaced, but that this affect could be species-specific.

Previous studies have shown that not all species are affected by the repellent equally (DeLiberto and Werner 2016), and this study observed 45 different bird species in the selected airports, including various species of blackbirds, sparrows, corvids, raptors, and waterfowl. Because these groups differ in regard to diet, foraging behavior, and habitat selection, it is not surprising that some species would interact with the repellent more than others. For example, some species may habituate to the repellent rather than leaving the treated area due to high site fidelity, competition, or a lack of other available resources. Other species may be diet generalists, enabling them to switch to untreated food sources within treated areas. This variation in site use among species could explain the relative decline of species richness in treated areas.

Although we found no evidence that the repellent reduced the abundance of most bird species with sufficient sample sizes for analysis, the abundance of two common species, Bobolinks and European Starlings, did change in response to treatment with the chemical repellent (Figure 3). There were no observations of Bobolinks in the control plots in the before period, so comparing control to treated airports was not possible. However, we did find a smaller decline in the unsprayed plots compared to the sprayed areas within treated airports, suggesting the repellent might be causing these birds to move from treated to untreated areas within the airport, or that the treatment is acting as an additive effect to otherwise regular movements out of these airport plots. Previous studies have shown this chemical repellent to be effective at deterring Red-Winged Blackbirds from consuming rice seed (DeLiberto and Werner 2016), and Bobolinks may respond to the chemical similarly as they belong to the same family as Red-winged Blackbirds (Icteridae) and their diets largely consist of grains and seeds, a food source that would have been impacted by the repellent in this study (Blackwell et al. 2009, Blackwell et al. 2013). Consistent with our predictions, we found that European Starling abundance decreased in sprayed areas, while abundance in all other plots increased. European Starling diets are highly variable but do include seeds, grains and berries that are likely to be present in these airfields, and previous studies with European Starlings and anthraquinone-based repellents have shown effective deterrence in some situations (Tupper

et al. 2014, DeLiberto and Werner 2016). We also found that Starling abundance increased similarly in unsprayed and control plots, thus it is unclear whether these birds are moving from treated to untreated areas within the airport, or leaving the airfield altogether.

The repellent does not appear to have an impact on the number of bird movements out of sprayed plots, including the frequency that bird flights intersect with runways. This is a promising result considering that most aircraft strikes occur at low altitudes, particularly during take-off and landing, and an increase in movements and intersections with runways would exacerbate this risk of collision (Schafer 2007). However, the abundance and species richness results do suggest movements out of the sprayed plots. A possible explanation for these seemingly conflicting results could be that the two movement results are representative of two different bird communities. The movements from sprayed to unsprayed areas could be characterizing the population that was affected by the repellent and generally moved away from the sprayed areas, while the movements captured day-to-day are representative of the bird community that remained in the plots after treatment. Birds directly observed flying out of the plots could simply indicate small, local movements that are common across airports and are not indicative of the broader shifts due to the treatment effect.

We found that bird abundance, bird species richness, and Bobolink abundance decreased over time throughout our study region. Our “before” period generally consisted of the month of May for both years, which is a time when birds are vocal and visible as they establish territories, and engage in courtship and mating. The “after” period consisted of the months of June, July, and August, which we would expect to be comparatively quieter, as birds shift to incubation, feeding nestlings and fledglings, and the post-breeding period. This disparity in activity could result in the decreasing trends we found, because the ability to detect birds visually would decrease with a reduction in activity. However, we note that evaluating study area-wide changes in bird abundance and richness over time was not our primary research question, and our BACI design allows us to interpret these trends independently of effects of the chemical repellent on our response variables.

More research is warranted to understand the mechanisms that explain the effects of the chemical repellent on bird abundance, richness, and behavior. For example, it appears that for three of the bird species observed, the repellent may increase the proportion of time spent on non-foraging activities in treated areas, which aligns with the known feeding mechanisms of the repellent and the ecology of these species (DeLiberto and Werner 2016). However, behavior shifts related to repellent usage in the field are not well studied. Devers et al. (1998) noted that Canada Geese did not enter the treated area but foraged nearby, while Barzen et al. (2020) found that Sandhill Cranes switched to foraging on untreated resources in a treated field. Future studies that focus on the behaviors of common species on airports could elucidate broader patterns in behavioral responses associated with the repellent and better inform management practices. Observing how birds react to encountering the repellent would give a clearer image of the exact impact of this chemical and its potential for effectiveness. For example, more information on the behavior of bird species that remain abundant following treatment could elucidate why these species are unaffected by the repellent (e.g., perhaps they feed on aerial insects, or use airport habitats for activities that do not include foraging). Similarly, risk of collision might not be reduced if birds move out of treated areas but stay within risk zones in the airfield. By using telemetry to track birds before and after treatment on airports, future research could determine spatial and temporal movement patterns, including directionality, at a much finer resolution than we were able to document. Such studies might be most important for large-bodied birds and birds that move in large flocks, which pose outsized collision risks (Dolbeer et al. 2021). Likewise, future research should extend beyond Wisconsin, as bird communities, vegetation communities, and human-wildlife conflict will vary among regions. Further, although avian species are struck by planes most often, some of the individuals that cause the most damage are mammals (Dolbeer et al. 2021). We recommend future studies extend our research questions to evaluate the effect of chemical repellents on mammals and conflict mitigation on airports. Finally, determining the relationship between reductions in bird abundance and richness and collision frequency and severity, and measuring the net economic and social costs and benefits of using this repellent for airport managers,

were both beyond the scope of this study. However, in our view, both analyses will be critical to assessing whether this tool can and should be widely adopted.

