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REVIEW

Runway roadkill: a global review of mammal strikes with aircraft

Samantha BALL* *School of Biological, Earth and Environmental Science, Distillery Fields, University College Cork, Cork, T23 TK30, Ireland and Dublin Airport Authority, Airport Fire and Rescue Service, Dublin, K67 CX65, Ireland. Email: Samantha.ball@ucc.ie*
Anthony CARAVAGGI *School of Applied Sciences, University of South Wales, 9 Graig Fach, Glyntaff, Pontypridd, CF37 4BB, UK. Email: anthony.caravaggi@southwales.ac.uk*
Fidelma BUTLER *School of Biological, Earth and Environmental Science, Distillery Fields, University College Cork, Cork, T23 TK30, Ireland. Email: f.butler@ucc.ie*

Keywords
aircraft, airfields, human–wildlife conflict, mammal strikes, strike mitigation, wildlife management, wildlife strikes

*Correspondence.

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ABSTRACT

1. 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.
2. 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.
3. We identified 40 families that were involved in strike events in 47 countries. Reported mammal strike events have been increasing by up to 68% annually. Chiroptera (4 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 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 was greatest during late summer, with some international variation. The total estimated cost of damage resulting from reported mammal strikes exceeded US$103 million in the USA alone, over 30 years.
4. Mammal strikes represent a substantial risk in airfield environments. Monitoring of existing wild mammal populations is required to understand temporal trends in 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.

Mots clés
aerodrome, atténuation des collisions, avion, collision de mammifères, collisions avec la faune, conflit homme-faune, prévention du risque animalier

RESUMÉ 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.

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

3. 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.

4. Les collisions impliquant un mammifère représentent un risque environnemental élevé pour les aéroports, tant pour l'intégrité des avions que pour la sécurité des passagers. 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 populations. Les études permettent d'accompagner les opérateurs d'aéroports dans la prise de décision liées à la prévention des risques naturels. A l'échelle mondiale, il est nécessaire de disposer de rapports plus nombreux et plus détaillés sur les cas de collisions afin d'enrichir les stratégies de gestion des risques animaliers et de réduire efficacement le nombre de collisions.

INTRODUCTION

Airports and the services that they provide are vital to the global economy. In 2018 alone, over four billion passengers were carried by aircraft, and airline industry revenues exceeded US$812 billion (IATA 2019). While airports can contextually constitute environmental disturbances (Blackwell et al. 2013), the airport environment can provide productive habitat for wildlife (Soldatini et al. 2010, Hauptfleisch & Avenant 2015), due to expanses of seminatural grasslands. In the USA alone, there is in excess of 3300 km^2 of grassland in airfields (DeVault et al. 2012, Washburn & Seamans 2013, Pfeiffer et al. 2018), creating favourable ecological habitats, often in heavily urbanised areas (DeVault et al. 2012). These grasslands can be 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).

Incidents with avian species make up the majority of wildlife strikes (e.g. 95% of strike events in the USA involve birds; Dolbeer & Begier 2019) and therefore the bulk of available literature focuses on avian taxa. Strike data are generally lacking for other taxa, including mammals, which are estimated to make up approximately 5% of strikes in the USA (Dolbeer & 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 (e.g. Dolbeer 2015). Airport operators have a legal obligation to reduce wildlife hazard at airfields (Mendonca et al. 2017). It is therefore important for airport managers and staff to understand the relative risk associated with each species, in order to prioritise and implement effective Wildlife Hazard Management Plans (WHMP).

Understanding the importance of wildlife strikes and associated hazards requires the collection and analysis of strike data. Long-term databases recording animal strike incidents and damage (Dolbeer & Wright 2009), kept by national aviation authorities, are valuable tools 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 the true frequency with which wildlife strikes occur (Biondi et al. 2011). For example, reporting is mandatory within the European Union (EU), but not in the USA. While previous work has been conducted on mammal strikes with aircraft by looking at specific mammal groups in the USA, such as bats (Biondi et al. 2013), deer (Biondi et al. 2011) and carnivores (Crain et al. 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 the baseline reference with little global context.

