*Human–Wildlife Interactions* 14(3):345–357, Winter 2020 • digitalcommons.usu.edu/hwi

# Population increases of large birds in North America pose challenges for aviation safety

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***Abstract:*** There is a strong correlation between bird mass and the likelihood of aircraft damage during a bird–aircraft collision. Thus, the U.S. Federal Aviation Administration (FAA) has established airworthiness standards related to bird mass for engines, airframes, and windshields. Most standards use large (1.8 kg) and medium (1.1 kg) birds as benchmarks (the empennage and certain large turbofan engines use a 3.6-kg bird). There are 20 large (≥1.8 kg) and 16 medium (1.1–1.7 kg) bird species in North America with ≥20 strikes reported for civil aircraft (FAA National Wildlife Strike Database), 1990 to 2018. I analyzed the population changes of these 36 species from 1990 to 2018 in relation to flocking behavior. For the 20 large species, the combined population had a net gain of 27.8 million birds (129% increase). For the 16 medium species, the combined population had a net gain of 6.7 million birds (20% increase). Notably, all 9 species with body mass ≥3.6 kg indicated population increases. In agreement with the increased numbers of birds, the number of strikes involving large and medium birds showed significant ($P < 0.01$) positive trends from 1990 to 2020 as did strikes involving multiple birds. The threat to aviation safety from large and medium birds, especially flocking species, was much higher in 2018 than in 1990. Although progress is being made to mitigate the risk by management programs to keep large and medium birds away from airport properties, these actions do little to mitigate the threat during climb and approach phases of flight. Enhanced airworthiness standards for aircraft components, bird-detecting radar to provide real-time warnings, and aircraft lighting schemes to improve visibility of aircraft to birds are priority areas of research and development to mitigate these off-airport threats to aviation safety.

***Key words:*** aircraft, airport, airworthiness standards, bird mass, bird strike, damage, flocking

About 72% of bird strikes to civil aircraft occur at ≤152 m above ground level during takeoff and landing (Dolbeer et al. 2019). Thus, implementation of integrated management programs to reduce populations of birds hazardous to aircraft in airport environments is essential to minimize bird strikes (Cleary and Dolbeer 2005, DeVault et al. 2013). However, given the diversity and mobility of avian species, programs to manage birds at airports will never exclude all hazardous birds from aircraft movement areas and will do nothing to prevent strikes outside the airport environment. Because there is a strong correlation between bird mass and the likelihood of aircraft damage during a bird–aircraft collision (Dolbeer et al. 2000, DeVault et al. 2011), a second critical component to reduce the risk and economic cost of bird strikes is the development of airworthiness standards for airframes, windshields, and engines, including shielding of important aircraft systems, that ensure aircraft can operate safely in the event of a bird strike. A third component involves the restriction of airspeeds to 250 knots (129 m/second) below 3,048 m (Code of Federal Regulations 2013).

The U.S. Federal Aviation Administration (FAA) has developed airworthiness standards for airframes and windshields of transport aircraft (>19 passenger seats) using a single 1.8-kg bird as the maximum mass that must be tested (with the exception of a 3.6-kg bird for the empennage). Standards for commuter aircraft (10–19 seats) are less stringent (FAA 2001). The bird mass required for turbine-engine testing varies by engine size but generally involves 1–3 birds with masses of 1.1 kg (medium bird test) and a single 1.8 or 3.6-kg bird (large bird test; Croft 2011, 14 CFR Part 33-77). For the large bird test, the engine does not have to keep operating after the ingestion to pass these standards; rather, the engine must contain the damage, not catch fire, and be capable of shut-down. MacKinnon et al. (2001) provide a more detailed discussion of airworthiness standards related to bird strikes.

The forced landing of U.S. Airways flight 1549 in the Hudson River in January 2009 after Canada geese (*Branta canadensis*; mean body mass >3.6

**Figure 1.** On January 15, 2009, U.S. Airways Flight 1549 (Airbus 320), with 155 persons aboard, made a forced landing in the Hudson River after ingesting Canada geese (*Branta canadensis*; mean mass >3.8 kg) into both engines. The strike occurred at about 870 m above ground level and 8 km from La-Guardia Airport, New York, USA, where the aircraft had just departed. This incident highlights the risk to aviation posed by large, flocking species of birds, especially at altitude outside the airport boundaries where traditional wildlife management techniques are not effective. Most turbofan engines are not certified to withstand the impact of birds with a mass >1.8 kg and none are certified for birds >3.6 kg (*photo courtesy of S. Day, Associated Press*).

kg) were ingested in both engines on an Airbus 320 (Marra et al. 2009, National Transportation Safety Board 2010; Figure 1) motivated the aviation industry to review engine certification standards related to birds. In March 2013, the FAA tasked the Aviation Rulemaking Advisory Committee (ARAC) to review the standards and advisory material for bird ingestion requirements of turbofan engines used on commercial aircraft. The ARAC recommended changes to testing regarding medium (1.1 kg) birds but left unchanged the tests for large (1.8 kg or 3.6 kg) birds (ARAC 2015).

