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## 1 **REVIEW**

# 2 Runway roadkill: a global review of mammal strikes with aircraft

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- 23 collisions, prévention du risque animalier, collisions avec la faune
- 24

## 25 ABSTRACT

The number of reported collisions (i.e. strikes) between aircraft and wildlife is
 increasing globally, with consequences for personnel and passenger safety as well as
 for industry economics. These are important considerations for airport operators that
 are obliged to mitigate wildlife hazards at airfields. Incidents involving mammals
 account for approximately 3-10% of all recorded strikes. However, relatively little
 research has been conducted on mammal strikes with aircraft outside of the USA.

- We collate mammal strike data from six major national aviation authorities and a global
   aircraft database and review the available scientific and grey literature. We aim to
   identify which mammal families are involved in strike events and how widespread the
   issue is on a global scale. We also aim to demonstrate the importance of consistently
   recording strike instances in national databases.
- 37 3. We identified 40 families that were involved in strike events in 47 countries. Reported 38 mammal strike events have been increasing by up to 68% annually. Chiroptera (4) 39 families) accounted for the greatest proportion of strikes in Australia, leporids and canids in Canada, Germany and the UK, and chiroptera (5 families) and cervids in the 40 41 USA. More mammals were struck during the landing phase of an aircraft's rotation than any other phase. Circa-diel strike risk was greatest at dusk and circa-annum strike risk 42 43 was greatest during late summer, with some international variation. The total estimated 44 cost of damage resulting from reported mammal strikes exceeded US\$103 million in 45 the USA alone, over 30 years.
- 46 4. Mammal strikes represent a substantial risk in airfield environments. Monitoring of
   47 existing wild mammal populations is required to understand temporal trends in
   48 presence, abundance and activity patterns and to inform management decisions.

- Increased and accurate reporting of strike events globally is needed to inform Wildlife
   Hazard Management Plans and support effective strike mitigation.

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# 52

# 53 RÉSUMÉ EN FRANÇAIS

1. La fréquence des collisions entre avions et animaux sauvages connait une augmentation constante à travers le monde, entrainant des conséquences pour la sécurité du personnel et des passagers ainsi que pour l'économie de l'industrie aéronautique. Il s'agit d'une considération importante pour les exploitants d'aéroports qui sont tenus d'atténuer les risques potentiels liés à la faune sauvage sur les terrains d'aviation. Les incidents impliquant des mammifères représentent environ 3 à 10 % des collisions enregistrées. Cependant, en dehors des États-Unis, relativement peu de recherches ont été menées sur les collisions entre mammifères et avions.

61 2. Nous rassemblons les données sur les collisions avec des mammifères provenant de six 62 directions nationales majeures de l'aviation civile ainsi que d'une base de données mondiale 63 sur les aéronefs et compulsons l'ensemble de la littérature scientifique et grise disponible. 64 Notre objectif est d'identifier les familles de mammifères impliquées dans les collisions et de 65 déterminer l'ampleur du phénomène à l'échelle mondiale. Parallèlement, nous cherchons à 66 démontrer l'importance de l'enregistrement systématique des cas de collisions dans les bases 67 de données nationales

Nous avons identifié 40 familles de mammifères impliquées dans des collisions dans 47
 pays, avec une forte augmentation des collisions signalées, pouvant aller jusqu'à 68% par an.
 Les chiroptères (4 familles) représentaient la plus grande proportion des collisions en Australie,
 au Canada, en Allemagne et au Royaume-Uni ce sont les léporidés et les canidés qui sont le
 plus souvent impliqués, et aux États-Unis, les chiroptères (5 familles) et les cervidés. Plus qu'à

toute autre phase, c'est pendant la phase d'atterrissage que le nombre d'impacts le plus importants se produit. Au cours de la journée, le risque d'impact est le plus élevé au crépuscule et il connait un pic annuel à la fin de l'été et en automne, avec cependant quelques variations internationales. Sur une période de 30 ans, le coût estimé des dommages résultant des collisions signalées avec des mammifères dépasse les 103 millions de dollars US rien qu'aux États-Unis.

78 4. Les collisions impliquant un mammifère représentent un risque environnemental élevé 79 pour les aéroports, tant pour l'intégrité des avions que pour la sécurité des passagers. 80 L'évaluation des populations de mammifères sauvages aux abords des aéroports est nécessaire pour prédire les évolutions temporelles de présence, d'abondance et d'activité de ces 81 82 populations. Les études permettent d'accompagner les opérateurs d'aéroports dans la prise de 83 décision liées à la prévention des risques naturels. A l'échelle mondiale, il est nécessaire de 84 disposer de rapports plus nombreux et plus détaillés sur les cas de collisions afin d'enrichir les 85 stratégies de gestion des risques animaliers et de réduire efficacement le nombre de collisions.

86

## 87 INTRODUCTION

88 Airports and the services that they provide are vital to the global economy. In 2018 alone, over 89 four billion passengers were carried by aircraft, and airline industry revenues exceeded US\$812 90 billion (IATA 2019). Whilst airports can contextually constitute environmental disturbances 91 (Blackwell et al. 2013), the airport environment can provide productive habitat for wildlife 92 (Soldatini et al. 2010, Hauptfleisch & Avenant 2015), due to expanses of semi-natural 93 grasslands. In the USA alone, there is in excess of 3300 km<sup>2</sup> of grassland in airfields (DeVault 94 et al. 2012, Washburn & Seamans 2013, Pfeiffer et al. 2018), creating favourable ecological 95 habitats, often in heavily urbanised areas (DeVault et al. 2012). These grasslands can be 96 attractive to a range of animal taxa (e.g. deer - Cervidae, geese - Anatidae, starlings - Sturnidae;

Belant et al. 2013, Coccon et al. 2015, Pfeiffer et al. 2018). Some of the animals can be
hazardous to aviation if they are involved in wildlife-aircraft collisions or 'strikes' (Blackwell
et al. 2013).