With the limitations of this study and priorities for future research in mind, it is important to note that our results indicate this repellent holds potential as an effective management tool in specific contexts. Since there is evidence that the repellent likely causes small, local movements within the airfield, it might be more effective in smaller airports, where a greater proportion of the airfield could be treated, minimizing the abundance of birds left in areas of management concern. Similarly, the use of this repellent in larger airfields could be concentrated in high-risk areas near the sides and ends of runways, so that even if birds remain on the airfield the risk of collision is reduced. Likewise, if the airport is experiencing conflicts with a specific species in this study that showed evidence of a response to the repellent, particularly European Starlings, then this chemical may be effective at reducing that conflict.

Wildlife management tools are a necessity when attempting to mitigate human-wildlife conflict (Decker et al. 2002). In airport settings, much work is needed to offer non-lethal management solutions that not only protect the lives of people, but also offer the opportunity for wildlife conservation (Askins et al. 2007, Dolbeer 2013). Here we examined one non-lethal tool and its potential for minimizing harm to both people and bird communities. We found that this chemical repellent is likely encouraging birds to move from sprayed to unsprayed areas within an airport, and that the treatment reduced the relative abundance of two common granivorous and insectivorous species. We also found that the repellent is not associated with an increase in local bird movement or runway intersects in treated airports, but that it may reduce the frequency of other behaviors, such as foraging. Mitigating human-wildlife conflict almost always requires a diverse array of tools to meet the needs of stakeholders (Dolbeer 2013), and wildlife collisions on airports are no exception. We suggest that this chemical repellent could be a part of that toolset. By reducing bird abundance without increasing movement across runways, this repellent could be an effective way to aid in protecting the lives of people and birds in airport settings.