We review the available literature and collate mammal strike data from six national 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). 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 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 of national databases as a tool to understand the patterns associated with mammal strike events. 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 with aircraft and inform wildlife management on both national and international scales.

METHODS

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 aircraft collisions with mammals. The search terms ‘mammal strike’, ‘wildlife-strike’, ‘animal strike’, ‘mammal collision’, ‘wildlife collision’, ‘animal collision’, ‘aircraft’, ‘aviation’ and ‘airplane’ were applied for two searches: 1) with just search terms; and 2) with search terms alongside mammal taxa frequently involved in strike events (Canidae, Cervidae, Chiroptera, 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 references within the literature. Relevant ‘grey literature’ (i.e. conference proceedings, government reports) were retained.

National aviation authorities were contacted to request mammal strike records (Appendix S1). Data on strikes were obtained from six aviation databases and record centres. Data were obtained from the website of: 1) the ‘Australian Transport and Safety Bureau’ (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’ (STAC; 2016–2018; STAC 2019); 4) the German ‘Deutscher Ausschuss zur Verhütung von Vogelschlägen im Luftverkehr e.V’. (DAVVL e.V.; 2010–2018; DAVVL e.V. 2019); and 5) the ‘UK Civil Aviation Authority’ (UKCAA; 1990–2018; UKCAA 2019). Finally, data were obtained from the website of: 6) the US ‘Federal Aviation Administration’ (FAA; 1990–2018; FAA 2019). All data were accessed and provided between February 2019 and March 2020. Wildlife strike reporting was mandatory in all countries analysed, except for the USA. 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 only mammals the size of a rabbit or larger are reported). All databases were screened to remove non-strike incidents (i.e. near misses, disruptions); a strike was deemed to have occurred if there was sufficient evidence (i.e. a carcass was found or damage was inflicted). In all databases, strikes involving helicopters, gyrocopters, and military aircraft (but see Zakrajsek & Bissonette 2005, Peurach et al. 2009) were removed, to isolate incidents with civil (commercial and private) airplanes. The databases included reports of strikes with domestic animals; thus, we included both wild and domestic non-human mammal taxa (e.g. Hesse et al. 2010). As there is no single, central reporting organisation and reporting of strike incidents is voluntary in some areas (e.g. USA), reporting falls to multiple organisations, airports, and individuals. Hence, data were largely inconsistent in terms of detail and temporal information. These limitations were overcome by applying a consistent data management framework that was compatible with all databases (i.e. categorising mammals according to taxon and categorising strike data, as outlined below). Available variables from databases are shown in Appendix S2.

For the ATSB, TC, DAVVL e.V., and FAA databases, strike incidents were summarised for time of day, where phase of flight was also provided, based on the local time reported. We defined both ‘day’ (08:00–18:00 h) and ‘night’

(20:00–06:00 h) as 10-hour periods, while ‘dawn’ (06:00–08:00 h) and ‘dusk’ (18:00–20:00 h) were each two hours (Washburn & 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 Organization’s (ICAO) aircraft damage taxonomy (ICAO 1989). We classified damage in the same way using data from the DAVVL e.V. and STAC databases, depending on where damage was inflicted. Data on damage from the TC and UKCAA databases were insufficient for 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 to aircraft from strikes with mammals for 397 strike events from a total of 1077 in which damage was inflicted (1990–2018). This was the only database which provided any detail on costings. To estimate the economic impact of damaging mammal strikes in the USA using these values, the average (mean) cost of repairs from a strike incident was determined for each damage category (‘minor’, ‘substantial’, ‘destroyed’, and ‘unspecified’). The mean cost was then multiplied by the total number of incidents within each category to obtain an overall estimate of damage costs inflicted by mammal strikes from 1990 to 2018, as per Biondi et al. (2011) and Crain et al. (2015).

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

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

RESULTS

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 (Table 1). In addition to these families, the Ursidae (bear) and the Otariidae (eared seals) were reported to have caused disruptions without resulting in strike events (FAA 2019) and the Old World leaf-nosed bats (Hipposideridae) were identified as having been involved in strike events with military aircraft (Peurach et al. 2009). A total of 15 families were identified to have been involved in a strike event with aircraft other than civil airplanes (e.g. Washburn et al. 2017; Appendix S4).

