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RESEARCH ARTICLE

Dispersal of blackbird flocks from sunflower fields: efficacy influenced by flock and field size but not drone platform

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Abstract

Crop depredation by blackbirds (Icteridae) results in substantial economic losses to the United States sunflower industry, and a solution to effectively reduce damage remains elusive. We evaluated the utility of uncrewed aircraft systems (UAS), or drones, as hazing tools to deter foraging blackbirds from commercial sunflower (*Helianthus annuus*) fields in North Dakota, USA, between September and October 2017. We compared the efficacy of 3 drones: a fixed-wing predator model mimicking the form of an aerial raptor, a fixed-wing airplane of similar size, and a multirotor drone. Multirotor drones are relatively easy to fly and are a multifunctional tool for agricultural use; however, they may not be an effective avian deterrent due to a lack of similarity in appearance with natural predators. Free-ranging blackbird flocks (n = 58) reacted to every drone approach by initiating flight and took flight 1.6 times sooner for the fixed-wing predator model (flight initiation distance [FID] = 90 m) and 1.8 times sooner for the fixed-wing airplane (FID = 98 m) compared to the multirotor drone (FID = 55 m). However, the probability of a blackbird flock (n = 53) abandoning a field was greater with smaller field and flock sizes, rather than the specific drone deployed. In an applied setting, the performance of drones as avian hazing devices will likely depend on a combination of

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factors including platform selection, drone trajectory, duration of use, season, landscape context, and natural history of the pest species.

KEYWORDS

Agelaius phoeniceus, agroecosystem, crop damage, frightening devices, hazing, human-wildlife conflict, North Dakota, UAV, unmanned aircraft systems, visual deterrent

Throughout the Prairie-Pothole Region (PPR) of the Northern Great Plains, red-winged blackbirds (*Agelaius phoeniceus*), common grackles (*Quiscalus quiscula*), and yellow-headed blackbirds (*Xanthocephalus xanthocephalus*) congregate in large post-breeding foraging flocks that can number over 100,000 birds (Linz and Hanzel 1997, Linz et al. 2011) and in communal roosts of over 1 million birds (Clark et al. 2020). Collectively, a population of about 75 million individuals occurs throughout the PPR, and their migration overlaps with the ripening of commercially grown sunflower (*Helianthus annuus*; Linz et al. 1983, 2011; Twedt and Linz 2015; Klug et al. 2019). Sunflower seeds are an important food resource for many migrating birds, as the seeds contain fats and proteins necessary to fuel energetic demands posed by feather molt and long-distance flights (Besser 1978, Homan et al. 1994). Consequently, the economic impact of blackbird damage to sunflowers in this region exceeds US $28 million annually (Linz et al. 2011, Ernst et al. 2019), and individual sunflower producers can experience field damage surpassing 20% crop loss (Klosterman et al. 2013). After reviewing the history of blackbird damage management strategies, Linz et al. (2017) identified the mobility of blackbird flocks as the greatest challenge and conceded that a cost-effective solution remains elusive.

Effective avian deterrents require a disturbance that shifts the costs of remaining in a resource patch (e.g., crop field) beyond the costs of fleeing (Ydenberg and Dill 1986), a challenge that may depend on a variety of factors including perceived predation risk, patch quality, and the availability and knowledge of other foraging areas on the landscape (Frid and Dill 2002, Avery 2003). If the energetic costs of devoting time to antipredator behavior (i.e., scanning and monitoring) outweigh the fitness benefits provided by a resource patch, given alternative resource patches are available and the animal has knowledge of these resources, an animal or group of animals may decide to leave an area entirely (Frid and Dill 2002, Bejder et al. 2009). Theoretically, wildlife managers could increase the costs of remaining by enhancing the perceived predation risk to ultimately encourage target species to abandon a resource patch in areas of human-wildlife conflict (Blumstein and Fernández-Juricic 2010, Blackwell et al. 2016).

Recently, uncrewed aircraft systems, or drones, have gained popularity as wildlife monitoring tools (Chabot and Bird 2015, Linchant et al. 2015, Wich and Koh 2018) and have been suggested to deter birds from areas of human-wildlife conflict (Klug 2017, Wandrie et al. 2019, Wang et al. 2019, Egan et al. 2020). Drones can provoke antipredator responses in birds (Blackwell et al. 2012, McEvoy et al. 2016, Weimerskirch et al. 2018) and can overcome mobility limitations faced by other deterrent strategies (Grimm et al. 2012, Klug 2017). Furthermore, land managers or farmers can deploy a drone to a specific location within minutes and the drone can reach the interior of large crop fields (4–250 ha) that are otherwise inaccessible for tool deployment.

Land managers have used common multirotor drones to deter birds from areas of human-wildlife conflict, but results are not often evaluated (Lilleboe 2015, Curtis et al. 2016) or drone operators did not pursue birds beyond a single overhead flight (Wandrie et al. 2019). However, Wang et al. (2019) suspended a prey effigy from a multirotor drone and successfully deterred nuisance bird species from small vineyards (25 ha). In contrast to the multirotor, companies also offer bird-control services to airports using drones that visually resemble falcons in color and wing flapping (Rosenberg 2017, Pfeiffer et al. 2021), but it remains unclear if visual aspects of a drone (e.g., predatory characteristics) can enhance the risk perceived by large foraging flocks of a nuisance bird species in an agricultural field setting (Blackwell et al. 2012, McEvoy et al. 2016, Egan et al. 2020).