100 Incidents with avian species make up the majority of wildlife strikes (e.g. 95% of strike 101 events in the USA involve birds; Dolbeer & Begier 2019) and therefore the bulk of available 102 literature focuses on avian taxa. Strike data are generally lacking for other taxa, including 103 mammals, which are estimated to make up approximately 5% of strikes in the USA (Dolbeer 104 & Begier 2019). Globally, there has been a general increase in the number of reported wildlife strikes with aircraft (Thorpe 2010), with evidence that mammal strikes may also be increasing 105 106 (e.g. Dolbeer 2015). Airport operators have a legal obligation to reduce wildlife hazard at 107 airfields (Mendonca et al. 2017). It is therefore important for airports to understand the relative 108 risk associated with each species, in order to prioritise and implement effective Wildlife Hazard 109 Management Plans (WHMP).

110 Understanding the importance of wildlife strikes and associated hazards requires the 111 collection and analysis of strike data. Long-term databases recording animal strike incidents 112 and damage (Dolbeer & Wright 2009), kept by national aviation authorities, are valuable tools 113 for this analysis. However, reporting is not always mandatory, and databases often have a large proportion of unidentified species. Additionally, these databases are likely to under-represent 114 115 the true frequency with which wildlife strikes occur (Biondi et al. 2011). For example, reporting 116 is mandatory within the European Union (EU), but not in the USA. While previous work has 117 been conducted on mammal strikes with aircraft by looking at specific mammal groups in the 118 USA, such as bats (Biondi et al. 2013), deer (Biondi et al. 2011) and carnivores (Crain et al. 119 2015), little work has been conducted looking at the class Mammalia as a whole (but see Schwarz et al. 2014), particularly outside the USA. Therefore, American data are often used as 120 121 the baseline reference with little global context.

122 We review the available literature and collate mammal strike data from six national 123 aviation authorities (Australia, Canada, France, Germany, UK and USA) and from a database of destroyed aircraft compiled by Avisure (a bird strike risk mitigation company; Avisure 2019). 124 125 By doing so, we aim to: 1) identify the mammal families reported to have been involved in strike events globally; 2) identify the countries where strike events with mammals have been 126 127 reported; 3) determine how the number of reported strikes has changed over time; 4) identify periods of increased risk based on reported strike incidents; and 5) emphasise the importance 128 129 of national databases as a tool to understand the patterns associated with mammal strike events. 130 We expect that reported strike events are increasing over time and that diverse mammalian taxa are involved in these events. This review will help to highlight the extent of mammal strikes 131 132 with aircraft and inform wildlife management on both national and international scales.

## 134 **METHODS**

135 We surveyed all available literature published before October 2020, using the search engines Web of Knowledge, Science Direct and Google Scholar, to identify published records of 136 137 aircraft collisions with mammals. The search terms 'mammal strike', 'wildlife-strike', 'animal 138 strike', 'mammal collision', 'wildlife collision', 'animal collision', 'aircraft', 'aviation' and 139 'airplane' were applied for two searches: 1) with just search terms; and 2) with search terms 140 alongside mammal taxa frequently involved in strike events (Canidae, Cervidae, Chiroptera, 141 Leporidae). Search results, which included both the title and the abstract, were manually sorted to remove irrelevant articles and duplicate publications. Results were also supplemented by 142 references within the literature. Relevant 'grey literature' (i.e. conference proceedings, 143 government reports) were retained. 144

145 National aviation authorities were contacted to request mammal strike records 146 (Appendix S1). Data on strikes were obtained from six aviation databases and record centres. 147 Data were obtained from the website of 1) the Australian 'Transport and Safety Bureau' 148 (ATSB: 2008 – 2017; ATSB 2018). Data were provided, upon request, by: 2) 'Transport Canada' (TC; 2008 – 2018; TC 2019); 3) the French 'Service Technique de l'Aviation Civile' 149 150 (STAC; 2016 – 2018; ); STAC 2019) 4) the German 'Deutscher Ausschuss zur Verhütung von 151 Vogelschlägen im Luftverkehr e.V.' (DAVVL e.V.; 2010 – 2018; DAVVL e.V 2019); and 5) 152 the 'UK Civil Aviation Authority' (UKCAA; 1990 – 2018; UKCAA 2019). Finally, data were obtained from the website of 6) the USA's 'Federal Aviation Administration' (FAA; 1990 -153 154 2018; FAA 2019). All data were accessed and provided between February 2019 and March 155 2020. Wildlife strike reporting was mandatory in all countries analysed, except for the USA. 156 However, reporting became mandatory in different countries at different times (e.g. 2000 in Australia, 2004 in the UK) and countries have different reporting conditions (e.g. in Germany 157

only mammals the size of a rabbit or larger are reported). All databases were screened to 158 159 remove non-strike incidents (i.e. near misses, disruptions); a strike was deemed to have 160 occurred if there was sufficient evidence (i.e. a carcass was found or damage was inflicted). In 161 all databases, strikes involving helicopters, gyrocopters and military aircraft (but see Zakraisek 162 & Bissonette 2005, Peurach et al. 2009) were removed, to isolate incidents with civil 163 (commercial and private) airplanes. The databases included reports of strikes with domestic 164 animals, thus we included both wild and domestic non-human mammal taxa (e.g. Hesse et al. 165 2010). As there is no single, central reporting organisation and reporting of strike incidents is 166 voluntary in some areas (e.g. USA), reporting falls to multiple organisations, airports and 167 individuals. Hence, data were largely inconsistent in terms of detail and temporal information. 168 These limitations were overcome by applying a consistent data management framework that 169 was compatible with all databases (i.e. categorising mammals according to taxon and 170 categorising strike data, as outlined below). Available variables from databases are shown in 171 Appendix S2.

