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ORIGINAL ARTICLE

Traffic in the sky: ranking the hazard bird species to aircraft-collision in Brazil

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Abstract
Birds pose a serious threat to aviation due to collisions, leading to both life and severe economic losses. To mitigate this problem and prevent further collisions, identifying the species with the highest aviation hazard should be the first step. Here we calculate a Relative Hazard Score (RHS) based on an extensive open-source database developed by CENIPA (Aircraft Accident Investigation and Prevention Center), which includes data on bird and mammal collisions between 2011 and 2022. We developed the ranking for (a) all vertebrate species, (b) all bird species, and (c) for bird families (including regional rankings); and for the second group, we investigated if there is a relationship between RHS, body mass, and group size. The black vulture (*Coragyps atratus*) appeared as the most dangerous animal for aviation, followed by dogs (including both domestic and wild), magnificent frigatebirds (*Fregata magnificens*), and unidentified vultures. According to our predictions, RHS presented a positive relation with body mass and group size. We reinforce the importance of this ranking for aerodrome management, which if added to more detailed information can be successfully used to decrease collisions. We appointed the most dangerous species in Brazil and, at the regional scale, to its biome, providing needed information to base actions to reach safer aviation in the country and similar regions.

Keywords Airport management · Brazil · Bird strikes · Neotropics relative hazard score

Introduction

Collisions between birds and aircrafts are an issue worldwide. They affect human safety (Dolbeer et al. 2000; DeVault et al. 2018), with 231 human lives lost between 1912 and 2002 (Thorpe 2003), and also bring economic costs of US$ 1.2 billion per year due to flight delays and cancellations (Allan 2000; El-Sayed 2019). Airport agents have taken several measures to make the airport environment less attractive to these species with the use of excluding measures such as fence building and land use management

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(Martin et al. 2011; Dolbeer 2013; El-Sayed 2019). However, more accurate knowledge about the species or species groups that can pose a risk to aircrafts is crucial to better understand the problem and to identify what actions can be implemented for safer aviation (Martin et al. 2011; Juračka et al. 2021).

Around the world, discussions on this subject had gained evidence in 1960, after an accident in the USA involving a Lockheed Electra. The aircraft, shortly after takeoff, collided with around 200 individuals of European starlings (*Sturnus vulgaris*), resulting in the loss of three out of four engines and crashing into a harbor. Sixty-two people died, and so far, this event is considered the most severe bird strike. These fatalities marked the dawn of wildlife management, leading to the creation of the Canada and Europe Bird Strike Committees in the 1960s (Dolbeer 2013). This started the compilation of collision data by researchers, which led to the first publications on the topic in the early 1970s (Brough 1971; Blockpoel 1976). In 1975, the International Civil Aviation Organization (ICAO) published the first edition of the first specific manual on the subject, called DOC 9137 – Bird Control and Reduction, which is now in its fifth edition (ICAO 2020). To guide more effective actions, rankings have been proposed to identify the hazardous species to aviation safety, some more focused in local characteristics (Allan 2006; Soldatini et al. 2010) and other with a broader range (Dolbeer et al. 2000; DeVault et al. 2011), which can serve as a basis for further analysis on both regional and local scales.

In Brazil, this topic is still in its infancy (Novaes 2022), despite it being one of the most biodiverse countries in the world with 1971 species of birds, 770 of mammals (Abreu et al. 2021; Pacheco et al. 2021), and a booming aviation market (the number of passengers tripled between 2000 and 2019; ANAC 2019). The Brazilian Air Force division called CENIPA (Aircraft Accident Investigation and Prevention Center) is the national agency responsible for investigating and preventing aeronautical accidents, and since 1987, it is responsible for organizing a database on fauna collisions, near collisions, and sightings from civil and military aviation reports, as required by the ICAO. However, only after the accident known worldwide as the “Miracle on the Hudson River” in 2009 (caused by Canada goose, *Branta canadensis*), the discussions about bird strike were boosted, resulting in the creation of an online reporting system approval on the Federal Law 12725 and managed by CENIPA. Following this, the National Civil Aviation Agency (ANAC) and CENIPA published in 2014 and 2017 regulatory documents about wildlife hazard management procedures at civil and military aerodromes, respectively (RBAC-164 2014; PCA 3–3 2017; MCA 3–8 2017).

Currently, Brazil has around 3040 public and private airfields approved by the federal agency, with an annual volume of air traffic of almost a million take-offs by year (ANAC 2022). However, only a low number of studies evaluated the relationship between environmental management with accidents and the use of techniques to be implemented in Brazilian airports, with a considerable knowledge gap to be filled (Novaes and Alvarez 2014; Santos et al. 2017; Mendonca et al. 2020; Medolago et al. 2021). It was only in 2022 that the first ranking for Relative Hazard Score was published (Novaes 2022) using data from 2011 to 2020 and being based on the Dolbeer et al. (2000) ranking. However, this ranking does not consider any regional aspects or species traits that could affect their risk to aviation.