In a broader context, the need for this review of engine standards was related to the fact that populations of many large bird species had increased in North America since the 1970s when government regulations and programs by public and private organizations were implemented for environmental protection (e.g., pesticide regulation, expansion of wildlife refuge systems, wetlands restoration). Dolbeer and Eschenfelder (2003) determined that populations of most of the bird species in North America with mean body masses ≥1.8 kg (large birds) had increased from the 1970s to about 2000. My objective is to update and expand this analysis on population trends for large species as well as for species with mean body masses from 1.1–1.7 kg (medium birds) that have been struck by civil aircraft from 1990 to 2018. The year 1990 was the initial year of data in the FAA National Wildlife Strike Database (NWSD; Dolbeer et al. 2019). The goal is to provide objective data on the population numbers, population trends, and flocking characteristics for these large and medium bird species as well as trends in the number of strikes and strikes involving multiple (≥2) birds, 1990–2018. This information will assist the FAA, ARAC, military aviation branches, and airport biologists in setting priorities for management actions and new technologies to mitigate the costs and risks of bird strikes.

## Methods

I determined from the NWSD (Dolbeer et al. 2019) the number of strikes, number of strikes causing damage, and number of strikes involving ≥2 birds for all bird species in North America with ≥20 strikes from 1990 to 2018 and with a mean body mass of ≥1.1 kg for at least 1 gender, or if data were unavailable by gender, a mean body mass ≥1.1 kg for unknown gender (Dunning 2008). For all analyses, I separated the species into 2 groups to correspond with the standards for bird ingestions into engines: large birds (≥1.8 kg) and medium birds (1.1–1.7 kg).

For waterfowl species (ducks and geese [Anatidae]), sandhill cranes (*Grus canadensis*), and wood storks (*Mycteria americana*), the mean population estimate for 1989 to 1991 and 2016 to 2018 was used for 1990 and 2018, respectively (U.S. Fish and Wildlife Service reports; see Appendix A). For other species, population data were obtained for various years from various sources (e.g., U.S. Fish and Wildlife Service reports, the Partners-in-Flight and North America Waterbird Conservation Plan population databases; Appendix A) and projected back to 1990 and forward to 2018 based on index and trend data from the North American Breeding Bird Survey (Sauer 2017). Population estimates were rounded to nearest 1,000.

To calculate the net change in the total population for a species from 1990 to 2018, I subtracted the estimated population in 1990 from the estimated population in 2018. I then divided the net change from 1990 to 2018 by the 1990 population estimate to calculate the percent change in the population, 1990 to 2018. Species with changes of greater than +10%, -10% to +10%, and less than

**Table 1.** Strike statistics for the 20 large bird species (mean body masses ≥1.8 kg) that have been struck by civil aircraft ≥20 times in North America, 1990 to 2018. Species are ranked by number of damaging strikes. See Appendix A for scientific names of species.

| | | | Strikes with civil aircraft (1990–2018) | | | |
|---|---|---|---|---|---|---|
| Damage rank | Species | Body mass (kg)[a] | Total | % with damage | % with ≥2 birds | Flocking behavior[b] |
| 1 | Canada goose | 4.18 | 1,775 | 48.8 | 40.8 | Strong |
| 2 | Turkey vulture | 2.00 | 817 | 50.1 | 5.4 | Limited |
| 3 | Black vulture | 2.16 | 213 | 62.0 | 6.1 | Limited |
| 4 | Snow goose | 2.74 | 173 | 72.8 | 53.2 | Strong |
| 5 | Bald eagle | 5.35 | 289 | 36.7 | 5.9 | Limited |
| 6 | Great blue heron | 2.48 | 463 | 18.8 | 1.7 | Limited |
| 7 | Sandhill crane | 4.80 | 158 | 38.6 | 27.8 | Strong |
| 8 | Double-crested cormorant | 2.09 | 166 | 32.5 | 15.7 | Intermediate |
| 9 | Greater white-fronted goose | 3.00 | 71 | 66.2 | 56.3 | Strong |
| 10 | Brown pelican | 3.70 | 76 | 42.1 | 11.8 | Intermediate |
| 11 | Wild turkey | 7.80 | 84 | 29.8 | 16.7 | Intermediate |
| 12 | Snowy owl | 2.28 | 309 | 7.8 | 0.6 | Solitary |
| 13 | Common loon | 5.46 | 42 | 54.8 | 0.0 | Solitary |
| 14 | Tundra swan | 7.20 | 23 | 73.9 | 52.2 | Strong |
| 15 | American white pelican | 6.33 | 23 | 65.2 | 39.1 | Strong |
| 16 | Greater black-backed gull | 1.83 | 128 | 9.4 | 8.6 | Limited |
| 17 | Greater sage-grouse | 3.19 | 41 | 29.3 | 36.6 | Strong |
| 18 | Wood stork | 2.70 | 21 | 28.6 | 19.0 | Intermediate |
| 19 | Golden eagle | 4.63 | 25 | 24.0 | 4.0 | Limited |
| 20 | Glaucous gull | 1.86 | 40 | 10.0 | 12.5 | Intermediate |
| Totals | | | 4,937 | 41.8 | 22.1 | |

[a]Mean body mass of heavier gender, or if gender unknown, mean body mass of all birds in sample (Dunning 2008).
[b]Based on % of strikes in which multiple birds were struck by aircraft (Strong = ≥20%; Intermediate = 10–19%; Limited = 1–9%; Solitary = <1%).