172 For the ATSB, TC, DAVVL e.V and FAA databases, strike incidents were summarised 173 for time of day, where phase of flight was also provided, based on the local time reported. We defined both 'day' (08:00 - 18:00h) and 'night' (20:00 - 06:00h) as 10-hour periods, whilst 174 'dawn' (06:00 - 08:00h) and 'dusk' (18:00 - 20:00h) were each two hours (Washburn & 175 176 Seamans 2013, Crain et al. 2015). Damage was categorised as 'none', 'minor', 'substantial' and 'destroyed' by both the FAA and ATSB, in accordance with International Civil Aviation 177 178 Organization's (ICAO) aircraft damage taxonomy (ICAO 1989). We classified damage in the 179 same way using data from the DAVVL e.V. and STAC databases, depending on where damage 180 was inflicted. Data on damage from the TC and UKCAA databases were insufficient for 181 inclusion. For all databases, strike incidents were summarised for the phase of flight and

categorised as 'approach', 'climb', 'en route', 'landing roll', 'take-off run' and 'taxi' (Biondi
et al. 2011, with the addition of 'en route').

The FAA database provided a value, in US dollars, for the cost of the damage inflicted 184 185 to aircraft from strikes with mammals for 397 strike events from a total of 1077 in which 186 damage was inflicted (1990 - 2018). This was the only database which provided any detail on 187 costings. To estimate the economic impact of damaging mammal strikes in the USA using these 188 values, the average (mean) cost of repairs from a strike incident was determined for each 189 damage category ('minor', 'substantial', 'destroyed' and 'unspecified'). The mean cost was 190 then multiplied by the total number of incidents within each category to obtain an overall 191 estimate of damage costs inflicted by mammal strikes from 1990 - 2018, as per Biondi et al. (2011) and Crain et al. (2015). 192

193 International guidelines generally report the number of strikes per 10000 aircraft 194 movements (ICAO 2012). However, such reports focus on individual airports, where the 195 proportion of strikes to movements is much higher than across entire countries. For ease of 196 interpretation, we calculated strike rates as the annual number of strikes per one million aircraft 197 movements (MAM), as per Crain et al. (2015). One movement was defined as a take-off run 198 or a landing manoeuvre; both figures were summed to give the total number of movements. 199 For Australia, the number of departures (take-off runs) was obtained for 2008 - 2016 from the 200 Aviation Occurrence Statistics Report (ATSB 2018b) and the number of landings from annual 201 Australian Government reports (BITRE 2008-2017). As only the number of landings could be 202 obtained for 2017, this was doubled to estimate the total number of aircraft movements. 203 Movements for Canada were obtained from Statistics Canada's annual reports (Statistics 204 Canada 2010, 2014, 2019). Aircraft movements for Germany for 2010 - 2017 were obtained 205 from the Deutsche Flugsicherung (DFS Deutsche Flugsicherung 2010-2017). Aircraft 206 movements for the UK for 1990-2018 were obtained from the Civil Aviation Authority's

annual summary data (www.caa.co.uk/Data-and-analysis). Finally, for the USA, the FAA
Terminal Area Forecast, which provides official data of aviation activity for US airports, was
queried as per Biondi et al. (2011; 2013) and Crain et al. (2015) in order to obtain aircraft
movement figures.

The Avisure database on destroyed aircraft attributed to wildlife strikes (www.avisure.com; Avisure 2019) was accessed in April 2019 and sorted to isolate incidents with mammals. Data were available for 1966-2015 and were used to identify mammal taxa and countries involved in strike events. Due to the low number of recorded events, some of which were also recorded by aviation authorities included in this review, these data were not included in any analyses.

217 Data were organised and summarised in the programme R (v. 3.6.1; R Core Team 2018). 218 We used General Linear Modelling with either a Poisson or Quasipoisson error structure, 219 implemented within the 'lme4' package (Bates et al. 2015), to evaluate trends in the number of 220 strike events over time (years), for each country. The strength of association between strikes 221 and year was tested with Spearman's Rho (p). As parametric modelling assumptions were not 222 met (for month and phase of flight), we used non-parametric Kruskal-Wallis tests with Dunn's 223 post-hoc test with a Benjamini–Hochberg P-value correction (Benjamini & Hochberg 1995) to 224 allow for multiple comparisons. To evaluate trends in strike events across 'month' (categorical 225 with 12 levels) and 'phase of flight' (categorical with six levels), countries were grouped 226 together based on geographic location, into: 1) Australia; 2) North America (Canada and the 227 USA); and 3) Europe (France, Germany and the UK). A further Kruskal-Wallis test was 228 conducted to evaluate trends in strike events across 'phase of flight', with mammal groups 229 divided up between volant (bats) and terrestrial taxa.

230

## 231 **RESULTS**

232 The literature survey yielded 44 relevant articles (Appendix S3). A total of 40 mammal families were identified as having been involved in wildlife strikes with airplanes, across 47 countries 233 234 (Table 1). In addition to these families, the Ursidae (bear) and the Otariidae (eared seals) were 235 reported to have caused disruptions without resulting in strike events (FAA 2019) and the leaf-236 nosed bats (Hipposideridae) were identified as having been involved in strike events with 237 military aircraft (Peurach et al. 2009). A total of 15 families were identified to have been 238 involved in a strike event with aircraft other than civil airplanes (e.g. Washburn et al. 2017; 239 Appendix S4).

240 A total of 13 mammal families were involved in strike events in Australia, amounting 241 to 1564 events, or 9.6% of the national total of all strike events (mammalian and non-242 mammalian species). Only 1024 strikes involved mammals that could be identified to family 243 level; many strikes (n = 540) involving members of the order Chiroptera were recorded as 244 'bats'. In the USA, 25 mammal families were identified as having been involved in strike 245 events from 6661 events, constituting 3.2% of the national total. A mammal family 246 (Pteropodidae) not naturally found in the USA was reported as the family involved in strike 247 events in two American airports. This may be as a result of misidentification, escaped captives 248 or the bat may have been carried on an airplane from the country of origin and subsequently 249 found in these airports in the USA (see Leader et al. 2006).

The TC, STAC, DAVVL e.V. and UKCAA databases provided bespoke data (i.e. mammal strikes only), thus the percentage of strikes attributed to mammals could not be determined. A total of 398 strikes involving 14 families were reported in Canada, 126 strikes involving six families were reported in France, 140 strikes involving five mammal families

were reported in Germany and 115 strikes involving eight families in the UK (Appendices S5and S6).