Here we have gone one step further, not only updating the previous ranking (Novaes 2022) with a more recent database, but also deepening the analysis by creating regional rankings and investigating how functional bird traits affect their hazardousness. The use of functional traits can contribute not only to increasing knowledge about which groups of birds may pose the greatest risk to aviation, but also to allowing extrapolation to other parts of the world. In addition, regional classifications can be important for better outlining management measures, since Brazil is continental in size and its fauna communities can be dissimilar. Therefore, the goal of this paper was to analyze the national database of fauna reports to create both national and regional hazard rankings for Brazil and to provide information that can help in preventing aircraft collisions. Specifically, we propose a hazard level ranking for (i) all vertebrate species, (ii) bird species, and (iii) bird families. For the last group, we created a ranking for each flight phase and a regional ranking (for biome and aerodromes near the coast) to identify the most dangerous families in each flight moment and across the country, respectively, and allow more specific actions. Finally, we investigated if bird hazard is related to functional traits, more specifically to body mass and group size. We aim to contribute to a better understanding of this topic and to base future studies and wildlife management in Brazilian airports, resulting in safer aviation in the country.

Methods

All reports involving wildlife and aircraft in Brazil, from January 2011 to December 2022, were obtained through the Fauna Risk Management System (SIGRA -Sistema de Gerenciamento de Risco de Fauna, available at: http://sistema.cenipa.fab.mil.br/cenipa/sigra/pesquisa_dadosExt). Pilots and airport employees fill the platform through an online report containing data on collisions, near-collisions (when the crash is avoided by the aircraft deviation with no effect on the aircraft operation), and sightings (alive animals sighted near the aircraft trajectory with no need of deviation), species and the number of individuals, as well as information about the aircraft, airport, eventual damages, effect on flight, among others. The species identification is made by using technical material provided by the same institutions. We used the ICAO aerodrome code to add geographic coordinates to all reports and selected only collision reports inside the Airport Security Areas (ASAs, defined as the area inside a 20-km radius from the geometric center of largest aerodrome runway) in Brazilian aerodromes, once they represent collisions more prone to be avoided by the aerodrome management. From a total of 627 aerodrome codes in the database, we considered 404 (64%) in our study (Fig. 1). The 223 remaining were excluded because they are outside Brazilian boundaries, or the code was missing in the ICAO code database. All the ICAO aerodromes codes are presented in Supplementary Material A. We excluded collisions involving multiple species, due to it being unlikely to know which species is responsible for the possible damage. We also excluded records of species that were registered outside their known geographic distribution, since these records are probably misidentifications, and collisions of unidentified species. In Supplementary Material B, we showed the number of reports excluded by each one of the criteria.

We calculate the Relative Hazard Score (RHS) using total collision number and the number of collisions with damage, major damage, and effect on flight (Dolbeer et al. 2000; DeVault et al. 2011) for each species or species groups (families or orders) with collisions ≥ 20, following DeVault et al. (2011). We chose to follow this method since it has been widely used worldwide and can be performed by the database used. Other analyses (Allan 2006; Soldatini et al. 2010) require more refined or local information, which makes them unsuitable to our data. For the damage criteria,