FIGURES

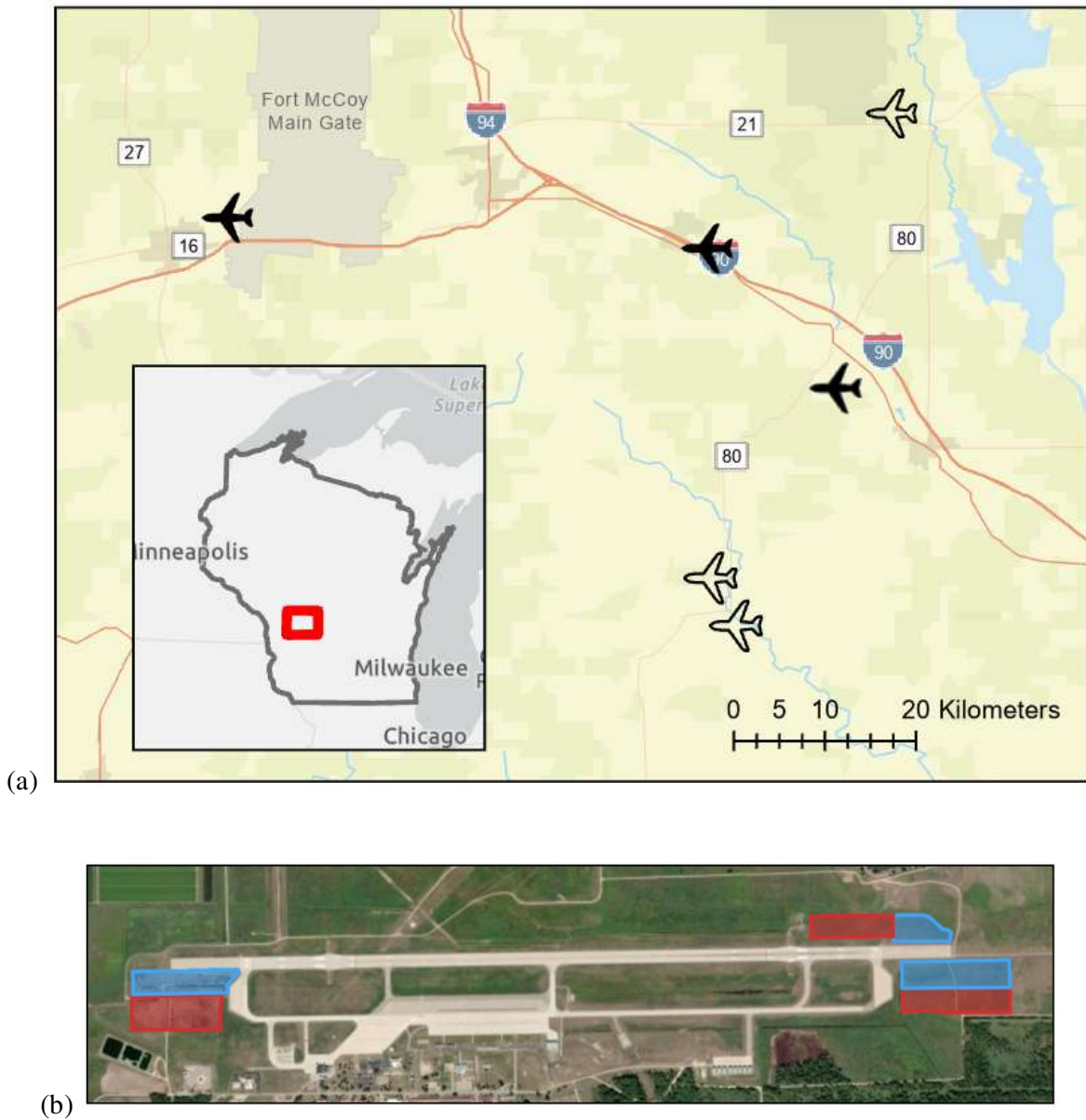


Figure 1. Location of the study sites in Wisconsin where we evaluated the effect of a non-lethal chemical repellent on bird communities: (a) Airports with sprayed plots are indicated by a red plane, and untreated airports are indicated by a blue plane; (b) Areas of sprayed (red) and unsprayed (blue) plot pairs at a treated airport (Volk Field).

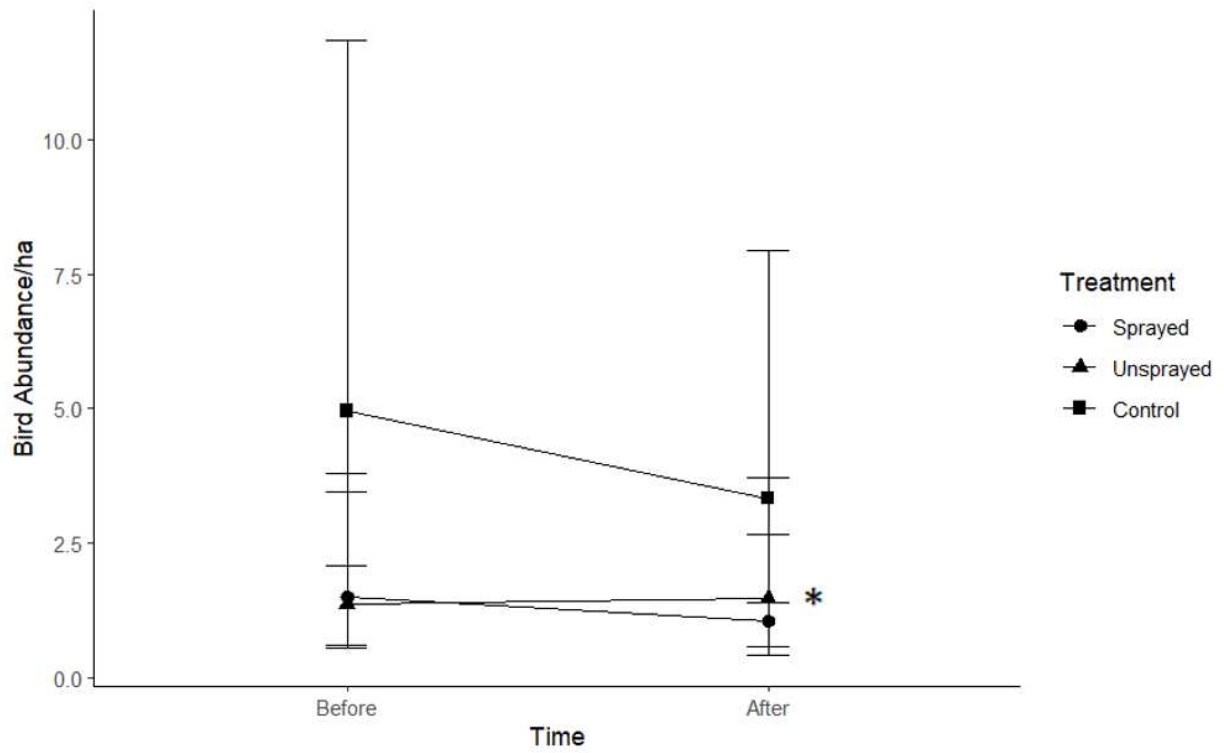


Figure 2. Mean overall bird abundance ( $\pm 95\%$  CI) in each airport plot type before and after treatment with a chemical repellent. Significant changes in bird abundance from the before to the after period, compared to the change found in the sprayed plots, are denoted with an asterisk (\*).