McEvoy et al. (2016) approached waterfowl with various drone platforms and found that birds showed the strongest behavioral reaction to the drone that resembled the contour of an aerial raptor. In contrast, waterfowl appeared less disturbed when approached by 2 multirotor platforms in the same study (McEvoy et al. 2016). In addition, captive red-winged blackbirds exhibited greater antipredator responses (e.g., alert time, alarm calls, and latency to resume foraging) when approached by a fixed-wing, predator-shaped drone (i.e., raptor silhouette) when compared with fixed-wing airplane and multirotor drones (Egan et al. 2020). In a landfill context, Pfeiffer et al. (2021) found that turkey vultures (*Cathartes aura*) escaped sooner in response to a fixed-wing airplane drone but a flapping ornithopter drone painted to resemble a peregrine falcon (*Falco peregrinus*) was ineffective at causing dispersal. Interestingly, Pfeiffer et al. (2021) also found that a multirotor drone was more effective in clearing vultures from the site (based on the number of vultures in the study area before and after a drone treatment), likely because of its ability to hold position at the site relative to fixed-wing or ornithopter airframes. Each of the previous studies suggest that drones designed to mimic aerial raptors can elicit amplified antipredator behaviors in prey birds when compared to drones typically used for wildlife monitoring (i.e., generic fixed-wing and multirotor aircraft), and that flight dynamics and maneuverability of the airframe within context are also important to enhancing perceived risk. For example, certain speeds are needed to maintain proper airflow over flight surfaces of fixed-wing platforms to avoid ascending, descending, or stalling; a multirotor platform can maintain altitude regardless of speed. Additionally, fixed-wing platforms have to take wider turns to return to a target area, whereas a multirotor drone can stop short to reverse direction. However, efficacy of various drone platforms to deter free-ranging passerine flocks from areas of human-wildlife conflict (e.g., agriculture) has not been empirically tested (Wandrie et al. 2019, Wang et al. 2019).

In an applied context, we evaluated whether a predator-shaped fixed-wing drone would be more effective at dispersing blackbirds from commercial sunflower fields, when compared to common drone platforms including a fixed-winged airplane and a multirotor drone. We predicted that blackbird flocks would differentially respond to the drone platforms (Blackwell et al. 2012, McEvoy et al. 2016, Egan et al. 2020), and escape responses would involve fleeing (Wang et al. 2019). Specifically, we predicted that blackbird flocks would initiate flight at farther distances in response to the predator model compared to the other drones (Egan et al. 2020). Additionally, when pursued using targeted, low-altitude flights we predicted blackbird flocks would abandon fields more frequently in response to the predator-shaped drone compared to the other platforms (Egan et al. 2020).

STUDY AREA

We conducted our study in the PPR of North Dakota, an area with historically large blackbird populations (Nelms et al. 1999, Peer et al. 2003). Red-winged blackbirds were the predominant species identified, although common grackles and yellow-headed blackbirds may have been minor components of the flocks. The distance between the observers and the flocks, the large number of blackbirds (≤6,000), and the constant movement of the foraging flocks made quantifying species composition difficult. From 18 September to 25 October 2017, we conducted drone flights between 08:40 and 17:40 above 32 sunflower fields, ranging in size from 4–250 ha ($\bar{x} \pm SD = 67 \pm 62$ ha; Table S1, Figure S1, available in Supporting Information). The sunflower fields where we approached blackbird flocks were on average 38 ± 30 km apart (min–max = 1–169 km) covering 6 counties (Emmons, Burleigh, Kidder, Stutsman, McIntosh, and Dickey; 23,546 km^2; Figure 1). Sunflower fields occurred in a heterogeneous matrix of agricultural land cover types (e.g., pasture, soybean, corn, barley, and harvested fields), interspersed with human development (e.g., farmsteads and roads), shelterbelts (i.e., rows of trees), and cattail (*Typha* ssp.) dominated wetlands (United States Department of Agriculture, National Agricultural Statistics Service 2018, Bansal et al. 2019). We recorded ambient air temperature (1.1–24.9°C), ambient light intensity (98.58–932.20 µmol m^{-2} s^{-1}), and average wind speed (0.3–28.5 km hr^{-1}) for each trial (Table S1).