A total of 13 mammal families were involved in strike events in Australia, amounting to 1564 events, or 9.6% of the national total of all strike events (mammalian and non-mammalian species). Only 1024 strikes involved

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

Taxon	Country/Countries	References
Antilocapridae	Nigeria, USA	Cleary et al. (1996, 2004, 2005, 2006), Cleary and Dolbeer (2005), ICAO (2009), Dolbeer et al. (2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and Wright (2008), FAA (2019), Schwarz et al. (2014), Usman et al. (2012)
Bovidae	Australia, Bolivia, China, Germany, Guyana, India, Kenya, South Sudan, UK, USA, Venezuela	ATSB (2014, 2018), Avisure 2019, Cleary et al. (2004, 2005, 2006), Cleary and Dolbeer (2005), Dolbeer et al. (2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and Wright (2008), Drey et al. (2014), FAA (2019), ICAO (2017), Schwarz et al. (2014), UKCAA (2019)
Canidae	Australia, Brazil, Canada, Costa Rica, Cyprus, Egypt, France, Germany, Greece, Italy, Namibia, Poland, Portugal, Sweden, UK, USA	ATSB (2014, 2018), Avisure (2019), Barras and Wright (2002), Bergman et al. (2009), CAA Poland (2019), Cleary et al. (1996, 2004, 2005, 2006), Cleary and Dolbeer (2005), Crain et al. (2015), DAVVL e.V. (2019), DeVault et al. (2011), Dolbeer (2000), Dolbeer et al. (2013), Dolbeer et al. (2000, 2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and Wright (2008, 2009), Drey et al. (2014), 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 and Begier (2019), FAA (2019), ICAO (2017), Schwarz et al. (2014)
Cercopithecidae	Namibia	Hauptfleisch et al. (2013)
Cervidae	Australia, Canada, France, Germany, Poland, Switzerland, UK, USA	ATSB (2018, Avisure (2019), Barras and Wright (2002), Biondi et al. (2011), CAA Poland (2019), Cleary et al. (1996, 2004, 2005, 2006), Cleary and Dolbeer (2005), DAVVL e.V. (2019), DeVault et al. (2011), Dolbeer (2000), Dolbeer et al. (2000, 2008, 2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and Franklin (2013), Dolbeer and Wright (2008, 2009), Dolbeer et al. (2014), Drey et al. (2014), FAA (2019), Fagerstone and Clay (1997), Hesse et al. (2012), ICAO (2017), Kelly and Allan (2006), Kitowski (2016), MacKinnon et al. (2004), Metscher et al. (2007), Scheideman et al. (2017), Schwarz et al. (2014), Seamans (2001), STAC (2019), TC (2019), UKCAA (2019), VerCauteren et al. (2013), Wenning et al. (2004), Wright et al. (1998), Wright and Dolbeer (2000), Wright et al. (2005)
Chiroptera*	American Samoa, Argentina, Australia, Barbados, China, El Salvador, Dominican Republic, Germany, Ghana, India, Ireland, Israel, Japan, Mauritius, Nigeria, Panama, Philippines, USA, Vietnam	ATSB (2018), Biondi et al. (2013), Cleary et al. (2004, 2005, 2006), Cleary and Dolbeer (2005), DAVVL e.V. (2019), DeVault et al. (2011), Dolbeer et al. (2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and Wright (2008), Dove et al. (2008b), FAA (2019), ICAO (2017), Kelly et al. (2017), Kelly and Allan (2006), Kasso and Balakrishnan (2013), Leader et al. (2006), Metscher et al. (2007), Parsons et al. (2008, 2009), Satheesan et al. (1992), Simons et al. (2014), STAC (2019), TC (2019), UKCAA (2019), Usman et al. (2012), Voigt et al. (2018), Peurach et al. (2009)
Cricetidae	Canada, USA	Cleary et al. (2004, 2005, 2006), Dolbeer et al. (2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and Wright (2008), 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 and Begier (2019), Dolbeer and Wright (2008), FAA (2019), ICAO (2017), Metscher et al. (2007), Schwarz et al. (2014)
Didelphidae	Brazil, Canada, USA	Biondi et al. (2014), Cleary et al. (1996, 2004, 2005, 2006), DeVault et al. (2011), Dolbeer et al. (2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and Wright (2008), FAA (2019), ICAO (2017), Metscher et al. (2007), Noaves et al. (2016), Schwarz et al. (2014), TC (2019)
Echimyidae	USA	Dolbeer and Begier (2019), FAA (2019), ICAO (2017)
Equidae	Ethiopia, Kenya, USA	Avisure (2019, Cleary et al. (2004, 2005, 2006), Cleary and Dolbeer (2005), Dolbeer et al. (2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and Wright (2008), FAA (2019), Schwarz et al. (2014)
Erethizontidae	USA	Cleary et al. (2004, 2005, 2006), Dolbeer et al. (2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and 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 and Begier (2019), Dolbeer and Wright (2008), FAA (2019), ICAO (2017), Schwarz et al. (2014), TC (2019), UKCAA (2019)