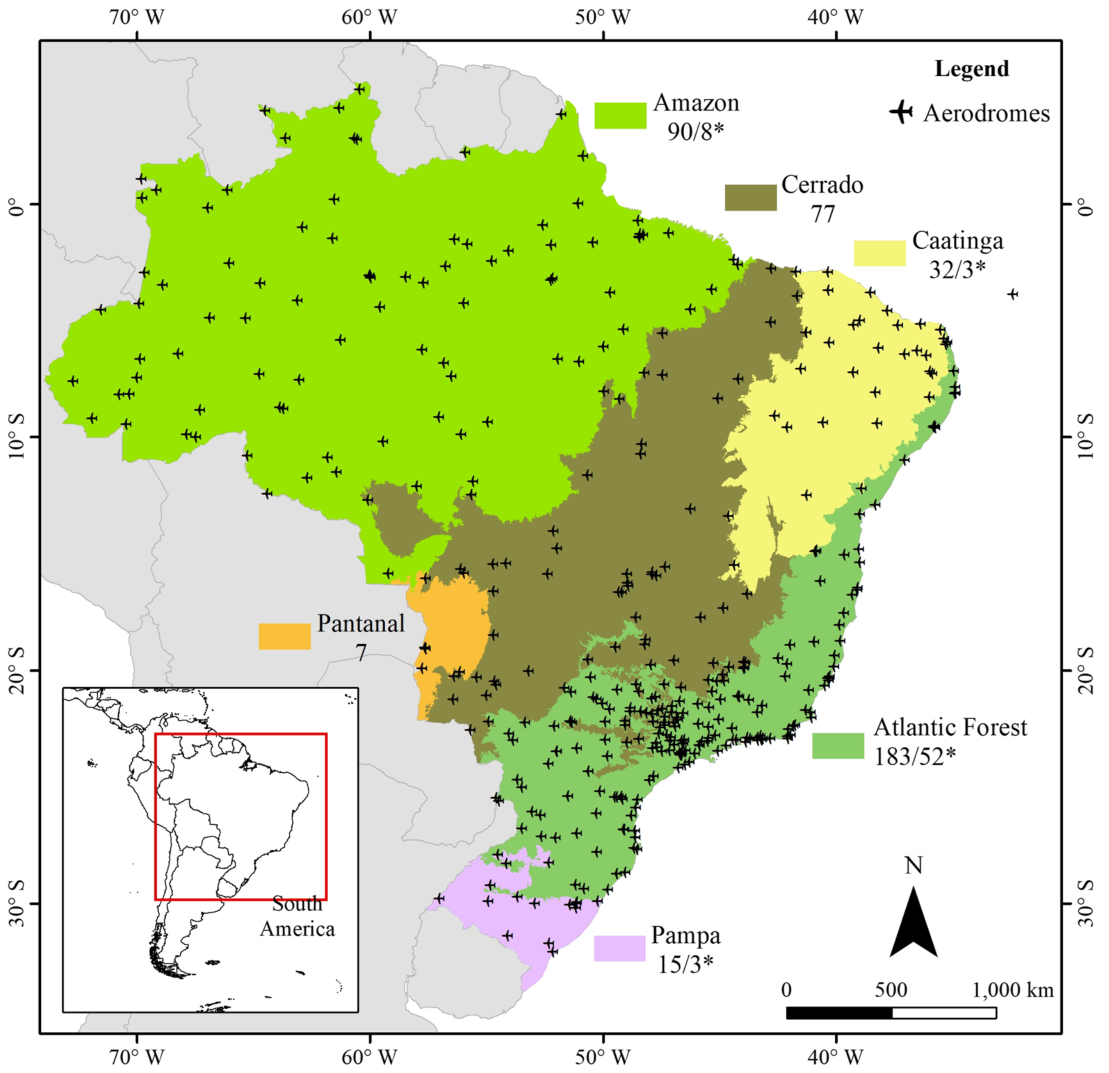

Fig. 1 Aerodrome's location in Brazil by biome. The number below the biome names represents the number of aerodromes inside their boundaries, and the asterisk shows the number of aerodromes in the biome near the coast (less than 10 km)

we considered those collisions in which the aircraft suffered any level of damage, such as materials and functional damage. Major damage was a subgroup of the former, when “the structural strength, performance or flight characteristics were affected, commonly requiring repair or replacement of the component” (DeVault et al. 2011; MCA 3–8 2017). Here we considered as major damage every report in which any of the following occurred: (i) aircraft unavailable for more than 24 h, event classified as “accident” or “severe incident” (i.e., when is impossible to maintain level flight, after cutting one of the aircraft’s engines; PCA 3–3 2020), or, (ii) when the windshield was damaged. To effect on flight, we considered collisions that affect the original flight profile (MCA 3–8 2017). We provide all the information about the categorization of damage, major damage, and effect on the flight in Supplementary Material C. For damages, major damage, and effect on flight, we calculated the percentage of collisions in each category compared with the total for each species/group. So, we add up the percentage values and consider the highest as RHS = 100, proportionally scaling down the remaining (Dolbeer et al. 2000; DeVault et al. 2011).

We calculated the RHS ranking for (i) all taxa reported (birds, mammals, and reptiles), considering the taxonomic level identified in the report. Accordingly, reports in which the animal was identified at the species level were not included in the family calculation index (e.g., Cathartidae family did not include birds identified to species levels, such as *Cathartes aura*); (ii) only for bird species, when the individual was identified at the species level; and (iii) for bird families (e.g., Cathartidae plus *Cathartes aura*, *Coragyps atratus*, and other species of the family). The third ranking was used because identifying family species that are hazardous for aviation can be enough to plan measures to increase safety, since species of the same family can share both behavioral and morphological traits. Also, there are misidentification issues in the database, and even excluding birds reported outside its geographic distribution, it is still possible that species were wrongly identified. As we considered most misidentification problems to involve birds from the same family (such as the four species of black vultures that live in Brazil), classification by family will present fewer taxonomic errors.

Bird family ranking was calculated for each one of the nine flight phases: climb, cruise, descent, approach, landing, RWY (runway) check, low-level navigation, turnaround check, and parking/taxi/take-off. We aggregated parking, taxi, and take-off in one category following CENIPA (2015), as in the three phases the airplane is on the ground. Creating this ranking could help in taking actions focused on the target species. In addition, as Brazil is continental in size and has different regions and fauna communities, we created six different rankings, spanning five Brazilian biomes (Atlantic Forest, Amazon, Caatinga, Cerrado, and Pampa) and the coastal region (i.e., including aerodromes within 10 km from the coast and which may receive migratory bird species) (Fig. 1). Pantanal was excluded due to the small number of collisions reported in this biome. It is worth mentioning that biome is the smallest spatial scale possible to the development of the ranking since the low number of samples in smaller scales (i.e., such as states or ecoregions) can jeopardize the analysis. For each flight phase and regional rankings category, we only considered taxa with at least 10 collisions.

Bird taxonomy followed the updated Brazilian bird’s checklist (Pacheco et al. 2021). Body mass followed Dunning (2007), since it is more reliable than the estimated body mass available in the reports. Group sizes were estimated by averaging the total number of individuals reported, which was checked by the authors. For the bird species ranking, we fitted the best model (linear or quadratic) to investigate the relationship between RHS against body mass and group size. We also plotted body mass against group size to have a visual distribution of both traits and their relationship with RSH. We did our analysis using the “tidyverse” package (Wickham et al. 2019) in R (R Core Team 2022).