-10% were classified as increasing, unchanged, or decreasing, respectively.

I objectively classified the flocking behavior of each species using data on the percentage of strikes involving multiple (≥2 birds) from 1990 to 2018: ≥20% = strong flocking; 10–19% = intermediate flocking; 1–9% = limited flocking; and <1% = solitary. I also provided a summary of strike data for species with body masses ≥1.1 kg struck <20 times by civil aircraft in North America from 1990 to 2018.

I examined trends in reported strikes with large and medium bird species for 1990 to 2018 by linear regression analysis (Steele and Torrie 1960). I also examined trends in strikes involving multiple birds.

## Results

### Number of large and medium species and flocking behavior

There were 20 large species with ≥20 strikes, 1990 to 2018 (Table 1; Appendix A). These 20

**Table 2.** Strike statistics for the 16 medium bird species (mean body masses 1.1–1.7 kg) that have been struck by civil aircraft ≥20 times in North America, 1990 to 2018. Species are ranked by number of damaging strikes. See Appendix A for scientific names of species.

| | | | Strikes with civil aircraft (1990–2018) | | | |
|---|---|---|---|---|---|---|
| Damage rank | Species | Body mass (kg)[a] | Total | % with damage | % with ≥2 birds | Flocking behavior[b] |
| 1 | Red-tailed hawk | 1.22 | 2,944 | 13.7 | 2.3 | Limited |
| 2 | Mallard | 1.25 | 1,063 | 20.3 | 22.5 | Strong |
| 3 | Herring gull | 1.15 | 1,442 | 9.0 | 10.3 | Intermediate |
| 4 | Osprey | 1.57 | 427 | 23.2 | 1.4 | Limited |
| 5 | Great horned owl | 1.56 | 299 | 13.0 | 0.7 | Solitary |
| 6 | Glaucous-winged gull | 1.18 | 138 | 18.8 | 12.3 | Intermediate |
| 7 | Swainson's hawk | 1.11 | 175 | 13.1 | 2.9 | Limited |
| 8 | Anhinga | 1.23 | 45 | 48.9 | 13.3 | Intermediate |
| 9 | Ring-necked pheasant | 1.32 | 95 | 18.9 | 6.3 | Limited |
| 10 | Western gull | 1.13 | 157 | 11.5 | 7.6 | Limited |
| 11 | Brant | 1.37 | 51 | 31.4 | 29.4 | Strong |
| 12 | Western grebe | 1.43 | 48 | 31.3 | 20.8 | Strong |
| 13 | Canvasback | 1.25 | 27 | 51.9 | 33.3 | Strong |
| 14 | American black duck | 1.40 | 69 | 11.6 | 27.5 | Strong |
| 15 | Crested caracara | 1.22 | 23 | 26.1 | 4.3 | Limited |
| 16 | Ferruginous hawk | 1.78 | 44 | 11.4 | 0.0 | Solitary |
| Totals | | | 7,047 | 15.0 | 8.0 | |

[a]Mean body mass of heavier gender, or if gender unknown, mean body mass of all birds in sample (Dunning 2008).
[b]Based on % of strikes in which multiple birds were struck by aircraft (Strong = ≥20%; Intermediate = 10–19%; Limited = 1–9%; Solitary = <1%).

**Table 3.** Estimated change in North American population from 1990 to 2018 for 36 bird species with mean body masses ≥1.1 kg that have been struck by civil aircraft ≥20 times in North America, 1990 to 2018 (see Tables 1, 2, 5 and 6 for data on individual species).

| | | Estimated population[a] | | Population change[b] | |
|---|---|---|---|---|---|
| Bird mass | Number of species | 1990 | 2018 | Net | Percent |
| Large (≥1.8 kg) | 20 | 21,621,000 | 49,448,000 | 27,827,000 | 129 |
| Medium (1.1–1.7 kg) | 16 | 33,796,000 | 40,508,000 | 6,712,000 | 20 |
| Total | 36 | 55,417,000 | 89,956,000 | 34,539,000 | 62 |

[a]See Appendix A for sources of population estimates and trend data.
[b]Percent change = 100 * Net population change/population estimate for 1990.

species had 4,937 strikes reported, of which 42% caused damage and 22% involved multiple birds. Flocking behavior was strong, intermediate, limited, and solitary for 7, 5, 6, and 2 of the 20 large species, respectively (Table 1).

There were 16 medium species with ≥20 strikes from 1990 to 2018 (Table 2; Appendix A). These 16 species had 7,047 strikes reported, of which 15% caused damage and 8% involved multiple birds. Flocking behavior was strong, intermediate, limited, and solitary for 5, 3, 6, and 2 of the 16 medium species, respectively (Table 2).