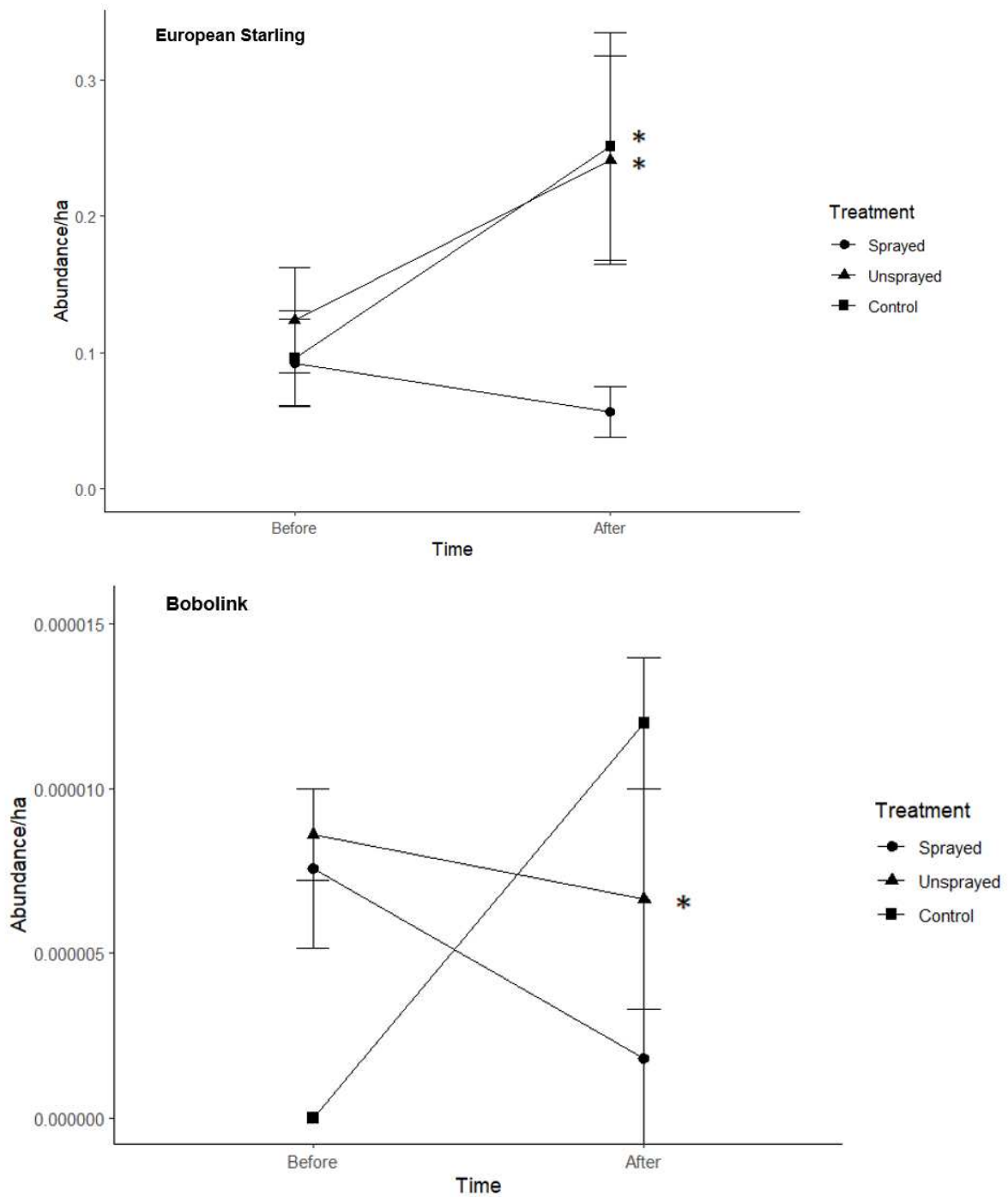


Figure 3. Mean ( $\pm 95\%$  CI) abundance of European Starling (top) and Bobolink (bottom) in all airport plot types in the periods before and after treatment with a chemical repellent. Significant changes in abundance from the before to the after period, compared to the change found in the sprayed plots, are denoted with an asterisk (\*).

