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Note

Identification of Off Airport Interspecific Avian Hazards to Aircraft

TRAVIS L. DEVAULT,[1] *USDA, APHIS, Wildlife Services, National Wildlife Research Center, Ohio Field Station, 6100 Columbus Avenue, Sandusky, OH 44870, USA*

BRADLEY F. BLACKWELL, *USDA, APHIS, Wildlife Services, National Wildlife Research Center, Ohio Field Station, 6100 Columbus Avenue, Sandusky, OH 44870, USA*

THOMAS W. SEAMANS, *USDA, APHIS, Wildlife Services, National Wildlife Research Center, Ohio Field Station, 6100 Columbus Avenue, Sandusky, OH 44870, USA*

JERROLD L. BELANT, *Carnivore Ecology Laboratory, Forest and Wildlife Research Center, Mississippi State University, Box 9690, Mississippi State, MS 39762, USA*

ABSTRACT Understanding relative hazards of wildlife to aircraft is important for developing effective management programs that can minimize hazards from wildlife strikes. Although interspecific differences in hazard level of birds and mammals on airport properties are described, no studies have quantified hazard level of bird species or identified factors that influence hazard level when birds are struck beyond airport boundaries (e.g., during aircraft climb or approach). We used Federal Aviation Administration National Wildlife Strike Database records from 1990 through 31 May 2014 to identify bird species involved most often in collisions with aircraft beyond airport boundaries in the United States and to quantify the interspecific hazard level of those birds. We also investigated whether body mass, group size (single or multiple birds), region (Flyway), and season influenced the likelihood of aircraft damage and substantial damage when strikes occurred using binary logistic regression analysis. Canada geese (*Branta canadensis*; $n = 327$), turkey vultures (*Cathartes aura*; 217), American robins (*Turdus migratorius*; 119), and mallards (*Anas platyrhynchos*; 107) were struck most often by aircraft beyond airport boundaries. Waterbirds (cormorants, ducks, geese, and to a lesser extent, gulls) and raptors (including vultures) were most likely to cause damage or substantial damage to aircraft when strikes occurred. Body mass was an important predictor of hazard level; group size, region, and season had lesser effects on hazard level. Management strategies to reduce bird strikes with aircraft beyond airport properties should be active throughout the year and prioritize waterbirds and raptors. Published 2016. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS aviation hazard, bird strike, body mass, risk, wildlife–aircraft collision, wildlife hazard score, wildlife strike.

Wildlife collisions with aircraft (wildlife strikes) continue to pose substantial human safety concerns and cause extensive economic losses to the civil aviation industry. A recent summary of data from the United States indicated there were 11,315 wildlife strikes reported to the Federal Aviation Administration (FAA) National Wildlife Strike Database in 2013 under a voluntary reporting system, costing the civil aviation industry up to $937 million in direct and indirect losses (Dolbeer et al. 2014).

Although these economic losses and safety concerns remain serious, the overall number of wildlife strikes causing damage to aircraft has declined from a peak of 764 in 2000 to 601 in 2013, suggesting that management efforts to mitigate wildlife strikes have been effective (Dolbeer et al. 2014). However, this decline in damaging strikes is due primarily to wildlife management efforts conducted on airport properties (Dolbeer 2011), where historically about 74% of wildlife strikes occur (Dolbeer 2006). Although the number of damaging strikes occurring on airport properties ($\leq$152 m above ground level [AGL] as determined by the glide-slope of departing and arriving aircraft; Dolbeer 2006) has declined since 2000, the number of damaging strikes occurring beyond airport boundaries (>152 m AGL) has gradually increased during that time (Dolbeer et al. 2014). Further, in 2012 there were more reported damaging wildlife strikes to commercial aircraft beyond ($n = 141$) than within ($n = 118$) airport boundaries for the first time since the FAA National Wildlife Strike Database originated in 1990 (Dolbeer et al. 2014).