Utilising the data from all six national aviation authorities resulted in a database of 9004 256 257 confirmed strike events with mammals. In Australia, order Chiroptera accounted for the 258 greatest proportion of reported strikes and were involved in 79% of strike events with mammals overall. In Canada, Germany and the UK, leporids (Leporidae; Canada: 20%, Germany: 79%, 259 UK: 52%) and Canidae (Canada: 21%, Germany: 16%, UK: 17%) were most frequently 260 261 involved in wildlife strikes, while Chiroptera (38%) and Cervidae (deer; 17%) accounted for the greatest proportion of strikes in the USA. Across all databases, strike events involving 262 263 multiple mammals accounted for 4.9% of all records.

264 All countries reported an increase over time in the annual recorded strike rate. In 265 Australia, there was an average of  $38.7 \pm 15.7$  (mean  $\pm$  standard deviation, SD) reported strikes 266 strikes/MAM/year. Strike frequency increased an average of 7% annually (confidence intervals, CI: 2% - 12%;  $\rho = 0.66$ ), with a significant difference between years ( $\chi^2_{8, 1564}$ , P<0.05). Canada 267 268 reported an average of  $8.1 \pm 2.9$  (mean  $\pm$  SD) strikes/MAM/year and an average annual increase of 9% (CI: 4% - 13%;  $\rho = 0.77$ ), with significant variation between years ( $\chi^2_{9,398}$ , P<0.01). 269 270 France reported an average of  $17.4 \pm 4.3$  (mean  $\pm$  SD) strikes/MAM/year and an average annual increase of 25% (CI: 4%; 47%;  $\rho = 1.0$ ) with significant annual variation ( $\chi^2_{1.126}$ , P <0.05). In 271 Germany, there was an average of  $3.6 \pm 4.9$  (mean  $\pm$  SD) reported strikes/MAM/year; strike 272 events increased by an annual average of 68% (CI: 56% - 80%;  $\rho = 0.95$ ), with significant 273 variation between years ( $\chi^2_{7,140}$ , P < 0.001). In the UK, there was an average of  $1.2 \pm 2.4$  (mean 274 275  $\pm$  SD) reported strikes/MAM/year; reported strike events with mammals increased annually by on average 16% (CI: 7% - 22%;  $\rho = 0.52$ ), with significant variation between years ( $\chi^2_{18, 115}$ , 276 P < 0.001). Finally, there were an average of  $2.3 \pm 2.1$  (mean  $\pm$  SD) reported strikes/MAM/year 277 278 in the USA; reported strike events with mammals increased annually by an average of 10%

279 (CI: 9% - 10.5%;  $\rho = 0.99$ ), with significant variation between years ( $\chi^2_{27, 6661}$ , *P*<0.001; Fig. 280 1). No country surpassed the ICAO acceptable level given in safety guidelines, of five strikes 281 per 10000 aircraft movements (500/MAM/yr; ICAO 2012).

In Australia (H  $_{(11)}$  = 41.27, P<0.01) and North America (H  $_{(11)}$  = 63.3, P<0.01), there 282 283 were identifiable peaks in strike frequency between months, but in Europe, strike frequency 284 fluctuated across the year without pattern. For Australia, highest strike numbers were recorded 285 during March to May (37% of strike events), with a significant difference between strike event 286 numbers in March and in all other months, except for April. For North America, the majority of strikes were recorded during July to November (74% of strike events). In Europe, 68% of 287 288 strike events were recorded between July and November, with the highest strike numbers recorded in October (18%; Fig. 2). 289

290 There were significant differences in strike frequency according to phase of flight 291 between volant taxa (H<sub>(5)</sub>=17.1, P<0.01) and terrestrial taxa (H<sub>(4)</sub>=88.0, P<0.01). Across all 292 taxa (volant and terrestrial), there were significant differences in strike frequency according to phase of flight for Australia (H  $_{(5)}$  = 47.67, P<0.01) and North America (H  $_{(5), 3113}$  = 98.9, 293 294 P < 0.01). Generally, the landing roll phase, followed by the take-off run, yielded the highest 295 frequency of strike events (Fig. 3). Australia formed an exception to this: both the landing roll 296 and the approach conferred the greatest strike risk (59% of all strikes). In North America, the 297 landing roll was the only phase that resulted in significantly elevated strike risk (21% of all 298 strikes). Australia and North America (USA; n=615, CAN; n=1) were the only two continents 299 with a high frequency of strikes on approach.

Daily strike patterns varied between countries. Strike incidents were most frequent at night in Australia (42%), Canada (56%), Germany (63%) and the USA (62%). Standardised time periods (number of strikes/ number of hours) provided arbitrary strike rates for each time

period. Dusk was identified as having the highest strike rate per hour for Australia and the USA (n=249 strikes/hour and n=139.5 strikes/hour, respectively) and night conferred the greatest risk in Canada and Germany (n=12.5 strikes/hour and 8 strikes/hour, respectively).

306 Mammal strikes frequently resulted in damage to aircraft in some areas: damage was 307 reported for 18%, 3%, 1% and 17% of strike events with mammals in Australia, France, 308 Germany and the USA respectively (Fig. 4). Damage could not be classified for UKCAA or 309 TC data. Damage costs were provided for only the USA, where total reported cost of repairs 310 caused by mammal strikes exceeded US\$56 million for 397 events across all taxa (1990-2018). Cervidae accounted for 91% of reported repair costs. The total estimated cost of repairs was 311 312 US\$103 million, for all 1077 events where damage was reported. In Australia, the Macropodidae and the Pteropodidae were collectively involved in 64% of damage-inducing 313 strikes. In France and Germany, the Canidae, Cervidae and Leporidae were involved in all 314 315 damaging strikes (Appendix S5). The FAA and ATSB provided data on human injuries within 316 the database: 25 people were reported to have been injured as a result of mammal strikes, and 317 there was one reported human fatality.

