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Sharing the Atmosphere: Conflicts and Potential Solutions

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Judy Shamoun-Baranes, Hans van Gasteren, and Viola Ross-Smith

Abstract

As our use of the atmosphere is increasing, so too are the conflicts that arise between our activities and those of aerial wildlife. As a result, numerous stakeholders are interested in monitoring, modelling and forecasting the aerial movements of animals in the context of anthropogenic impacts. Birds can pose a serious threat to aviation, resulting in delays, damage to aircraft, lost flight hours and even the loss of lives. Military and civil aviation use a range of measures to monitor the movements of birds and to try and reduce the risk of wildlife strikes. Increasingly, Unmanned Aerial Vehicles are sharing an already crowded air-space, although just how problematic this may become remains to be seen. The wind energy industry, another important stakeholder, may pose serious threats for aerial wildlife, due to collisions with turbines, or the extra energetic costs and risks entailed with avoiding wind farms. Similarly, other tall structures pose a threat for aerial wildlife. In this chapter, we describe the nature of these different conflicts and provide an overview of the factors that influence the risk associated with aerial movement. We also describe how movement is being studied to provide essential information for these different stakeholders and discuss several

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of the solutions that have been implemented to reduce potential conflicts. We conclude by discussing future perspectives for reducing conflicts by integrating different technologies for studying aerial movement, diverse approaches for modelling movement and working across international borders.

1 Human–Wildlife Conflicts in the Atmosphere

Human activities are increasingly encroaching on the atmosphere, the airspace used by wildlife for their daily and seasonal movements, resulting in numerous types of aerial conflicts (Fig. 18.1). Whether it's the large structures we build that extend into this space, such as wind turbines, skyscrapers, power lines, or aircraft flying through the atmosphere, conflicts are bound to occur. This competition for aerial space can be detrimental to wildlife, both directly due to collisions between wildlife and anthropogenic structures or aerial vehicles and indirectly due to disruption of normal movement patterns of wildlife. It can also result in the loss of human lives and heavy financial costs. As a result, there is a diverse array of stakeholders interested in quantifying and predicting potential conflicts and implementing measures to try and reduce them. In this chapter, we briefly review conflicts that arise during animal flight and focus on aviation, wind turbines and static structures (without moving parts, e.g. blades), providing a brief overview of the factors that influence the risk of aerial collisions. We show how ongoing research is helping to provide the information and even solutions needed to reduce human–wildlife conflicts within the atmosphere. Understanding the external and intrinsic factors that influence aerial movement is often the first step in this process.



Fig. 18.1 Schematic representation of the aerial conflicts associated with collisions between aerial organisms and human structures and vehicles that encroach on the atmosphere, such as civil aviation during take-off and landing, military aviation, wind turbines and other tall structures. The most problematic part of the atmosphere is the lowest few hundred metres. However, birds can also regularly fly at altitudes of several thousand metres, especially during migration, bringing them into conflict with military aviation at these altitudes as well

2 Aviation

2.1 Problems for Aviation

Collisions between wildlife and aircraft have been recorded since the earliest days of aviation. In most cases, these collisions are detrimental to wildlife but have little or no impact on the aircraft concerned. However, the small proportion of collisions that do impact aviation can result in flight delays, damage to aircraft, loss of aircraft and on rare occasions the loss of human lives. Tens of thousands of animals die each year as a direct result of collisions with aircraft (McKee et al. 2016) and probably a tenfold more are culled as part of wildlife strike management programmes worldwide (Dolbeer et al. 1993; McKee et al. 2016). Most of the research and development related to wildlife–aircraft collisions has focused on reducing the risk of collisions from the perspective of human safety or amenity rather than species conservation or animal welfare per se, although, ideally, all three issues should be considered simultaneously (Buurma 1994; Froneman 2005; Kumar 2014; Leshem and Froneman 2003). Collisions between wildlife and aircraft resulted in the loss of at least 229 lives and the destruction of 221 aircraft worldwide from 1988 to 2009 (Dolbeer 2011). In the USA, over 82,000 collisions with civil aircraft were reported to the Federal Aviation Authority (FAA) between 1990 and 2007 Anonymous (2015). Birds were involved in 97.5% of these, and bats in 0.3%. The rest involved terrestrial mammals and reptiles on the runways (Dolbeer and Wright 2008).

Economic losses due to such collisions are difficult to estimate as they include direct costs related to damage but also indirect costs related to the disruption of flights, human safety and fatality (Sodhi 2002). It is estimated that worldwide, bird aircraft collisions (“bird strikes”) with commercial transport aircraft result in 1.2 billion USD in direct and indirect costs annually due to damage and delays (Allan 2002). Additional costs generally not included in these estimates are costs related to risk assessment and development plans prior to establishing new aerodromes or extending existing airports, money spent on project proposals which are not granted and costs accrued by setting up mitigation measures, all of which should finally result in a net reduction of costs if successful. This section focuses predominantly on birds, the taxa for which the most information is available and related research and development has been conducted. It is important to note that collisions with bats do occur and while they are in general far less common than collisions with birds they can be problematic in certain regions, for example the South Pacific and Palearctic (Parsons et al. 2009; Biondi et al. 2013). While many of the issues described in this section and examples provided are from bird-related studies, numerous aspects are relevant for bats as well.

The number of bird strikes decreases exponentially with altitude, with most bird strikes occurring below 400 m above the earth surface (Dolbeer 2006; Lovell and Dolbeer 1999). While several species do fly up to altitudes of several thousand meters, especially during migration (Bishop et al. 2015; Leshem and Yom-Tov 1996b; Kemp et al. 2013; Able 1970), flight altitudes during local movements are predominantly within the first few hundred metres of the earth surface (Shamoun-Baranes et al. 2006; Larsen and Guillemette 2007; Avery et al. 2011). Figure 18.2

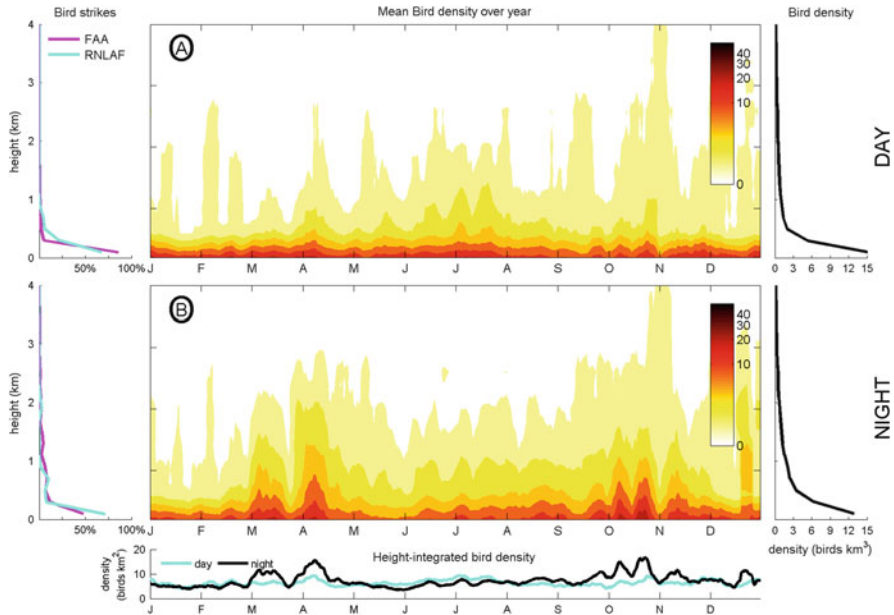


Fig. 18.2 The altitude distribution of bird strikes and aerial bird density (birds/km³) during the day (a) and night (b). Left panels: the frequency distribution of bird strikes at different altitudes for the FAA (civil aviation) and the RNLAf (military aviation). Centre panels: 7-day running average of mean daily aerial bird density (birds/km³) at 200 m altitude bins during the year measured by five weather radar (three in Belgium, two in the Netherlands) from 1 April 2012–1 July 2014; darker colours indicate higher densities. Right panels. Frequency distribution of average bird density with altitude (200 m bins). Bottom panel: the height integrated bird density (birds/km²) for daytime and night-time. Most bird strikes occur in the lowest 500 m (left) overlapping with altitudes where average bird density is highest (right). Nocturnal bird densities (birds/km³) are highest during spring (e.g. March, April) and autumn migration (e.g. October)