The continued increase in damaging wildlife strikes beyond airport boundaries can be attributed in part to limited mitigation methods for these high-altitude strikes. Although wildlife management techniques for use at airports are established (Cleary and Dolbeer 2005, Blackwell et al. 2009*a*, Belant and Martin 2011, DeVault et al. 2013, Belant and Ayers 2014), fewer management options for high-altitude

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[1]*E-mail: travis.l.devault@aphis.usda.gov*

strikes are available. Even so, several methods designed to reduce wildlife strikes with aircraft beyond airport boundaries are being developed or are already in use. These include Bird Avoidance Models and similar efforts to predict bird occurrence in 2- or 3-dimensional space (Lovell and Dolbeer 1999, DeVault et al. 2005, Van Belle et al. 2007, Avery et al. 2011, Walter et al. 2012), avian radar systems designed to detect and track birds out to 11 km from airport properties (FAA 2010, Beason et al. 2013, Gauthreaux and Schmidt 2013, Gerringer et al. 2016), and the development of onboard lighting systems intended to alert birds to the presence of oncoming aircraft and elicit earlier escape behaviors (Blackwell and Bernhardt 2004; Blackwell et al. 2009*b*, 2012; Blackwell and Fernández-Juricic 2013; Doppler et al. 2015).

The continued development of methods to reduce wildlife strikes with aircraft beyond airport boundaries would benefit from an improved understanding of the bird species involved most often in these high-altitude strikes and their hazard level (i.e., the likelihood of aircraft damage when strikes occur; Dolbeer et al. 2000). For example, management of food resources and preferred habitats in airport approach and departure corridors (where most off-airport strikes occur; Dolbeer 2006) could be facilitated by prioritizing species of concern (DeVault and Washburn 2013, Belant and Ayers 2014). Sensitivity settings of avian radar systems could be adjusted to more accurately track larger or smaller birds, although there is a tradeoff with increased extraneous signals (i.e., ground clutter) when sensitivity is high (Gerringer et al. 2016). Also, onboard aircraft lighting systems can be tuned to the visual systems of specific bird species to improve effectiveness (Blackwell et al. 2009*b*, 2012; Doppler et al. 2015).

Although several studies have investigated hazard level of birds and other wildlife to civil aircraft, these were conducted using data from all reported strikes (Dolbeer et al. 2000, Dolbeer and Wright 2009), or using only strikes that occurred within airport boundaries (DeVault et al. 2011). No studies have quantified interspecific hazard level of bird species when they are struck beyond the physical boundary of an airport (e.g., during aircraft climb or approach). Because of the increase in wildlife strikes reported to the FAA National Wildlife Strike Database in recent years (Dolbeer et al. 2014), sufficient data are now available to address interspecific wildlife hazards to aircraft, including only strikes that occurred >152 m AGL. Given the altitude of such strikes and phase of flight of the aircraft, we predicted that the birds involved in damaging strikes would be the larger, flocking species (DeVault et al. 2011). Our objective was to identify bird species involved most often in collisions with aircraft beyond airport boundaries in the United States and to quantify the interspecific hazard level of those birds. We also sought to elucidate factors that contributed to hazard level by assessing the effects of bird mass, flocking behavior (i.e., group size), region (Flyway), and season on the likelihood of aircraft damage and substantial damage when strikes occurred.

METHODS

We downloaded wildlife strike data from the FAA National Wildlife Strike Database (FAA 2014) on 16 October 2014, which included 146,029 strike records with incident dates from 1990 through 31 May 2014. We first removed records that met one or more of the following criteria: 1) altitude of aircraft at the time of strike was ≤152 m or unknown, 2) strikes with bats, 3) species involved in strike was unknown, 4) strikes for which damage level to aircraft was unknown, 5) strikes for which location (i.e., state) was unknown, and 6) strikes for which date was unknown. We then removed records for species with <20 strikes (DeVault et al. 2011). The resulting dataset used for analyses included 1,788 records from 29 species.

We used the database to calculate the percentage of total reported strikes for each species that resulted in any level of damage to the aircraft and substantial damage to the aircraft. Strikes incur damage when any repair or replacement of an aircraft component is required, whereas substantial damage occurs when aircraft are damaged to the point where structural strength, performance, or flight characteristics are adversely affected and require major repair or replacement (International Civil Aviation Organization 1989, Dolbeer et al. 2000). By definition, strikes resulting in substantial damage were included for calculation of any level of damage. We categorized each reported strike by region using 1 of 4 migratory flyways (Pacific, Central, Mississippi, or Atlantic; http://www.fws.gov/birds/management/flyways.php); we included the entire states of Montana, Wyoming, Colorado, and New Mexico in the Central Flyway. Lastly, we categorized each reported strike by season (spring: Mar–May, summer: Jun–Aug, fall: Sep–Nov, winter: Dec–Feb).

