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Mammal management: Strike mitigation measures and practices at European airports

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ABSTRACT

Airfield environments can be attractive to a broad range of wildlife, including mammals, and rates of wildlife-aircraft collisions are generally increasing, globally. It is important, therefore, that the components of an airfield that may be attractive to wildlife and the effectiveness of current mammal-exclusion and strike mitigation measures, are understood. However, the suite of applied measures and the efficacy thereof differs between airfields. The collation of such information would represent a useful tool in potentially mitigating strike frequency or severity for airfield managers. To this end, an online survey was distributed to personnel responsible for wildlife management at airfields in Europe (Belgium, France, Greece, Ireland, Spain and the UK) between July 2020–March 2021. Mammals were recorded at all responding airfields (n = 22), while mammal strikes were recorded at 21 locations. A mammal sightings index scored foxes (91% of airfields) and rabbits (81% of airfields) as the most frequently recorded species. The presence of specific habitat (mainly heathland/peatland) airside was associated with a high mean mammal diversity at airfields in Ireland, the UK and Belgium which reported the presence of this habitat type. The erection of fencing and grassland management measures were the most frequently implemented mitigation measures, while managing water sources within the airfield environment was ranked as the most successful mitigation measure. Our study highlights the need for Wildlife Hazard Management Plans to consider an integrated management approach that not only mitigates general strike risk but is also adaptable to species of particular concern.

1. Introduction

Airfield environments can create vast expanses of semi-natural habitat (DeVault et al., 2012) in often heavily anthropogenically modified landscapes, including urban and agricultural areas. As such, land management beyond the boundaries of the airfield is often outside of the control of airport authorities, but can render airfield environments attractive to wildlife (Martin et al., 2011). This can be due to airfields acting as resource ‘islands’ in urban areas (Hesse et al., 2010) or due to undeveloped land surrounding an airfield providing habitat to support species which could be considered hazardous to aviation (VerCauteren et al., 2013). Some wildlife species can be hazardous to aviation and result in wildlife-aircraft collisions, hereafter referred to as ‘strikes’. While the majority of strike events are recorded with avian species (94% of strikes in the USA in 2019; Dolbeer and Begier 2021), strikes with mammals are reported to constitute between 3 and 10% of events, depending on geographical location and national faunal composition (Ball et al., 2021b). The number of reported strike events involving mammals has been increasing in Australia, North America and Europe (France, Germany, Poland, UK; Ball et al. 2021). Identifying the components of the landscape (both airside and landside) which could be deemed attractive to wildlife need to be carefully considered and implemented into Wildlife Hazard Management Plan’s (WHMP) to aid strike mitigation efforts (Coccon et al., 2015). This is particularly relevant as there have been increased instances of mammal species utilising modified landscapes and food sources in recent decades (e.g. Gil-Fernández et al., 2020), potentially leading to increased potential for strikes (but see Pfeiffer et al., 2020).

Whilst strikes with avian species can occur within (e.g., Kelly et al., 2017) or outside of the aerodrome, strikes with non-volant mammals are

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limited to the airfield environment. Airfields are inherently physically-protected environments with measures in place to exclude mammals - including humans - from gaining access to critical areas. Despite this, many species still access the airfield (e.g. white tailed deer (*Odocoileus virginianus*; Biondi et al., 2011) and black bear (*Ursus americanus*, Scheideman et al., 2017), or even establish populations inside the airfield boundary, where they are relatively undisturbed (e.g. Irish hare *Lepus timidus hibernicus*; Ball et al., 2021a). The presence of mammals on airfields not only causes disruptions to ongoing airfield operations (e.g. go-arounds, aborted take-offs), but present hazards that have substantial economic impacts. For example, Air France was awarded €4 million in 2005, after a bird strike event with gulls that were scavenging an undetected hedgehog (*Erinaceus europaeus*) carcass, resulted in engine damage (Dale, 2009).

Airfield managers use various mitigation measures to exclude, disperse and harass wildlife utilising the airfield environment. Both 'active' (lethal and non-lethal) and 'passive' mitigation measures are implemented to varying degrees. Active measures involve the exclusion or removal of wildlife from the airfield (e.g. fencing; DeVault et al., 2008) and dispersing animals from critical areas (e.g. noise harassment; Hesse et al., 2010). Passive measures include habitat modification to alter the attractiveness of the airfield (e.g. maintaining long grass; dos Santos et al., 2017). Active exclusion techniques are thought to be one of the most effective methods for reducing terrestrial mammal hazard at airfields by reducing access to the airfield environment (Stull et al. 2011; VerCauteren et al., 2013). Strike events with mammals are rarely completely eliminated, however, with several species (e.g. deer, canids, bears) having been known to breach airport fencing (Scheideman et al., 2017; VerCauteren et al., 2013).

Despite increasing strike rates and associated complexities associated with implementing mitigation measures, there is a dearth of information on the use of available measures and their effectiveness in airfields in Europe. As the vast majority of wildlife strike mitigation and airfield wildlife management research focuses on avian taxa in the USA (e.g. Askren et al., 2019), there are few accessible data of the mammal taxa utilising airfields in the European context, or of the recording and incorporation of mammals into airfield's WHMPs. Here, we describe the mammal communities and identify the most frequently sighted mammal taxa at airfields. We also investigated the response of airfield managers to mammal presence at airfields by evaluating the mitigation measures implemented by airfields and the perceived effectiveness of available methods for mammal exclusion and strike mitigation.