provides an overview of the altitude distribution of wildlife collisions recorded in the FAA wildlife strike database from 1990 to July 2014 for large aircraft (>27,000 kg) (Dolbeer and Wright 2008) and the Royal Netherlands Air Forces (RNLAf) jet fighter aircraft between 1976 and 2014, showing the concentration of bird strikes at low altitude and the sharp decrease in collisions at higher altitudes. Height distributions of bird movements and mean bird density estimated using weather radar are also shown in Fig. 18.2. To estimate the mean bird density, methods described in (Dokter et al. 2011) were applied to five Doppler weather radar in the Netherlands (two radar) and Belgium (three radar) using data collected from 1 April 2012–1 July 2014. All measurements from five weather radars were averaged for each day (sunrise to sunset) or night (sunset to sunrise). In order to smooth out short-term fluctuations, a 7-day moving average was applied to the data to create the daily density height profiles over the year for bird densities during daytime (Fig. 18.2a) or night-time (Fig. 18.2b). The average density height profile of all five weather radars, averaged over the whole year (Fig 18.2, right), shows a

significant overlap with bird strike occurrence (aggregated in 200 m altitude bins) for both daytime and night-time height distributions (day: $R^2_{\text{adj}} = 0.994$, $P < 0.0001$, $n = 20$; night: $R^2_{\text{adj}} = 0.847$, $P < 0.0001$, $n = 20$). As large commercial aircraft quickly climb above altitudes where birds are present (Fig. 18.2), most bird strikes usually occur in and around airfields, during take-off and landing and at relatively low aircraft flight speeds (Fig. 18.3a). Military aircraft, however, generally operate at low altitudes and at high speeds en route. As a result, there is a bimodal distribution of the aircraft flight speeds at which bird strikes occur (Fig. 18.3b), with bird strikes at relatively low speeds occurring during take-off and landing and bird strikes at high speeds occurring en route. While aircraft flight speeds are relatively low during take-off and landing, ingestion of birds into an

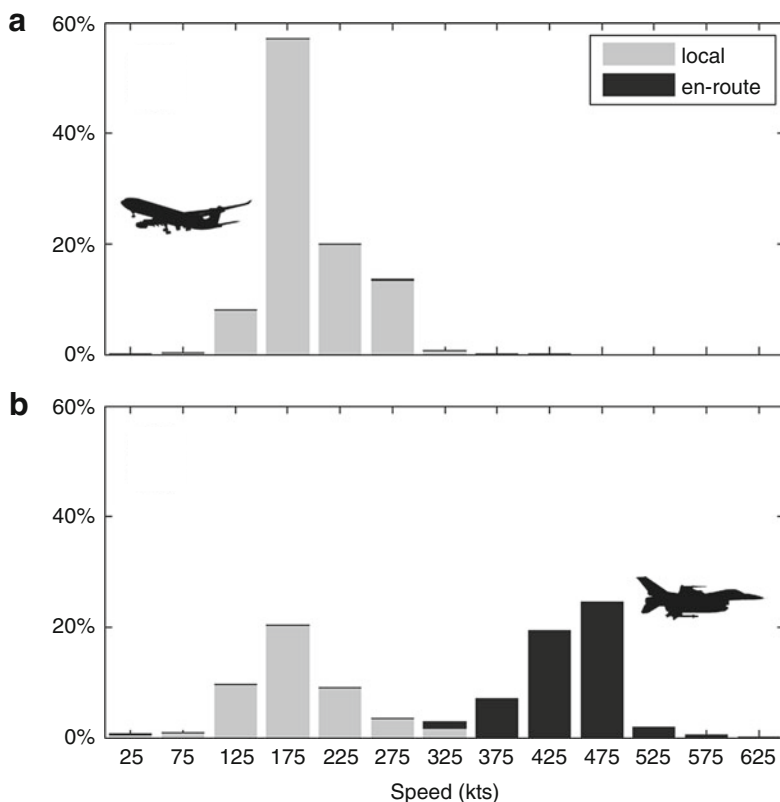


Fig. 18.3 The percentage of bird strikes that have been reported at different aircraft flight speeds. (a) FAA Wildlife strike database 1990–July 2014, large aircraft >27,000 kg ($n = 39785$) and (b) the RNLAf, Jet fighter aircraft, 1976–2014 ($n = 2292$). Note that as civil aviation (a) generally flies above the altitude where birds are found, bird strikes occur locally in and around the airfield, during terminal flight phases (take-off, initial climb, initial approach, final approach and landing) and at relatively low speeds. Military jet fighters experience bird strikes both at relatively low speed during take-off and landing and at higher speeds en route as most of their flights occur within the same airspace shared by birds

engine during take-off will cause more damage than during landing. During take-off, engines are at full thrust, increasing mechanical stress and thus the risk of significant engine damage or engine failure. Thus, the bird strike problem is often divided into local bird strikes, problematic for both civil and military aircraft, and bird strikes that occur en route, relevant predominantly for military aviation.

The severity of a collision depends on several biological and structural factors including the mass of the animal, the number of individuals striking an aircraft, the speed of the aircraft, the point of impact on the aircraft and the type of aircraft (Table 18.1). Direct impact with the aircraft's landing gear, canopy and the engine, especially if there is only a single engine, can all be detrimental. For commercial and military aircraft, airworthiness standards define the impact by birds of different masses that aircraft structures (e.g. canopy, engine, wing) must be able to withstand and still be able to fly and land safely (Dennis and Lyle 2009). New materials and structural designs are being tested to improve impact resistance of aircraft (e.g. Guida et al. 2009; Reglero et al. 2011; Amoo 2013), without losing its specific flight capabilities the aircraft was designed for. Civil and military helicopters tend to fly at altitudes that often coincide with the flight altitudes of birds and bats (Fig. 18.2) and therefore are also susceptible to damaging and sometimes fatal collisions, especially when relatively large birds penetrate the canopy. In general though, military jet aircraft which fly low and fast and often have only one or two engines are more susceptible to serious and fatal collisions than other aircraft (Richardson and West 2005; Allan 2002; Washburn et al. 2013). An assessment of bird strikes reported to the FAA with civil aviation below approximately 152 m (500 ft) revealed that collisions with waterfowl and turkey vultures (*Cathartes aura*) were a higher risk for aviation than other species (DeVault et al. 2011). Collisions with flocks of birds can also have a high negative impact on aviation, especially with the ingestion of several birds in a single engine or birds striking multiple engines (Avrenli and Dempsey 2014). Thus, larger birds and flocking species usually cause more severe bird strikes than other species. One such example is the crash of the US Airways flight 1549 on the Hudson River. On 15 January 2009, the aircraft struck multiple Canada geese (*Branta canadensis*) shortly after take-off at approximately 800 m above ground level and 8 km from the airport, causing both engines to fail (Marra et al. 2009). Fortunately, the experienced crew was able to conduct an emergency landing in the Hudson River saving all crew members and passengers. However, sometimes it takes only one bird to destroy an engine and thus even single birds regularly flying through the same airspace as aircraft can create a flight safety hazard; for example, a Royal Netherlands Air Force F-16 crashed at Volkel airbase on 21 September 2006 due to a collision with one Wood pigeon (*Columba palumbus*, mean mass = 201 g, Dunning 1993).