There were 15 large (≥1.8 kg) and 17 medium (1.1–1.7 kg) species that were struck <20 times by

**Table 4.** Net change in estimated population by flocking behavior for 36 species of birds in North America with mean body masses ≥1.1 kg and at least 20 strikes with civil aircraft, 1990 to 2018 (see Tables 1, 2, 5 and 6 for data on individual species).

| | Net change in population (1990–2018) | | | | |
|---|---|---|---|---|---|
| | Flocking behavior[a] | | | | |
| Body mass (kg) | Strong | Intermediate | Limited | Solitary | Total |
| 1.1–1.7 | 5,029,000 | -249,000 | 1,918,000 | 14,000 | 6,712,000 |
| ≥1.8 | 16,260,000 | 3,560,000 | 7,857,000 | 150,000 | 27,827,000 |
| Total | 21,289,000 | 3,311,000 | 9,775,000 | 164,000 | 34,539,000 |

[a]Based on percent of strikes in which multiple birds were struck by aircraft (Strong = ≥20%; Intermediate = 10–19%; Limited = 1–9%; Solitary = <1%).

**Table 5.** Estimated change in North American population from 1990 to 2018 for 20 large bird species (mean body masses ≥1.8 kg) that have been struck by civil aircraft ≥20 times in North America, 1990 to 2018. Species are listed in descending order by net population change.

| | Estimated population[a] | | Population change[b] | |
|---|---|---|---|---|
| Species | 1990 | 2018 | Net | Percent |
| Snow goose | 4,270,000 | 15,120,000 | 10,850,000 | 254 |
| Turkey vulture | 4,807,000 | 10,469,000 | 5,662,000 | 118 |
| Canada goose[c] | 3,112,000 | 7,499,000 | 4,387,000 | 141 |
| Wild turkey[c] | 3,900,000 | 6,200,000 | 2,300,000 | 59 |
| Black vulture | 616,000 | 2,756,000 | 2,140,000 | 347 |
| Double-crested cormorant | 460,000 | 2,259,000 | 1,799,000 | 391 |
| Greater white-fronted goose | 1,023,000 | 1,587,000 | 564,000 | 55 |
| American white pelican[c] | 53,000 | 567,000 | 514,000 | 969 |
| Brown pelican[c] | 107,000 | 423,000 | 316,000 | 296 |
| Bald eagle[c] | 35,000 | 230,000 | 195,000 | 556 |
| Common loon[c] | 548,000 | 698,000 | 150,000 | 27 |
| Sandhill crane[c] | 473,000 | 609,000 | 136,000 | 29 |
| Wood stork | 196,000 | 248,000 | 52,000 | 26 |
| Tundra swan[c] | 16,000 | 56,000 | 40,000 | 253 |
| Great blue heron | 74,000 | 96,000 | 22,000 | 30 |
| Golden eagle[c] | 57,000 | 64,000 | 7,000 | 12 |
| Snowy owl | 30,000 | 30,000 | 0 | 0 |
| Greater black-backed gull | 252,000 | 83,000 | -169,000 | -67 |
| Greater sage-grouse | 652,000 | 409,000 | -243,000 | -57 |
| Glaucous gull | 940,000 | 45,000 | -895,000 | -95 |
| Total | 21,621,000 | 49,448,000 | 27,827,000 | 129 |

[a]See Appendix A for sources of population estimates and trend data.
[b]Percent change = 100 * Net population change/population estimate for 1990.
[c]Species with body masses >3.6 kg (Table 1).

civil aircraft in North America from 1990 to 2018 (Appendix B). These 32 species had 195 strikes reported (1.6% of the 11,984 strikes reported for the 36 species with ≥20 strikes), of which 34% caused damage and 14% involved multiple birds.

## Population changes

From 1990 to 2018, 26 of the 36 species with mean body masses ≥1.1 kg indicated population increases, 5 indicated declines, and 5 had no change (Table 3). The combined population

**Table 6.** Estimated change in North American population from 1990 to 2018 for 16 medium bird species (mean body masses 1.1–1.7 kg) that have been struck by civil aircraft ≥20 times in North America, 1990 to 2018. Species are listed in descending order by net population change.

| | Estimated population[a] | | Population change[b] | |
|---|---|---|---|---|
| Species | 1990 | 2018 | Net | Percent |
| Mallard | 6,689,000 | 11,598,000 | 4,909,000 | 73 |
| Red-tailed hawk | 1,960,000 | 3,065,000 | 1,105,000 | 56 |
| Osprey | 194,000 | 547,000 | 353,000 | 183 |
| Swainson's hawk | 646,000 | 861,000 | 215,000 | 33 |
| Canvasback | 503,000 | 718,000 | 215,000 | 43 |
| Crested caracara | 28,000 | 163,000 | 135,000 | 485 |
| Ring-necked pheasant | 17,397,000 | 17,499,000 | 102,000 | 1 |
| Western grebe | 101,000 | 137,000 | 36,000 | 36 |
| Anhinga | 21,000 | 54,000 | 33,000 | 150 |
| Ferruginous hawk | 89,000 | 117,000 | 28,000 | 32 |
| Brant | 280,000 | 303,000 | 23,000 | 8 |
| Western gull | 84,000 | 92,000 | 8,000 | 10 |
| Great horned owl | 4,011,000 | 3,997,000 | -14,000 | 0 |
| Glaucous-winged gull | 392,000 | 358,000 | -34,000 | -9 |
| American black duck | 970,000 | 816,000 | -154,000 | -16 |
| Herring gull | 431,000 | 183,000 | -248,000 | -58 |
| Total | 33,796,000 | 40,508,000 | 6,712,000 | 20 |

[a]See Appendix A for sources of population estimates and trend data.
[b]Percent change = 100 * Net population change/population estimate for 1990.