(Continues)

Table 1. (Continued)

Taxon	Country/Countries	References
Geomyidae	USA, Canada	Dolbeer et al. (2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and 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 and Begier (2019), Dolbeer and Wright (2008), FAA (2019), ICAO (2017), Schwarz et al. (2014)
Hyaenidae	Kenya	UKCAA (2019)
Leporidae	Australia, Canada, Cyprus, Denmark, France, Germany, Greece, Holland, Ireland, Italy, Mexico, Namibia, Poland, Spain USA, UK	ATSB (2014, 2018), Ball et al. (2020), Biondi et al. (2014), CAA Poland (2019), Cleary et al. (2004, 2005, 2006), Cleary and Dolbeer (2005), DAVVL e.V. (2019), DeVault et al. (2011), Dolbeer et al. (2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and Wright (2008, 2009), FAA (2019), Hauptfleisch et al. (2013), Hesse et al. (2012), ICAO (2017), Kelly and Allan (2006), Kitowski (2016), MacKinnon et al. (2004), Metscher et al. (2007), Schwarz et al. (2014), STAC (2019), TC (2019), UKCAA (2019)
Macropodidae	Australia	ATSB (2014, 2018)
Mephitidae	Canada, USA	Cleary et al. (2004, 2005, 2006), DeVault et al. (2011), Dolbeer et al. (2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and 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 and Begier (2019), Dolbeer and 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 and Dolbeer (2005), DeVault et al. (2011), Dolbeer et al. (2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and 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 and Begier (2019), Dolbeer and 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 and Begier (2019), Dolbeer and 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 and Begier (2019), Dolbeer and Wright (2008), FAA (2019), Schwarz et al. (2014)
Unidentified	Barbados, Brazil, Canada, France, Gambia, Mauritius, USA	Barras and Wright (2002), Cleary et al. (2004, 2005, 2006), Dolbeer et al. (2009, 2013, 2014, 2015), Dolbeer and Begier (2019), Dolbeer and Wright (2008), FAA (2019), Mendonca et al. (2018), Schwarz et al. (2014), STAC (2019), TC (2019), UKCAA (2019), VerCauteren et al. (2005)
Vombatidae	Australia	ATSB (2014, 2018)

* Families: Emballonuridae, Molossidae, Phyllostomidae, Pteropodidae, Rhinolophidae, Unknown, Vespertilionidae.
[X] Denontes that the lowest taxonomic classification provided was order.

mammals that could be identified to family level; many strikes ($n = 540$) involving members of the order Chiroptera were recorded as 'bats'. In the USA, 25 mammal families were identified as having been involved in strike events from 6661 events, constituting 3.2% of the national total. A mammal family (Pteropodidae) not naturally found in the USA was reported as the family involved in strike events in two American airports. This may be as a result of misidentification, escaped captives or the bat may have been carried on an airplane from the country of origin and subsequently 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 S5 and S6).

Utilising the data from all six national aviation authorities resulted in a database of 9004 confirmed strike events with mammals. In Australia, order Chiroptera accounted for the 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%, UK: 52%) and Canidae (Canada: 21%, Germany: 16%, UK: 17%) were most frequently 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 multiple mammals accounted for 4.9% of all records.