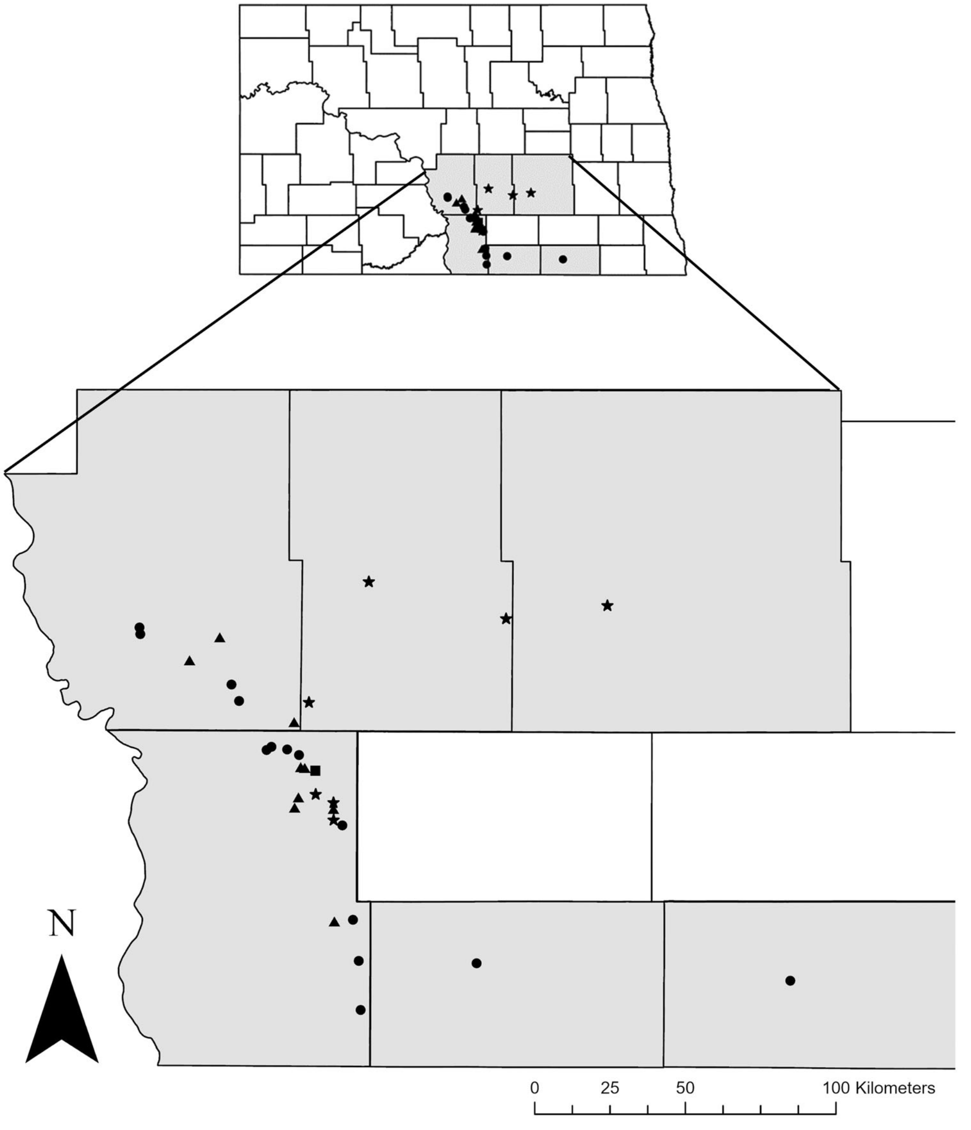

FIGURE 1 We evaluated flight initiation distance of mixed blackbird (Icteridae) flocks in response to a drone approach followed by 2 minutes of drone hazing on blackbird flocks foraging in sunflower (*Helianthus annuus*) fields in North Dakota, USA (Emmons, Burleigh, Kidder, Stutsman, McIntosh, and Dickey counties; 23,546 km^2), between September and October 2017. We visited 15 fields once (circles), 7 fields twice (stars), 9 fields 3 times (triangles), and 1 field 4 times (square). Flocks were mainly red-winged blackbirds (*Agelaius phoeniceus*).

METHODS

We used 3 drone platforms: a fixed-wing modeling the form of an aerial raptor (United States Department of Agriculture, Animal Plant and Health Inspection Service, Wildlife Services, Aviation Safety, Training, and Operations Center, Cedar City, UT, USA), a fixed-wing resembling an airplane (FT Explorer; Flight Test, New Philadelphia, OH, USA), and a multirotor (DJI Phantom 4 Pro; DJI, Shenzhen, China; Figure 2A). We hereafter refer to the platforms as the predator model, fixed-wing, and multirotor, respectively. The multirotor was white, 350 mm in diagonal length, and we disabled the factory-installed lights to prevent the influence of lighting on behavior (Figure 2A; Blackwell