**Table 7.** Population status (increase, no change, decrease)[a] for 36 species of birds in North America with mean body masses ≥1.1 kg and at least 20 strikes with civil aircraft, 1990 to 2018 (see Tables 1, 2, 5, and 6 for data on individual species). Species are classified by flocking behavior.

| | 20 species ≥1.8 kg | | | 16 species 1.1–1.7 kg | | |
|---|---|---|---|---|---|---|
| Flocking behavior[b] | Increase | Decrease | No change | Increase | Decrease | No change |
| Strong | 6 | 1 | | 3 | 1 | 1 |
| Intermediate | 4 | 1 | | 1 | 1 | 1 |
| Limited | 5 | 1 | | 5 | | 1 |
| Solitary | 1 | | 1 | 1 | | 1 |
| Totals | 16 | 3 | 1 | 10 | 2 | 4 |

[a]Increase = Population change greater than +10%; No change = -10% to +10%; Decrease = less than -10%.
[b]Based on % of strikes in which multiple birds were struck by aircraft (Table 1; Strong = ≥20%; Intermediate = 10–19%; Limited = 1–9%; Solitary = <1%).

of these 36 species showed a net gain of 34.5 million birds (62% increase). Bird species with strong flocking behavior were responsible for 21.3 million (62%) of the net gain of 34.5 million birds (Table 4).

***Large species***. From 1990 to 2018, 16 of the 20 species indicated population increases, 3 indicated declines, and 1 had no change (Tables 5 and 7). The combined population of large species showed a net gain of 27.8 million birds (129% increase; Table 5). Snow geese (*Anser caerulescens*; 10.9 million), turkey vultures (*Cathartes aura*; 5.7 million), Canada geese (*Branta canadensis*; 4.4 million), wild turkeys

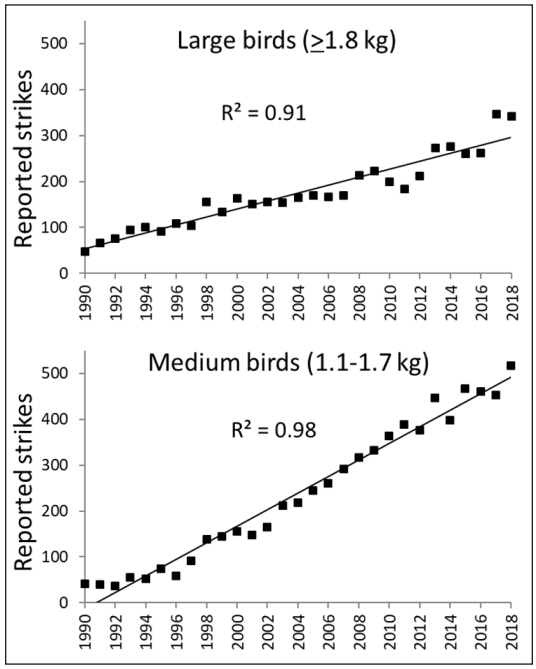


**Figure 2.** Trend in number of strikes in National Wildlife Strike Database involving large (≥1.8 kg; top graph) and medium (1.1–1.7 kg) bird species (bottom graph) in North America, 1990–2018. See Tables 1, 2, and Appendix B for total number of strikes by species. R2 values >0.33 indicate a significant trend (linear regression) at the 0.01 level of probability (Steele and Torrie 1960).

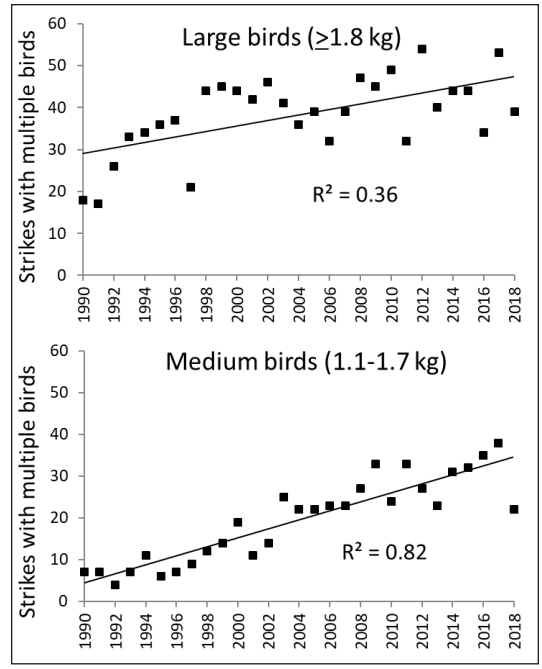


**Figure 3.** Trend in number of strikes in National Wildlife Strike Database involving large (≥1.8 kg; top graph) and medium (1.1–1.7 kg) bird species (bottom graph) in which multiple (≥2) birds were struck in North America, 1990–2018. See Tables 1, 2, and Appendix B for total number of strikes by species. R2 values >0.33 indicate a significant trend (linear regression) at the 0.01 level of probability (Steele and Torrie 1960).