All countries reported an increase over time in the annual recorded strike rate. In Australia, there was an average of 38.7 ± 15.7 (mean ± standard deviation, SD) reported strikes 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 reported an average of 8.1 ± 2.9 (mean ± SD) strikes/MAM/year and an average annual increase of 9% (CI: 4%–13%; $\rho = 0.77$), with significant variation between years ($\chi^2_{9,\ 398}$, $P < 0.01$). France reported an average of 17.4 ± 4.3 (mean ± 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 Germany, there was an average of 3.6 ± 4.9 (mean ± SD) reported strikes/MAM/year; strike events increased by an annual average of 68% (CI: 56%–80%; $\rho = 0.95$), with significant variation between years ($\chi^2_{7,\ 140}$, $P < 0.001$). In the UK, there was an average of 1.2 ± 2.4 (mean ± 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 ($\chi^2_{18,\ 115}$, $P < 0.001$). Finally, there was an average of 2.3 ± 2.1 (mean ± SD) reported strikes/MAM/year in the USA; reported strike events with mammals increased annually by an average of 10% (CI: 9%–10.5%; $\rho = 0.99$), with significant variation between years ($\chi^2_{27,\ 6661}$, $P < 0.001$; Fig. 1). No country surpassed the ICAO acceptable level given in safety guidelines, of five strikes per 10000 aircraft movements (500/MAM/year; ICAO 2012).

In Australia ($H_{(11)} = 41.27$, $P < 0.01$) and North America ($H_{(11)} = 63.3$, $P < 0.01$), there were identifiable peaks in strike frequency between months, but in Europe, strike frequency fluctuated across the year without pattern. For Australia, highest strike numbers were recorded during March to May (37% of strike events), with a significant difference between strike event 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 strike events were recorded between July and November, with the highest strike numbers recorded in October (18%; Fig. 2).

There were significant differences in strike frequency according to phase of flight between volant taxa ($H_{(5)} = 17.1$, $P < 0.01$) and terrestrial taxa ($H_{(4)} = 88.0$, $P < 0.01$). Across all 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 ($H_{(5),\ 3113} = 98.9$, $P < 0.01$). Generally, the landing roll phase, followed by the take-off run, yielded the highest frequency of strike events (Fig. 3). Australia formed an exception to this: both the landing roll and the approach conferred the greatest strike risk (59% of all strikes). In North America, the landing roll was the only phase that resulted in significantly elevated strike risk (21% of all strikes). Australia and North America (USA; $n = 615$, CAN; $n = 1$) were the only two continents 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).

Mammal strikes frequently resulted in damage to aircraft in some areas: damage was reported for 18%, 3%, 1%, and 17% of strike events with mammals in Australia, France, Germany, and the USA, respectively (Fig. 4). Damage could not be classified for UKCAA or TC data. Damage costs were provided for only the USA, where total reported cost of repairs 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 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 strikes. In France and Germany, the Canidae, Cervidae, and Leporidae were involved in all damaging strikes (Appendix S5). The FAA and ATSB provided data on human injuries within the database: 25 people were reported to have been