2. Methods

2.1. Ethical approval

The survey was approved by University College Cork's Social Sciences Ethics Committee.

All participants were provided with an information sheet in addition to the main survey and the consent form was embedded into the start of the survey. All participants were given the option to remain anonymous and were informed of their ability to withdraw their consent from the survey. Both the information sheet and associated consent form are available in the supplementary material (A.1 and A.2).

2.2. Survey

An online survey similar to Hesse et al. (2010) was conducted between July 2020–March 2021. The survey was primarily concerned with the order 'Mammalia' in Europe to: (i) gather information on the presence and diversity of mammalian taxa utilising airfields; (ii) identify physical environmental factors that may be attractive to mammals both airside (i.e. beyond passport and customs control) and within a 2 km radius (i.e. non-airfield habitat) of the airfield; and (iii) collate information on the response to mammals by airfield managers, including mammal presence, strike recording systems, and mitigation measures and their perceived success (see A.3 for survey questions). The survey originally focused on airfields throughout Ireland, incorporating both the Republic (ROI) and Northern Ireland (NI) due to faunal similarities. The survey was subsequently extended to respondents in Britain and several European countries (Belgium, France, Greece, Italy, Spain).

The survey comprised a combination of open format (i.e. prose responses) and closed format questions (i.e. multiple choice, rating, matrix). We included both wild and domestic (e.g. dog) taxa in the survey, as animal management of domestic species on the airfield often falls to the responsibility of wildlife management personnel. Surveys were distributed by the authors, via email, to 13 wildlife management personnel in Ireland (Republic of Ireland, n = 10; Northern Ireland, n = 3) and 25 in Britain. A further five contacts in continental Europe (Belgium, France, Greece and Spain) were emailed based on prior agreements regarding participation. Surveys were also sent via a contact in the UK Civil Aviation Authority (UK CAA) to wildlife management personnel in Britain. Due to data protection concerns, the identity of personnel contacted cannot be provided.

2.3. Mammal sighting index

The frequency with which each wildlife group was recorded at an airfield (question 14, A.3) was assessed using a weighted, three-point rating scale: 'frequently' (3); 'occasionally' (2); and 'never' (1). Respondents were also provided with the option to select 'unsure', which was subsequently excluded from index analysis and used as a measure of uncertainty. The number of responses for each variable was then multiplied by the corresponding weighting and the mean used as an indication of how frequently a taxon was recorded at airfields overall (adapted from Fernandez-Bellon et al., 2020). Values closer to 3 indicated that they were frequently observed whereas values closer to 1 indicated that they were not frequently encountered. The diversity of mammals recorded at each responding airfield was calculated according to the number of taxa that were reported as being seen either 'frequently' or 'occasionally'.

2.4. Wildlife attractants

Respondents were asked to identify if particular land uses which could be deemed attractive to wildlife were present either airside (i.e. past airport security) or landside (i.e. external to the airfield), within a 2 km radius of the airfield (question 12, S I3). Respondents were asked to record if any of the 9 following land uses, hereafter referred to as wildlife attractants, were present: Agricultural crops, diverse habitat (e.g. woodland), fresh water source (e.g. stream), heath land or bog-land, improved grassland (e.g. pastoral grassland), recreational areas (e.g. golf courses, parks), semi-natural grassland, grassland for silage and waste storage (e.g. landfill). The mean number of taxa associated with each attractant type was determined by dividing the number of reported taxa by the number of airfields which reported the presence of an attractant for both airside and landside.

2.5. Statistical analysis

All data were managed in R4.0.4 (R Development Core Team, 2021). The percentage of airfields implementing a mitigation measure was calculated by summarising the number of responses per category, within a question and dividing it by the number of responses to that question. We defined successful outcomes as those that were ranked as being successful by over 70% of survey respondents (Hesse et al., 2010), where a method was implemented by $\geq$ 11 airfields (>50% of airfields). Answers for one airfield (AP8) regarding the implementation of mitigation measures were excluded from analysis due to inconsistencies between responses to mitigation measures which were implemented on the airfield (question 15a, A.3) and the outcome success of these measures (question 15b; A.3). Here, the definition of success was not provided to respondents and therefore relies on uncertain and likely varying definitions of success by the respondents.

Cluster analysis was used to examine associations between implemented mitigation measures, using the packages '*cluster*' (Maechler et al., 2021) and '*dendextend*' (Galili, 2015). Given the inherent uncertainty of the 'unsure' response category regarding the implementation of measures (question 15a, A.3), any such answers (n = 16) were re-categorised as 'no', creating a binary dataset. Agglomerative hierarchical clustering with a binary distance function was used, with Ward's minimum variance as the agglomeration method, informed by the clustering coefficient. The optimal number of clusters (k_t) was identified using both the average silhouette and elbow method. Approximately Unbiased (AU) p-values for clusters were calculated with multiscale bootstrap resampling (B = 10,000), using '*pvclust*' (Suzuki et al., 2019). Clusters with a value of $p \geq 0.95$ were strongly supported by the data (Suzuki and Shimodaira, 2006).

The strength of association between the number of mammal taxa recorded as being present airside (diversity) and the diversity of mammal taxa recorded as being struck was tested with Spearman's Rho (ρ). Lastly, the strength of association between the diversity of mammal taxa recorded airside and the quantity of attractants present both airside and landside, was also tested with Spearman's Rho (ρ).