We used binary logistic regression to evaluate how bird body mass (from Dunning 2007 and averaged between sexes), group size involved in the strike (single or multiple birds; DeVault et al. 2011), region, and season influenced the probability of any level of damage or substantial damage. For each model set (damage or substantial damage), we evaluated all possible models using the 4 predictor variables and interactions region × season, group size × season, and body mass × group size using Akaike's Information Criterion (AIC; Burnham and Anderson 2002). We considered models equally parsimonious with ΔAIC <2. Statistical significance was set at $\alpha = 0.05$. We used SPSS version 23.0 (IBM Corporation 2014) for all statistical analyses.

RESULTS

Of the 29 species included in analyses (Table 1), 4 species were reported struck by aircraft >100 times: Canada goose (*Branta canadensis*; $n = 327$), turkey vulture (*Cathartes aura*; 217), American robin (*Turdus migratorius*; 119), and mallard (*Anas platyrhynchos*; 107). Species with the highest percentage of reported strikes causing damage to aircraft were double-crested cormorant (*Phalacrocorax auritus*; 87.0%), snow goose (*Chen caerulescens*; 84.5%), greater white-fronted goose (*Anser albifrons*; 84.0%), and bald eagle (*Haliaeetus leucocephalus*; 83.9%). Species with the highest percentage of reported strikes causing substantial damage to the aircraft were double-crested cormorant (52.2%), greater white-fronted goose (48.0%), snow goose (47.6%), and bald eagle (41.9%). Across species, 919 of 1,788 reported strikes

Table 1. Bird species involved in ≥20 total reported strikes with civil aircraft in the United States at altitudes >152 m above ground level (beyond airport boundaries) in spring (Mar–May), summer (Jun–Aug), fall (Sep–Nov), and winter (Dec–Feb). Species are sorted in descending order based on the percentage of strikes causing damage to the aircraft. Data are from the Federal Aviation Administration National Wildlife Strike Database and limited to strikes from 1 January 1990 through 31 May 2014.

	Strikes reported during:								
Species	Spring	Summer	Fall	Winter	Total strikes	% with damage[a]	% with substantial damage[a]	Body mass (g)	% of strikes with multiple birds
Double-crested cormorant	9	4	7	3	23	87.0	52.2	1,674	34.8
Snow goose	18	1	27	38	84	84.5	47.6	2,641	64.3
Greater white-fronted goose	1	0	9	15	25	84.0	48.0	2,530	68.0
Bald eagle	13	3	8	7	31	83.9	41.9	4,740	0.0
Black vulture	18	25	15	14	72	80.6	41.7	2,159	9.7
Turkey vulture	55	48	64	50	217	75.1	28.6	2,006	4.1
Canada goose	92	21	142	72	327	72.8	26.6	3,564	41.3
Mallard	30	4	33	40	107	68.2	32.7	1,171	41.1
American wigeon (*Anas americana*)	4	0	6	11	21	66.7	9.5	756	38.1
Red-tailed hawk	28	17	16	12	73	65.8	27.4	1,126	0.0
Herring gull (*Larus argentatus*)	5	4	7	4	20	65.0	30.0	1,085	5.0
Northern shoveler (*Anas clypeata*)	8	0	11	7	26	61.5	23.1	613	50.0
Northern pintail	4	1	18	50	73	56.2	20.5	947	49.3
Ring-billed gull (*Larus delawarensis*)	15	3	8	12	38	55.3	15.8	519	18.4
American coot (*Fulica americana*)	9	0	32	6	47	51.1	12.8	642	4.3
American crow (*Corvus brachyrhynchos*)	9	5	8	3	25	28.0	0.0	506	4.0
Mourning dove (*Zenaida macroura*)	12	13	28	5	58	22.4	1.7	118	12.1
American robin	36	3	75	5	119	19.3	0.0	79	11.8
Cedar waxwing (*Bombycilla cedrorum*)	10	3	6	3	22	18.2	0.0	32	27.3
Rock pigeon (*Columba livia*)	20	11	29	9	69	17.4	2.9	355	27.5
Killdeer (*Charadrius vociferus*)	5	7	5	4	21	9.5	4.8	97	9.5
Swainson's thrush (*Catharus ustulatus*)	23	0	23	0	46	6.5	2.2	30	13.0
Dark-eyed junco (*Junco hyemalis*)	3	0	17	0	20	5.0	5.0	20	10.0
Hermit thrush (*Catharus guttatus*)	10	0	11	0	21	4.8	0.0	30	0.0
Chimney swift (*Chaetura pelagica*)	11	18	16	0	45	4.4	0.0	24	6.7
European starling	25	15	40	10	90	4.4	0.0	86	24.4
Barn swallow (*Hirundo rustica*)	5	10	6	0	21	0.0	0.0	16	19.0
White-throated sparrow (*Zonotrichia albicollis*)	6	0	21	0	27	0.0	0.0	24	22.2
Yellow-rumped warbler (*Setophaga coronata*)	6	0	13	1	20	0.0	0.0	12	0.0
Totals	490	216	701	381	1,788				

