CHAPTER

14

Reducing collisions with structures

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Introduction

Avian collisions with human infrastructure are one of the top anthropogenic causes of mortality in landbirds and waterbirds, killing hundreds of millions of birds annually in North America alone (Erickson et al., 2005; Loss et al., 2015). Avian collisions often result when artificial light causing attraction or disorientation increases collision risk with buildings, towers, boats, and offshore oil platforms when they are lighted (Barrios and Rodríguez, 2004; Brown et al., 2013; Ellis et al., 2013; Gehring et al., 2009; Loss et al., 2019; Rodríguez et al., 2017; Ronconi et al., 2015). This type of collision risk can be eliminated or greatly reduced when lights are managed to prevent avian issues, which is discussed from a seabird perspective in Chapters 6 and 13. Collisions occur independently of artificial lights when birds fly at infrastructure that is difficult to detect and or avoid such as windmill blades (see Chapter 7), communication towers, and various wires including guy wires on communication towers, communication wires, and powerlines (Gehring et al., 2011; Murphy et al., 2016b; Savereno et al., 1996; Travers et al., 2021).

Powerlines are of particular concern for avian conservation because of their immense footprint on the landscape and the high levels of mortality documented at subsampled sections of powerlines. As an example of the linear scale of powerlines, in the early part of this decade, the United States and Canada had 862,207 and 231,966 km, respectively, of the higher voltage long-distance transmission powerlines on the landscape and, although there is limited data, several times more by length of the shorter lower voltage distribution powerlines (Loss et al., 2014; Rioux et al., 2013). Owing in large part to the geographic scale of powerlines, mortality estimates for Canada and USA alone indicate that powerlines kill tens of millions of birds annually (Loss et al., 2014, 2015; Rioux et al., 2013). More than 30 years of research on avian powerline collisions (Bevanger, 1994, 1995; Bevanger and Brøseth, 2004; Demerdzhiev, 2014; Janss, 2000; Marcelino et al., 2021; Murphy et al., 2016b; Savereno et al., 1996; Shaw et al., 2021) have shown that when powerlines are present in avian airspace, collisions will occur (APLIC, 2012; Barrientos et al., 2018;

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Bernardino et al., 2018; Bevanger, 1994, p. 2; Drewitt and Langston, 2008; Erickson et al., 2005; Jenkins et al., 2010; Loss et al., 2014, 2015; Rioux et al., 2013).

Researchers have also begun to document powerline collisions across several groups of seabirds and have reported that powerline collisions can have population-level impacts (Bureau d'Etudes Environnement Agronomie, 2008; Cooper and Day, 1998; Garcia-del-Rey and Rodriguez-Lorenzo, 2011; Gómez-Catasús et al., 2021; Podolsky et al., 1998; Travers et al., 2021; Verbeke et al., 2020). In seabirds, powerline collisions have been documented for Bulwer's Petrels (*Bulweria bulwerii*) and Cory's Shearwaters (*Calonectris borealis*) on multiple islands within the Canary Islands archipelago (Garcia-del-Rey and Rodriguez-Lorenzo, 2011; Gómez-Catasús et al., 2021) and White-tailed Tropicbirds (*Phaethon lepturus*), Wedge-tailed Shearwaters (*Ardenna pacifica*), and Tropical Shearwaters (*Puffinus bailloni*) on Reunion Island (Bureau d'Etudes Environnement Agronomie, 2008; Verbeke et al., 2020). On the island of Kauai, Hawaii, seabird powerline research has spanned 37 years beginning in 1993 (Ainley et al., 2001; Cooper and Day, 1998; Podolsky et al., 1998; Travers et al., 2021, n.d.). Several seabird species have been documented to collide with powerlines on Kauai, including White-tailed Tropicbirds, Red-footed Boobies (*Sula sula*), Wedge-tailed Shearwaters (Travers et al., n.d.), Hawaiian Petrels (*Pterodroma sandwichensis*) (Travers et al., 2021), and Newell's Shearwaters (*Puffinus newelli*) (Cooper and Day, 1998; Podolsky et al., 1998; Travers et al., 2021).

The list of seabird species documented to collide with powerlines is most certainly incomplete as research focused on seabird powerline collisions has been limited to date. Furthermore, collision risk is likely to expand to species and regions that do not currently have collision risk as powerlines are expected to expand globally at 5% per year (Erickson et al., 2005). Seabird biologist may expect that much of the development will occur closer to large urban centers away from remotely breeding seabirds. However, the promotion of renewable energy production for decarbonization will result in the decentralization of power production into areas with abundant renewable energy resources (Lienert et al., 2015; Smith and Dwyer, 2016) such as high wind, high solar, wave and tidal action, and geothermal (Østergaard et al., 2020). Decentralization of power production will result in the expansion of powerlines connecting power production to distant urban centers increasing the overall length of powerlines on the landscape (Lienert et al., 2015; Smith and Dwyer, 2016) such that species not currently exposed to powerlines may in the future be at risk of collisions (Smith and Dwyer, 2016).