The flight behaviour of birds is highly relevant when trying to understand and mitigate bird strikes (Table 18.1). The flight altitude, the amount of time spent in the air and how abundant the species is in areas where aircraft are active are all relevant factors that influence the probability of a bird strike occurring. Not all species are equally prone to bird strikes (Both et al. 2010; Allan 2006) and even within a species the susceptibility to bird strikes may change during the course of a bird's

Table 18.1 Factors influencing collision risk during flight posed by human structures and aircraft to wildlife, classified by factors intrinsic to the animals concerned, and those related to their environment or the human structure/activity itself

Factor	Description	Examples
Intrinsic factors		
Morphology	Factors such as body mass, wing loading, aspect ratio and wing span affect flight behaviour and hence collision vulnerability	<ul style="list-style-type: none"> • Large birds that rely almost entirely on thermal soaring with relatively high wing loading compared to other soaring birds or birds that are less manoeuvrable during flight are more prone to collision with wind turbines and power lines than other species (de Lucas et al. 2012; Janss 2000) • Birds with a higher body mass pose a higher threat for aviation than smaller birds (DeVault et al. 2005, 2011; Dolbeer et al. 2000)
Perception	Limitations of sensory perception and cues attended to may affect species' ability to detect objects with which they might collide	<ul style="list-style-type: none"> • Visual fields of perception may be limited in frontal vision of birds or leave certain birds blind to structures erected in their direction of travel (Martin et al. 2012; Martin 2011) • Motion smear means birds cannot detect fast-moving objects, e.g. wind turbine blades, at certain speeds and in particular conditions (Hodos 2003) • Bats may be attracted to tall structures which are not readily distinguished from trees (Cryan et al. 2014; Jameson and Willis 2014) • Migrating bats may rely on linear features for navigation and get confused by wind farms (Kunz et al. 2007)
Avoidance	The ability to avoid structures reduces collision risk. Closely linked to morphology and perception.	<ul style="list-style-type: none"> • Some birds can take last-minute action to avoid wind turbine blades (Cook et al. 2014). • Common terns while often crossing power lines did not collide often, perhaps due to high manoeuvrability during flight and timely adjustment of flight paths despite proximity between the breeding colony and the power lines (Henderson et al. 1996) • Some birds are more strike prone than others, a factor which is incorporated in some bird hazard risk models in aircraft safety (Allan 2006; Both et al. 2010; Soldatini et al. 2010; Shaw and McKee 2008)

(continued)

Table 18.1 (continued)

Factor	Description	Examples
Age	Age and experience may influence flight capacity, collision risk and recognition of danger	<ul style="list-style-type: none"> • Juvenile common terns (<i>Sterna hirundo</i>) fly closer to power lines than adults putting them at higher collision risk (Henderson et al. 1996). • Subadult white-tailed eagles (<i>Haliaeetus albicilla</i>) were more active in a wind-power plant than adults (Dahl et al. 2013) • Juveniles appear to be more prone to bird strikes than adults (Sodhi 2002; Kelly et al. 2001)
Behaviour	Flight behaviour and motivation for flight which can change during different stages in the annual routine might affect vulnerability to collision	<ul style="list-style-type: none"> • The frequency of trips of adult terns increased during the nestling phase compared to courtship coinciding with an increase in the proportion of terns crossing power lines (Henderson et al. 1996) • Male Skylarks engaged in song flights to attract mates are more vulnerable to collision with wind turbines than females (Morinha et al. 2014) • Flocking birds or those engaged in social interaction can be more vulnerable to collisions than solitary individuals (Dahl et al. 2013) • Birds that fly at wind turbine blade height are more likely to collide than those that do not (Drewitt and Langston 2006)
External factors		
Weather	Weather strongly influences animal flight behaviour and hence can influence collision risk. Weather can also influence ability to perceive and avoid risk	<ul style="list-style-type: none"> • Offshore bird strikes occurred at high levels at night with poor visibility (Huppopp et al. 2006) • Species dependent on thermals for lift, e.g. Griffon Vultures, encounter scarcer and weaker updrafts in winter and are more likely to collide with wind turbines as they are flying lower (Barrios and Rodriguez 2004) or on days and in areas where vertical lift was weak (Lucas et al. 2008) • Birds and bats are more likely to collide with wind turbines at particular wind speeds (Cryan et al. 2014; Johnston et al. 2014; Arnett et al. 2011) • Weather strongly influences the intensity and altitude of bird migration and bird migration prediction models

(continued)

Table 18.1 (continued)

Factor	Description	Examples
		are used to warn military pilots against peak migration (high collision risk) (www.flysafe-birdtam.eu) (Kemp 2012; Shamoun-Baranes et al. 2014; Ginati et al. 2010)
Topography	Animals may concentrate in particular corridors, or use topographical features to facilitate flight and navigation increasing the likelihood of collision in these places	<ul style="list-style-type: none"> • Species of birds that use soaring flight are more likely to collide with wind turbines placed along coastal cliffs, ridges and steep slopes used to generate lift (Barrios and Rodriguez 2004; Kitano and Shiraki 2013; Lucas et al. 2008) • Wind farms constructed in migratory bottlenecks have a high number of avian collisions (Barrios and Rodriguez 2004) • Most military low-level bird strikes occur along the migration flyway from SW Sweden towards SW Europe (Dekker and van Gasteren 2005)
Resource availability	Resource availability such as food, shelter, and breeding sites can strongly influence attraction to particular areas and hence collision risk	<ul style="list-style-type: none"> • Bats attracted to wind turbines because of high invertebrate concentrations (Horn et al. 2008) • Areas attracting large numbers of birds such as waste treatment sites within the vicinity of airfields greatly increase the probability of bird strikes (Baxter et al. 2003; Leshem and Ronen 1998)
Structural design	Aspects such as height, speed, sound and lighting can influence attraction to and avoidance of structures and aircraft	<ul style="list-style-type: none"> • Fast-moving objects are more dangerous and harder to avoid than slow-moving ones (DeVault et al. 2015) • Some types of lighting may enhance detection and avoidance of aircraft (Doppler et al. 2015; Larkin et al. 1975) • Birds are attracted to certain lighting regimes, increasing their collision risk, e.g. mass fatalities at lighthouses (Jones and Francis 2003) • Certain structures may attract bats and birds looking for roosting sites, making them vulnerable to collision (Kunz et al. 2007; Osborn et al. 1998) • Specific aircraft design specifications exist to withstand bird impact collisions, and improvements in structural design are ongoing (e.g. Amoo 2013; Dolbeer 2013; Dennis and Lyle 2009; Federal Aviation Regulations 2017)

Many factors described here are interrelated

life (van Gasteren et al. 2014) or due to environmental conditions (Manktelow 2000; Steele 2001; Shaw and McKee 2008). Numerous studies (e.g. Sodhi 2002 and references therein) have reported seasonal patterns in bird strikes with peaks in spring and autumn that correspond to migration in many regions. Peaks in aerial bird densities during spring and autumn migration over the Netherlands and Belgium are also visible in Fig. 18.2 despite data smoothing. Due to the large concentrations of birds in the air during the migration season, the risk of serious bird strikes can be quite high, yet it is predominantly military aviation that specifically addresses the higher collision risk during migration (see Sect. 2.2). The increased risk during the migration seasons also depends on the region, time of day and type of migrants passing through the 3D airspace within which aircraft would be exposed to bird strikes. Passerines are by far the most abundant species groups and travel mainly along broad fronts. While these are very small birds, their sheer numbers during migration can, at times, completely fill up radar screens. As a result, in some regions, such as the Netherlands and Belgium, nocturnal migration is closely monitored. In other areas, especially along leading lines or geographic convergent zones, soaring migrants can pose a major risk to aviation during the day. These are often relatively large birds, flying in flocks (or kettles) through a broad altitude band as they climb through the air to gain altitude and then glide to gain distance. One such area in which military aviation is particularly concerned with soaring migration is Israel, a crossroads for migrants travelling between Eastern Europe and Asia to eastern Africa. On 10 August 1995, for example, two pilots were killed when an F-15 from the Israeli Air Force hit several white storks (*Ciconia ciconia*) during migration. Two storks were ingested into one of the engines and the plane crashed after 2 s (Ovadia 2005).