## 318 **DISCUSSION**

319 Collisions between wildlife and aircraft are a considerable concern for airport authorities, 320 particularly as the number of reported strikes per annum is generally increasing (Dolbeer 2015). 321 However, given the heightened awareness of the importance of reporting strike events in recent 322 years, these increases could merely reflect recording effort rather than an increase in incidences. 323 Mammalian taxa comprise a small proportion of total strikes. Nevertheless, mammals pose a 324 considerable risk, with economic and human health-related consequences. Here, we observed 325 an annual increase in the frequency with which mammals are involved in reported strike events. 326 Strike events were recorded on every continent except Antarctica, confirming that mammal

strike events are a global issue involving a broad range of taxa. While a general increase in air traffic is likely to be partially responsible for this annual increase (but see Soldatini et al. 2011), both the ecological and behavioural traits of mammal populations in proximity to and inhabiting airports need to be understood and integrated into WHMPs if effective management policies are to be developed and implemented.

332 There is a paucity of information available on mammal taxa involved in strike events, 333 with the exception of Canidae, Cervidae and the Chiroptera. The mammal taxa involved in 334 strike events, the frequency of strikes, and the proportion of strikes that resulted in damage to aircraft vary between countries. This demonstrates the need for more specific recording of 335 336 information about wildlife strikes by aircraft on a country-by-country basis. Moreover, mammals from different geographical areas represent different threats to aircraft, and this 337 338 demonstrates the need for more accurate and complete recording of information from each 339 area. The majority of mammal strike research is focused on just two families, the Canidae (e.g. 340 Crain et al. 2015) and the Cervidae (e.g. Biondi et al. 2011), as these two families are involved 341 in 94% of damaging strikes involving mammals in the USA, where the majority of strike 342 research has been undertaken. Elsewhere, damaging strikes were dominated by the Chiroptera 343 in Australia and the Leporidae in Europe. Therefore, mitigiation measures developed in the 344 USA for the specific fauna of North America may not be effective for high-risk species in other 345 parts of the world. As air travel is a global industry, increased research efforts targeted at high-346 risk mammal families outside the USA would benefit not only the national aviation authorities 347 responsible for the research, but also international authorities and airline operators. A more 348 thorough understanding of the ecology of mammal groups inhabiting and using airfields is 349 required to maximise the efficacy of any mitigation measures (e.g. Scheideman et al. 2017).

In the USA, it is estimated that mammal strikes are five times more likely to cause damage to aircraft than bird strikes (Schwarz et al. 2014), and mammals are estimated to be 352 involved in 8.7% of wildlife strikes causing damage to aircraft in the USA (Dolbeer & Begier 353 2019). We estimated that the total cost of repairs to aircraft after mammal strikes in the USA 354 exceeded US\$103 million between 1990 and 2018. While terrestrial mammals are arguably 355 some of the easiest animals to control at airfields through adequate exclusion (e.g. fencing) and 356 habitat management measures, these measures can be costly to implement (>\$20/m for fencing; 357 VerCauteren et al. 2006, 2013). Additionally, many strike events occur despite the presence of 358 fencing, thereby representing a substantial additional cost. Damage costings highlight the need 359 for targeted wildlife management in addition to the importance of the upkeep of implemented 360 mitigation measures (VerCauteren et al. 2013). While estimates of damage and costs are 361 conservative (Biondi et al. 2011), they nevertheless highlight the economic severity of the issue. 362 Estimates also allow us to identify the mammal taxa that are most economically damaging if 363 struck (MacKinnon et al. 2004) and to test current WHMPs (Dolbeer & Wright, 2009). 364 Therefore, accurate reporting of all costs associated with each strike event (i.e. parts, labour, 365 time out of service) is needed to quantify the true financial impacts of mammal strikes on local, 366 national and global scales.

367 Wildlife-strike databases allow for the identification of periods of increased risk at 368 national (e.g. Biondi 2011, Biondi et al. 2013) and global (ICAO 2017) scales. We found dusk 369 and night to be the most hazardous times for four countries analysed (see also Parsons et al. 370 2009, Biondi et al. 2011, Schwarz et al. 2014). Indeed, over 70% of mammal species are 371 nocturnal or crepuscular (Bennie et al. 2014), including taxa frequently involved in strike 372 events. For example in Australia, dusk was identified as having the highest strike risk, where 373 85% of strikes were recorded with Chiroptera, most species of which are most active at dusk 374 and dawn (e.g. Welbergen 2006). Additionally, seasonal peaks in strikes coincide with the end 375 of Summer, which is a time of dispersal in many species. Identifying periods of high risk such 376 as these can allow for targeted mitigation measures, such as increased patrols during these

times (Crain et al. 2015) or slight modifications to flight schedules to reduce risk. This also demonstrates that data need to be collected at the local scale, to identify periods of risk and adjust mitigation measures accordingly. Data on the number of aircraft movements occurring within each time period were not available, but it is possible that increased air traffic during these times may pose risks additional to those related to faunal activity patterns.

382 Strike frequency is thought to be influenced by local occurrence and abundance of 383 species (e.g. Schwarz et al. 2014), in addition to seasonal life-history traits, such as activity and 384 breeding cycles, that make it difficult to mitigate against strike events. However, once these periods of increased risk are identified, depending on the faunal composition of wildlife in the 385 386 vicinity of an airport, mitigation measures can be implemented year after year. For example, 387 strikes involving Pteropodidae in Australia occurred most frequently during the breeding 388 season (Vardon et al. 2001). Similarly, Leporidae were the most commonly struck family in 389 three of five countries analysed, inclusive of during high-risk periods. Their high fecundity 390 (Caravaggi 2018), coupled with the potential for airfields to offer good quality, resource-rich 391 habitats that consequently support high density populations (Anthony Caravaggi, unpublished 392 data), can make population management at airfields difficult and expensive (e.g. Dublin Airport, 393 Ireland; Dublin Airport Authority, personal communication). Therefore, management 394 processes aimed at reducing strike frequency and severity should account for species' traits, 395 such as breeding seasons, or aim to exclude mammals entirely. However, mammals are 396 charismatic and popular, and public attitudes are an important consideration in modern wildlife 397 management processes (Liordos et al. 2017, van Eeden et al. 2017, 2019). Moreover, species 398 recorded in strikes may be of conservation concern, be subject to protective legislation, or 399 provide important ecosystem services (e.g. Birkhofer et al. 2018). Hence, the drive to reduce 400 the number of strikes also has a broad, ecological remit that must not be discounted.