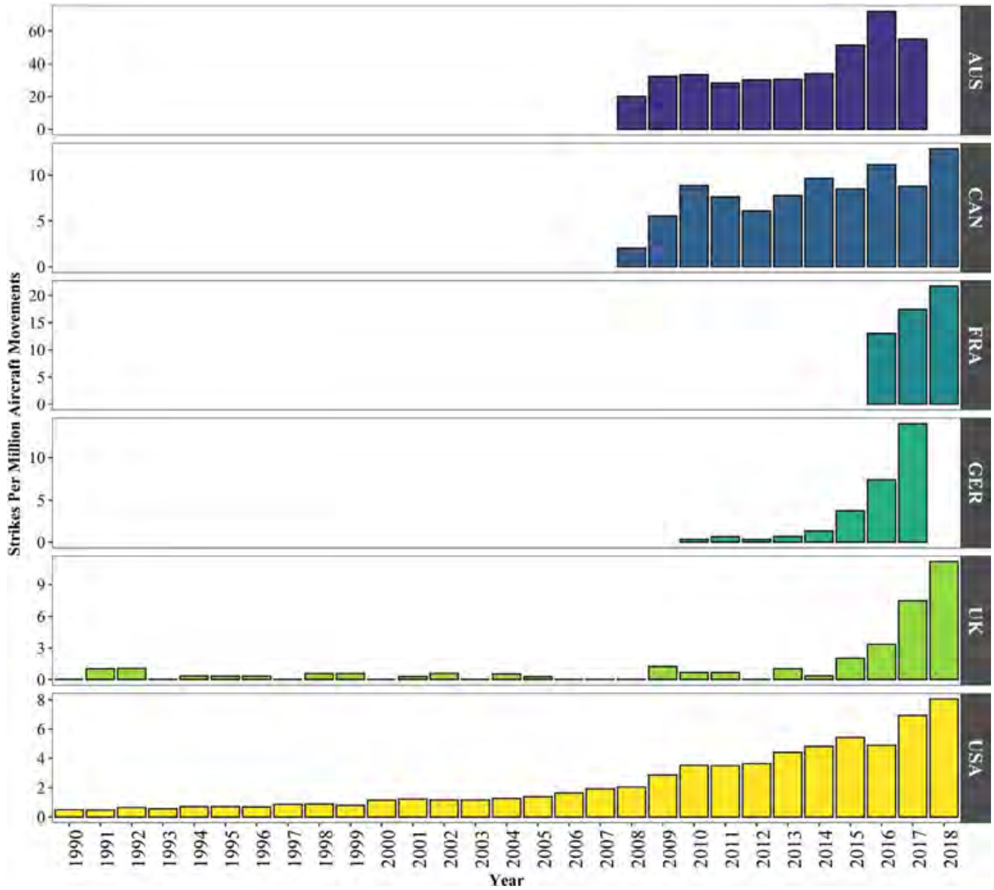

Fig. 1. Number of strikes with mammals per one million aircraft movements (take-off run and landing only) for civil airplanes from Australia (2008–2016, AUS), Canada (2008–2018, CAN), France (2016–2018, FRA), Germany (2010–2017, GER) the UK (1990–2018, UK) and the USA (1990–2018, USA).

injured as a result of mammal strikes, and there was one reported human fatality.

DISCUSSION

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

There is a paucity of information available on mammal taxa involved in strike events, with the exception of Canidae, Cervidae, and the Chiroptera. The mammal taxa involved in 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 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 demonstrates the need for more accurate and complete recording of information from each area. The majority of mammal strike research is focused on just two families, the Canidae (e.g. Crain et al. 2015) and the Cervidae (e.g. Biondi et al. 2011), as these two families are involved in 94% of damaging strikes involving mammals in the USA, where the majority