The risk of collisions with birds and bats during non-migratory flights has mainly been considered in aviation within the boundaries of airfields, where mitigation measures can be applied to reduce the likelihood of damaging encounters during take-off and landing. However, in civil aviation the proportion of damaging collisions just outside aerodrome boundaries has increased, seemingly due to improved mitigation within aerodromes and only limited efforts just outside aerodromes in combination with an increase in populations of hazardous species (Dolbeer 2011). For military aviation and other low-flying aircraft (e.g. rotary wing aircraft), non-migratory movements can also be problematic en route (Fig. 18.3). Again, large aggregations of birds can increase the risk of a bird strike. Species such as common starlings (*Sturnus vulgaris*), which flock during the non-breeding season, and birds like gulls and waterfowl that forage in groups in areas of high resource availability, such as around waste treatment sites or recently ploughed fields, and make regular commuting movements between foraging and roosting sites can pose a high collision risk, especially if these flights intercept airfields (Baxter et al. 2003; Leshem and Ronen 1998). Another example is the aggregation of thousands of Greylag geese (*Anser anser*) in the Netherlands in August foraging on grains left after harvesting. In addition to factors that might result in large aggregations of birds, individual experience and knowledge of the surroundings may also influence how prone a bird is to aerial collisions. Although often not conclusive, studies that summarize bird strike statistics have suggested that

migrants passing through an area may be more prone to bird strikes than residents, non-breeding birds more prone than breeding birds and juveniles of the same species may be more prone to bird strikes than adults (Brown et al. 2001; Burger 1983; Sodhi 2002). Similar patterns have been noted in regard to collisions with wind turbines and tall static structures (see e.g. Sect. 3.1.2 and Table 18.1).

In recent years, the use of Unmanned Aerial Vehicles (UAVs) has increased greatly in military and civil applications and UAVs may start replacing many human-based forms of aerial surveillance (Beard et al. 2006; Shahbazi et al. 2014; Marris 2013). The potential for conflict between these relatively small vehicles and wildlife is unclear but likely to increase in the coming years as their use in diverse applications increases, yet the risk of collisions between UAVs and wildlife has still received limited attention. Interestingly, recent engineering studies focusing on on-board systems to detect other aerial vehicles to avoid collisions (Moses et al. 2011) may also help reduce the risk of wildlife UAV collisions. The use of UAVs in ecological research is also expected to increase in the near future and researchers have already begun outlining ethical guidelines on how to minimize the potential impact on animal behaviour when using drones in wildlife research (Vas et al. 2015; Jones et al. 2006).

2.2 Current Solutions in Aviation

There are two general approaches to reducing the probability of collisions between aerial wildlife and aircraft: reducing the number of individuals or types of species present in and around airfields and avoiding flying in areas (location and altitude) or at times when high concentrations of birds and bats are measured or predicted in the air. While commercial aviation usually focuses on a range of solutions that falls into the first class of risk reduction, military aviation often deals with both. Regardless, understanding the ecology of the species in question is often paramount in designing efficient solutions. Methods for managing wildlife populations in and around airfields will not be discussed in this chapter as they have been reviewed elsewhere (Anonymous 2006; Blokpoel 1976; MacKinnon et al. 2004; McKee et al. 2016). Here, we focus on solutions related to avoiding bird strikes by separating the flight paths of aircraft and wildlife in space and time.

2.2.1 Monitoring Aerial Bird Movement

Different types of systems have been applied to remotely monitor aerial movement of wildlife for aviation safety. These systems, as well as visual observations, are used to provide near real-time warnings to pilots via air traffic controllers, as well as advance warnings based on expected aerial densities of wildlife and to collect information on aerial densities in order to develop models that can be used to predict aerial movements. Military aviation has been using medium- and long-range radar for real-time monitoring of bird movements in several countries. For example, the Israeli Air Force has been using air surveillance radar and Doppler weather radar to monitor bird movement during migration in order to warn pilots

and either delay or reroute flights where needed. During diurnal migration of large soaring migrants, radar observations are often augmented by visual observations of large flocks either at specific military airfields or along a visual observation network that transects the migration flyway (Alon et al. 2004; Dinevich and Leshem 2010). In the Netherlands, Belgium and Germany, air forces have been using air surveillance radars to monitor bird movement on a daily basis and use this information to produce bird strike warnings during daily flight planning. Due to imminent changes in the military radar monitoring systems, the Netherlands and Belgium air forces have tested the use of operational weather radars for monitoring aerial bird movements en route, as part of an international project (FlySafe) funded by the European Space Agency (Ginati et al. 2010). Currently, both air forces have incorporated the use of operational weather radar into their operational warning system (see <http://www.flysafe-birdtam.eu/>). One of the major advantages of using existing operational weather radars is that they provide more detailed information on altitude distributions than that given by air surveillance radar previously used. Furthermore, as the weather radars are organized in an international network for the exchange of weather data, there is now a huge potential for an early warning system based on measurements beyond the borders of each country, encompassing the international flyways used by birds (Shamoun-Baranes et al. 2014).

In addition to near-real-time monitoring of large-scale movements, dedicated bird radar systems are increasingly used to monitor local movements in and around airfields. This is mainly to reduce the risk of collisions during take-off and landing. Several different bird radar systems are currently deployed at both military and civil airfields around the world, and this application is quickly growing. These systems are primarily used in three ways: (1) inform ground-based crews who can then take action to reduce the risk through activities on the ground, (2) inform air crews and delay or redirect flights if needed and (3) monitor movements to learn about flight behaviour of wildlife and apply knowledge to develop better measures for risk mitigation (e.g. identify areas of high species abundance, roosts). Currently, there are systems that are being used where individual birds or flocks can be tracked within several kilometres of the radar, and runway crossings can be monitored and identified automatically. These systems include mobile applications enabling ground personnel to monitor aerial behaviour from any location and respond quickly to potential risks (Fig. 18.4).

An additional tool to measure bird movement, which is being used extensively in ecological research but rarely within the context of flight safety, is bio-logging. With GPS tracking technology, the daily movements of some species, depending on their size, can be tracked in 3D and at a very fine scale, providing detailed information on their flight behaviour and aerial space use throughout the annual routine (Bouten et al. 2013; Kays et al. 2015). The time spent in the air, the airspace used by an individual, the number of runway crossings, flight altitudes, response to disturbance and how these aspects may change in relation to external or intrinsic factors can all be measured using GPS and utilized to better inform programmes for flight safety risk reduction. One example is a case study conducted in the Netherlands which monitored the daily movements of adult and juvenile common