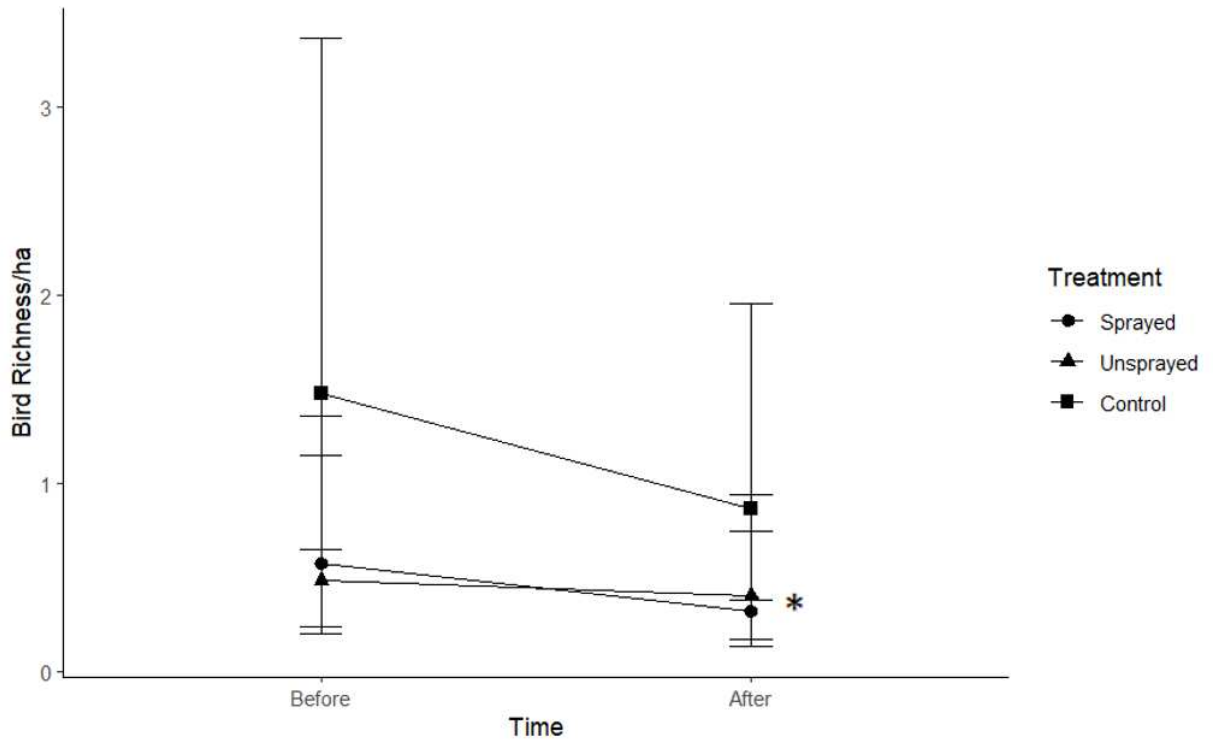


Figure 4. Mean ( $\pm 95\%$  CI) bird species richness in each airport plot type before and after treatment with a chemical repellent. Significant changes in species richness from the before to the after period, compared to the change found in the sprayed plots, are denoted with an asterisk (\*).

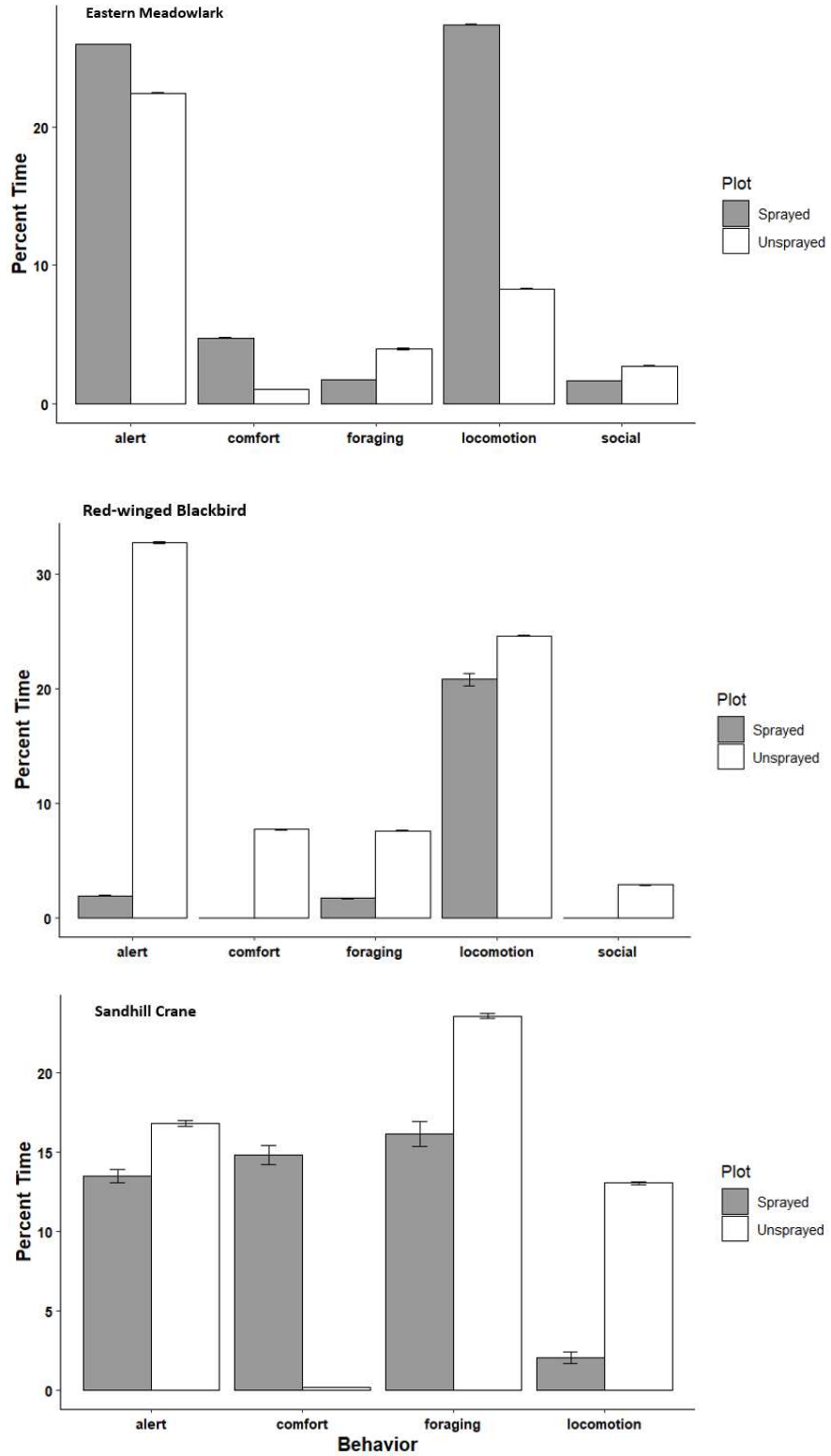


Figure 5. The mean percent time ( $\pm$ SE) spent on each behavior in unsprayed and sprayed plots after an application of a chemical repellent on airports for three common species: Eastern Meadowlark (top), Red-winged Blackbird (middle), and Sandhill Crane (bottom).