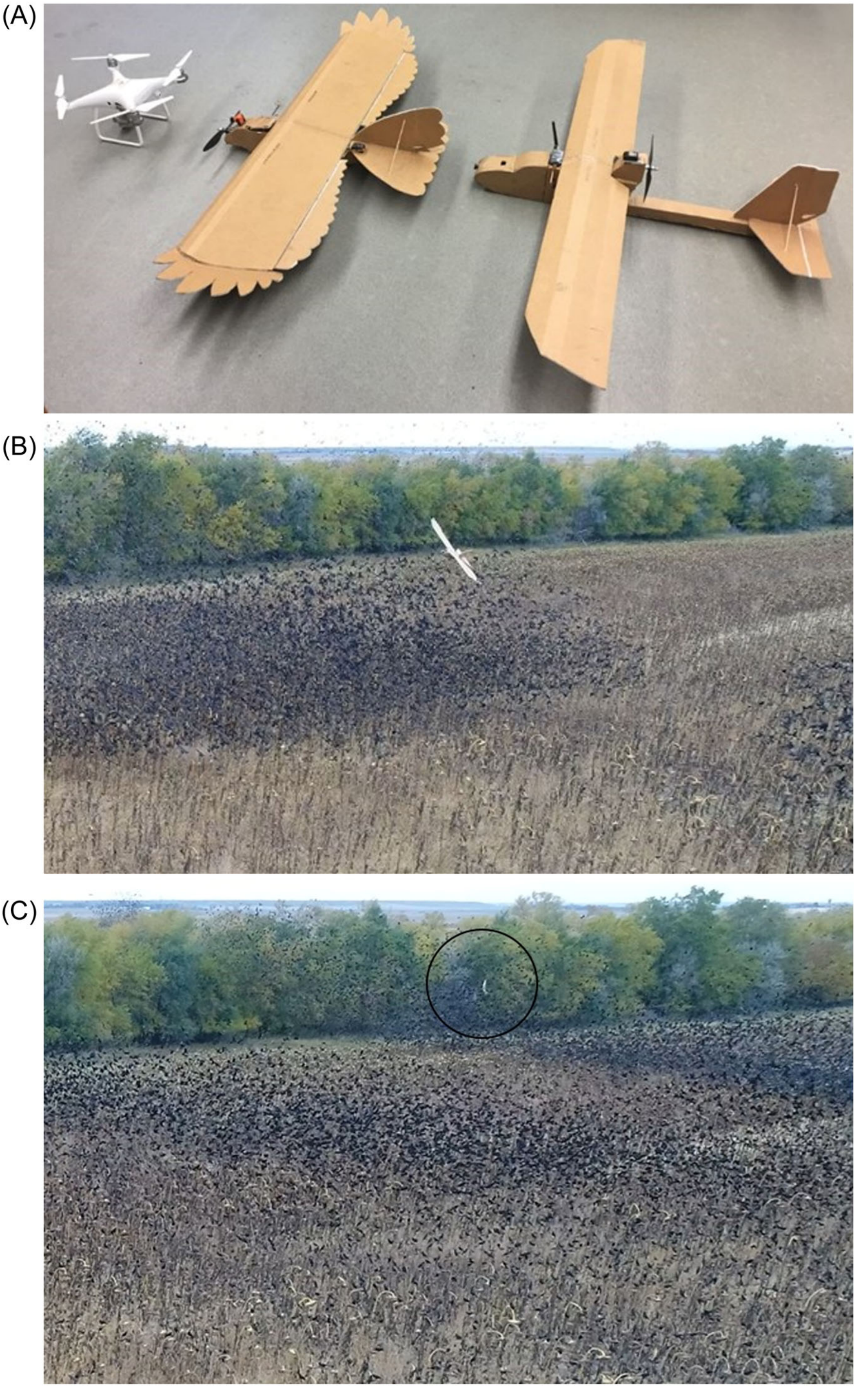

FIGURE 2 We conducted drone hazing trials on mixed blackbird flocks (Icteridae) foraging in sunflower (*Helianthus annuus*) fields in North Dakota, USA, between September and October 2017. Drone platforms included a predator model, a fixed-wing airplane model, and a DJI Phantom 4 Pro (multirotor; A). A flock of red-winged blackbirds (*Agelaius phoeniceus*) responding to an incoming predator model (B) and an apparent attack by a northern harrier (*Circus hudsonius*), circled on the photograph (C).

et al. 2012, Doppler et al. 2015). The predator model and fixed-wing had wingspans of 1,430 mm, similar profiles and lengths, no lights, and identical structural material (i.e., brown foam). In a related study, Egan et al. (2020) used the receptor noise limited visual model (Vorobyev and Osorio 1998) adjusted to the retinal properties of the red-winged blackbird to understand the visual saliency of the 3 drone platforms (Fernández-Juricic et al. 2019). Egan et al. (2020) found that the multirotor was less visually conspicuous than the fixed-wing and predator models under both sunny and cloudy conditions. Egan et al. (2020) also found that the predator model (50.6 dB) was the quietest, followed by the multirotor (54.0 dB), where the fixed-wing (56.3 dB) was the loudest of the 3 airframes.

Upon locating a blackbird flock, a single observer (C.C.E.) visually estimated species composition (using binoculars to gauge size, shape, and color of individual birds) and flock size ($\bar{x} \pm$ SD birds; 1,288 ± 939; min–max = 150–6,000 birds; Table S1, Figure S1). Compared to aerial photo counts, visual estimates of large bird-flocks by human observers are often inaccurate (Erwin 1982, Boyd 2000, Frederick et al. 2003). However, we suggest that our estimates were consistent relative to other flocks observed throughout the season, thus any overall effect of flock size in our analysis should reflect a true biological effect. Escape behavior can be influenced by the starting distance of an approaching threat (Blumstein 2003). Thus, we used a rangefinder and compass to estimate the location of the flock relative to our launch point by targeting the nearest visible bird as a proxy for the flock edge. Launch distances (i.e., starting distance) ranged from 74–401 m ($\bar{x} \pm$ SD = 202 ± 74 m; Table S1). We used the polygon ruler tool and top-down view in Google Earth to measure field size (ha). The drone platforms did not require any specialized launching or retrieval equipment given the multirotor was a vertical-takeoff-and-landing model and the fixed-wing models were launched by hand.

If we operated above a single field multiple times (i.e., 2–4 flights) throughout the season, we used a different drone and allowed at least 6 days to pass between subsequent flights. Of the 32 fields we visited 15 fields once, 7 fields twice, 9 fields 3 times, and 1 field 4 times (Figure 1). We allowed 6 to 36 days to pass between subsequent flights in the same field ($\bar{x} \pm$ SD days; 12 ± 6.6; Table S1). Flock composition likely changed throughout the season due to population turnover with incoming migrant birds and flocks mixing at roosting sites (Linz et al. 1991). However, blackbirds were unmarked, so we cannot exclude that we approached individual blackbirds multiple times, and we incorporated day of treatment in our analyses (see below). We considered our methods as comparable to an active hazing program, where birds would be approached repeatedly over the sunflower damage season (August to October) for repeated short flights over the course of the day. In a given trial, we exposed each blackbird flock to one drone flight treatment composed of one direct flight approach and a subsequent second approach for extended hazing (120 seconds).