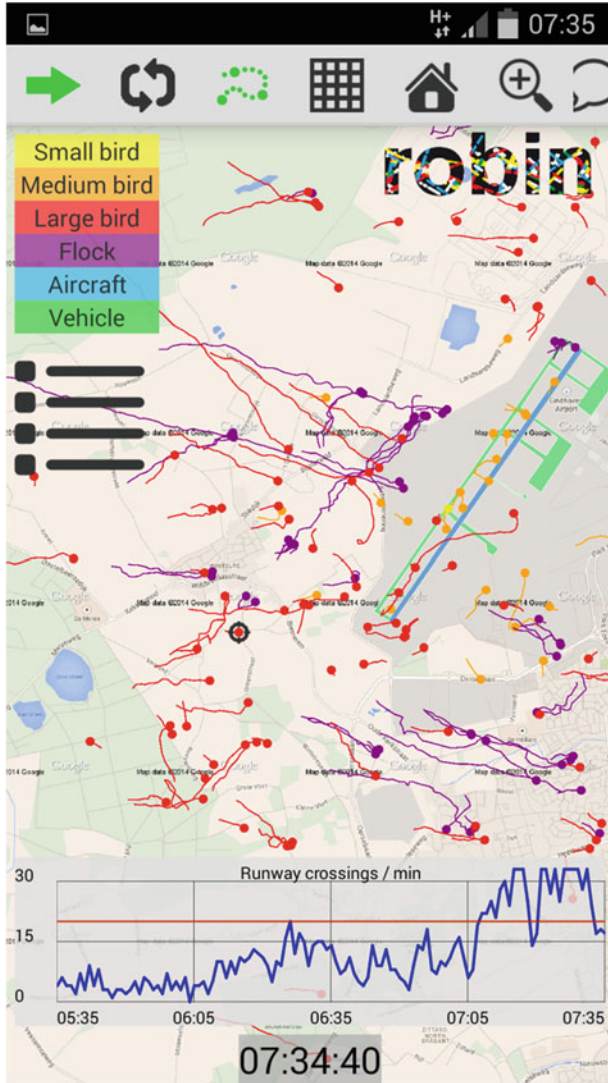


Fig. 18.4 Screenshot (10 March 2015 07:34 UTC) of the bird radar system from Robin Radar systems on Eindhoven airport (The Netherlands) showing bird movements in and around the airport (blue and green linear structures indicate the runway environment at Eindhoven airport). The system has an automated algorithm which distinguishes between the movements of birds from different size classes, aircraft and terrestrial vehicles registered by the radar. The system shows the number of runway crossings per minute as one of the collision probability indicators. On this morning, migration of Chaffinches (*Fringilla coelebs*) was visually observed

buzzards (*Buteo buteo*) monitored with a flexible GPS tracking system in and around military airfields (van Gasteren et al. 2014). Buzzards that were breeding within the Leeuwarden airfield boundaries were territorial and spent about 10% of their time in flight and rarely crossed the runways. This was in contrast to movement measured at another airfield (Eindhoven) in which non-breeding birds were monitored. Birds from Eindhoven spent less time in the air on average but crossed the runways more frequently. Although the sample size was very small, the study did suggest that non-breeding birds were far more likely to cross the runways than breeding adults were. Such findings can have important consequences for relocation programmes and can improve the likelihood of targeting the right individuals within a population.

2.2.2 Predicting Aerial Movements

Understanding how, when and why animals use the aerosphere has important implications for flight safety. This knowledge can be used to develop predictive models to better inform flight planners and adopt a proactive approach to reducing the risk of aerial collisions. Aircraft can reduce the risk of colliding with wildlife by changing their flight times, their flight routes and their flight altitudes, flying for example above the altitudes where the majority of aerial wildlife is found. Predictive models may focus on migration or local daily movements, predicting aerial densities of wildlife in 3D space and time.

Different types of models, with varying degrees of complexity and capacity to capture spatio-temporal dynamics, have been designed for flight safety purposes. When enough data or expert knowledge is available, static models can be generated that reflect mean seasonal patterns in aerial densities during migration. Such an approach has been adopted in Israel where the general flyways, altitude and diurnal and seasonal timing of soaring bird migration have been studied (Leshem and Yom-Tov 1996a, b, 1998) and converted into a static model providing guidelines for military training within periods of time and regions of high risk. This static model is then augmented with real-time and near-real-time warnings from different monitoring systems (radar and visual observations). In the first 10 years that this system was implemented, it resulted in an 88% reduction in damaging bird strikes and estimated financial savings of 30 million USD per year (Leshem 1994). Similar baseline models for broad front nocturnal migration can be established using seasonal aerial densities and altitude distributions (e.g. Fig. 18.2). Information about the distribution of species on the ground has been used to develop Bird Avoidance Models predicting the bird strike hazard for a given region throughout the year (Shamoun-Baranes et al. 2008). In these systems, visual observations from different sources are integrated and used to develop 2D species distribution models at a predetermined temporal resolution (approximately 2 weeks). Expert knowledge was then used to distribute the birds within altitude bands of interest. These models do not account for dynamics in environmental conditions, and while they may be helpful in predicting the densities of birds on the ground, their weakness is extrapolating this information to estimate aerial densities of birds.

Weather conditions influence the migratory behaviour of birds, affecting travel speeds, flight altitudes, flight routes, departure decisions and even flight modes (e.g. Shamoun-Baranes et al. 2010; Vansteelant et al. 2015; Gill et al. 2014). Predictive models can therefore be refined by incorporating environmental dynamics. Forecast models of aerial density of birds have been developed for the Netherlands and Belgian air forces based on the statistical relationship found between local weather conditions at the surface and aloft and measured bird densities (van Belle et al. 2007; Kemp 2012). Once models have been fit to existing data, weather forecasts are used as model input to provide a 3-day migration forecast. These models are site specific and limited in their capacity to estimate the altitudes at which birds are expected to migrate. The use of weather radar has generated new opportunities for modelling flight altitude distributions in response to weather. Predictive models that incorporate the influence of weather on flight altitude distribution of birds during migration have been developed (Kemp 2012; Kemp et al. 2013) and are being tested for operational use by the Netherlands and Belgian air forces. Once models are considered robust enough for operational purposes, they can be used to predict 3D and temporal distribution of birds in the air based on local weather forecasts. This data-driven approach generally requires data on bird movement from several seasons in order to capture enough environmental variability to fit robust models (van Belle et al. 2007). While these models are based on statistical correlations between migration intensity and weather conditions, understanding how birds respond to wind could greatly improve the selection of appropriate derivatives of wind speed and direction to be incorporated in the model fitting procedure (Kemp et al. 2012).

The predictive models described above can generally be considered a Eulerian description of animal movement; they provide information about the flux of migrants through a specific area over time, predicting temporal and altitudinal changes in aerial bird densities at a particular site, but they do not predict the movement of birds per se. Another approach is a Lagrangian description of animal movement in which organisms (or groups of organisms) can be followed in space and time, creating individual trajectories (Turchin 1998). From a modelling perspective, spatially explicit models of animal movement based on behavioural decision rules in dynamic environments could have great potential for flight safety. From a methodological perspective, a rather simple approach would be to interpolate movement parameters in space and time between radar as a type of null model to provide a Lagrangian representation of flow. More complex models that simulate behaviour under varying environmental conditions would be a more advanced approach. Simulation models of nocturnal migration and diurnal soaring migration of birds using information about bird movement derived from radar and other sources have been developed for research purposes and when well calibrated could be applied for flight safety (Erni et al. 2003; McLaren et al. 2012; Shamoun-Baranes and van Gasteren 2011; van Loon et al. 2011). Within the context of flight safety, simulation models could be used for scenario testing, for example, testing the consequence of different environmental conditions en route, to

fill in gaps between distant monitoring sensors and if run and updated with near real-time data can be used to predict migration hours or days in advance over a broad scale.

3 Anthropogenic Structures

3.1 Wind Turbines

Humans have been harnessing the wind's energy for thousands of years, but it is only since the 1980s, with the advent of increasingly large and numerous turbines to generate electricity, that the potential of these structures to cause significant effects on the animals that use the aerosphere has been considered and assessed. Commercially available wind turbines now include towers of over 100 m in height, with blades sweeping a diameter of 180 m and moving at up to 320 km/h at their tips (<http://www.4coffshore.com/windfarms/turbines.aspx>).