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APPENDIX

Table S1. The airports, and the characteristics of each airport, where the efficacy of a chemical repellent in mitigating wildlife-human conflict was assessed.

<b>Airport</b>	<b>Size of Runway(s) (meters)</b>	<b>Runway Surface</b>	<b>Size of Airfield (hectares)</b>	<b>Average Aircraft Operations</b>	<b>Treated or Untreated Airport</b>
<b>Volk Field ANGB</b>	2743 x 6	Concrete/ grooved	~ 235	No info	Treated
<b>Sparta – Fort McCoy</b>	1432 x 31 924 x 29	Asphalt	~113	33/day	Treated
<b>Mauston – New Lisbon</b>	1124 x 23	Asphalt	~48	28/day	Treated
<b>Necedah</b>	829 x 18	Asphalt	~30	25/day	Untreated
<b>Elroy Municipal</b>	777 x 11	Gravel on top of turf	~9	83/month	Untreated
<b>Three Castles Airpark</b>	835 x 27	Turf	~56	21/week	Untreated

Table S2. The total number of individuals observed in the 2022 field season for the eleven most-abundant bird species. The behavioral surveys focused on these species in 2023.

Species	Number of Individuals Seen in 2022
Red-winged Blackbird ( <i>Agelaius phoeniceus</i> )	532
Brown-headed Cowbird ( <i>Molothrus ater</i> )	270
American crow ( <i>Corvus brachyrhynchos</i> )	227
Eastern Meadowlark ( <i>Sturnella magna</i> )	207
American Robin ( <i>Turdus migratorius</i> )	205
European Starling ( <i>Sturnus vulgaris</i> )	110
Canada Goose ( <i>Branta canadensis</i> )	81
Mourning Dove ( <i>Zenaida macroura</i> )	78
Killdeer ( <i>Charadrius vociferous</i> )	43
Bobolink ( <i>Dolichonyx oryzivorus</i> )	36
Sandhill Crane ( <i>Antigone canadensis</i> )	29

Table S3. The behavior category and description of each behavior, used to document the activities of the most common species on the airfields.

<b>Behavior Category</b>	<b>Description of Behavior</b>
Locomotion	Walking, running, flying
Comfort	Any form of maintenance/grooming (preening, bathing, etc.)
Feeding	Foraging (probe, peck) and/or ingestion
Social	Vocalizations/aggressive, defensive or submissive display
Resting	Lying down, sitting, or sleeping
Alert/Vigilant	Cocked head or obvious alert reaction to disturbance

Table S4. Comparison and ranking of Poisson mixed effects and zero-inflated models with the inclusion of different random effects to analyze the effect of a chemical repellent on six variables: bird abundance, species richness, and the abundance of four species, American Crow, Bobolink, European Starling, and Sandhill Crane. The AIC,  $\Delta$ AIC and rank are shown for each model.

<b>Variable</b>	<b>Model</b>	<b>AIC</b>	<b><math>\Delta</math>AIC</b>	<b>Rank</b>
Abundance	Plot + Airport + Year	6627.1	0	1
	Plot + Airport	6642.1	15	2
Richness	Plot + Airport	2525.7	0	1
	Plot + Airport + Year	2526.3	0.6	2
American Crow	Plot + Airport	1418.3	0	1
	Plot + Airport + Year	1420.3	2	2
Bobolink	Plot + Airport + Year	423	0	1
	Plot + Airport	431.5	8.5	2
European Starling	Plot + Airport	668.1	0	1
	Plot + Airport + Year	670	1.9	2
Sandhill Crane	Plot + Airport	512.8	0	1
	Plot + Airport + Year	513.2	0.4	2

Table S5. The common name, scientific name, and total abundance of each bird species observed over the two-year study of bird communities and human-wildlife conflict on Wisconsin airports.