[a] Damage occurs when any repair or replacement of an aircraft component is required; substantial damage occurs when aircraft are damaged to the point where structural strength, performance, or flight characteristics are adversely affected and require major repair or replacement.

(51.4%) caused damage and 358 reported strikes (20.0%) caused substantial damage.

Overall, 1,191 of 1,788 reported strikes (66.6%) occurred during spring and fall, potentially representing birds struck during migration (Table 1). This trend was especially evident with the 10 passerine species represented in our data, for which 353 of 411 strikes (85.9%) occurred during spring and fall. Comparatively, of the 19 non-passerine species, 838 of 1,377 strikes (60.9%) occurred during spring and fall. The percentage of reported strikes causing damage and substantial damage by season, respectively, was as follows: spring (51%, 19%), summer (45%, 21%), fall (47%, 15%), and winter (65%, 29%). By region, 378 strikes (56% causing damage, 21% causing substantial damage) were reported from the Pacific, 213 (56%, 22%) from the Central, 448 (50%, 22%) from the Mississippi, and 749 (49%, 18%) from the Atlantic Flyways.

The 2 competing logistic regression models predicting the probability of (any) damage to the aircraft when strikes occurred included bird mass, group size, region, and season, although bird mass had the greatest relative influence as indicated by Wald statistics (Table 2). Similarly, bird mass, group size, and season were included in the best model predicting substantial damage to aircraft, with bird mass again having the greatest effect. None of the interactions considered improved model fit in either model set. Probability of damage was less during fall than during other seasons. Probability of damage was greater in the Pacific Region, and more likely with flocks of birds and birds of greater body mass.

Based on predictions from our logistic regression models, the probability of damage to aircraft exceeded 40% when bird mass of the species involved reached approximately 700 g for strikes involving single birds, and 250 g for strikes involving multiple birds (Fig. 1). The probability of substantial damage exceeded 40% when bird mass of the species involved reached approximately 4,900 g for strikes involving single birds, and 2,900 g for strikes involving multiple birds.

DISCUSSION

Most species likely to be reported struck by aircraft beyond airport boundaries in the United States were also species likely to cause aircraft damage when struck. For example, of the 9 species with >70 total strikes, only strikes with American robins and European starlings (*Sturnus vulgaris*) resulted in aircraft damage in <20% of strikes (Table 1). The

Table 2. Binary logistic regression models predicting damage or substantial damage to aircraft caused by bird strikes with civil aircraft in the United States at altitudes >152 m above ground level (beyond airport boundaries). The models reported here were the best models for each model set (damage or substantial damage) as indicated by Akaike's Information Criterion (AIC) values and selected from all possible models using the predictor variables bird mass, group size (single or multiple birds), region (Pacific, Central, Mississippi, and Atlantic Flyways), and season (spring: Mar–May, summer: Jun–Aug, fall: Sep–Nov, winter: Dec–Feb), and the interactions region × season, group size × season, and body mass × group size. For the model set predicting aircraft damage, 2 competing models are shown because they had ΔAIC values <2; all other candidate models had ΔAIC values ≥5.29. All models presented were significant at $P < 0.001$ as evaluated by the model χ^2. Data are from the Federal Aviation Administration National Wildlife Strike Database from 1 January 1990 through 31 May 2014.