Results

The database contained 25,447 collision reports caused by animals from a total of 80,262 reports. After the selection following our criteria, 12,605 reports were used in our analysis. The number of collisions with damages, major damage, and effect on the flight was 1400 (11.1%), 182 (1.44%), and 1012 (8.02%), respectively. The phases of flight with the highest reported collisions were RWY check ($n = 4103$, 32.55%), landing (3836, 30.43%), and parking/taxi/take-off (3321, 26.34%). It is worth mentioning that out of 25,128 collisions caused by only one species, 11,650 (46.36%) did not have the species identified.

Black vulture (*Coragyps atratus*) appeared as the most dangerous animal for aviation (RHS = 100; Table 1), followed by domestic dog (RHS = 99), a group formed by dog or wild dog (potentially crab-eating fox, *Cerdocyon thous*) (RHS = 82), magnificent frigatebird (*Fregata magnificens*, RHS = 72), and Cathartidae (unidentified vultures, RHS = 67). Considering only bird species, after the two already mentioned, the ranking was headed by red-legged seriema (*Cariama cristata*, RHS = 63), picui ground-dove (*Columbina picui*, RHS = 33), and turkey vulture (*Cathartes aura*, RHS = 27; Table 2). The species with the highest number of collisions was southern lapwing (*Vanellus chilensis*, $n = 4156$, 32.97% of the collisions), crested caracara (*Caracara plancus*, $n = 1550$, 12.29% of the collisions), and burrowing owl (*Athene cunicularia*, $n = 515$, 4.09% of the collisions).

Table 1 Relative Hazard Score (RHS) of the wildlife taxa to aircrafts in Brazil. The table also presents the number of collisions, damage, major damage, and effect on flight. Percentages are shown in parentheses and the color on the RHS column varies from white (0) to red (100)

Species/Family/Group	Collisions	Damage	Major damage	Effect on flight	Relative Hazard Score (RHS)
Coragyps atratus	423	213 (50%)	57 (13%)	178 (42%)	100
domestic dog	59	23 (39%)	1 (2%)	38 (64%)	99
domestic or wild dog	44	7 (16%)	2 (5%)	29 (66%)	82
Fregata magnificens	75	28 (37%)	7 (9%)	22 (29%)	72
Cathartidae	681	288 (42%)	48 (7%)	144 (21%)	67
Cariama cristata	27	4 (15%)	0 (0%)	14 (52%)	63
Columbina picui	20	3 (15%)	2 (10%)	2 (10%)	33
Accipitridae	120	25 (21%)	1 (1%)	13 (11%)	31
Laridae	42	11 (26%)	1 (2%)	2 (5%)	31
Cathartes aura	56	7 (13%)	2 (4%)	7 (13%)	27
Ardeidae	59	10 (17%)	0 (0%)	6 (10%)	26
Caracara plancus	1550	215 (14%)	17 (1%)	153 (10%)	23
Amazonetta brasiliensis	46	4 (9%)	2 (4%)	4 (9%)	21
Ardea alba	52	6 (12%)	0 (0%)	5 (10%)	20
Columbidae	183	22 (12%)	0 (0%)	16 (9%)	20
Egretta thula	42	5 (12%)	1 (2%)	3 (7%)	20
Anatidae	21	2 (10%)	1 (5%)	1 (5%)	18
Columba livia	211	20 (9%)	1 (0%)	19 (9%)	18
Nycticorax nycticorax	41	6 (15%)	1 (2%)	1 (2%)	18
Theristicus caudatus	32	4 (13%)	0 (0%)	2 (6%)	18
Heterospizias meridionalis	54	4 (7%)	0 (0%)	5 (9%)	16
Passer domesticus	41	4 (10%)	0 (0%)	3 (7%)	16
Patagioenas picazuro	141	11 (8%)	1 (1%)	11 (8%)	15
Cathartes burrovianus	48	4 (8%)	0 (0%)	3 (6%)	14
Strigidae	164	16 (10%)	1 (1%)	7 (4%)	14
Bubulcus ibis	58	4 (7%)	0 (0%)	4 (7%)	13
wild dog	73	2 (3%)	0 (0%)	8 (11%)	13
Milvago chimachima	21	1 (5%)	0 (0%)	2 (10%)	13
mammals > 1.5 kg	369	19 (5%)	5 (1%)	21 (6%)	12
Passeriformes	246	19 (8%)	1 (0%)	11 (4%)	12
Vanellus chilensis	4156	300 (7%)	24 (1%)	191 (5%)	12
Hirundo rustica	42	2 (5%)	2 (5%)	1 (2%)	11

Table 1 (continued)