Bird Species	Total Number of Observations
Red-Winged Blackbird ( <i>Agelaius phoeniceus</i> )	865
Eastern Meadowlark ( <i>Sturnella magna</i> )	488
American Crow ( <i>Corvus brachyrhynchos</i> )	424
Brown-headed Cowbird ( <i>Molothrus ater</i> )	392
American Robin ( <i>Turdus migratorius</i> )	388
European Starling ( <i>Sturnus vulgaris</i> )	258
Canada Goose ( <i>Branta canadensis</i> )	158
Bobolink ( <i>Dolichonyx oryzivorus</i> )	136
Blackbird sp. (Icteridae)	114
Mourning Dove ( <i>Zenaida macroura</i> )	107
Sandhill Crane ( <i>Antigone canadensis</i> )	99
Killdeer ( <i>Charadrius vociferus</i> )	92
Sparrow sp. (Passeridae)	87
Eastern Kingbird ( <i>Tyrannus tyrannus</i> )	66
Small bird sp.	45
American Kestrel ( <i>Falco sparverius</i> )	32
Horned Lark ( <i>Eremophila alpestris</i> )	30
Barn Swallow ( <i>Hirundo rustica</i> )	28
Mallard ( <i>Anas platyrhynchos</i> )	22
Wild Turkey ( <i>Meleagris gallopavo</i> )	21
Grasshopper Sparrow ( <i>Ammodramus savannarum</i> )	12
Savannah Sparrow ( <i>Passerculus sandwichensis</i> )	12
Eastern Bluebird ( <i>Sialia sialis</i> )	12
American Goldfinch ( <i>Spinus tristis</i> )	12
Northern Flicker ( <i>Colaptes auratus</i> )	12
Chipping Sparrow ( <i>Spizella passerina</i> )	11
Blue Jay ( <i>Cyanocitta cristata</i> )	11
Cedar Waxwing ( <i>Bombycilla cedrorum</i> )	10
Song Sparrow ( <i>Melospiza melodia</i> )	10
Swallow sp. (Hirundinidae)	7
Northern Harrier ( <i>Circus hudsonius</i> )	6
Vesper Sparrow ( <i>Pooecetes gramineus</i> )	6
Turkey Vulture ( <i>Cathartes aura</i> )	5
Green Heron ( <i>Butorides virescens</i> )	4
Brown Thrasher ( <i>Toxostoma rufum</i> )	4
Northern Cardinal ( <i>Cardinalis cardinalis</i> )	4
Eastern Phoebe ( <i>Sayornis phoebe</i> )	3
Indigo Bunting ( <i>Passerina cyanea</i> )	3
Grey Catbird ( <i>Dumetella carolinensis</i> )	2
Rough-winged Swallow ( <i>Stelgidopteryx serripennis</i> )	2
Lark Sparrow ( <i>Chondestes grammacus</i> )	2
Common Grackle ( <i>Quiscalus quiscula</i> )	2
Tree Swallow ( <i>Tachycineta bicolor</i> )	2
Red-tailed Hawk ( <i>Buteo jamaicensis</i> )	2
Downy Woodpecker ( <i>Dryobates pubescens</i> )	1
Eastern Wood-peewee ( <i>Contopus virens</i> )	1
House Sparrow ( <i>Passer domesticus</i> )	1
Rock Pigeon ( <i>Columba livia</i> )	1
Raptor sp.	1

Table S6. The percent change in overall bird abundance, bird species richness, the abundance of four common species, movement, and runway intersects before and after the application of a chemical repellent in each plot type (sprayed, unsprayed, and control). A negative value indicates a decrease in the mean value of a specified variable, and a positive value indicates an increase.

	Percent Change from Before to After Period		
	Sprayed	Unsprayed	Control
<u>Overall</u> Bird Abundance	-29.5	7.5	-32.7
Bird Richness	-44.4	-16.8	-41.5
Bobolink Abundance	-76.2	-22.8	N/A
European Starling Abundance	-38.9	94.9	162.3
American Crow Abundance	282.1	141.1	159.3
Sandhill Crane Abundance	109.4	439.2	116.7
Movements	58.6	31.0	132.4
Runway intersects	183.9	71.3	929.1

Table S7. The mean abundance and standard error (per kilometer squared) of the eight species for which models evaluating the impact of treatment by a chemical repellent on common bird abundance did not converge, by plot type (sprayed, unsprayed, control) and time period (before or after treatment).

Plot Type	Time	Species (mean ( $\pm$ SE))							
		American Robin	Eastern Meadowlark	Brown-headed Cowbird	Killdeer	Mourning Dove	Red-winged Blackbird	Eastern Kingbird	Canada Goose
Sprayed	Before	0.41 ( $\pm$ 0.41)	22.00 ( $\pm$ 4.07)	0 ( $\pm$ 0)	1.00 ( $\pm$ 1.00)	0.29 ( $\pm$ 0.29)	18.39 ( $\pm$ 4.52)	0 ( $\pm$ 0)	0.60 ( $\pm$ 0.60)
	After	0 ( $\pm$ 0)	19.31 ( $\pm$ 2.96)	8.03 ( $\pm$ 4.64)	2.56 ( $\pm$ 1.10)	1.54 ( $\pm$ 0.80)	8.46 ( $\pm$ 2.45)	0.97 ( $\pm$ 0.56)	0 ( $\pm$ 0)
Unsprayed	Before	0 ( $\pm$ 0)	15.92 ( $\pm$ 4.72)	3.65 ( $\pm$ 2.25)	0.64 ( $\pm$ 0.64)	0.79 ( $\pm$ 0.79)	67.48 ( $\pm$ 14.92)	1.93 ( $\pm$ 1.17)	0 ( $\pm$ 0)
	After	0.27 ( $\pm$ 0.20)	33.03 ( $\pm$ 4.63)	0.94 ( $\pm$ 0.50)	3.56 ( $\pm$ 1.28)	7.84 ( $\pm$ 4.49)	39.15 ( $\pm$ 8.49)	3.65 ( $\pm$ 1.35)	0 ( $\pm$ 0)
Control	Before	164.30 ( $\pm$ 36.61)	4.55 ( $\pm$ 3.23)	119.97 ( $\pm$ 25.87)	19.38 ( $\pm$ 8.08)	0 ( $\pm$ 0)	83.30 ( $\pm$ 18.14)	1.71 ( $\pm$ 1.21)	146.51 ( $\pm$ 46.56)
	After	89.72 ( $\pm$ 15.47)	0 ( $\pm$ 0)	83.27 ( $\pm$ 27.79)	6.26 ( $\pm$ 1.98)	1.66 ( $\pm$ 1.09)	66.53 ( $\pm$ 21.05)	3.14 ( $\pm$ 0.96)	11.62 ( $\pm$ 5.73)

Table S8. Results of the models evaluating the relationship between treatment with a chemical repellent and abundance of the most common species. Of the 12 most common species, models converged for American Crow, Bobolink, European Starling and Sandhill Crane. The fixed effect of the interaction of time (before or after) and treatment (plot type) was referenced to the before period and the sprayed plots. Significant results are denoted with an asterisk (\*).