3. Results

A total of 22 responses were received from airfields; 11 from airfields throughout Ireland (85% response rate), seven from Britain and four from continental Europe (Belgium n = 1; Greece n = 1; Spain n = 2). Responses came from a range of airfield categories (n = 13 international, n = 7 regional, n = 1 local and n = 1 military). All airfields surveyed had a Wildlife Hazard Management Plan (WHMP) in place, with 91% recording mammal sightings at the airfield and 95% specifically incorporating mammals into the WHMP. All airfields recorded near misses with birds as part of their recording process, with 95% also recording near misses with mammals specifically. The majority of responding airfields (68%, n = 15) reported that the number of strike events with mammals had remained the same over the last 5 years, with 53% (n = 8) of those attributing this stability to increased management efforts. An increase in strike rate was reported by 18% (n = 4) and a decrease was reported by 10% (n = 2).

The diversity of mammals reported ranged from 2 to 13 taxa ($\overline{X}$= 7) across all airfields. Birds were more frequently recorded at airfields (index values, *i*, 2.24–2.90) than mammals (*i* = 1.16–2.43, Table 1). Foxes (Canidae, *i* = 2.43 ± SD 0.70) and rabbits (Leporidae, *i* = 2.43 ± SD 0.81) were the most frequently sighted mammals at airfields, followed by hares (Leporidae, *i* = 2.18 ± SD 0.68) and rodents (Rodentia, *i* = 2.10 ± SD 0.98). Strikes with wildlife, including birds, were reported by all airfields except one (95%) and strikes with mammal taxa were reported by 82% (n = 18) of responding airfields. Hares were the most commonly recorded mammal taxon involved in strikes, across airfields (n = 12), followed by foxes (n = 11; Fig. 1). There was no significant correlation between the diversity of mammal taxa struck and the diversity of mammal taxa reported as being present at the airfield (ρ = 0.33, P = 0.1).

Overall, 77% (n = 17) of airfields reported having one or more of the 9 landscape wildlife attractants present airside. Two attractants (recreational areas and agricultural crops), were not reported airside for any of the responding airfields (Fig. 2). 100% of airfields reported having one or more landscape wildlife attractant within a 2 km radius of the airfield, with all attractants reported by at least one airfield (Fig. 2). A fresh water source was the most commonly reported wildlife attractant both airside (45%) and within 2 km (91%) of responding airfields. Airside, the presence of heath/bogland was associated with the highest number of mammal taxa ($\overline{X}$= 9.0 ± SD 2.8) and was reported as being present by five airfields in Belgium, Ireland and the UK. For landside attractants, the presence of improved grassland was associated with the highest number of mammal taxa airside ($\overline{X}$= 7.8 ± SD 2.4), reported as being present by ten airfields, also by airfields in Belgium, Ireland and the UK (Appendix B). There was no significant correlation between the diversity of mammal taxa present at the airfield and the number of potential wildlife attractants present either airside (ρ = 0.04, P = 0.8) or landside (ρ = 0.11, P = 0.6). There was no significant correlation between the diversity of mammal taxa present at the airfield and the number of potential wildlife attractants present either airside (ρ = 0.04, P = 0.8) or landside (ρ = 0.11, P = 0.6).

Grassland management methods were the most commonly used passive mitigation measures, including a long grass policy (≥15 cm; 90% of responding airfields) and a grass cutting regime to maintain grasslands (85.7%; Table 2). The most commonly implemented active mitigation measures were the erection of fencing (100%) and use of noise harassment to disturb and disperse animals from the airfield

Table 1
The percentage of how often 19 taxa were recorded as being seen at 22 airfields in Europe, from 22 survey responses (Question 16, A.3), for mammals and birds. The index value, on a scale of 1–3, represents how frequently taxa are observed across all airfields (n = 22). Values closer to 1 indicate that taxa were seen infrequently. Values closer to 3 indicate that taxa were seen frequently. The uncertainty rate shows how many (n) respondents answered with 'Unsure' for each taxon, which were excluded from the index value analysis.

Animals		*Survey responses*				Index value	SD	Uncertainty (±)
Taxa	Bird/Mammal	Frequently seen (%)	Occasionally seen (%)	Never seen (%)	Unsure (%)			
Corvids	Bird	90	10	0	0	2.90	1.52	0
Shore birds	Bird	81	19	0	0	2.81	1.32	0
Raptors	Bird	81	9.5	9.5	0	2.71	1.34	0
Flocking birds	Bird	71	24	5	0	2.67	1.13	0
Woodpigeon	Bird	71	14	10	5	2.52	1.21	1
Rabbit	Mammal	52	29	14	5	2.43	0.81	1
Fox	Mammal	43	48	5	5	2.43	0.70	1
Waterfowl	Bird	29	67	5	0	2.24	0.64	0
Hare	Mammal	52	24	24	0	2.18	0.68	0
Rodent	Mammal	5	90	0	5	2.10	0.98	1
Bats	Mammal	5	62	24	10	1.80	0.70	2
Domestic cat	Mammal	0	67	29	5	1.71	0.76	1
Domestic dog	Mammal	0	52	38	10	1.60	0.61	2
Hedgehog	Mammal	0	38	43	19	1.50	0.50	4
Badger	Mammal	5	33	57	5	1.43	0.29	1
Small mustelid	Mammal	0	29	53	18	1.40	0.42	3
Deer	Mammal	5	19	71	5	1.29	0.31	1
Other wild mammal	Mammal	5	14	29	52	1.27	0.14	11
Livestock	Mammal	0	14	71	14	1.16	0.43	3