Progne tapera	86	5 (6%)	0 (0%)	4 (5%)	10
Leistes superciliaris	79	5 (6%)	0 (0%)	3 (4%)	10
Tyrannidae	47	2 (4%)	0 (0%)	3 (6%)	10
Tyrannus savana	29	2 (7%)	0 (0%)	1 (3%)	10
Syrigma sibilatrix	62	4 (6%)	0 (0%)	2 (3%)	9
Zenaida auriculata	182	7 (4%)	1 (1%)	9 (5%)	9
Guira guira	69	4 (6%)	0 (0%)	2 (3%)	8
Hirundinidae	183	7 (4%)	0 (0%)	9 (5%)	8
Picidae	70	2 (3%)	0 (0%)	4 (6%)	8
Tachycineta leucorrhoa	61	3 (5%)	0 (0%)	2 (3%)	8
Tyto furcata	186	8 (4%)	1 (1%)	6 (3%)	8
Progne chalybea	46	3 (7%)	0 (0%)	0 (0%)	6
reptiles > 1.5 kg	179	4 (2%)	0 (0%)	8 (4%)	6
Rupornis magnirostris	34	1 (3%)	0 (0%)	1 (3%)	6
Falco femoralis	58	3 (5%)	0 (0%)	0 (0%)	5
Falco sparverius	136	2 (1%)	0 (0%)	5 (4%)	5
bats	481	18 (4%)	0 (0%)	6 (1%)	5
Podager nacunda	277	7 (3%)	0 (0%)	7 (3%)	5
Athene cunicularia	515	13 (3%)	1 (0%)	10 (2%)	4
Chaetura meridionalis	68	2 (3%)	1 (1%)	0 (0%)	4
Nothura maculosa	22	0 (0%)	0 (0%)	1 (5%)	4
Pygochelidon cyanoleuca	141	5 (4%)	0 (0%)	1 (1%)	4
Scolopacidae	24	1 (4%)	0 (0%)	0 (0%)	4
Pitangus sulphuratus	95	1 (1%)	0 (0%)	2 (2%)	3
Caprimulgidae	85	2 (2%)	0 (0%)	0 (0%)	2
Gallinago paraguaiae	23	0 (0%)	0 (0%)	0 (0%)	0
Tachornis squamata	26	0 (0%)	0 (0%)	0 (0%)	0
Tachycineta albiventer	85	0 (0%)	0 (0%)	0 (0%)	0
Nengetus cinereus	59	0 (0%)	0 (0%)	0 (0%)	0

The family ranking presented Cathartidae (RHS = 100), Fregatidae (RHS = 97), Cariamidae (RHS = 85), Laridae (RHS = 42), and Accipitridae (RHS = 31) as the most hazardous (Supplementary Material D). The same families dominated the rankings by phase of flight, but the following also show RHS above 50 in at least one situation: Anatidae, Columbidae, Falconidae, Picidae, and Tyrannidae.

Almost half of the collisions were recorded in Atlantic Forest (6262; 49.68%), followed by Cerrado (2402; 19.06%), and Amazon (1092; 8.66%). All the regional rankings (biomes and near the coast) were headed by the Cathartidae family (Supplementary Material D). In the biomes ranking, Cariamidae also has a high RHS in the Atlantic Forest (100) and Cerrado (73), and Fregatidae showed a high RHS in Atlantic Forest (95). No other family led a RHS higher than 50 in any biomes, but some particularities can be identified, such as Ardeidae in Amazon (RHS = 45) and Strigidae and Anatidae in Pampas (RHS = 36 and 30, respectively). In addition to Cathartidae, the ranking of RHS near the coast appointed families Fregatidae (RHS = 94), Laridae (RHS = 57), and Ardeidae (RHS = 52) as the most dangerous for aviation.

Table 2 Number of collisions and Relative Hazard Score (RHS) of bird species to airdromes in Brazil. The table also shows the group size and body mass, and the color on the RHS column varies from white (0) to red (100)

Rank	Species - English name	Collisions	Relative Hazard Score	Group size	Body mass (g)
1	*Coragyps atratus* - black vulture	423	100	11	1640
2	*Fregata magnificens* - magnificent frigatebird	75	72	14	1585
3	*Cariama cristata* - red-legged seriema	27	63	4	1400
4	*Columbina picui* - picui ground-dove	20	33	4	46
5	*Cathartes aura* - Turkey vulture	56	27	6	1325
6	*Caracara plancus* - crested caracara	1550	23	5	1348
7	*Amazonetta brasiliensis* - Brazilian teal	46	21	4	500
8	*Ardea alba* - great egret	52	20	2	874
9	*Egretta thula* - snowy egret	42	20	4	371
10	*Columba livia* - rock pigeon	211	18	6	355
11	*Nycticorax nycticorax* - black-crowned night-heron	41	18	1	810
12	*Theristicus caudatus* - buff-necked ibis	32	18	4	1726
13	*Heterospizias meridionalis* - savanna hawk	54	16	3	808
14	*Passer domesticus* - house sparrow	41	16	2	28
15	*Patagioenas picazuro* - picazuro pigeon	141	15	9	279
16	*Cathartes burrovianus* - lesser yellow-headed vulture	48	14	12	935
17	*Bubulcus ibis* - cattle egret	58	13	10	366
18	*Milvago chimachima* - yellow-headed caracara	21	13	2	306
19	*Vanellus chilensis* - Southern lapwing	4156	12	5	327
20	*Hirundo rustica* - barn swallow	42	11	10	16
21	*Progne tapera* - brown-chested martin	86	10	6	32
22	*Leistes superciliaris* - white-browed meadowlark	79	10	2	46
23	*Tyrannus savana* - Southern fork-tailed flycatcher	29	10	4	32
24	*Syrigma sibilatrix* - whistling heron	62	9	2	463
25	*Zenaida auriculata* - eared dove	182	9	3	136
26	*Guira guira* - guira cuckoo	69	8	3	141
27	*Tachycineta leucorrhoa* - white-rumped swallow	61	8	11	15
28	*Tyto furcata* - American barn owl	186	8	2	520
29	*Progne chalybea* - gray-breasted martin	46	6	12	43
30	*Rupornis magnirostris* - roadside hawk	34	6	2	269
31	*Falco femoralis* - aplomado falcon	58	5	1	344
32	*Falco sparverius* - American kestrel	136	5	1	116
33	*Podager nacunda* - nacunda nighthawk	277	5	5	159
34	*Athene cunicularia* - burrowing owl	515	4	2	150
35	*Chaetura meridionalis* - Sick's swift	68	4	4	22
36	*Nothura maculosa* - spotted nothura	22	4	1	231
37	*Pygochelidon cyanoleuca* - blue-and-white swallow	141	4	6	10
38	*Pitangus sulphuratus* - great kiskadee	95	3	2	61