Drone flights

Using flight-initiation distance (FID) as our metric of perceived risk (Ydenberg and Dill 1986), we launched a drone (predator model, fixed-wing, or multirotor) and approached the free-ranging blackbird flocks directly (5–10 m above ground level; AGL) at an average speed of 14 m s^{-1} until the flock initiated a flight response. We attempted to control flight altitude and speed; however, uneven terrain and high wind gusts resulted in slight variations. Once we observed a flock escape response, we stopped our approach and returned the drone to the pilot location. We scored an escape response as the moment when >50% of the birds within a flock became airborne, which was always a conspicuous event (i.e., dense group of birds). We collected drone coordinates via an onboard GPS for every moment in flight, which we used to pinpoint the drone's location when the blackbird flock initiated flight. The drone flight was always a straight line between our launch point (known GPS coordinates) and the flock edge, which we estimated with a compass and range finder. We used Google Earth to calculate the horizontal distance between the drone and flock location when the flock initiated flight, giving us an estimate of flock FID.

Following the initial direct approach, we allowed blackbirds to resume foraging behavior (i.e., land on sunflower), before approaching the same flock again and performing aggressive flight maneuvers (e.g., swooping, diving, and herding) at variable speeds and altitudes with the intent of motivating the flock to leave the sunflower field. We did not have the ability to monitor the drone path (i.e., length, tortuosity, altitude, and speed) due to the limited technology and batteries in the platforms, availability of such software at the time of the study, and scale of the field sites. Due to battery constraints, flights were limited to 120 seconds, and we scored whether the entire flock exited the sunflower field as a binary response. Hazing required advanced piloting maneuvers (i.e., repetitive turning). Thus, if we conducted an initial direct approach, but the pilot (C.C.E.) determined flocks were too distant to safely maneuver the drone for hazing, we did not haze the flock.

Statistical analyses

Our calculations of FID depended on accurate estimates of flock location. Variable flock sizes, uneven terrain, complex land cover, and birds under the crop canopy made estimating flock dimensions (e.g., edge, center, diameter) challenging, but each treatment was subject to similar inaccuracies in the location of the flock edge used in the FID measurements. Thus, we used FID as an index of escape behavior rather than an accurate estimate of FID for blackbird flocks foraging in sunflower.

For each trial, we collected environmental data (i.e., wind speed, temperature, and light intensity). However, the degree of association between temperature and light intensity was higher than 60% (Pearson's product moment correlation $r = 0.71$, $P < 0.001$); thus, we only retained the former in our statistical analysis to avoid collinearity issues. We used linear mixed models for analyses. Our models included the following independent factors: drone platform (categorical with 3 levels: predator model, fixed-wing, and multirotor), and the following potential continuous confounding factors: starting distance, field size, flock size, wind speed, and temperature. We chose not to include interaction effects due to the uneven distribution of samples across platforms, particularly in the case of the probability of field abandonment. Starting distance did not vary significantly among platforms ($F_{2,55} = 0.94$, $P = 0.399$). Because we collected more than one data point on a given day in fields that could be within flying distance from each other for blackbirds (18 km; Dolbeer 1990), we decided to use day as a random factor in our mixed models (i.e., random intercepts) for FID and field abandonment. We checked for the normality of residuals, homogeneity of variances, and multicollinearity of our models. We analyzed FID with a general linear mixed model and the probability of field abandonment with a generalized linear mixed model (binomial distribution). We used R (version 4.2.2, R Core Team 2022), and the afex package (Singmann et al. 2022) to run the linear mixed models, the emmeans package (Lenth 2022) to obtain least square means and run post-hoc tests following the t-distribution that corrected for multiple comparisons, and the interactions package (Long 2019) to get the predicted values in the probability scale for the generalized linear mixed model. We used a significance threshold of $\alpha = 0.05$.

RESULTS

Every blackbird flock initiated flight in response to the 58 initial drone approaches (FID $\bar{x} \pm SD = 79 \pm 43$ m; min–max = 10–209 m). Flight initiation distance was significantly affected by platform ($F_{2,43} = 8.26$, $P < 0.001$) and starting distance ($F_{1,47} = 10.78$, $P = 0.002$), but field size ($F_{1,48} = 0.13$, $P = 0.718$), flock size ($F_{1,49} = 0.78$, $P = 0.381$), wind speed ($F_{1,37} = 0.01$, $P = 0.910$), and temperature ($F_{1,43} = 0.79$, $P = 0.378$) had no effects. Flight initiation distance response to the predator model ($t_{47} = 3.12$, $P = 0.009$; FID = 90 ± 11 m) and the fixed-wing ($t_{41} = 3.77$, $P = 0.002$; FID = 98 ± 9 m) were greater than to the multirotor (FID = 55 ± 7 m), and we found no differences between the former 2 platforms ($t_{42} = -0.72$, $P = 0.753$; Figure 3). We recorded greater FIDs when we launched the drones farther from the flock (coefficient, 0.23 ± 0.07; $\bar{x} \pm SD = 202 \pm 74$ m, min–max = 74–401 m).