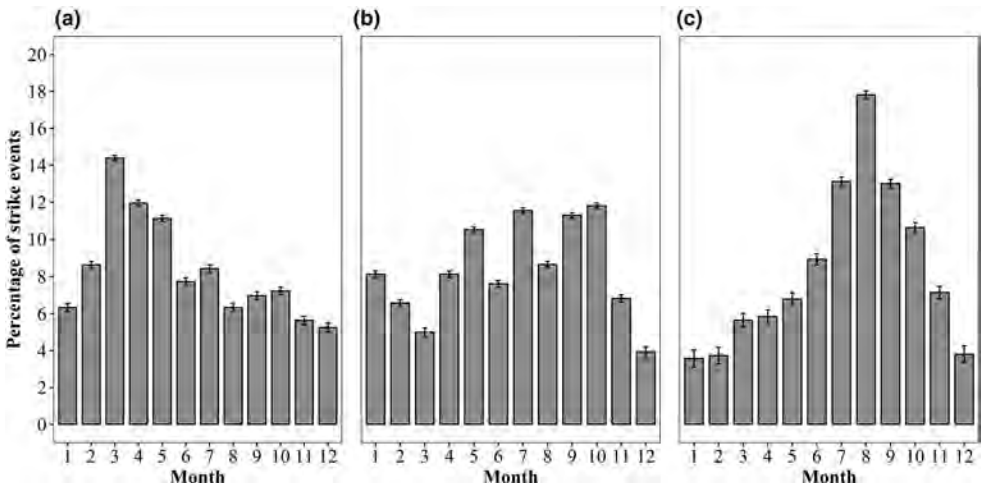

Fig. 2. Percentage (%) of overall strike events (±95% Confidence Intervals) occurring in each month (1 = January, 12 = December) for (a) Australia (n = 1564), (b) Europe (France, Germany, UK; n = 381) and (c) North America (Canada and USA; n = 7059).

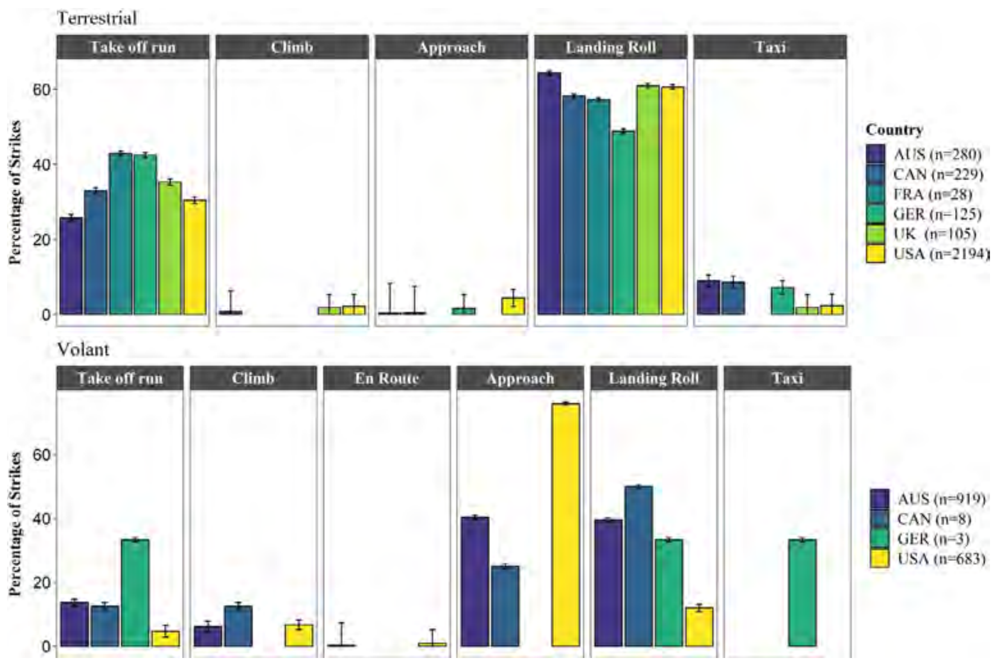

Fig. 3. Percentage (%) of overall strike incidents (±95% Confidence Intervals) with mammals for each phase of flight by country: Australia (2008–2017, AUS; n = 1199), Canada (2010–2018, CAN; n = 237), France (2016–2018, FRA; n = 28), Germany (2010–2018, GER; n = 128), the UK (1990–2018; UK; n = 105)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

of strike research has been undertaken. Elsewhere, damaging strikes were dominated by the Chiroptera in Australia and the Leporidae in Europe. Therefore, mitigiation measures developed in the USA for the specific fauna of North America may not be effective for high-risk species in other parts of the world. As air travel is a global industry, increased research efforts targeted at high-risk mammal families outside the USA would benefit not only the national aviation authorities responsible for the research, but also international authorities and airline operators. A more thorough understanding of the ecology of mammal groups inhabiting and using airfields is required to maximise the efficacy of any mitigation measures (e.g. Scheideman et al. 2017).