(*Meleagris gallopavo,* 2.3 million), black vultures (*Coragyps atratus*; 2.1 million), and double-crested cormorants (*Phalacrocorax auratus*; 1.8 million) had the greatest increases. These 6 species accounted for 97% of the net population increase (Table 5). Notably, all 9 species with body mass ≥3.6 kg, including 7 with strong or intermediate flocking behavior, indicated population increases since 1990 (Table 5). The 7 large species with strong flocking behavior contributed 59% (16.3 million) of the 27.8 million net increase in large bird numbers (Tables 1 and 5).

***Medium species.*** From 1990 to 2018, 10 of the 16 species indicated population increases, 2 indicated declines, and 4 had no change (Tables 6 and 7). The combined population of medium species showed a net gain of 6.7 million birds (20% increase, Table 6). Mallards (*Anas platyrhynchos*; 4.9 million) and red-tailed hawks (*Buteo jamaicensis*; 1.1 million) contributed 90% of the net increase for medium birds. Three species with strong flocking behavior (mallard, canvasback [*Aythya valisineria*], and western grebe [*Aechmophorus occidentalis*]) contributed 75% of the net gain of 6.7 million birds in the population (Tables 2 and 6).

## Trends in reported strikes and strikes involving multiple birds

The number of strikes per year involving large and medium bird species showed significant ($P < 0.01$) positive trends from 1990 to 2020 (Figure 2). Strikes involving large species increased from <100 annually in the early 1990s to >300 during 2017–2018. Strikes involving medium species increased from about 50 annually in the early 1990s to >400 during 2017–2018. Strikes involving multiple birds also showed positive trends for large and medium bird species (Figure 3).

# Discussion

A meta-analysis by Rosenberg (2019) indicated that the overall bird population in North America had declined by 3 billion birds (29%) since 1970 with the decline primarily coming from small species such as grassland birds and neotropical migrants. In contrast to this overall

decline, my analysis indicates that populations of most large and medium (≥1.1 kg) bird species have increased, many substantially. Thus, the threat to aviation safety from large and medium bird species, especially flocking species, was much higher in 2018 than in 1990. In agreement with the increased numbers of large and medium bird species, the number of strikes involving large and medium bird species also increased from 1990 to 2020.

One area of particular concern is the increase in strikes involving multiple birds of these large and medium bird species from 1990 to 2018. Commercial air carriers have replaced their older 3- or 4-engine aircraft fleets with more efficient and quieter 2-engine aircraft. In 2017, only 4% of the 6,900 turbine-powered aircraft registered in the United States had 3 or 4 engines compared to 40% in 1990 (Aeroweb 2020, U.S. Department of Transportation 2020). In the event of a multiple ingestion event with large or medium flocking birds (e.g., the US Airways Flight 1549 incident on January 15, 2009), aircraft with 2 engines do not have the added redundancies of their 3- or 4-engine counterparts. In addition, previous research has indicated that birds are less able to detect and avoid modern jet aircraft with quieter turbofan engines (Chapter 3, International Civil Aviation Organization 1993) than older aircraft with noisier (Chapter 2) engines (Burger 1983, Kelly et al. 1999).

## Management implications

Although progress is being made to mitigate risks of bird strikes by management programs to keep large and medium birds away from airport properties (Dolbeer et al. 2014, Rutledge et al. 2015, Begier et al. 2019, Dolbeer et al. 2019, Washburn 2019), these actions do little to mitigate the threat during climb and approach phases of flight (Dolbeer 2011). Because wildlife management actions to mitigate these off-airport strikes are limited, enhanced airworthiness standards for aircraft engines and airframes, bird-detecting radar to provide real-time warnings of flocking bird activity (Gerringer et al. 2016, Nohara et al. 2011), and aircraft lighting schemes to enhance visibility of aircraft to birds (Blackwell et al. 2012, Dolbeer and Barnes 2017, Mandernach 2018, Dwyer et al. 2019) are priority areas of research and development to mitigate these threats to aviation safety.

## Acknowledgments

I thank S. Wright and P. Miller, U.S. Department of Agriculture (USDA), for their diligence in entering bird strike reports into the NWSD and for assistance with analysis of data. M. Begier (USDA) provided comments and advice, as did A. de Hoon (Ministry of Defense, the Netherlands). G. Linz, HWI associate editor, as well as 2 anonymous reviewers provided excellent guidance to improve the manuscript. I acknowledge the financial support of the FAA in maintaining the database. Findings expressed in this study do not necessarily reflect current FAA policy with regard to mitigating the risks of bird strikes.