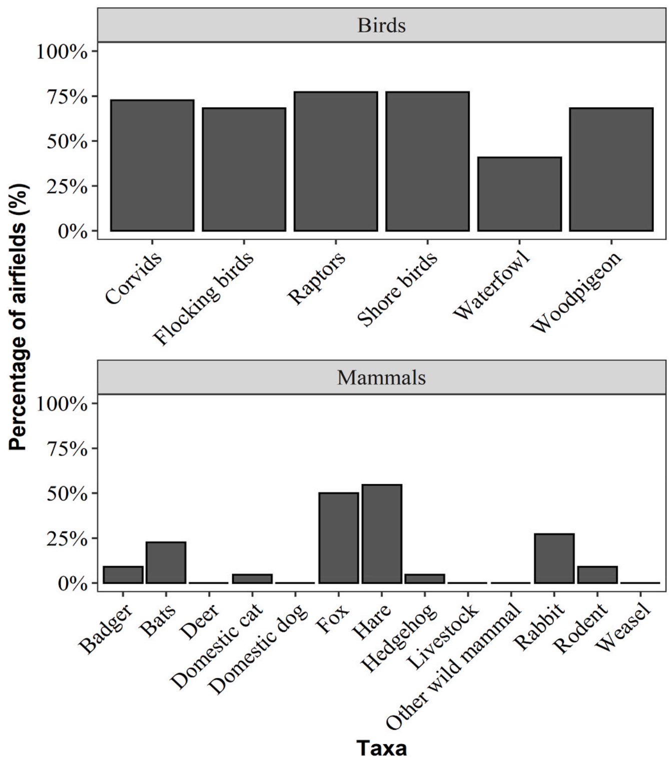

Fig. 1. Percentage of reporting airfields (n = 22) reporting strike events with bird and mammal taxa for airfields in Britain (n = 7), Ireland (n = 11) and continental Europe (n = 4).

(90%). Mitigation measures perceived as successful included: (i) the management of watercourses within the airfield (100% of respondents who reported freshwater present); (ii) the implementation of specific grass cutting regimes (94.4%); (iii) the management of waste products at the airfield so as not to attract or sustain wildlife (93.8%); (iv) the removal of favourable habitat so as not to attract or provide suitable habitat for wildlife (93.3%); (v) the erection of fencing to prevent airfield access to wildlife (90.4%); (vi) using noise harassment (88.8%); (viii) the culling of wildlife via shooting (88.2%); and maintaining long grass (≥15 cm) at the airfield (84.2%; Table 2; Appendix C.1).

Two distinct clusters of mitigation measures were identified via cluster analysis (AU $p \geq 0.95$; C.2). The first cluster contained eight management measures that were the most infrequently implemented mitigation measures used by airfields and included some measures which could be considered to be targeted towards specific species (e.g. translocation). The second cluster contained the nine most frequently implemented measures, which included passive, active lethal and active non-lethal measures (Fig. 3). The erection of fencing and maintaining long grass were the two most frequently co-implemented measures.

A total of 20 (91%) of respondent airfields used internal systems (e.g. airfield specific reporting systems, specialists and committees) to determine if an implemented mitigation method was successful. External methods (i.e. national and international aviation authorities, external consultants/professionals), were used by 45% (n = 10) of airfields to determine the success of a mitigation measure, all of which were utilised in addition to internal systems. Only 9% (n = 2) of airfields did not use any assessment methods (i.e. internal or external systems) to evaluate the effectiveness of implemented mitigation measures.

4. Discussion

Mammal strikes with aircraft are increasingly common, both within Europe and further afield (e.g. Dolbeer 2015; Ball et al., 2021b). Despite this, relatively little research has been conducted on mammals in airfield environments, particularly in the European context. Airfield managers have a legal obligation to reduce wildlife hazard at airfields (see Regulation (EC) No 1108/2009, Commission Regulation (EU) No 139/2014). Hence, understanding the fauna of airfields, as well as the potential attractants drawing taxa to these critical areas, is greatly beneficial in maximising the efficient use of management resources and mitigation of the impact of future strikes. The kinetic energy of a strike event between a mammal and an aircraft is sufficient to inflict considerable damage (e.g. Ball et al., 2021a). Therefore, reducing the opportunity for strike events through landscape management and the implementation of