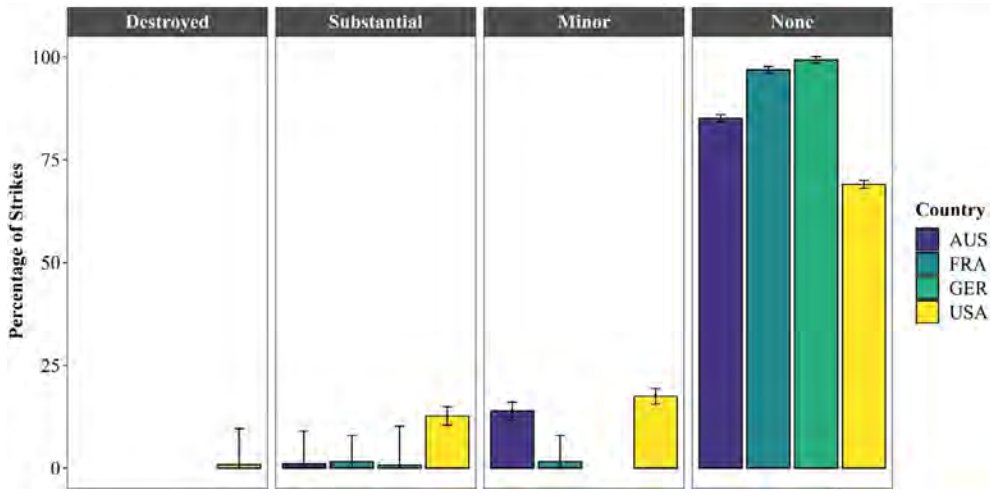

Fig. 4. Percentage of strikes (±95% Confidence Intervals) categorised into each damage class inflicted to airplanes in Australia (2008–2017, AUS; *n* = 1179), France (2016–2018, FRA; *n* = 126), Germany (2010–2018, GER; *n* = 140) and the USA (1990–2018; USA; *n* = 3055).

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

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

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

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

Under-reporting of strikes is recognised on both an international and national level: estimates suggest that only 5%–47% of wildlife strikes are reported to aviation authorities (Linnell et al. 1999, Wright et al. 2005, Dolbeer & Wright 2009, Dolbeer 2015). Indeed, the reporting of strike events remains voluntary in many countries. A total of 2295 mammal strikes were reported to the ICAO during the years 2008–2015. However, during this same time period, 4263 mammal strike events were recorded by five civil aviation authorities included in 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 (ICAO 2009). Therefore, it is unlikely that current estimates are accurate reflections of numbers of mammal strike events. Such discrepancies represent important caveats to, and limit the utility of, broad guidelines developed by civil aviation authorities and the ICAO (e.g. ICAO 2012). Despite the FAA's assurance that current data are adequate to track national trends (Dolbeer 2015), improvements are nevertheless required to identify the true extent of the risks posed to and by mammals, and to evaluate the effectiveness of WHMPs and mitigation practices (Dolbeer & Wright 2009). This is particularly true for areas outside of the USA, as the numbers reported to the ICAO indicate severe under-reporting 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 (Australia, Europe and North America). Differences in economic development may, in part, be reflective of differences in national flight capacity and frequency, or of levels of compliance to international organisations from other nations. Therefore, it is not possible to infer global strike rates from our data. Nevertheless, the observed increase in strike events over time per million aircraft movements (MAM/year) in all the countries we studied suggests that our findings have broad relevance. Furthermore, terrestrial mammals involved in strikes were not identified to the species level in <1% of instances, and bats were not identified to the species level in 17% of instances in the current study. The specific identification of taxa involved in strike events is 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 recommend the use of forensic DNA analysis (Peurach et al. 2009, Kelly et al. 2017) to identify otherwise 'unknown' species, thereby giving more nuanced ecological insight and subsequently improving management strategies.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's website.

Appendix S1. Aviation authorities researched and/ or contacted in order to obtain mammal-strike data. Data were only available from six countries.
Appendix S2. Retained variables across datasets for six countries, provided by aviation authorities.
Appendix S3. Relevant articles that were retained from the literature survey.
Appendix S4. Mammal families involved in wildlife strike events with aircraft other than civil airplanes reported in organisational, grey and scientific literature, and the country or countries of occurrence.
Appendix S5. Strike numbers and percentages of each mammal family involved in strikes in the USA, Australia, Germany and France.
Appendix S6. Strike numbers and percentages for each mammal family involved in strikes in Canada and the UK.