401 Higher strike rates were recorded during the landing phase in all six countries, possibly 402 because the reduced speed and agility of aircraft during this phase makes it difficult for pilots 403 to avoid obstacles (Biondi et al. 2011). This, paired with the ability of mammals to habituate 404 to mechanical noises (Weisenberger et al. 1996, Ditmer et al. 2018), reduced engine noise 405 during landing, and a lack of aerial predators, particularly for larger mammals, may mean that 406 incoming (landing) aircraft are not always perceived as a threat (but see Lima et al. 2015). 407 Additionally, the phase of flight in which a strike can occur with a terrestrial mammal is limited 408 to when an aircraft is in contact with the ground (e.g. landing), whereas strike events with 409 volant taxa can occur at all phases of flight.

410 Under-reporting of strikes is recognised on both an international and national level: 411 estimates suggest that only 5-47% of wildlife strikes are reported to aviation authorities 412 (Linnell et al. 1999, Wright & Dolbeer 2005, Dolbeer & Wright 2009, Dolbeer 2015). Indeed, 413 the reporting of strike events remains voluntary in many countries. A total of 2295 mammal 414 strikes were reported to the ICAO during the years 2008-2015. However, during this same time 415 period, 4263 mammal strike events were recorded by five civil aviation authorities included in 416 this review (France only had records from 2016 onwards); this number surpasses the globally reported numbers by 1968 strikes. A similar pattern was observed for the period 2001-2007 417 418 (ICAO 2009). Therefore, it is unlikely that current estimates are accurate reflections of numbers 419 of mammal strike events. Such discrepancies represent important caveats to, and limit the 420 utility of, broad guidelines developed by civil aviation authorities and the ICAO (e.g. ICAO 421 2012). Despite the FAA's assurance that current data are adequate to track national trends 422 (Dolbeer 2015), improvements are nevertheless required to identify the true extent of the risks 423 posed to and by mammals, and to evaluate the effectiveness of WHMPs and mitigation 424 practises (Dolbeer & Wright 2009). This is particularly true for areas outside of USA, as the 425 numbers reported to the ICAO indicate severe underreporting or a complete lack of reporting

for many regions globally. Focusing on the accurate and timely reporting of strike events is important to help improve data in the near future, particularly for regions with established reporting systems (e.g. USA). However, in the long term, we suggest the uptake of mandatory reporting schemes and the centralisation of accurate and timely strike data, to support knowledge synthesis, the derivation of accurate strike statistics and the collaborative development of management procedures on a global scale.

Our findings are derived from some of the more economically developed countries 432 433 (Australia, Europe and North America). Differences in economic development may, in part, be 434 reflective of differences in national flight capacity and frequency, or of levels of compliance to 435 international organisations from other nations. Therefore, it is not possible to infer global strike 436 rates from our data. Nevertheless, the observed increase in strike events over time per million 437 aircraft movements (MAM/year) in all the countries we studied suggests that our findings have 438 broad relevance. Furthermore, terrestrial mammals involved in strikes were not identified to 439 the species level in <1% of instances, and bats were not identified to the species level in 17%440 of instances in the current study. The specific identification of taxa involved in strike events is 441 not only important to improve WHMPs, but can also play an important role in accident or strike event investigations (Dove et al. 2008a) and in subsequent mitigation. Therefore, we 442 443 recommend the use of forensic DNA analysis (Peurach et al. 2009, Kelly et al. 2017) to identify 444 otherwise 'unknown' species, thereby giving more nuanced ecological insight and 445 subsequently improving management strategies.

446

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# 452 **Tables and Figures:**

# 453 454 Table 1. Mammal families involved in civil airplane wildlife strikes reported in organisational, grey and scientific literature, and the country or countries of