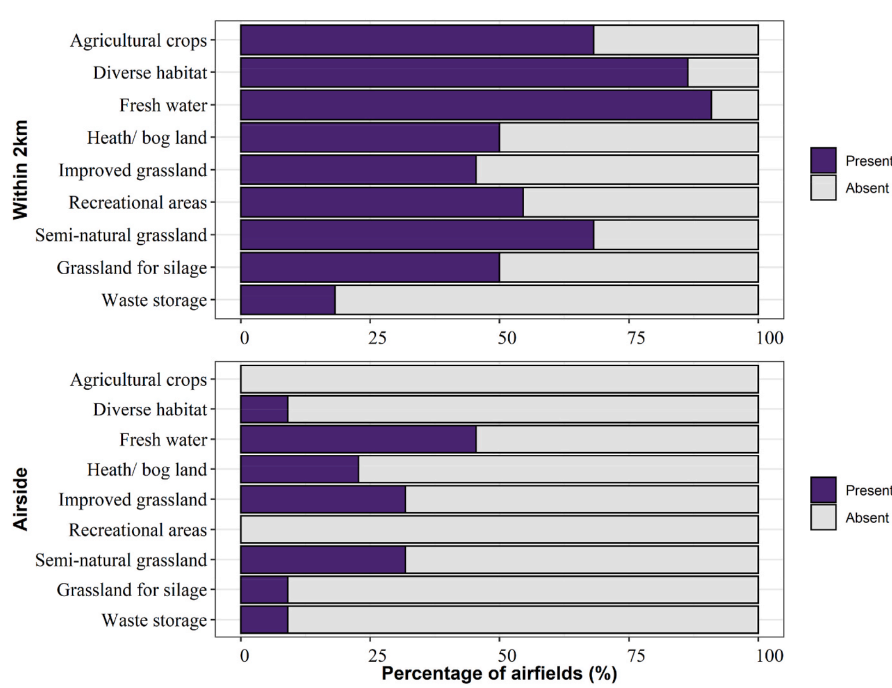

Fig. 2. The percentage of responding airfields (n = 22) reporting the presence of wildlife attractants within 2 km of the airfield (landside) and within the airfield environment (airside), for airfields in Britain (n = 7), Ireland (n = 11) and continental Europe (n = 4).

Table 2
Percentage of airfields implementing each active and passive strike mitigation measure, at n = 21 airfields in Europe and the perceived outcome of each mitigation measure. Outcome percentages are based on airfields which reported that they used this mitigation measure only. Numbers of responses can be seen in Appendix C.1

Measure	Implemented			Outcome			
	Yes	No	Unsure	Successful	Unsuccessful	Unsure	Unanswered
Passive methods							
Grass cutting regime[X†]	85.7% (n = 18)	4.8% (n = 1)	9.5% (n = 2)	94.4% (n = 17)	0% (n = 0)	5.6% (n = 1)	0% (n = 0)
Long grass policy (≥15 cm)[X]	90.5% (n = 19)	9.5% (n = 2)	0% (n = 0)	84.2% (n = 16)	5.2% (n = 1)	5.2% (n = 1)	5.2% (n = 1)
Management of waste products[X]	76.2% (n = 16)	14.3% (n = 3)	9.5% (n = 2)	93.8% (n = 15)	0% (n = 0)	0% (n = 0)	6.2% (n = 1)
Management of water courses[X]	61.9% (n = 13)	33.3% (n = 7)	4.8% (n = 1)	100% (n = 13)	0% (n = 0)	0% (n = 0)	0% (n = 0)
Removal of favourable habitat[X]	71.4% (n = 15)	23.8% (n = 5)	4.8% (n = 1)	93.3% (n = 14)	0% (n = 0)	0% (n = 0)	6.7% (n = 1)
Short grass policy (≤15 cm)	23.8% (n = 5)	66.7% (n = 14)	9.5% (n = 2)	80% (n = 4)	0% (n = 0)	20% (n = 1)	0% (n = 0)
Use of unpalatable grass species	23.8% (n = 5)	66.7% (n = 14)	9.5% (n = 2)	80% (n = 4)	0% (n = 0)	20% (n = 1)	0% (n = 0)
Active methods							
Buried fencing[†]	52.4% (n = 11)	47.6% (n = 10)	0% (n = 0)	81.8% (n = 9)	9.1% (n = 1)	0% (n = 0)	9.1% (n = 1)
Cattle grids at entry posts *	5.0% (n = 1)	90.0% (n = 18)	5.0% (n = 1)	100% (n = 1)	0% (n = 0)	0% (n = 0)	0% (n = 0)
Chemical control (i.e. poisoning)	9.5 (n = 2)	90.5 (n = 19)	0% (n = 0)	50% (n = 1)	0% (n = 0)	50% (n = 1)	0% (n = 0)
Electrified mats at entry posts	0% (n = 0)	95.2% (n = 20)	4.8% (n = 1)	–	–	–	
Erection of fencing[X†]	100% (n = 21)	0% (n = 0)	0% (n = 0)	90.4% (n = 19)	4.8% (n = 1)	0% (n = 0)	4.8% (n = 1)
Live trapping for translocation[†]	28.5% (n = 6)	66.7% (n = 14)	4.8% (n = 1)	33.3% (n = 2)	33.3% (n = 2)	33.3% (n = 2)	0% (n = 0)
Shooting of animals[X]	81.0% (n = 17)	19.0% (n = 4)	0% (n = 0)	88.2% (n = 15)	5.9% (n = 1)	5.9% (n = 1)	0% (n = 0)
Trapping of animals for culling	14.3% (n = 3)	85.7% (n = 18)	0% (n = 0)	100% (n = 3)	0% (n = 0)	0% (n = 0)	0% (n = 0)
Use of dogs	4.8% (n = 1)	90.4% (n = 19)	4.8% (n = 1)	100% (n = 1)	0% (n = 0)	0% (n = 0)	0% (n = 0)
Use of falconry	33.3 (n = 7)	66.7 (n = 14)	0% (n = 0)	71.4% (n = 5)	14.3% (n = 1)	14.3% (n = 1)	0% (n = 0)
Use of noise harassment *[X]	90.0% (n = 18)	10.0% (n = 2)	0% (n = 0)	88.8% (n = 16)	5.6% (n = 1)	5.6% (n = 1)	0% (n = 0)

* 20 = Responses; X = Reported as successful by ≥ 70% of responding airfields, where ≥11 airfields implemented the method; † = measure implemented specifically to manage/mitigate against hare strikes (n = 3 airfields).