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**Appendix A.** Scientific names and sources of information on population status for 36 species of birds in North America with a mean body mass ≥1.1 kg and ≥20 reported strikes with civil aircraft in North America, 1990 to 2018. Species are ranked by body mass.

| Body mass rank | Species common name | Species scientific name | Mean mass (kg)[a] | Source for most recent population estimate[b] | Source for population trend (1990–2018)[b] |
|---|---|---|---|---|---|
| 1 | Wild turkey | *Meleagris gallopavo* | 7.80 | NWTF 2020, PIF 2019 | NWTF 2020, Kobilinsky 2018 |
| 2 | Tundra swan | *Cygnus columbianus* | 7.20 | USFWS 2018 | USFWS 2018 |
| 3 | American white pelican | *Pelecanus erythrorhynchos* | 6.33 | Kushlan et al. 2002 | Sauer et al. 2017 |
| 4 | Common loon | *Gavia immer* | 5.46 | Evers 2004 | Sauer et al. 2017 |
| 5 | Bald eagle | *Haliaeetus leucocephalus* | 5.35 | PIF 2019 | Sauer et al. 2017 |
| 6 | Sandhill crane | *Grus canadensis* | 4.80 | Dubovsky 2018 | Dubovsky 2018 |
| 7 | Golden eagle | *Aquila chrysaetos* | 4.63 | PIF 2019 | Sauer et al. 2017 |
| 8 | Canada goose | *Branta canadensis* | 4.18 | USFWS 2018 | USFWS 2018 |
| 9 | Brown pelican | *Pelecanus occidentalis* | 3.70 | Kushlan et al. 2002 | Sauer et al. 2017 |
| 10 | Greater sage-grouse | *Centrocercus urophasianus* | 3.19 | PIF 2019 | Sauer et al. 2017 |
| 11 | Greater white-fronted goose | *Anser albifrons* | 3.00 | USFWS 2018 | USFWS 2018 |
| 12 | Snow goose | *Anser caerulescens* | 2.74 | USFWS 2018 | USFWS 2018 |
| 13 | Wood stork | *Mycteria americana* | 2.70 | USFWS 2015 | Sauer et al. 2017 |
| 14 | Great blue heron | *Ardea herodias* | 2.48 | Kushlan et al. 2002 | Sauer et al. 2017 |
| 15 | Snowy owl | *Bubo scandiacus* | 2.28 | PIF 2019 | Audubon CBC 2019 |
| 16 | Black vulture | *Coragyps atratus* | 2.16 | PIF 2019 | Sauer et al. 2017 |
| 17 | Double-crested cormorant | *Phalacrocorax auritus* | 2.09 | Kushlan et al. 2002 | Sauer et al. 2017 |
| 18 | Turkey vulture | *Cathartes aura* | 2.01 | PIF 2019 | Sauer et al. 2017 |
| 19 | Glaucous gull | *Larus hyperboreus* | 1.86 | Kushlan et al. 2002 | Audubon CBC 2019 |
| 20 | Great black-backed gull | *Larus marinus* | 1.83 | Kushlan et al. 2002 | Sauer et al. 2017 |
| 21 | Ferruginous hawk | *Buteo regalis* | 1.78 | PIF 2019 | Sauer et al. 2017 |
| 22 | Osprey | *Pandion haliaetus* | 1.57 | PIF 2019 | Sauer et al. 2017 |

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|---|---|---|---|---|---|
| 23 | Great horned owl | *Bubo virginianus* | 1.56 | PIF 2019 | Sauer et al. 2017 |
| 24 | Western grebe | *Aechmophorus occidentalis* | 1.43 | Kushlan et al. 2002 | Sauer et al. 2017 |
| 25 | American black duck | *Anas rubripes* | 1.40 | USFWS 2018 | Sauer et al. 2017 |
| 26 | Brant | *Branta bernicla* | 1.37 | USFWS 2018 | USFWS 2018 |
| 27 | Ring-necked pheasant | *Phasianus colchicus* | 1.32 | PIF 2019 | Sauer et al. 2017 |
| 28 | Canvasback | *Aythya valisineria* | 1.25 | USFWS 2018 | USFWS 2018 |
| 29 | Mallard | *Anas platyrhynchos* | 1.25 | USFWS 2018 | USFWS 2018 |
| 30 | Anhinga | *Anhinga anhinga* | 1.24 | Kushlan et al. 2002 | Sauer et al. 2017 |
| 31 | Red-tailed hawk | *Buteo jamaicensis* | 1.22 | PIF 2019 | Sauer et al. 2017 |
| 32 | Crested caracara | *Caracara cheriway* | 1.22 | PIF 2019 | Sauer et al. 2017 |
| 33 | Glaucous-winged gull | *Larus glaucescens* | 1.18 | Kushlan et al. 2002 | Sauer et al. 2017 |
| 34 | Herring gull | *Larus argentatus* | 1.15 | Kushlan et al. 2002 | Sauer et al. 2017 |
| 35 | Western gull | *Larus occidentalis* | 1.14 | Kushlan et al. 2002 | Sauer et al. 2017 |
| 36 | Swainson's hawk | *Buteo swainsoni* | 1.11 | PIF 2019 | Sauer et al. 2017 |

[a]Mean body mass of heavier gender, or if gender unknown, mean body mass of all birds in sample (Dunning 2008).
[b]Audubon CBC = Audubon Christmas Bird Count; NWTF = National Wild Turkey Federation; PIF = Partners in Flight; USFWS = U.S. Fish and Wildlife Service.