As governments around the world are investing in wind power as a “clean” technology that does not emit carbon dioxide and other pollutants associated with fossil fuels, wind turbines are being constructed at unprecedented rates. Global wind generation capacity grew from 1.7 GW in 1990 to 282 GW in 2012 (International Energy Agency 2014). Some of this capacity has been delivered through micro-turbines—small, often single devices, typically found on private land or mounted on buildings—but increasingly policymakers are relying on large arrays of turbines in wind farms, or wind parks, to meet renewable energy needs.

To be effective, wind farms must be built in exposed areas with high average wind speeds. Initially, many wind farms were sited on plains and in coastal and upland areas, including on mountainsides. Recently, largely due to aesthetic objections over wind farms in the countryside, offshore developments have been favoured. These offshore wind farms contain turbines that are greater in number, larger in size and distributed over a wider area than any other developments to date. They are also being installed in ever deeper water and further from the coast, meaning that a wider suite of wildlife in the aerosphere could potentially be exposed to the effects of turbines.

3.1.1 Effects of Wind Turbines on Wildlife

The potential impacts of wind turbines on aerial wildlife are many and complex (Schuster et al. 2015). Birds are the species on which the majority of research to date on the effects of wind turbines has focused, perhaps because of high-profile reports of deaths to charismatic species and those of conservation concern, such as Griffon Vultures (*Gyps fulvus*) in Spain and Golden Eagles (*Aquila chrysaetos*) in the USA, in areas where wind farms have been constructed (Drewitt and Langston 2006; Barrios and Rodriguez 2004). It is also increasingly recognized that bats can be affected by wind turbines in different ways, from fatal collisions to changes in their flight behaviour around wind turbines (Cryan and Brown 2007; Horn et al. 2008; Cryan et al. 2014; Lehnert et al. 2014; Arnett et al. 2016; Arnett and Baerwald 2013).

Birds and bats can be adversely affected by wind turbines in several different ways. The most obvious direct effect is death or injury through collision, which is generally with turbine blades, but can also be with turbine masts and associated structures, such as guy cables, power lines and meteorological masts (Horn et al. 2008; Drewitt and Langston 2006). Mortality due to barotrauma can be a problem, particularly for bats, whereby a reduction in air pressure close to moving blades causes tissue damage and pulmonary haemorrhage (Baerwald et al. 2009). There are also several indirect effects which have been studied in different taxa. Animals can be displaced from an area due to disturbance during construction and/or once wind farms become operational, which effectively amounts to habitat loss (Farfán et al. 2009; Pearce-Higgins et al. 2009). Another form of displacement is the so-called “barrier effect”, whereby individuals increase their energy expenditure by flying around a wind farm in their normal flight path (Desholm et al. 2006), be it on migration or during daily journeys between feeding, nesting and roosting sites. Actual habitat loss or change resulting from wind farm development can also occur (Drewitt and Langston 2006; Perrow et al. 2011).

Not all habitat changes associated with wind energy deter wildlife (Table 18.1). Bats and birds may be attracted to wind turbines by these structures’ effect on insects, which are drawn in turn by the colours of paint chosen or by the heat generated by turbines (Kunz et al. 2007; Long et al. 2011; Cryan et al. 2014). Wind farms may also attract birds and bats looking for places to roost. The lattice turbine design found in older installations (as opposed to modern monopole designs) was thought to be especially appealing in this respect (Kunz et al. 2007; Osborn et al. 1998), while bats have also been observed investigating turbine blades, both moving and stationary, again possibly in an attempt to find sites for roosting or mating (Horn et al. 2008; Cryan et al. 2014). The presence of wind turbines may actually enhance habitat for some species. For example, offshore wind farm structures not only provide roosting sites, but can act as artificial reefs, thereby attracting fish and their predators, including some species of seabird (Inger et al. 2009; Lindeboom et al. 2011). Wind turbine installations may also act as *de facto* nature reserves, as other damaging human activities, for example shipping and fishing in offshore areas, can be limited or excluded in the wind farm zone (Inger et al. 2009).

All effects of wind turbines may also be cumulative in time and space (i.e. the effect of multiple installations that an individual encounters over time), such that population level impacts are not seen until several years post-construction (Drewitt and Langston 2006; Hill and Arnold 2012). Effects also vary throughout the year and depend on the season (e.g. Fijn et al. 2015). For example, birds migrating over the sea are more likely to collide with turbines in poor weather, when individuals are more likely to fly at altitudes swept by turbine blades and visibility is reduced (Table 18.1). In these conditions, birds or bats can become disorientated and even attracted to turbines if they are illuminated in particular ways (Hüppop et al. 2006; Cryan and Brown 2007; Ahlén et al. 2007). Similarly, individuals might be more likely to encounter a wind farm site and be vulnerable to negative effects at particular stages of their life cycle, such as during breeding or on migration. For

instance, migrating bats are thought to spend a higher proportion of their time flying at blade height and echolocate less frequency than residents, hence increasing their susceptibility to collision [reviewed in (Cryan and Barclay 2009)]. In a more specific example, a Belgian wind farm constructed in the foraging flight path of breeding terns caused significant colony-level mortality as birds were exposed to the risk of collision so frequently (Everaert and Stienen 2007). Individuals may also habituate to the presence of a wind farm (or indeed to mitigation measures designed to discourage wildlife from approaching turbines—see Sect. 3.1.3), such that although initially displacement and disturbance may occur, over time the wind farm area might be used again (May et al. 2015). The benefit of reclaiming this former habitat might be outweighed by the risks associated with collision, although it is possible that residents may learn to avoid turbines, while non-habituated individuals, for example migrants, may suffer higher levels of mortality due to collision (Langston and Pullan 2003). Thorough long-term monitoring is therefore required to fully understand the consequences of wind farm installation (Stewart et al. 2007).

The overall detrimental effects of wind turbines on animals that use the aerosphere have been much debated in the literature, but there is mostly consensus that the levels of mortality are seriously worrisome. The number of bats killed is estimated at approximately 300,000 per year in Germany and 500,000 per year in the USA (Arnett and Baerwald 2013; Lehnert et al. 2014; Voigt et al. 2012; Hayes 2013; Smallwood 2013), while approximately 230,000 birds are thought to be killed annually by onshore monopole wind turbines in the contiguous USA (Loss et al. 2013). Many authors point out that the number of individuals killed or displaced by wind developments is less than that associated with other anthropogenic structures, for instance power lines and buildings (see Sect. 3.2), and also lower than that caused by human activities such as driving and even domestic cat ownership (Erickson et al. 2005; Calvert et al. 2013). It is worth remembering that the number of wind turbines installed is small compared to the number of buildings, cars etc., although this will change if the wind energy sector continues to grow. The negative impacts of wind turbines need to be considered on a species by species basis. For species that are slow to mature and reproduce, any mortality or reduction in fitness brought about directly or indirectly by wind turbines could be critical. Such species include bats, seabirds and raptors, and local population declines have been reported in some studies (e.g. Everaert and Stienen 2007; Marques et al. 2014).

3.1.2 Monitoring the Effects of Wind Turbines

Ecologists assessing the effects of wind turbines often aspire to the “BACI” model (Before-After-Control-Impact), where wildlife surveys are carried out before and after turbines have been installed, in two different sites—the site of the wind farm and a control area with similar characteristics that is far enough away to be unaffected by the development (Pérez Lapeña et al. 2010). This can show changes such as species redistribution or changes in abundance due to wind farms. The number of fatal collisions due to wind turbines can be assessed through counts of carcasses. These counts can be confounded by scavengers removing carcasses,

although a correction factor based on experimental removal rates has been calculated in a number of studies (e.g. Krijgsveld et al. 2009). Moreover, carcass counts are difficult or impossible to carry out in some locations, for example offshore (Desholm et al. 2006).