Model set	ΔAIC	Nagelkerke R^2	Parameter[a]	Coefficient	SE	Wald statistic	P
Damage	0	0.313	Intercept	−0.674	0.190	12.523	<0.001
			Bird mass	0.001	0.001	305.339	<0.001
			Group size (single)	−0.430	0.135	10.120	0.001
			Region (Pacific)	0.388	0.147	6.955	0.008
			Region (Central)	0.309	0.178	3.007	0.083
			Region (Mississippi)	−0.070	0.141	0.246	0.620
			Season (spring)	−0.184	0.161	1.311	0.252
			Season (summer)	−0.355	0.198	3.205	0.073
			Season (fall)	−0.341	0.150	5.180	0.023
Damage	0.023	0.310	Intercept	−0.906	0.158	32.912	<0.001
			Bird mass	0.001	0.001	318.041	<0.001
			Group size (single)	−0.463	0.132	12.257	<0.001
			Region (Pacific)	0.446	0.144	9.581	0.002
			Region (Central)	0.311	0.178	3.050	0.081
			Region (Mississippi)	−0.064	0.141	0.206	0.650
Substantial damage	0	0.168	Intercept	−1.374	0.173	62.783	<0.001
			Bird mass	0.001	0.001	109.234	<0.001
			Group size (single)	−0.817	0.136	35.819	<0.001
			Season (spring)	−0.274	0.172	2.539	0.111
			Season (summer)	0.027	0.215	0.016	0.901
			Season (fall)	−0.658	0.163	16.269	<0.001

[a] Reference categories include group size (multiple), region (Atlantic), and season (winter).

remaining 7 species in this group (Canada goose, turkey vulture, mallard, snow goose, red-tailed hawk [*Buteo jamaicensis*], black vulture [*Coragyps atratus*], and northern pintail [*Anas acuta*]) resulted in aircraft damage ≥55% of the time. We note that non-damaging strikes that occur beyond airport properties are more likely to go unreported than non-damaging strikes that occur on airports. For example, 22% of strike reports in the FAA National Wildlife Strike Database are carcass found strikes (i.e., they are based on bird carcasses found within 76.2 m of a runway centerline with no strike observed; Dolbeer et al. 2014). Even so, because damaging strikes are likely to be reported to the FAA (Dolbeer 2015), our analysis should be reliable in terms of the identification of species most likely to be involved in damaging strikes, and can inform research aimed at developing mitigation methods for reducing strikes that occur beyond airport properties.

We found evidence for an increased total number of off airport bird strikes during the spring and fall migratory seasons, though much of this increase was attributed to strikes with passerines, which generally are smaller and less hazardous than other taxa such as waterfowl and raptors (DeVault et al. 2011). Thus, the actual risk of experiencing a strike involving damage or substantial damage to the aircraft during migration is somewhat less than would be expected based on strike frequency alone. The relatively strong effect of damaging strikes in the Pacific Region could in part be explained by increases in populations of hazardous species (e.g., waterfowl; Olson 2015) in this region.

Like earlier studies investigating the hazard level of birds and other wildlife to aircraft (Dolbeer et al. 2000, DeVault et al. 2011, Schwarz et al. 2014), body mass was the most important factor influencing the likelihood of damage or substantial damage to aircraft when strikes occur (Figs. 1 and 2). From our models, hazard level for species ≥700 g could be considered extremely high (Dolbeer and Wright 2009). Based on the asymptotic nature of our models, aircraft damage is almost inevitable when birds >3,500 g are struck at altitudes >152 m. Group size (single or multiple birds), region, and season also appeared to influence hazard level, but the effect was less.