**Appendix B.** The 32 species of birds in the National Wildlife Strike Database for Civil Aviation with a mean body mass ≥1.1 kg and <20 reported strikesa with civil aircraft in North America, 1990 to 2018. Species are ranked by body mass.

| Body mass rank | Species common name | Species scientific name | Mean mass (kg)[b] | Total strikes | Strikes with damage | Strikes with ≥2 birds |
|---|---|---|---|---|---|---|
| 1 | Trumpeter swan | *Cygnus buccinator* | 11.90 | 2 | 2 | 1 |
| 2 | Mute swan[c] | *Cygnus olor* | 11.80 | 9 | 2 | 2 |
| 3 | Whooping crane[d] | *Grus americana* | 5.83 | 1 | 1 | 0 |
| 4 | Black-footed albatross | *Phoebastria nigripes* | 3.40 | 5 | 1 | 0 |
| 5 | Laysan albatross[e] | *Phoebastria immutabilis* | 3.30 | 37 | 8 | 1 |
| 6 | Great cormorant | *Phalacrocorax carbo* | 2.86 | 2 | 1 | 2 |
| 7 | Muscovy duck[c] | *Cairina moschata* | 2.68 | 4 | 1 | 0 |
| 8 | Brandt's cormorant | *Phalacrocorax penicillatus* | 2.37 | 1 | 1 | 0 |
| 9 | Emperor goose | *Anser canagica* | 2.22 | 2 | 1 | 0 |
| 10 | Common eider | *Somateria mollissima* | 2.18 | 4 | 2 | 1 |
| 11 | Cackling goose | *Branta hutchinsii* | 2.17 | 19 | 11 | 7 |
| 12 | Hawaiian goose | *Branta sandvicensis* | 2.07 | 2 | 1 | 1 |
| 13 | Pelagic cormorant | *Phalacrocorax pelagicus* | 1.92 | 2 | 0 | 0 |
| 14 | White-winged scoter | *Melanitta fusca* | 1.87 | 4 | 3 | 2 |

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|---|---|---|---|---|---|---|
| 15 | Egyptian goose[c] | *Alopochen aegyptiana* | 1.83 | 1 | 0 | 1 |
| 16 | Pacific loon | *Gavia pacifica* | 1.75 | 1 | 1 | 0 |
| 17 | Gyrfalcon | *Falco rusticolus* | 1.71 | 2 | 0 | 0 |
| 18 | Common merganser | *Mergus merganser* | 1.70 | 8 | 2 | 1 |
| 19 | Magnificent frigatebird | *Fregata magnificens* | 1.66 | 8 | 4 | 0 |
| 20 | Great frigatebird | *Fregata minor* | 1.49 | 13 | 4 | 0 |
| 21 | Roseate spoonbill | *Platalea ajaja* | 1.49 | 5 | 1 | 0 |
| 22 | Red-throated loon | *Gavia stellata* | 1.44 | 13 | 6 | 0 |
| 23 | Helmeted guineafowl[c] | *Numida meleagris* | 1.34 | 2 | 1 | 2 |
| 24 | Clark's grebe | *Aechmophorus clarkii* | 1.28 | 3 | 1 | 1 |
| 25 | Great gray owl | *Strix nebulosa* | 1.22 | 2 | 0 | 0 |
| 26 | Red-footed booby | *Sula sula* | 1.15 | 3 | 0 | 0 |
| 27 | Surf scoter | *Melanitta perspicillata* | 1.15 | 2 | 0 | 0 |
| 28 | Northern goshawk | *Accipiter gentilis* | 1.14 | 4 | 0 | 0 |
| 29 | Red-breasted merganser | *Mergus serrator* | 1.13 | 9 | 1 | 1 |
| 30 | Barrow's goldeneye | *Bucephala islandica* | 1.12 | 3 | 0 | 0 |
| 31 | Common goldeneye | *Bucephala clangula* | 1.12 | 8 | 2 | 0 |
| 32 | Redhead | *Aythya americana* | 1.11 | 14 | 8 | 5 |
| | Total | | | 195 | 66 | 28 |

[a]List does not include California condor (*Gymnogyps californianus*), which has no strikes reported. However, this species is worth noting because of its large mass (8.8 kg), soaring behavior, and the increase in the wild population from 0 in 1987 to 337 in 2019 (U.S. Fish and Wildlife Service 2019).
[b]Mean body mass of heavier gender, or if gender unknown, mean body mass of all birds in sample (Dunning 2008).
[c]Feral population of non-native species.
[d]Wild population increased from 159 in 1990 to 668 in 2018 (International Crane Foundation 2019).
[e]Laysan albatross was not included in main analysis (species with ≥20 strikes) because all strikes were reported from Henderson Field at Midway Atoll, where >70% of the world population of 1.6 million adult birds breed (Dolbeer et al. 1996, U.S. Fish and Wildlife Service 2017). The population was considered stable, 1992–2005 (BirdLife International 2018).