RHS was positively related to body mass (r^2 adjusted = 0.55, $P < 0.05$; Fig. 2a and Fig. 3) and to group size (r^2 adjusted = 0.13, $P < 0.05$; Fig. 2b and Fig. 3).

Discussion

The first step to avoiding a bird strike is to understand which bird species have the potential to be involved in it. Our ranking shows the bird species and families which need to be considered by aerodromes managers to increase aviation safety, such as vultures, which partially corroborates results worldwide (Dolbeer et al. 2000, 2021; Novaes 2022). From this ranking, it is possible to consider why those species are being attracted by aerodromes and how we can change this scenario. Although not simple, measures to avoid particularly large and gregarious species, which are related to hazard, seem to be a logical pathway to avoid bird strike collisions. We also highlight that this ranking does not consider the economic damage or the frequency of species in collisions but the species with a higher probability of damage when struck by aircraft (DeVault et al. 2011).

Vultures are the hazardous species for Brazilian aviation, with two main species, black and turkey vultures (*Coragyps atratus* and *Cathartes aura*, respectively) and unidentified Cathartidae are among the top five-ranked group species. Black vulture causes damage and affects the flight in 50% and 42% of the collision, respectively. Both species are considered heavy (> 1.3 kg; Dunning 2007), form large groups while soaring in updrafts reaching hundreds of individuals (Fergunson-Lees and Christie 2001), and are attracted by garbage dumps and rubbish bins located nearby the aerodromes (Novaes and Cintra 2013; Araujo et al. 2018). Even with a regulation to avoid dumps in a radius of 10 km (Law 12.725, 16/10/2012), illegal trash discards still exist (Arana and Hespanhol 2015; Costa 2017), and together with legal, but inappropriate human waste disposal, can promote vulture aggregations, and consequently, a severe risk for aerodromes

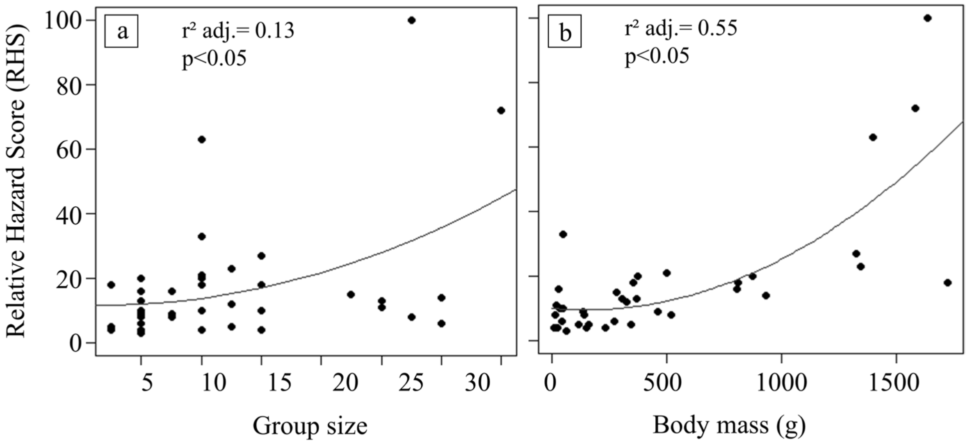

Fig. 2 Quadratic regression showing the relation between Relative Hazard Score (RHS) and body mass (**a**) and group size (**b**) for bird species