455 occurrence

Taxon	Country/Countries	References
Antilocapridae	Nigeria, USA	Cleary et al. 1996, 2004, 2005, 2006, Cleary & Dolbeer 2005, ICAO 2009, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008, EAA 2019, Schwarz et al. 2014, Usman et al. 2012
Bovidae	Australia, Bolivia, China, Germany,	ATSB 2014, 2018, Avisure 2019, Cleary et al. 2004, 2005, 2006, Cleary & Dolbeer 2005, Dolbeer et al. 2009, 2013, 2014,
	Guyana, India, Kenya, South Sudan, UK,	2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008, Drey et al. 2014, FAA 2019, ICAO 2017, Schwarz et al. 2014,
Canidae	Australia, Brazil, Canada, Costa Rica,	ATSB 2014, 2018, Avisure 2019, Barras & Wright 2002, Bergman et al. 2009, CAA Poland 2019, Cleary et al. 1996,
	Cyprus, Egypt, France, Germany, Greece,	2004, 2005, 2006, Cleary & Dolbeer 2005, Crain et al. 2015, DAVVL e.V 2019, DeVault et al. 2011, Dolbeer 2000, 2013,
	Italy, Namibia, Poland, Portugal, Sweden,	Dolbeer et al. 2000, 2009, 2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008, 2009, Drey et al. 2014,
	UK, USA	FAA 2019, Hauptfleisch et al. 2013, ICAO 2017, Kitowski 2016, MacKinnon et al. 2004, Metscher et al. 2007, Schwarz et al. 2014, STAC 2019, TC 2019, UKCAA 2019
Castoridae	USA	Dolbeer et al. 2013, 2014, 2015, Dolbeer & Begier 2019, FAA 2019, ICAO 2017, Schwarz et al. 2014
Cercopithecidae	Namibia	Hauptfleisch et al. 2013
Cervidae	Australia, Canada, France, Germany,	ATSB 2018, Avisure 2019, Barras & Wright 2002, Biondi et al. 2011, CAA Poland 2019, Cleary et al. 1996, 2004, 2005,
	Poland, Switzerland, UK, USA	2006, Cleary & Dolbeer 2005, DAVVL e.V 2019, DeVault et al. 2011, Dolbeer 2000, Dolbeer et al. 2000, 2008, 2009,
		2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Franklin 2013, Dolbeer & Wright 2008, 2009, 2014, Drey et al.
		2014, FAA 2019, Fagerstone & Clay 1997, Hesse et al. 2012, ICAO 2017, Kelly & Allan 2006, Kitowski 2016, Markingen et al. 2004. Materia et al. 2007. Scheidergen et al. 2017. Schwarz et al. 2014. Scamper 2001. STAC 2010.
		MacKinnon et al. 2004, Meischer et al. 2007, Scheideman et al. 2017, Schwarz et al. 2014, Seamans 2001, STAC 2019, TC 2019, LIKCAA 2019, VerCauteren et al. 2013, Wenning et al. 2004, Wright et al. 1998, Wright & Dolbeer 2000, 2005
Chiroptera*	American Samoa Argentina Australia	ATSB 2018 Biondi et al. 2013, Cleary et al. 2004, 2005, 2006, Cleary & Dolbeer 2005, DAVVI, e V 2019, DeVault et
ennopteru	Barbados, China, El Salvador, Dominican	al. 2011. Dolbeer et al. 2009. 2013. 2014. 2015. Dolbeer & Begier 2019. Dolbeer & Wright 2008. Dove et al. 2008b.
	Republic, Germany, Ghana, India, Ireland,	FAA 2019, ICAO 2017, Kelly et al. 2017, Kelly & Allan 2006, Kasso & Balakrishnan 2013, Leader et al. 2006, Metscher
	Israel, Japan, Mauritius, Nigeria, Panama,	et al. 2007, Parsons et al. 2008, 2009, Satheesan et al. 1992, Simons et al. 2014, STAC 2019, TC 2019, UKCAA 2019,
	Philippines, USA, Vietnam	Usman et al. 2012, Voigt et al. 2018, Peurach 2003, Peurach et al. 2009
Cricetidae	Canada, USA	Cleary et al. 2004, 2005, 2006, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008,
D 11		FAA 2019, ICAO 2017, Schwarz et al. 2014, TC 2019
Dasypodidae	USA	Cleary et al. 2004, 2005, 2006, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008,
Didalphidea	Prozil Canada USA	FAA 2019, ICAO 2017, Michelle et al. 2007, Schwalz et al. 2014 Biondi et al. 2014, Cleany et al. 1006, 2004, 2005, 2006, DeVeult et al. 2011, Delbeer et al. 2000, 2012, 2014, 2015
Dideipilidae	Blazil, Callada, USA	Dolbeer & Begier 2010, Dolbeer & Wright 2008, EAA 2019, ICAO 2017, Metscher et al. 2007, Noaves et al. 2016,
		Schwarz et al. 2019 Schwarz et al. 2019
Echimvidae	USA	Dolbeer & Begier 2019, FAA 2019, ICAO 2017
Equidae	Ethiopia, Kenya, USA	Avisure 2019, Cleary et al. 2004, 2005, 2006, Cleary & Dolbeer 2005, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer &
		Begier 2019, Dolbeer & Wright 2008, FAA 2019, Schwarz et al. 2014
Erethizontidae	USA	Cleary et al. 2004, 2005, 2006, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008,
		FAA 2019, ICAO 2017, Schwarz et al. 2014, TC 2019
Erinaceidae	France, Italy, Poland, UK	CAA Poland 2019, STAC 2019, UKCAA 2019
Felidae	Australia, Canada, Poland, USA, UK	ATSB, 2014, CAA Poland 2019, Cleary et al. 2004, 2005, 2006, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier
		2019, Dolbeer & Wright 2008, FAA 2019, ICAO 2017, Schwarz et al. 2014, IC 2019, UKCAA 2019

Geomyidae	USA, Canada	Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008, FAA 2019, Schwarz et al. 2014, TC 2019
Giraffidae	Botswana	Avisure 2019
Herpestidae	USA	Cleary et al. 2006, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008, FAA 2019, ICAO 2017, Schwarz et al. 2014
Hyaenidae	Kenya	UKCAA 2019
Leporidae	Australia, Canada, Cyprus, Denmark, France, Germany, Greece, Holland, Ireland,	ATSB 2014, 2018, Ball et al. 2020, Biondi et al. 2014, CAA Poland 2019, Cleary et al. 2004, 2005, 2006, Cleary & Dolbeer 2005, DAVVL e.V 2019, DeVault et al. 2011, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019,
	Italy, Mexico, Namibia, Poland, Spain USA,	Dolbeer & Wright 2008, 2009, FAA 2019, Hauptheisch et al. 2013, Hesse et al. 2012, ICAO 2017, Kelly & Allah 2006, Kitoweli 2016, MacKimpan et al. 2004, Matsahar et al. 2007, Sahwarz et al. 2014, STAC 2010, TC 2010, LIKCAA 2010
Maaranadidaa	UN Australia	ATCD 2014, 2019, IC 2019, UKCAA 2019
Maclopouluae	Ausualia Canada USA	A15D 2014, 2010 Cleary et al. 2004, 2005, 2006, DeVault et al. 2011, Dolbeer et al. 2000, 2013, 2014, 2015, Dolbeer & Regier 2010, Dolbeer
Mephitidae	Callada, USA	& Wright 2008, FAA 2019, Hesse et al. 2012, ICAO 2017, MacKinnon et al. 2004, Metscher et al. 2007, Schwarz et al. 2014, TC 2019
Muridae	Australia, Canada	ATSB 2018, Cleary et al. 2004, 2005, 2006, FAA 2019, ICAO 2017, TC 2019
Mustilidae	France, Germany, Poland, UK, USA	ATSB 2018, CAA Poland 2019, Cleary et al. 2004, 2005, 2006, DAVVL e.V 2019, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008, FAA 2019, ICAO 2017, Schwarz et al. 2014, STAC 2019, TC 2019, UKCAA 2019
Myrmecophagidae	Brazil	Noaves et al. 2016
Order Pilosa X	Brazil	Noaves et al. 2016
Peramelidae	Australia	ATSB 2014, 2018
Phalangeridae	Australia	ATSB 2014, 2018
Potoroidae	Australia	ATSB 2014
Procyonidae	Canada, USA	Cleary et al. 2004, 2005, 2006, Cleary & Dolbeer 2005, DeVault et al. 2011, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008, FAA 2019, ICAO 2017, Schwarz et al. 2014, TC 2019
Sciuridae	Canada, USA	Cleary et al. 1996, 2004, 2005, 2006, Biondi et al. 2014, DeVault et al. 2011, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008, 2009, FAA 2019, Metscher et al. 2007, Schwarz et al. 2014, ICAO 2017, TC 2019
Suidae	Poland, USA, Zimbabwe	CAA Poland 2019, Cleary et al. 2004, 2005, 2006, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008, FAA 2019, ICAO 2017, Kitowski 2016, Schwarz et al. 2014, Smith 2009
Tachyglossidae	Australia	ATSB 2014, 2018
Tayassuidae	USA	Cleary et al. 2004, 2005, 2006, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019, Dolbeer & Wright 2008,
Unidentified	Barbados, Brazil, Canada, France, Gambia,	Barras & Wright 2002, Cleary et al. 2004, 2005, 2006, Dolbeer et al. 2009, 2013, 2014, 2015, Dolbeer & Begier 2019,
	Mauritius, USA	Dolbeer & Wright 2008, FAA 2019, Mendonca et al. 2018, Schwarz et al. 2014, STAC 2019, TC 2019, UKCAA 2019,
Vombatidae	Australia	ATSB 2014, 2018