Species	Fixed Effect	Coefficient	P-value
American Crow	Unsprayed:After	-0.46	0.31
	Control:After	-0.39	0.33
Bobolink	Unsprayed:After	1.18	0.008*
	Control:After	20.18	0.99
European Starling	Unsprayed:After	1.14	0.047*
	Control:After	1.45	0.014*
Sandhill Crane	Unsprayed:After	0.91	0.5
	Control:After	0.03	0.97

Table S9. Results of the models evaluating the relationship between treatment with a chemical repellent and bird movement, and intersection with runways. The fixed effect of the interaction of time (before or after) and treatment (plot type), and time as a singular effect, was referenced to the before period and the treated plots. Significant results are denoted with an asterisk (\*).

Variable	Fixed Effect	Coefficient	P-value
Movements	Unsprayed:After	-0.19	0.58
	Control:After	0.38	0.23
	Time	0.46	0.05*
Runway Intersects	Unsprayed:After	-0.51	0.52
	Control:After	1.28	0.37
	Time	1.04	0.07

Table S10. The number of observations (n) and the mean ( $\pm$ SE) time observed in seconds for each bird species for which behavioral data were recorded on airports. Results are shown for each plot type (control, sprayed with chemical repellent, and unsprayed) in each time period (before and after treatment). Species that had sufficient sample sizes to discuss the effects between sprayed and unsprayed plots in the after period are marked with an asterisk (\*).

Species	Before (n, (mean $\pm$ SE))			After (n, (mean $\pm$ SE))		
	Control	Sprayed	Unsprayed	Control	Sprayed	Unsprayed
American Robin	7 (228 $\pm$ 29.6)	0 (0 $\pm$ 0)	0 (0 $\pm$ 0)	19 (236.21 $\pm$ 19.77)	0 (0 $\pm$ 0)	2 (127 $\pm$ 102)
Eastern Meadowlark*	0 (0 $\pm$ 0)	6 (270.33 $\pm$ 22.63)	0 (0 $\pm$ 0)	0 (0 $\pm$ 0)	16 (255.25 $\pm$ 20.66)	11 (232.36 $\pm$ 25.72)
Red-winged Blackbird*	0 (0 $\pm$ 0)	0 (0 $\pm$ 0)	5 (207.6 $\pm$ 43.94)	2 (272.5 $\pm$ 27.5)	3 (235 $\pm$ 39.37)	11 (217.6 $\pm$ 29.67)
Sandhill Crane*	0 (0 $\pm$ 0)	2 (155 $\pm$ 145)	0 (0 $\pm$ 0)	9 (300 $\pm$ 0)	4 (260.25 $\pm$ 39.75)	4 (300 $\pm$ 0)
American Crow	2 (253 $\pm$ 47)	1 (45 $\pm$ N/A)	1 (300 $\pm$ N/A)	6 (216 $\pm$ 28.95)	3 (230.33 $\pm$ 69.67)	1 (300 $\pm$ N/A)
Killdeer	0 (0 $\pm$ 0)	0 (0 $\pm$ 0)	1 (300 $\pm$ N/A)	7 (213.71 $\pm$ 35.64)	2 (300 $\pm$ 0)	3 (315 $\pm$ 90)
Brown-headed Cowbird	2 (287 $\pm$ 13)	0 (0 $\pm$ 0)	1 (300 $\pm$ N/A)	4 (174.5 $\pm$ 53.58)	0 (0 $\pm$ 0)	0 (0 $\pm$ 0)
Canada Goose	4 (174.25 $\pm$ 54.68)	1 (248 $\pm$ N/A)	0 (0 $\pm$ 0)	1 (300 $\pm$ N/A)	0 (0 $\pm$ 0)	0 (0 $\pm$ 0)
Bobolink	0 (0 $\pm$ 0)	0 (0 $\pm$ 0)	0 (0 $\pm$ 0)	0 (0 $\pm$ 0)	1 (300 $\pm$ N/A)	4 (269.25 $\pm$ 30.75)
European Starling	0 (0 $\pm$ 0)	1 (300 $\pm$ N/A)	0 (0 $\pm$ 0)	1 (300 $\pm$ N/A)	0 (0 $\pm$ 0)	2 (300 $\pm$ 0)
Mourning Dove	0 (0 $\pm$ 0)	0 (0 $\pm$ 0)	0 (0 $\pm$ 0)	0 (0 $\pm$ 0)	1 (300 $\pm$ N/A)	1 (26 $\pm$ N/A)