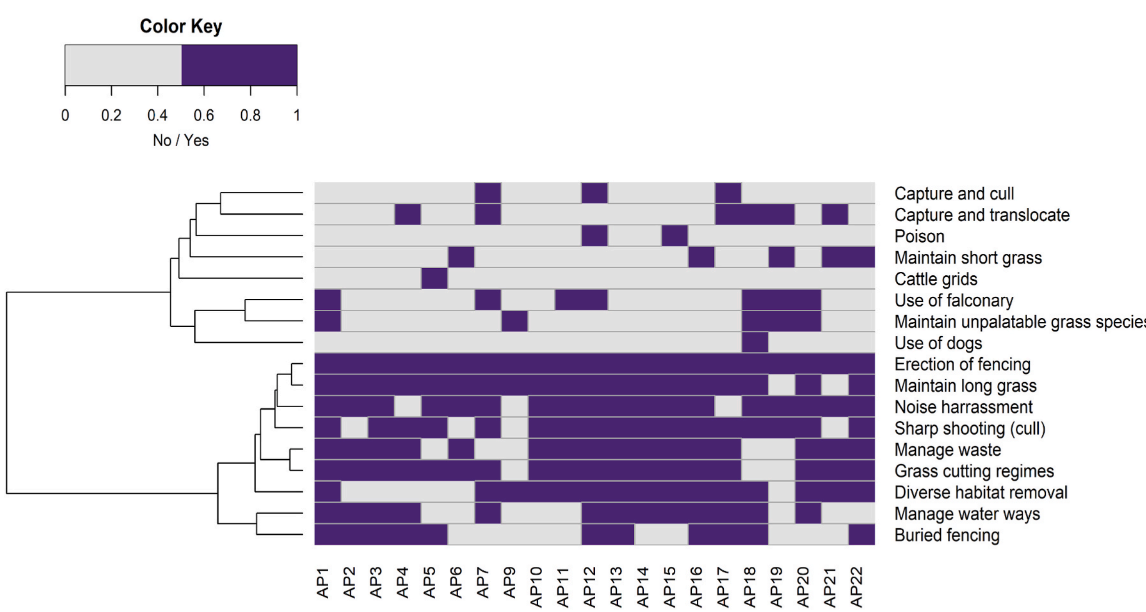

Fig. 3. Associated implemented mitigation measures according to airfield, for n = 21 airfields in Britain (n = 7), Ireland (n = 10) and continental Europe (n = 4). Airport 'AP8' was excluded from analysis. One mitigation measure (electric mats) included in the survey is excluded, as it was not implemented by any of the responding airfields. Purple squares indicate that respondents answered that the measure was implemented at their airfield. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

mitigation measures is necessary to reduce wildlife hazard at an airfield. Across responding airfields, 53% reported that strike rates with mammals had largely remained the same over the past five years and that several measures, including improvement of mitigation measures, were responsible for this outcome. This suggests that despite increased management efforts, these efforts are currently required to keep strike rates at levels similar to those five years previously.

Responding airfield managers were more aware of the bird taxa present at the airfield, compared to mammals (<1% vs 8% 'unknown' taxa - excluding the 'other wild mammal' - respectively). This could be a result of birds being more visible to personnel as most species of interest are diurnal, due to greater presence of birds at airfields compared to mammals, or greater awareness of the hazards of bird strikes. As the majority of mammals are often elusive, this reduced detectability is likely to create a sampling error in relation to species diversity and the frequency in which these species are utilising an airfield, particularly if there are no local strike records with a species. Among mammals, the red fox (*Vulpes vulpes*) and the European rabbit (*Oryctolagus cuniculus*) were the most frequently sighted species, according to the sightings index. The red fox is a generalist predatory species which is widespread across Europe. This, paired with the foxes increasing association with anthropogenically modified landscapes (e.g. Scott et al., 2014), large size and easy identification may explain why foxes were frequently encountered throughout airfields in Europe. Likewise, airfields are ecologically suitable for several common prey species of the red fox, including rabbits, hares and rodents (Ball et al., 2021a). The presence of mammals at airfields, particularly small prey species, can potentially lure predatory and scavenger species to the airfield (Hauptfleisch and Avenant, 2015), introducing differential strike risk (Pennell et al., 2016). In the present study, 54% of responding airfields felt that the presence of mammals on the airfield resulted in secondary strike events with predatory or scavenger species. This highlights that mammals may play an important role in exacerbating avian strike risk, hence the entire faunal species composition of an airfield needs to be considered when designing WHMPs.