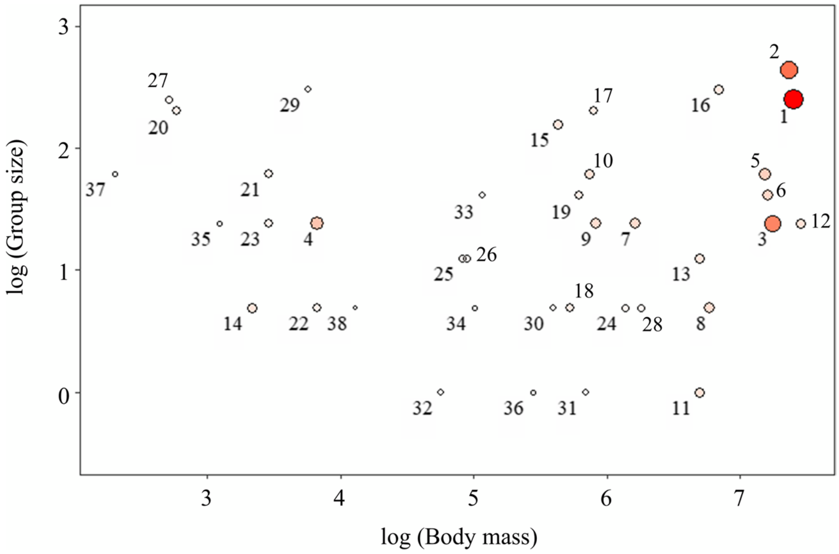

Fig. 3 Species distribution according to body mass and group size (both in log) showing heavy and gregarious species as hazardous for aviation. Each circle represents one species, and its color varies from white (RHS = 0) to red (RHS = 100), and its size varies according to RHS. The number close to the circles represents the rank present in Table 2

(Araujo et al. 2018). Other species can also be attracted by trash, such as the crested caracara (*Caracara plancus*), the second species with the most collisions (Bouker et al. 2021). Although soaring is a natural behavior of vultures, planning the land use to avoid non-natural concentration is necessary to decrease the risk for aviation. Considering the aerodrome environment, grass height control can be an appropriate management (but always following the ICAO recommendations) since crested caracara follows a trend of being less abundant when the grass is tall (> 30 cm) (Abreu et al. 2017). Another critical concern is the grass-cutting process. As an opportunistic species, the abundance of crested caracara increases during and in the first hours after the cutting process, when the animals forage on arthropods and small vertebrates frightened or injured by machinery (Medolago CAB, personal observation). In this sense, the mowing process must be carried out at periods of lower aerial activity or at night since the crested caracara is a diurnal species.

The magnificent frigatebird (*Fregata magnificens*), the second species in the bird species RHS ranking, is also a gregarious soarer, with wings adapted to stay soaring or gliding day and night for long periods along the shoreline (Pennycuick 1983). For aerodromes located on the coast, identification of more favorable areas for updraft formation can be helpful for avoidance by airplane routes, as they are used both by frigatebirds and vultures. Other species filling the top of the ranking are the red-legged seriema (*Cariama cristata*), which uses areas with open vegetation, such as the grass which usually surrounds the aerodromes runways (Costa 2017); water-associated species, such as Brazilian teal (*Amazonetta brasiliensis*), great egret (*Ardea alba*), and snowy egret (*Egretta thula*); and two Columbidae species: picui ground-dove (*Columbina picui*) and rock pigeon (*Columba livia*). For red-legged seriema, as well as for southern lapwing (*Vanellus chilensis*), strategies such as nest removal and bird translocations have already been proposed (Costa 2017). Southern lapwing, despite its moderate RHS value (12), was the bird with the highest number of collisions totalizing 4156, which represents 33% of the total. For the waterfowls, wetlands and other areas which attract those species should be identified and avoided in the proximity of new airports and used to plan airplane routes for those already in operation. Picui ground-dove is a small-sized bird and was involved in only 20 collisions, the threshold number of collisions we used to include birds in our analysis, so it is possible their high RSH value (33) was inflated by the small sample.

Our results for the ranking with all taxa are close to those presented in Novaes (2022), but differences can be noted once we used a 2-year updated database and different criteria for ranking. We based our ranking on consolidated and pioneer works about Relative Hazard Score (Dolbeer et al. 2000; DeVault et al. 2011), so we exclude our analysis taxa with less than 20 collisions (while Novaes 2002 used 5 collisions as a threshold), which is responsible for the main difference in ranking composition. Also, the database from CENIPA is not clear about some criteria used in Novaes (2022), such as “destroyed aircraft” and “substantial damage to the aircraft structure”, so we select the reports using the best information we have, which are detailed in the Supplementary Material D to allow the ranking to be updated in the future with the same criteria.

When compared with rankings from North America (DeVault et al. 2011), differences in species composition can be found. Those differences are predicted once taxonomic composition changes across the world, mainly in temperate and tropical regions, and shows how important it is to consider the species we want to avoid near aerodromes to take the more appropriate measures. More than only different species, the ranking is composed of species with different traits. Canada goose (*Branta canadensis*), for example, can be three times heavier than the buff-necked ibis (*Theristicus caudatus*), the heaviest species in our ranking, and the average weight of the ten top-ranked species in USA is three-fold higher than the ten top-ranked species in Brazil (3015 kg and 944 g, respectively). Simply adopting techniques from the USA, for example, can be effective for some species but utterly useless for others.

Even in Brazil, the measures to avoid bird collisions can be more specific according to aerodrome location. The Cathartidae family was hazardous in the six regional rankings, but we found variation in RHS due to species distribution, such as for Fregatidae (exclusive of Atlantic Forest) and Cariamidae (Atlantic Forest and Cerrado), and to specific biomes traits. Atlantic Forest and Cerrado rankings were similar to the general ranking, which was expected since they hold almost 50% and 19% of the collisions, while Amazon, Caatinga, and Pampa had a different set of families in the top-5 ranking. In Pampa, Strigidae showed a much higher RHS value (36) when compared to the general ranking (9), probably because its open areas can be more attractive for some species such as burrowing owl (*Athene cunicularia*). This biome was unique in which Strigidae and Anatidae showed a high RHS value, confirming the importance of local scale analysis to identify the target taxa better aiming to avoid collisions.