Bird strike reduction for aircraft operating at altitudes ≥152 m AGL (i.e., beyond the range of wildlife management efforts at airports) will likely rely on enhancing bird detection of approaching aircraft, assessment of the aircraft as a threat, and avoidance responses by birds (Bernhardt et al. 2010, Blackwell et al. 2012). Making aircraft more noticeable to bird species that pose the highest relative risk will involve, in part, an understanding of the physiological and cognitive processes involved in object detection and threat assessment, and how those capabilities translate to avoidance responses (Lima et al. 2015). For example, DeVault et al. (2014, 2015) reported that turkey vultures and brown-headed cowbirds (*Molothrus ater*) based escape behavior on the distance from them to an approaching vehicle, with little regard to the speed of the vehicle. Aircraft operating beyond airport properties travel in excess of 120 km/hr, speeds at which antipredator responses become ineffective under experimental conditions (DeVault et al. 2015). Assuming that decisions by birds to avoid an approaching aircraft are based on distance to the aircraft, enhancing the detection of the

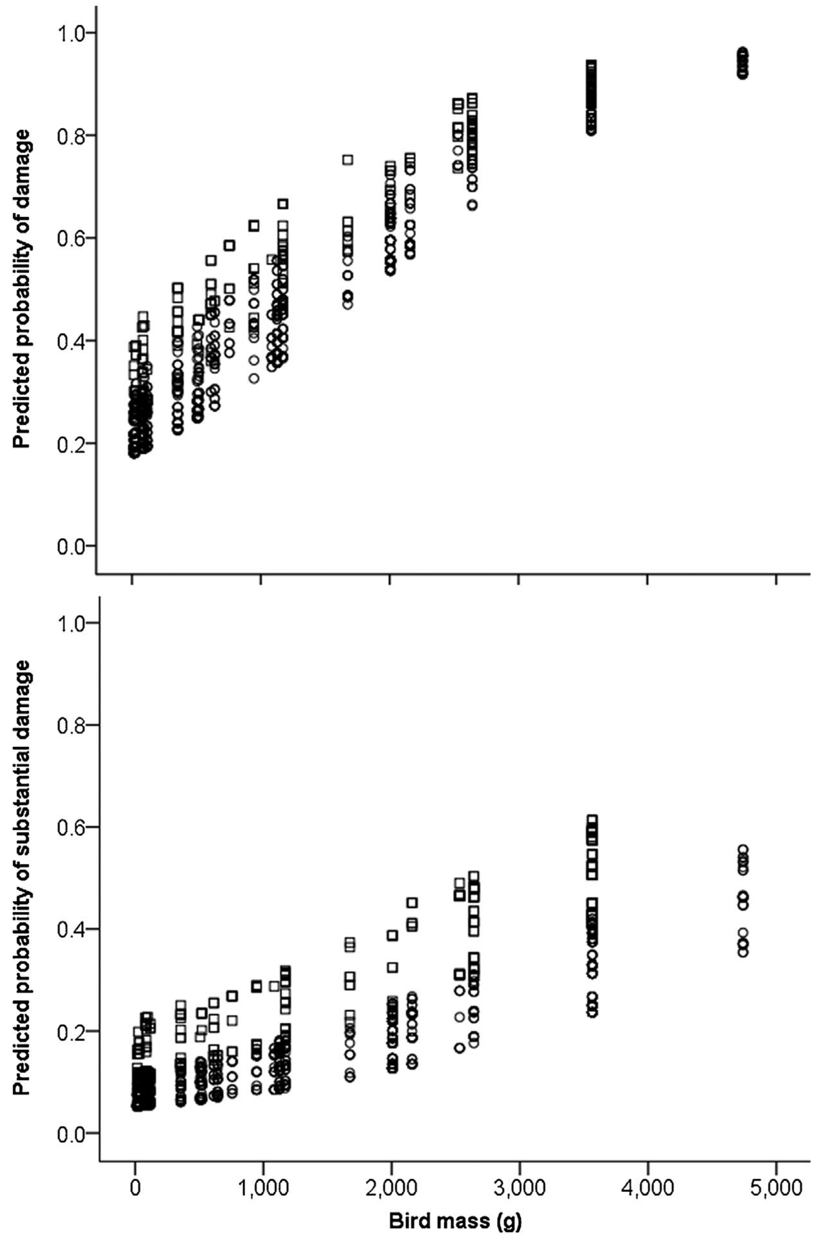

Figure 1. Logistic regression predictions for probability of damage (upper panel) or substantial damage (lower panel) to aircraft from bird strikes >152 m above ground level in the United States. In each panel, squares represent strikes when multiple birds were involved; circles represent strikes with single birds. Data are from the Federal Aviation Administration National Wildlife Strike database. Each point ($n = 1{,}788$) represents a strike involving a species with ≥20 strikes at altitudes >152 m above ground level and occurring from 1 January 1990 through 31 May 2014.

aircraft via visually salient stimuli could enable earlier avoidance responses. This approach necessitates knowledge of avian visual capabilities combined with assessments of antipredator behaviors in response to vehicle approach to assess how potential modifications to aircraft (e.g., via paint schemes or use of onboard lighting; Blackwell et al. 2009*b*, 2012; Fernández-Juricic et al. 2011; Doppler et al. 2015) might yield effective avoidance responses for species likely to be involved in damaging strikes.