The local presence and abundance of species is thought to influence strike events and their frequency (Schwarz et al., 2014). However, we found a low correlation between the number of mammal taxa reported as being present at the airfields and the diversity of mammal taxa reported as being struck. While a higher mammal diversity may mean that broader mitigation measures need to be implemented, a low mammal diversity does not necessarily denote a low strike rate, with some airfields reporting a high proportion of wildlife strike incidents with a single mammalian species (e.g. Ball et al., 2021a). Likewise, management measures can still be challenging, even with low species diversity, particularly in high density populations. Many (>70%) mammal species exhibit either nocturnal or crepuscular life histories (Bennie et al., 2014) and many airfields have long operating hours, thus strike events between mammals and aircraft have the potential to occur 24-h a day, making exclusion and mitigation of paramount importance. With considerable staff numbers required to cover such long operating hours, particularly at international airports, reporting of strikes often falls to multiple individuals, which has the potential to result in reporting inconsistencies. In this study, we identified several airfields where survey respondents did not record some mammal taxa as having been struck at their respective airfield, despite published records of such events (excluded here to retain airfield anonymity), further highlighting the potential for sampling error associated with mammal reporting at airfields. This is particularly the case for bats, which are generally small, inconspicuous species in Europe, e.g. the Soprano Pipistrelle (*Pipistrellus pygmaeus*) weighs <7.6g (Lysaght and Marnell, 2016). Discrepancies such as these may arise due to several reasons including observer bias, an emphasis on recording bird strikes, and the relative infrequency of mammal strikes.

The Airport Planning Manual (ICAO, 2002) sets out guidelines regarding the types of land uses which could be considered within a 3 km and 8 km radius of an airfield, so as not to attract hazardous birds. However, as land use and development surrounding airfields can often be determined by national legislation and landowners, controlling land use patterns to reduce hazards across Europe, a region made up of 44 countries with associated legal jurisdictions, adds additional complexities to land use management. Despite many land uses surrounding an airfield being appropriate mammal refuges (e.g. foxes in urban areas), little consideration in existing guidelines (ICAO, 2002) is given to land use management and practises surrounding airports, regarding mammal attraction. Although difficult to achieve and requiring the cooperation of many stake holders, modifying and managing the landscape, and thereby land use patterns, is considered to be the most effective, long term solution in an integrated wildlife management approach (Washburn and Seamans, 2004). Therefore, understanding the wildlife attractants within- and in proximity to-an airfield, and the wildlife potentially utilising these attractants, is of paramount importance to deliver effective, long term solutions to wildlife hazards. Indeed, several airfields in the USA have reported on the success of reducing bird presence on airfields by managing and modifying wildlife attractants (e.g. Stevens et al., 2005; Kennamer et al., 2013). With 77% of airfields in this study reporting the presence of wildlife attractants airside, and 100% within 2 km of the airfield, the benefits of airfields working closely with local planning authorities, land owners and ecologists to ensure land use patterns in proximity to airfields are in line with current guidelines (e.g. International Civil Aviation Organisation 2002) and are not favourable towards wildlife cannot be over looked. For example, organic waste storage (landfill) impacts favourably on vertebrate demography (Plaza and Lambertucci, 2017) and indeed waste storage was associated with a high mammal diversity in the current study. While control and surveillance of such facilities in proximity to an airfield could help control hazardous taxa, field data are required to understand the risks associated with the presence of wildlife attractants to inform potential control measures for future implementation.

The risks associated with the presence of wildlife attractants are likely to be country or regionally specific, depending on the type of attractants present and the how wildlife species are interacting with these attractants. For example, we found that the presence of a specific habitat type (bog land/heath land) airside, was associated with an increase in average mammal diversity. This likely reflects the geographical bias of respondents from climates favouring these habitat types, with Ireland (21%) and the UK (11%) having a particularly high percentage coverage of peat bog land compared to other locations (Tanneberger et al., 2017). Indeed, only Ireland, Britain and Belgium reported the presence of this habitat type, the latter of which has limited coverage of both habitat types (e.g. Piessens et al., 2004; Tanneberger et al., 2017). We found only a weak positive effect on mammal diversity and the number of wildlife attractants present landside, perhaps because an increased number of attractants (e.g. recreational areas) may be indicative of an airfield in a more developed location. While the presence of landside attractants may not support a high diversity of mammals, they could still support a low number of species which can be hazardous to aviation. For example, while we found that the presence of recreational areas reduced mammal diversity, golf courses are known to support high densities of urban adapted wildlife species (Hodgkison et al., 2007) and are particularly attractive to rabbits. Therefore, understanding specifically which species may be associated with different land use patterns surrounding the airfield is of paramount importance for effective mitigation management.

Other attractants reported as being present within the airfield environment included high invertebrate biodiversity and long grass, which provides hares (*Lepus*) with suitable habitat. As hares were frequently seen by more than half of reporting airfields (index value 2.18) and were the most commonly struck mammal taxa, this unwanted consequence associated with a mitigation measure implemented to reduce the attractiveness of airfields to many problematic bird species, needs to be carefully considered when designing airfield specific WHMP's. Despite hares being common at the responding airfields, only three airfields reported explicitly implementing mitigation measures specifically targeted towards hares. Hares are highly fecund (Caravaggi, 2018) and airfields provide habitat suitable to supporting high density populations, hence management of lagomorphs at airfields can be both challenging and costly. Additional landside attractants included the presence of specific diverse habitats (wetlands and loughs). One airfield associated with these features reported a regionally important population of Golden Jackal (*Canis aureus*) that resided at the airfield, attracted by the presence of a lowland wetland immediately outside the airport perimeter and which extended airside. The responding airfield has initiated a project to sustainably manage the population, given their vulnerable status, by managing the habitat airside, with the aim of it becoming unfavourable for the canid. This example, along with the presence of the endemic Irish hare (*Lepus timidus hibernicus*) at several airfields in Ireland (e.g. Ball et al., 2021a) demonstrates that mammal species utilising airfields may be subject to protective legislation, or be of conservation concern, adding additional complexity to management efforts.