The ranking of aerodromes near the coast, besides Cathartidae, Fregatidae, and Laridae, also showed a disproportional RHS to Ardeidae and Hirundinidae when compared with the general ranking. Laridae and Ardeidae share some similarities with vultures, which can be attracted by garbage dumps and rubbish bins and form large groups (Sick 1997) so vulture control by avoiding garbage disposal can be at least partially effective for those families. Also, both families can form large groups to forage or to nest in the coastal environment, such as beaches and mangroves.

We split the rankings into the different phases of flight to identify bird families with higher hazard levels at different moments. The top three families in the general ranking, Cathartidae, Fregatidae, and Cariamidae, were also dominant in almost all phases of flight ranking. The exception was RWY and turnaround check when the bird is identified after the end of the flight and does not allow knowledge of when the collision happened. Other groups also have a higher RHS in these two phases, such as Columbidae, Falconidae, Picidae, and Tyrannidae, but since they are mainly composed of light and small species, it is expected that the impact is not always perceived during the flight. Some families did not show considerable risk in the ranking with all collisions (RHS < 25) but can be hazardous in particular phases of flight, such as Ardeidae (RHS = 50 during approach), Threskiornithidae (RHS = 42 during landing), and Columbidae (RHS = 37 during parking/taxi/take-off). Ardeidae and Threskiornithidae are composed of species that use wet and open areas, such as the grass around runways, which can be managed to control the birds' presence (Abreu et al. 2017), while Columbidae can form large groups to search for seed in the grass close to the runways.

We find a positive relationship between RHS and body mass, corroborating other studies elsewhere (Dolbeer et al. 2000; DeVault et al. 2011; Nilsson et al. 2021). From the top five bird species in our ranking, only one weighs less than 1.3 kg, and considering the top 10 species, only one weighs less than 300 g. The heavier the bird, the bigger the damage to the airplane, and the consequences can be worse for multiple collisions (Thorpe 1998). In regard to group size, we used only one value for each species, which obviously can hide variations across time and populations (Downing et al. 2020). Even in the same location, species such as black vulture (*C. atratus*), turkey vulture (*C. aura*), and cattle egret (*Bubulcus ibis*) can be found solitary, in few individuals, or forming large flocks (> 100 individuals; Sick 1997). As discussed below, this variation highlights how important it is to know and understand the local conditions to guide measures for an aerodrome, since the size group can be closely related to the land use in the surroundings. All the species with RHS > 20 can form groups, with their size varying from a few individuals to more than hundreds.

Since this data represents all the aerodromes in Brazil, a similar approach at the airport level can identify situations when specific measures of prevention have a high cost–benefit (Cardoso et al. 2014; Costa 2017; Silva and Neto 2018; Hu et al. 2020). For example, after identifying the main birds in an airport, such as black vulture and southern lapwing, Costa (2017) suggested several indirect ways to manage the aerodrome environment and make it less attractive for the targets, and direct methods to repel and control bird population. Indirect measures include vegetation cover management, food supply control, and land use control in the vicinities, while direct action includes bird repellency, nest destruction, bird translocation, pyrotechnics, gas cannons, bioacoustics, falconry, and visual techniques (Costa 2017; El-Sayed 2019; Hu et al. 2020). Following this individualized approach, promising help comes from new technologies, such as the use of portable thermographs (Medolago et al. 2021), avian radar (van Belle et al. 2007; Gerringer et al. 2016; Chen et al. 2022), and intelligent decision-making (Chen et al. 2018). With those technologies, it is possible to identify the bird usage of the aerodrome space in real-time and forecast migration movements and guide more specific actions to avoid aircraft collisions (Chen et al. 2018, 2022). Also, considering the atmosphere condition and its variation (daily and seasonally) is an important factor that affects temperature and consequently the soaring behavior of large-sized species (Péron et al. 2017).

Finally, despite the important findings of this work, we highlighted a useful addition to the collision database which could improve it and allow more complex analysis in the future. Of more than 20,000 collisions, 47.9% ($n = 9737$) are caused by unidentified animals, generating a gap in qualitative data. It is justifiably not easy to identify all the specimens, but those animals were not identified even at the class level, which limits deeper investigation. This is possibly due to non-experts being responsible for animals' identification and for cases when the bird who crashed was not recovered (see Abra et al. 2018). For the first case, when the carcass of an animal was available, a photographic database for posterior identification could help to improve the animal identification by experts or depending on the level of the damage of the carcass, it is also possible to collect DNA samples for further identification.

We provided an updated Ranking of Hazard Score for Brazilian birds, and the first including regional analysis, which is now available to help managers and practitioners. These rankings can be used as base measures to decrease the number of bird-aircraft collisions, benefiting aviation and human safety and economics for direct and indirect losses. We showed the big picture of the bird collision issue in Brazil. From this point, more site-specific analysis using data on a smaller scale is recommendable for guiding measures in the Brazilian aerodromes in the short and medium term.

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Data Availability The data used in our analysis are available as open data via: https://sistema.cenipa.fab.mil.br/cenipa/sigra/pesquisa_dadosExt.

Declarations

Conflict of interest The authors declare no competing interests.

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