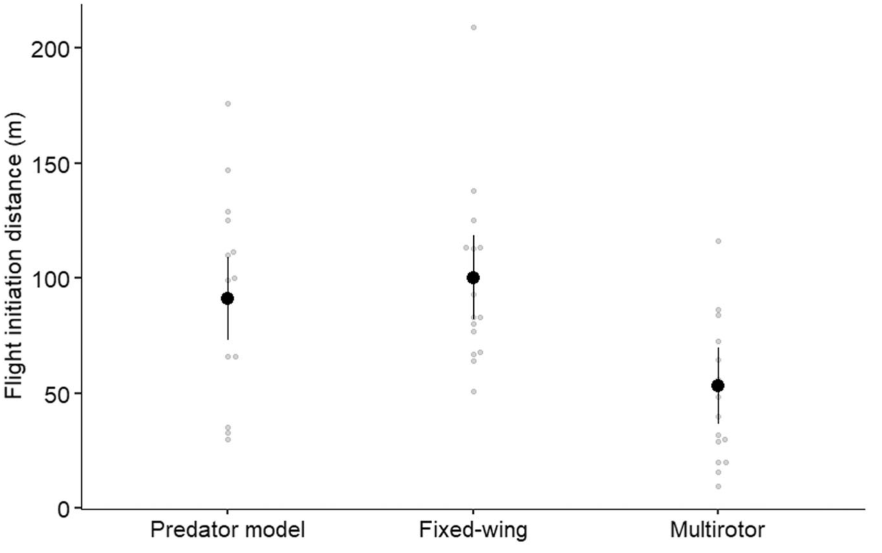

FIGURE 3 Flight initiation distance (FID) of mixed blackbird (Icteridae) flocks upon initial approach by 3 different drone platforms (i.e., predator model, fixed-wing airplane, and multirotor). Shown are least square means (±SE) and raw data in the background. We evaluated FID for 58 flocks foraging in sunflower (*Helianthus annuus*) fields in North Dakota, USA, from September to October 2017.

We conducted hazing flights on a total of 53 blackbird flocks, and motivated 9 flocks (predator model, $n = 4$ out of 18; fixed wing, $n = 1$ out of 17; multirotor, $n = 4$ out of 18) to abandon fields. We did not observe a significant effect of drone platform on the probability of field abandonment ($X^2_2 = 3.28$, $P = 0.193$). Additionally, starting distance ($X^2_1 = 0.55$, $P = 0.459$), wind speed ($X^2_1 = 0.69$, $P = 0.407$) and temperature ($X^2_1 = 0.66$, $P = 0.416$) did not significantly affect the probability of field abandonment. However, we observed a significant effect of field size ($X^2_1 = 9.36$, $P = 0.002$) and flock size ($X^2_1 = 6.85$, $P = 0.009$) on field abandonment. The probability of a flock abandoning a field in response to a 2-min drone flight decreased as field size increased, with overall probabilities higher than 50% in fields <50 ha (Figure 4A). The probability of abandoning the field after a hazing event decreased with an increase in flock size, but with less pronounced effects (i.e., probabilities >10% in flocks <500 individuals; Figure 4B).

DISCUSSION

Every blackbird flock reacted to the drone approach by taking flight. In contrast, Wandrie et al. (2019) found that no blackbird flocks showed a flight response during approaches by a fixed-wing drone flying 52 m AGL, and several flocks showed no flight response during approaches by a multirotor flying 15 or 30 m AGL. Although we used different drone platforms, our findings suggest blackbird flocks likely perceive drone approaches at lower altitudes (i.e., 5–10 m AGL) as more disturbing than approaches at higher altitudes (i.e., >15 m AGL). In waterfowl, Ryckman et al. (2022) found that multirotor flights at 45 m AGL caused more frequent flushing when compared to ducks on control wetlands, but Ellis-Felege et al. (2021) found little behavioral responses of nesting common eiders (*Somateria mollissima*) to overhead flights. In a study where drones approached turkey vultures in a landfill, targeted approaches were perceived as riskier to the vultures than overhead approaches (Pfeiffer et al. 2021). Thus, species' ecology, season, and landscape context influence responses and the flightiness of the target organism.