Monitoring of species abundance and behaviour in and around wind farms can be carried out through visual observations, but technology is increasingly being harnessed to greatly improve our understanding of how wildlife responds to installations, especially since effects may occur outside the human visible range (for example, at high altitudes) or in weather conditions during which visual surveys cannot easily be carried out. Such technology includes digital aerial surveys, ranger finders, vertical and horizontal radar, thermal imaging and acoustic detection of animal calls in the vicinity of turbines (e.g. Desholm et al. 2006; Hüpopp et al. 2006; Cryan et al. 2014). These methods allow information on a large number of individuals from a broad range of species to be captured over a long time period and (in the case of radar) over a broad spatial scale. However, it can be difficult to separate species, age/sex cohorts and individuals with these techniques (e.g. Desholm et al. 2006).

GPS tracking, whereby small devices are placed on individual animals, overcomes many of these problems. Individuals can be followed, providing fine-scale information on movement patterns (Fig. 18.5), elucidating the connectivity between particular wind farm developments and the population that the focal animal represents, for example an adult seabird breeding at a particular colony.

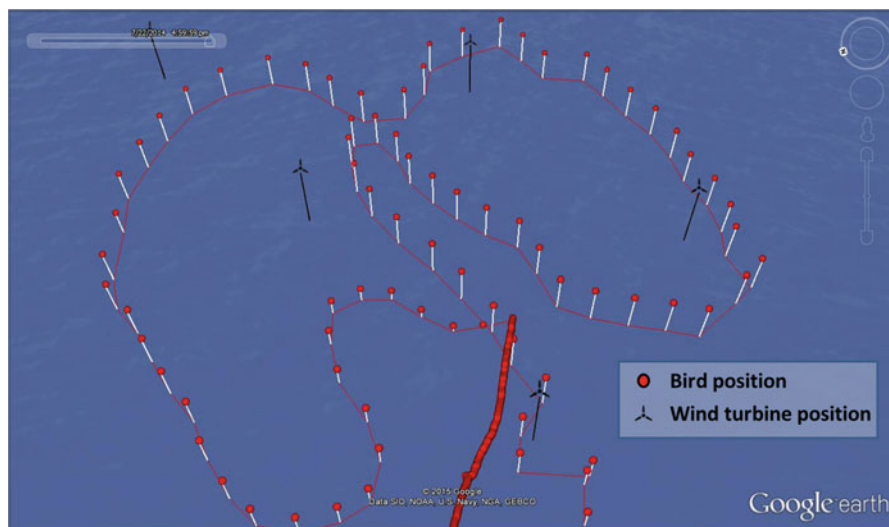


Fig. 18.5 GPS measurements providing location, altitude and ground speed every 10 s of a lesser black-backed gull (*Larus fuscus*) floating first on the sea surface and then flying through a wind farm in the Irish Sea. Vertical line length is proportional to height above sea level. This lesser black-backed gull tagging was funded as part of the UK Department of Energy and Climate Change's Offshore Energy Strategic Environmental Assessment programme

Long-lived GPS tags can also reveal how individuals' interactions with wind turbine installations can vary throughout different stages of their life cycle (Thaxter et al. 2015) and can provide information on whether individuals fly at altitudes that could expose them to collisions with turbine structures (Cleasby et al. 2015; Ross-Smith et al. 2016).

All these technologies can help calculate a species' so-called "collision risk". This is typically determined by models incorporating a number of factors, including the abundance and morphology (including flight altitude) of the species concerned along with properties of the wind farm (Band 2012) (Table 18.1). Collision risk models include a term called "avoidance", which is the rate at which animals take evasive action to successfully eliminate their risk of collision. "Macro-avoidance" occurs when animals avoid an entire wind farm, as has been observed in several species, including migrating Eider (*Somateria mollissima*) (Desholm and Kahlert 2005). "Micro-avoidance" occurs when an individual alters its flight path to prevent collision at the last second. An intermediate stage, "meso-avoidance", allows birds to avoid turbines within wind farms (Cook et al. 2014).

Similar to aviation, collision risk posed by wind turbines varies depending on environmental conditions, aspects of the turbine design and location, behavioural and physiological characteristics of the species concerned, as well as with the time of year, as individuals from the same species can be more exposed to turbines at particular points of their life cycle (Table 18.1). In bats, for example, the majority of deaths appear to occur during migration and migratory bats make up a large proportion of the observed fatalities (Arnett et al. 2008). In birds that rely on thermal convection or slope updrafts to sustain soaring flight, larger soaring birds such as Griffon Vultures that rely almost entirely on soaring flight and rarely on flapping flight are more likely to collide with turbines than more abundant soaring species with comparatively lower wing loading and higher manoeuvrability; Griffon Vultures are also more susceptible to fatal collisions when and where soaring conditions are poorer (De Lucas et al. 2008; Barrios and Rodriguez 2004). Similarly, animals may not perceive the danger of moving wind turbine blades and therefore may not take action to avoid them. Although this is not yet fully understood, it could occur either because a species' sensory abilities are such that individuals cannot detect turbines (which for birds may be compounded at certain blade speeds because of "motion smear") or because individuals are not adapted and attuned to turbines during flight (Martin et al. 2012).

3.1.3 Mitigating the Effects of Wind Turbines

When it comes to mitigation, there is no "one-size-fits-all" approach and several proposed mitigation methods remain under- or untested (Marques et al. 2014, but see Arnett et al. 2011; de Lucas et al. 2012). Although easier said than done, the most effective mitigation is to ensure wind farms are not placed in areas where susceptible wildlife is abundant, especially when the species concerned are of conservation interest. Wind farms can be situated outside protected areas and away from major roosts, breeding colonies, migration bottlenecks and topographic features on which particular species rely for thermals (Drewitt and Langston 2006).

Informed decisions about where to place a wind farm to minimize the impact on wildlife rely on pre-construction monitoring, which is typically carried out as part of an environmental impact assessment process.

Once a wind farm has been built, there are a series of measures that can improve its compatibility with wildlife. Wind turbines need to be “repowered”, whereby structures are remodelled and upgraded, and turbines that are more wildlife friendly can be installed during this process. For example, monopole designs and fewer, larger, turbines can generate the same energy as a greater number of small, more densely packed turbines, and may have a lower avian collision rate per megawatt (Barrios and Rodriguez 2004; Johnston et al. 2014; Everaert 2014), although larger turbines may be more dangerous for bats (Barclay et al. 2007). “Micro-siting” can also be effective, whereby particular turbines that cause high levels of mortality are removed (de Lucas et al. 2012; May et al. 2015). Turbines can also be selectively temporarily shut down at times when vulnerable species (both in terms of collision susceptibility and conservation concern) might be present. This method halved Griffon Vulture mortality with only a 0.07% decline in energy production at a wind farm in southern Spain (de Lucas et al. 2012). Similarly, raising the minimum wind speed threshold at which turbines generate power (i.e. reducing turbine operation at low wind speeds) has been found to reduce levels of bat mortality with marginal annual power loss (Arnett et al. 2011).

Measures can also be taken to make the wind farm less attractive to animals, or more conspicuous in the case of enhancing avoidance. Such techniques include altering the paint colour, lighting regime, using lasers, electromagnetic fields and acoustic deterrents (Cook et al. 2011; Nicholls and Racey 2007). However, care must be taken that animals do not habituate to these measures, as has been noted in collision mitigation measures implemented on aerodromes (MacKinnon et al. 2004), and it is difficult to find an effective way to discourage all vulnerable species (May et al. 2015). Areas around the wind farm could also be made more attractive, for instance providing alternative foraging habitat, to encourage wildlife to concentrate there instead of within the wind farm itself (Martin et al. 2012).

In today’s world, concerns about climate change mean wind farms play an integral part in reducing humankind’s carbon footprint. However, care must clearly be taken to ensure that the impact of this technology on biodiversity is kept to a minimum. To do this, a consistent and holistic approach, incorporating a range of survey and specifically tailored mitigation techniques embedded in a framework of sound aeroecological understanding, is required, ensuring that all negative effects on wildlife are recognized, understood and prevented where possible.