A total of eight mitigation measures were reported as being successful by over 70% of airfields utilising the method (for measures implemented by over 50% of responding airfields), out of a possible eighteen options. Only two mitigation measures - the management of waste products at the airfield and the removal of diverse habitat - were deemed to be successful both in the present study and by Hesse et al. (2010) that focussed on Canadian airports. Mitigation measures associated with the management of waterways and the maintenance of grasslands were ranked amongst the most successful measures in Europe and may explain why the presence of water airside was associated with a 35% reduction in mammal diversity. In contrast, respondents to the Canadian study ranked the use of dogs and the removal of shrubs/-brush/diverse habitat as the most successful. This may be reflective of the differences in faunal composition or differences in management preferences between the two regions. While only one airfield reported using domestic dogs as a mitigation measure in the present study, five airfields in Canada reported using dogs with a 100% success rate. Several active mitigation measures utilised by airfields aim to mimic the effects of a predator (e.g. use of hawk kites; O'Shea et al., 2020). For example, the use of falcons can achieve this desired effect and was utilised more frequently by airfields in Europe (n = 7; 71% successful) than by Canadian airfields (n = 2; Hesse et al., 2010). Indeed, the use of trained raptors has been used since the 1940's in Europe to disperse birds from airfields, and is still used with success (e.g. Kitowski et al., 2011). A more appropriate method for prey mammals may be the controlled introduction of a predatory species into the airfield environment, either through handled dogs, or through the use of predatory olfactory cues such as faeces or synthetic repellents (see Hegab et al., 2015). Indeed, several airfields in the USA have reported reduced wildlife sightings and strikes following the incorporation of trained dogs into wildlife management plans (Carter, 2000). However, the use of olfactory cues as a deterrent at airfields remains unstudied and should be rigorously tested with local fauna before implementation.

Responses in the uses and applications of mitigation measures by responding airfields were varied, demonstrating that there is no one 'hard and fast' approach to mammal management and strike mitigation at airfields in Europe. Certainly, the mitigation measures required are likely to be country and even airfield specific. Nevertheless, we successfully identified frequently implemented, co-occurring methods via cluster analysis. Here we identified that fencing, along with maintaining a long grass management policy were the most frequently implemented co-occurring measures. This is to be expected, given that most airfields require fencing as a basic safety feature (Commission Implementing Regulation (EU) 2015/1998) and maintaining long grass is common practice for airfields in temperate regions, where the majority of responding airfields were located. Therefore, perhaps it is more useful to understand which measures are frequently implemented around these core practices-in this instance, active management via sharp shooting and noise harassment-to further develop and research these techniques and their use at airfields (Baxter, 2000). Regardless, effective management cohorts for individual airfields must be appropriate to the local fauna and their ecologies. For example, foxes were actively managed at 54% (n = 12) of airfields. One such airfield reported that young, naive foxes were removed from the airfield by means of translocation, allowing for territorial, adult foxes to remain, while another reported relocating badger sets off the airfield-a species which was only reported as being actively managed by 9% (n = 2) of airfields. Certainly, given the diversity of life histories occupied by mammals, multiple mitigation measures are required to successfully exclude a cohort of mammals. For example, while physical barriers may be effective at excluding larger mammals (VerCauteren et al., 2013), habitat manipulation measures such as insect reduction (Washburn et al., 2011) and the planting of unpalatable grasses (Finch et al., 2015) may be more effective at deterring smaller mammals such as rodents and bats.

Many mammal species recorded at the responding airfields are charismatic species and can be of local or cultural significance (e.g. Irish hare). While lethal control methods are utilised by airfields, public attitudes are an important consideration in modern wildlife management processes (van Eeden et al., 2019). Nevertheless, mammal exclusion and strike mitigation often require a combination of both passive and active measures, sometimes including lethal management. However, exclusion measures can be costly to implement (>$20/m for fencing; VerCauteren et al., 2006, 2013) and strike events still occur despite their presence, adding often substantial cost. While some mitigation measures are a once-off main cost and effort (e.g. fencing), many more require routine application and repetition (e.g. grass mowing regimes). Indeed, in addition to the cost of implementing mitigation measures themselves, airfield managers have the associated additional costs of employing sufficient numbers of personnel to implement mitigation measures which require constant input (e.g. noise harassment, patrols). While 50% of airfields reported that fewer than 10 people were responsible for wildlife management and control at the airfield, one international airport reported that this fell to between 100 and 150 people. Additionally, 23% of responding airfields reported spending in excess of €20,000 annually on the implementation of mammal strike mitigation measures and an additional 18% reporting spending between €5000–10,000 annually.

5. Conclusion

With mammal strikes increasing in many regions worldwide, including in Europe, airfields need to implement an integrated management approach, targeted towards mammals. Despite airfields in Europe utilising a matrix of mitigation measures, the presence of mammals on the responding airfields was widespread, with many species frequently being sighted. Additionally, despite these efforts, strikes with mammals still occurred at many airfields. With the removal of wildlife attractants from the environment being regarded as an effective, long term management solution, WHMP's need to consider an integrated management approach whereby both internal and external attractants are controlled, alongside ongoing airside wildlife dispersal practises. Likewise, airfields need to consider the species present at the airfield and adapt management plans for specific species.

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Data availability

Raw data are available on Figshare: https://figshare.com/articles/dataset/Mammal_management_practices_at_airfields_in_Europe/20505480

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jairtraman.2023.102408.

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