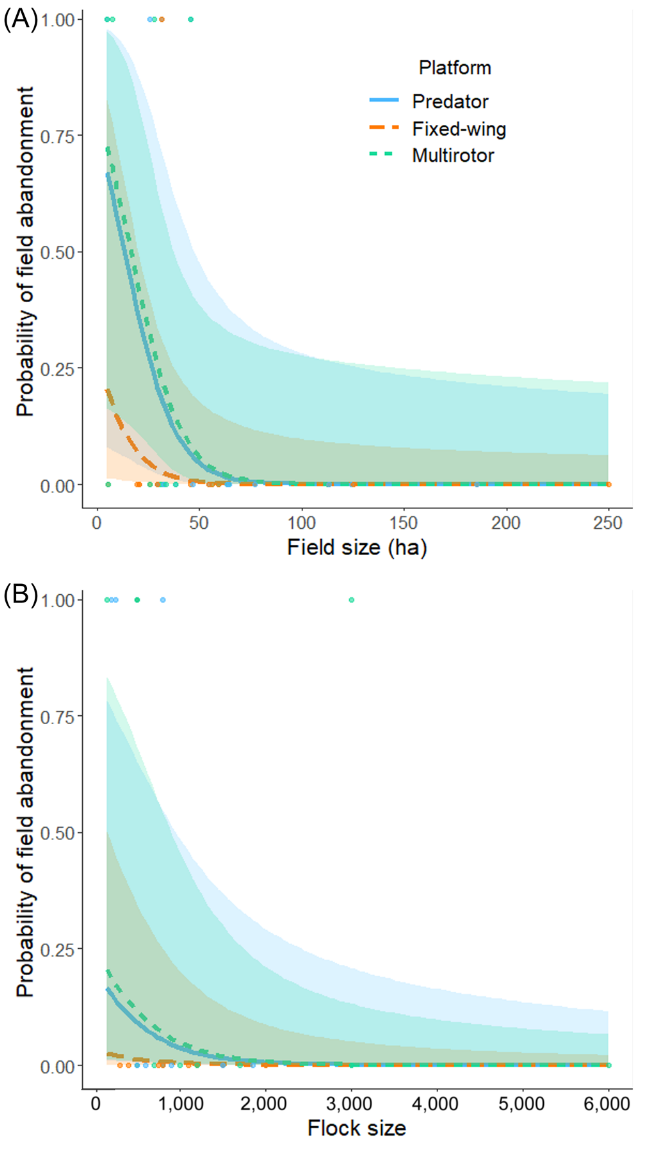

FIGURE 4 Probability of field abandonment by mixed blackbird (Icteridae) flocks after 2 minutes of hazing by 3 drone platforms (i.e., predator model, fixed-wing airplane, and multirotor) relative to field size (A) and flock size (B). Shown are predicted mean probabilities with 95% confidence intervals, along with raw data. We conducted hazing trials on 53 flocks foraging in sunflower (*Helianthus annuus*) fields in North Dakota, USA, from September to October 2017.

In response to hazing, the probability of a flock abandoning a sunflower field depended on flock size and field size, but not drone platform. Although blackbird flocks did not respond as quickly to the multirotor upon initial approach, its maneuverability and speed compared to the fixed-wing models might have compensated for its lack of perceived riskiness when considering field abandonment (Pfeiffer et al. 2021). Regarding flock size, large groups of prey may take advantage of dilution effects, whereby prey realize they have safety in numbers when a predator can only capture a single individual among many (Krause and Ruxton 2002). Thus, the chances of an individual prey being captured decreases as group size increases, and larger groups may tolerate predation pressure that a smaller group would not (Krause and Ruxton 2002). Group size has been observed to influence wildlife reaction distances to drones (Vas et al. 2015, Mulero-Pázmány et al. 2017, Jarrett et al. 2020), and future studies should identify species-specific group size thresholds where effects of drone disturbance stabilize, despite the number of individuals (Laursen et al. 2005). Future studies should also consider response variables such as latency to return to the field after abandonment, percent decline when the flock does not fully abandon the field, or changes in foraging behavior after drone exposure (White 2021).

Regarding field size, the effect is likely due to scale, timing, and duration of drone flights. Depending on location, blackbirds will need to travel considerable distances (i.e., >500 m) to exit large fields in response to hazing. Furthermore, from August to mid-September, blackbirds might suffer impaired flight performance due to feather molt and may seek cover instead of flying (Linz et al. 1983, Handegard 1988, Swaddle and Witter 1997, Twedt and Linz 2015, Klug et al. 2019). Over a span of 120 seconds, drone hazing was largely ineffective at encouraging blackbird flocks to abandon sunflower fields. In comparison, hazing gulls on rooftops to deter nesting resulted in most gulls leaving the rooftop after the first drone hazing event (Pfeiffer et al. 2023). Future studies should consider landscape factors as explanatory variables, including the prevalence of alternative forage or refugia adjacent to the field (White 2021). Decoy crops might improve the efficacy of drones in protecting agriculture by providing forage and refugia where birds are not harassed (Hagy et al. 2008, 2010; Kotten et al. 2022).

Longer drone flights are more effective (e.g., White 2021; 52% of the flocks abandoning after 10 minutes of hazing); however, contracting drone services or independently operating drones will likely cost producers money and time, warranting a cost-benefit analysis before regulations and technology allow for completely autonomous systems (Linz et al. 2011). Nevertheless, 80% of sunflower farmers responding to a survey about blackbird damage indicated they would allow blackbirds to be hazed by drones on their property and 7% of respondents have already added drones for such use to their agricultural practices (White 2021). Unsurprisingly, the impact of blackbirds on profits and the maximum amount producers are willing to spend on bird damage prevention influenced willingness to use drones (White 2021).

A bioenergetic model based on red-winged blackbird consumption of commercial sunflower seeds indicates that a single male red-winged blackbird eats roughly 0.009 kg of seed daily (Peer et al. 2003). Accordingly, a flock of 2,000 blackbirds foraging in a sunflower field, during the 6-week period when sunflowers are the most vulnerable to damage, is expected to consume approximately 756 kg of seed (Peer et al. 2003). At 2017 prices ($17.35/cwt; $0.34/kg; National Sunflower Association 2018) this equates to approximately $257 in damage. However, a flock of 50,000 birds over the same period might cause $6,426 worth of damage. Thus, the cost/benefit of deploying drones to deter and disperse birds from crop fields will depend on the timing of blackbird aggregations (Clark et al. 2020) and may not be appropriate for every bird-damage scenario. Future studies should incorporate the efficacy of drones to not only reduce the presence or abundance of pest birds but evaluate the reduction in crop damage compared to other damage management tools (Wang et al. 2020).