3.2 Other Tall Structures

Tall static structures in the landscape such as buildings, communication towers and their guy wires, large monuments and power lines are also a collision risk for numerous species. Some estimates suggest that millions of birds a year die due to collisions with these structures; for some species, annual mortality has been

estimated at several percent of the total population (Bevanger 1998; Erickson et al. 2005; Longcore et al. 2013). Numerous reviews of avian collisions with power lines and other structures are available (Jenkins et al. 2010; Erickson et al. 2005; Drewitt and Langston 2008), and we will not provide a comprehensive overview here. Interestingly, the numbers provided suggest a massive mortality rate, but population effects or adaptive evolutionary consequences are rarely discussed. However, similarities can be found with collisions with wind turbines and even with aircraft, several of which we will briefly highlight.

As with other anthropogenic threats in the air, mortality rates at tall structures are often species specific and not directly related to species abundance (Longcore et al. 2013) with certain species being more susceptible to collisions than others, and numerous external factors influence the probability of collisions as well (Table 18.1). As mentioned for wind farms, animals may even be attracted to such structures. For example, a recent study has shown that several species of tree bats (*Lasiurus sp*) are attracted to tall towers during autumn migration and results support the hypothesis that this attraction is linked to social behaviour (Jameson and Willis 2014). In addition to chronic collisions, collisions with tall and conspicuous structures in landscape can result in episodic mass mortality events, sometimes involving thousands of individual birds over the course of a few days (Erickson et al. 2005). In North America, the highest mortality has been recorded for nocturnal migrating passerines and studies suggest that collisions generally occur on nights with poor weather when birds are attracted to and potentially trapped by lighting of these structures (Longcore et al. 2013; Erickson et al. 2005).

In contrast to collisions with large towers but in common with collisions with wind turbines, the species that appear to be most susceptible to collisions with power lines are large and have low manoeuvrability such as cranes, bustards, flamingos, waterfowl and gamebirds (Jenkins et al. 2010). Familiarity with the surroundings also influences how risk prone birds are, with juvenile and migrants birds being more susceptible than adults and residents (Jenkins et al. 2010). Similarly, the aim of flight might influence the risk of collision, where aerial displays, predator prey interactions or foraging flights to feed nestlings may put a bird at higher risk than when flying for other purposes. Other factors influencing perception are also important, such as ambient light, and flying in flocks when individuals are potentially paying more attention to conspecifics during flight and less to their direct surroundings.

Mitigation measures suggested to reduce the risk of collision with tall structures are related to either improving detection of these structures or reducing potential distraction caused by lighting (Poot et al. 2008). For example, several studies suggest that pulsed lighting on communication towers and guy cables is preferable to constant light, regardless of the colour. For power lines, marking lines to make them more visible is an option although finding a solution that works for a broad range of species and environmental conditions seems more difficult, and field tests have produced different and sometimes conflicting results (Jenkins et al. 2010).

4 Future Perspectives

Aerial conflicts between wildlife and humans are a problem that is likely to persist, especially as human population and economic growth continues, leading to ever further encroachments of human structures and activities in the atmosphere. However, it is also clear that there are numerous types of solutions and that our knowledge and understanding of the internal and external factors that influence animal movement can be put to use in order to reduce these conflicts. While advances in the design of human structures and aerial vehicles may reduce the risk of collisions and other adverse impacts, aeroecologists can contribute a great deal by improving our understanding of aerial movement and finding ways to communicate and apply this knowledge to reduce aerial conflicts.

The different types of sensors and methods used to monitor aerial movement are often complementary in many ways. The integration of these multiple sensors, where possible, to monitor, understand and predict movement, collision risk and the other ways in which wildlife might be affected by human activities/structures is likely to produce better results than single sensors alone. This might become increasingly feasible as individual tracking studies are increasing and biological data from existing sensor networks such as weather radars become more readily accessible (Shamoun-Baranes et al. 2014; Chilson et al. 2012). The development and improvement of algorithms to differentiate between different types of aerial organisms monitored by radar is ongoing (e.g. size classes, species groups, single vs. multiple animals) and will improve the quality of monitoring and real-time warning systems (Gürbüz et al. 2015). This will both reduce the chance of false warnings and unnecessary mitigation measures (e.g. rerouting flights, stopping turbines) and the absence of warnings which are in fact needed, hence exposing wildlife (and humans) to unnecessary risk. Tracking individual birds or bats can often provide the ecological context needed to better understand and model behaviour from a mechanistic perspective, and sensors that scan the atmosphere, such as radar providing information about the densities of animals travelling through the aerospace at a given time, can indicate how representative tracked individuals are of larger scale patterns. Advances in tracking technology will also improve this process, allowing more information to be captured from an ever-wider range of species (Bridge et al. 2011; Robinson et al. 2010).

Tracking data collected for studies not directly related to risk assessment can also be extremely informative, providing information on the general flight behaviour of different species under a range of environmental conditions. By pooling data across studies, we can start filling knowledge gaps about basic flight behaviour per species that would be relevant for a range of stakeholders, such as the amount of time spent in flight, flight altitude distributions and flight speeds. Such studies would be complementary to other comparative studies such as flight speeds measured using tracking radar (Bruderer and Boldt 2001). Tracking studies could also provide information about the timing, routes and altitudes of local commuting flights where risk can be more concentrated. Similarly, ongoing efforts to coordinate the use of weather radar networks for ecological research in Europe and North America can result in

large-scale monitoring of aerial movement of wildlife (Shamoun-Baranes et al. 2014; Kelly et al. 2012). Large-scale monitoring efforts should not only focus on migratory movements but also on local commuting flights. Data from different tracking studies and large-scale monitoring programmes can be used to provide baseline information for assessing collision risk at large scales, identifying hotspots of aerial activities, as well as seasonal and diurnal patterns of movement, especially high aerial densities, which are of particular interest from a conservation perspective as well as for flight safety. In time, we can also begin to map the 3D space use of different species for establishing baseline assessments of risk at the species specific level.

Models for predicting aerial movement can be developed with different levels of complexity and capacity to incorporate the diverse factors that influence aerial movement. Gaps between sensors can be filled with a simple model interpolating properties of aerial movement (e.g. density, ground speed) between sensors. Data-driven models can be used to predict temporal variability in aerial movements. When developing models, data-driven and more mechanistic approaches can potentially be combined to provide more realistic and spatially explicit representations of movement through the atmosphere. Modelling need not only focus on what is happening in the air, but also on the ground, the source areas and destinations of flight, which will influence local aggregations and help understand why collision risk may be higher in certain areas and times of the day or year. For example, radar monitoring can also be used to assess habitat use of large aggregates of birds and identify hotspots from which aerial activity will be initiated (Buler and Dawson 2014; Buler et al. 2012). Simulation models that incorporate individual response to environmental conditions can be used to explore changes in collision risk due to specific environmental conditions. Individual-based models have already been developed to address collision avoidance and the impact of group size, social structure and obstacle placement (Croft et al. 2015). Research that improves our understanding of animal perception and how species' life cycles affect their susceptibility to aerial conflicts will also provide information that could fine-tune such models. Animals' sensory abilities must be taken into account when predicting how they will respond to and be affected by human structures and activities in the atmosphere (Martin 2012), while incorporating knowledge of ontogeny and social dynamics will help pinpoint certain times of the year (e.g. the breeding season) when particular species might be especially vulnerable.

We are confident that in the coming years, the combination of improved sensor networks and advances in bio-logging and modelling of animal movement will enormously enhance our fundamental understanding of aerial behaviour. This, combined with the cross-fertilization of ideas and expertise across disciplines and applications, will contribute greatly to establishing a holistic approach to sharing the skies safely for humans and wildlife alike.

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