We stress that prioritization for management of wildlife strikes with aircraft should not be based only on interspecific hazard level (i.e., the probability of damage or significant damage when strikes occur); frequency of occurrence should also be considered. For example, although double-crested cormorants scored the highest in terms of hazard level in our analyses (for both damage and substantial damage), that does not mean that management of cormorants should be prioritized over management of Canada geese. Canada geese were involved in >14× more strikes than cormorants, and, although not scoring as high as cormorants in our analyses, are extremely hazardous. Management priorities should be based on relative risk, which includes both hazard level or some metric of cost (Anderson et al. 2015), likelihood of a strike with a particular species, and a measure of the relative frequency of the species (e.g., a seasonal density estimate) within the context of the altitude

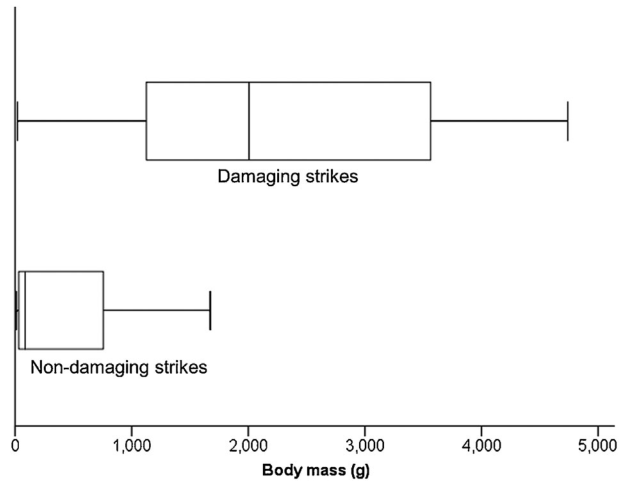

Figure 2. Frequency distribution of body masses for birds involved in damaging and non-damaging strikes with aircraft. Boxes outline the midrange (25–75 percentiles), medians are indicated by the vertical lines within boxes, and whiskers mark 10th and 90th percentiles. Data are from the Federal Aviation Administration National Wildlife Strike Database from bird species that incurred ≥20 total strikes with aircraft at altitudes >152 m above ground level from 1 January 1990 through 31 May 2014 ($n = 1{,}788$).

distribution and geographic region of the strike (Soldatini et al. 2010, 2011; Blackwell et al. 2013).

MANAGEMENT IMPLICATIONS

Waterbirds (e.g., cormorants, geese, ducks, gulls) and raptors (including vultures) should be prioritized during research and development of mitigation strategies to reduce bird strikes with aircraft beyond airport properties. In particular, the use of aircraft lighting to increase bird detection of oncoming aircraft (Blackwell et al. 2012, Doppler et al. 2015) and working with landowners beyond airport properties to reduce attractiveness to hazardous species (Martin et al. 2011) can be implemented to mitigate risk. Though damaging strikes varied seasonally, they occurred throughout the year. Thus, these mitigation strategies need to be available and implemented year-round, particularly within the Pacific Region of the United States.

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