Perceived risk of natural predators

Biologically, one might argue that our predator model failed to effectively mimic a raptor from the perception of free-ranging blackbirds. Egan et al. (2020) evaluated the same 3 drone platforms and found that individual red-winged blackbirds perceived the simple silhouette of the fixed-wing predator model as riskier than the fixed-wing airplane and multirotor. When observing free-ranging blackbird flocks, we found the FIDs for the 2 fixed wings (predator model and airplane) were similar but significantly greater than the multirotor, suggesting flocks reacted to drones simply resembling the contour of an aerial raptor when directly approaching the foraging flock (McEvoy et al. 2016).

Throughout the study period, we observed multiple interactions between raptors and blackbird flocks. Raptors observed on multiple occasions included merlins (*Falco columbarius*), Cooper's hawks (*Accipiter cooperii*), red-tailed hawks (*Buteo jamaicensis*), and northern harriers (*Circus hudsonius*). We observed 2 separate occasions where a merlin and a Cooper's hawk approached a blackbird flock and caused the flock to abandon the field. In contrast, we also observed a merlin actively consuming a deceased blackbird, while a flock actively foraged within 50 m of the predator. We also witnessed scenarios where blackbird flocks remained in fields following attacks by Cooper's hawks. Similarly, the presence of northern harriers and red-tailed hawks appeared ineffective at deterring blackbirds from sunflower fields or displacing them from a roosting site. On one occasion we observed a red-tailed hawk perched among roosting blackbirds (i.e., same tree). The behavioral response of blackbird flocks to our drones appeared visually similar to the way flocks responded to northern harriers, in that they generally created a rift within the flock to allow predator passage, but the blackbirds did not move very far beyond what was necessary to avoid contact or collision. Although our observations are opportunistic and anecdotal, it appears large, migratory blackbird flocks tolerate the predation risk associated with local raptors, suggesting a single drone resembling a predator or passive raptor management to increase predator presence (Kay et al. 1994, Kross et al. 2012) is unlikely to deter blackbird flocks from sunflower fields. However, like drone disturbance, efficacy might depend on field size and flock size (Wang et al. 2019).

Future technology will likely increase the efficacy and cost-effectiveness of drones deployed as avian hazing devices. For example, Ampatzidis et al. (2015) conceptually designed an autonomous drone capable of detecting pest bird flocks, moving to the flock's active location, and spraying the impacted area directly with a nonlethal chemical repellent. The next phase of implementing a drone to spray an avian repellent should determine application strategies, and if drones can approach bird flocks within a distance where liquid spray can spot treat areas of the crop being actively damaged. Furthermore, using a drone in combination with negative stimuli (e.g., chemical repellents, lasers, auditory deterrents, or nonlethal projectiles; Penny et al. 2019, Wang et al. 2020, Werrell et al. 2021) might counter dilution effects within flocks (Krause and Ruxton 2002), if the stimuli directly impacts a greater number of individuals. If birds do not perceive drones as particularly disturbing or threatening, but will move short distances to avoid collision, drones could potentially be used to herd flocks of birds out of a field (Paranjape et al. 2018, White 2021, King et al. 2023) or move them closer to alternative management tools (e.g., propane cannons, firearms, capture devices, or decoy crops; Klug et al. 2023). Alternatively, wildlife managers could use a drone to ferry other deterrents to the problem location. For example, a drone could carry and activate pyrotechnics near problematic wildlife species where access by wildlife managers would otherwise be difficult (e.g., large crop fields). An integrated management strategy for controlling blackbird damage to crops will be superior to any single tool used in isolation (Dolbeer 1990), and combining auditory, visual, or chemical deterrent tools to a drone hazing regimen may increase effectiveness (Werrell et al. 2021, White 2021).

MANAGEMENT IMPLICATIONS

The performance of drones as avian deterrents will likely depend on a combination of factors including drone platform, drone size, drone trajectory, drone speed, number of platforms, duration of use, landscape context, season, and natural history of the pest species. Wildlife managers should weigh the monetary costs associated with drone flights against the benefits provided by reduced bird presence. We suggest that future research include assessments of stimuli that might enhance perceived risk posed by drones, including evaluations of salient on-board lighting (Blackwell et al. 2012, Doppler et al. 2015, Fernández-Juricic 2015, Goller et al. 2018), evaluation of multiple drones used in coordination (Wang et al. 2019), or negative stimuli (e.g., avian repellents or bioacoustics) integrated with drones (Ampatzidis et al. 2015, Chabot and Bird 2015). We also recommend that efficacy be assessed for multiple species in different contexts (e.g., day roosts, night roosts, and foraging areas) or other wildlife conflict scenarios (e.g., airports). Using drones as wildlife-hazing tools is a novel concept, but the rapidly evolving technology suggests a promising future for integrating these tools into global pest management (Klug et al. 2023).

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CONFLICTS OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

We adhered to relevant regulations and guidelines regarding the ethics of animal welfare. The United States Department of Agriculture, Animal Plant Health and Inspection Service, Wildlife Services, National Wildlife Research Center (QA-2731), North Dakota Game and Fish Department (Scientific Collection No. GNF04326470), and the North Dakota State University Animal Care and Use Committee (No. A17032) approved all procedures used in this study.

DATA AVAILABILITY STATEMENT

Data and R Code available upon request and will be publicly available within U.S. Forest Service's Research Data Archive: https://www.fs.usda.gov/rds/archive/catalog.

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SUPPORTING INFORMATION

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