\*Families: Emballonuridae, Molossidae, Phyllostomidae, Pteropodidae, Rhinolophidae, Unknown, Vespertilionidae <sup>x</sup> Denontes that lowest taxonomic classification provided was Order.

457	Fig. 1. Number of strikes with mammals per one million aircraft movements (take-off run
458	and landing only) for civil airplanes from Australia (2008-2016, AUS), Canada (2008-2018,
459	CAN), France (2016-2018, FRA), Germany (2010-2017, GER) the UK (1990-2018) and the
460	USA (1990-2018).
461	
462	Fig. 2. Percentage (%) of overall strike events ( $\pm$ 95% Confidence Intervals) occurring in
463	each month (1 = January, 12 = December) for (A) Australia ( $n$ =1564), (B) Europe (France,
464	Germany, UK; <i>n</i> =381) and (C) North America (Canada and USA; <i>n</i> = 7059).
465	
466	Fig. 3. Percentage (%) of overall strike incidents (± 95% Confidence Intervals) with
467	mammals for each phase of flight by country: Australia (2008-2017, AUS; <i>n</i> =1199), Canada
468	(2010-2018, CAN; <i>n</i> =237), France (2016-2018, FRA; <i>n</i> =28), Germany (2010-2018, GER;
469	<i>n</i> =128), the UK (1990-2018; <i>n</i> = 105) and the USA (1990-2018; <i>n</i> =2877) for terrestrial (top)
470	and volant (bottom) mammals.
471	
472	Fig. 4. Percentage of strikes (± 95% Confidence Intervals) categorised into each damage
473	class inflicted to airplanes in Australia (2008-2017, AUS; <i>n</i> = 1179), France (2016-2018,
474	FRA; <i>n</i> = 126), Germany (2010-2018, GER; <i>n</i> = 140) and the USA (1990-2018; <i>n</i> = 3055)
475	

## 477 SUPPORTING INFORMATION

- 478 Additional supporting information may be found in the online version of this article at the
- 479 publisher's website.
- 480 Appendix S1. Aviation authorities researched and/ or contacted in order to obtain mammal-
- 481 strike data. Data were only available from six countries.
- 482 Appendix S2. Retained variables across datasets for six countries, provided by aviation
- 483 authorities.
- 484 **Appendix S3.** Relevant articles that were retained from the literature survey.
- 485 Appendix S4. Mammal families involved in wildlife strike events with aircraft other than
- 486 civil airplanes reported in organisational, grey and scientific literature, and the country or
- 487 countries of occurrence.
- 488 Appendix S5. Strike numbers and percentages of each mammal family involved in strikes in
- 489 the USA, Australia, Germany and France.
- 490 Appendix S6. Strike numbers and percentages for each mammal family involved in strikes in
- 491 Canada and the UK.
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**Fig. 1.** Number of strikes with mammals per one million air movements (take-off run and landing only) for civil airplanes from Australia (2008-2016, AUS), Canada (2008-2018, CAN), France (2016-2018, FRA), Germany (2010-2017, GER) the UK (1990-2018) and the USA (1990-2018).



**Fig. 2**. Percentage (%) of overall strike events ( $\pm$  95% Confidence Intervals) occurring in each month (1 = January, 12 = December) for (A) Australia (*n*=1564), (B) Europe (France, Germany, UK; *n*=381) and (C) North America (Canada and USA; *n*= 7059).



**Fig. 3**. Percentage (%) of overall strike incidents ( $\pm$  95% Confidence Intervals) with mammals for each phase of flight by country: Australia (2008-2017, AUS; *n*=1199), Canada (2010-2018, CAN; *n*= 237), France (2016- 2018, FRA; *n*= 28), Germany (2010-2018, GER; *n*=128), the UK (1990-2018; *n*= 105) and the USA (1990-2018; *n*=2877) for terrestrial (top) and volant (bottom) mammals.



**Fig. 4.** Percentage of strikes ( $\pm$  95% Confidence Intervals) categorised into each damage class inflicted to airplanes in Australia (2008-2017, AUS; *n*= 1179), France (2016-2018, FRA; *n*= 126), Germany (2010-2018, GER; *n*= 140) and the USA (1990-2018; *n*= 3055)



47 countries reported strike events with • mammals

- 44 relevant articles highlighting strike events 9 with mammals
- Reported strike events with mammals have ~~ been increasing since 1990
- An estimated \$103 million in repair costs caused by mammal strikes in the USA alone since 1990



#### Conclusion

Monitoring of existing wild mammal populations is required to understand temporal trends in presence, abundance and activity patterns to inform management decisions

Graphical abstract

338x190mm (96 x 96 DPI)