From a seabird conservation perspective, the most important aspect of the powerline collision problem is the high likelihood of collisions occurring without documentation, which erroneously obscures the need for conservation interventions such as seabird-friendly powerline modifications (discussed in "Methods for reducing seabird collisions with powerlines and similar infrastructure" section) or conservation mitigation offsets (Travers et al., 2021). Powerlines are a continuous linear barrier that can have landscape-level impacts on birds (Richardson et al., 2017), but documenting collisions across the immense length of existing powerlines is challenging (Barrientos et al., 2018; Bevanger, 1995; Loss et al., 2014; Travers et al., 2021) and can result in dramatic underestimation of collisions (Murphy et al., 2016b; Savereno et al., 1996; Travers et al., 2021). Even relatively small islands can have several hundred to more than a thousand kilometers of powerlines, and these lines can cross rugged terrain that is difficult or effectively impossible for humans to access, resulting in logistical difficulties determining the scale and extent of collisions (Travers et al., 2021; Verbeke et al., 2020). Here, we present two case studies, one from Kauai, Hawaii, and one from Reunion Island. Research from both locations has indicated that even when powerline collisions are occurring in high numbers, they can be difficult to detect at a landscape scale with a subsequent underestimation of risk directly impeding seabird conservation.

Research on Kauai has indicated that powerline collisions are the most significant anthropogenic source of mortality for Newell's Shearwaters and Hawaiian Petrels (Travers et al., 2021). Direct mortality is primarily the result of injuries from the impact force when colliding with powerlines (Cooper and Day, 1998; Travers et al., 2021). However, mortality can also occur from electrocutions when the birds' wings are sufficiently long to connect two separate powerlines (Travers et al., n.d.). Powerline collisions also have indirect effects such as abandoned breeding attempts as documented in seabirds rehabilitated after powerline grounding (Raine et al., 2017a,b), mortality of a chick when a breeding adult is killed or does not return to the island postcollision (Raine et al., 2017a,b), and skipped years of breeding while the surviving adult reestablishes a breeding partner.

In midsize seabirds like the Newell's Shearwater and Hawaiian Petrel, collisions causing mortality and groundings are most commonly the result of head injuries (70%) and can present as broken/bifurcated bills, crushed eyes, skull fracture, and feather removal on the forehead/cheek/neck (Travers et al., 2021). Twenty percent of powerline-grounded seabirds lack externally visible injury, but unseen head and neck trauma can sometimes be detected as neurological problems causing delayed mortality in live birds admitted for rehabilitation (Travers et al., 2021). Relative to head and neck injuries, surprisingly far fewer powerline-grounded seabirds present with wing injuries (10%) but broken humerus, including Newell's Shearwaters with compound fracture and wing amputation, along with elbow, and wrist injuries have been detected in powerline-grounded seabirds (Travers et al., 2021). On Kauai, seabird electrocutions are far less frequently detected but have been both directly observed and detected in grounded birds as burn injuries (clear smell of burnt feathers) for a limited number of Red-footed Boobies when these birds have flown inland across powerlines at night on Kauai (Travers et al., n.d.).

On Kauai, the tallest transmission powerlines (high voltage) extend for hundreds of kilometers and the shorter distribution powerlines (lower voltage) extend for an additional several hundred kilometers across the landscape, collectively creating a barrier around much of the suitable inland seabird breeding habitat while also being in close proximity to coastal seabird colonies (Travers et al., 2021, n.d.). Originally, Podolsky et al. (1998) estimated the number of seabird powerline collisions based on grounded Newell's Shearwaters detected under powerlines while conducting driving searches along roads near the coast (Cooper and Day, 1998; Podolsky et al., 1998).

These estimates clearly showed powerlines as a collision risk to breeding adults and subadult Newell's Shearwaters, a finding that was supported by direct observations that a large percentage of Newell's Shearwaters and Hawaiian Petrels transiting past powerlines flew very close to and nearly collided with the powerlines (Cooper and Day, 1998). The estimated level of collisions, based on ground searches, did not trigger powerline minimization actions (collision reduction solutions), leaving endangered seabird powerline collisions to continue unabated for nearly four decades (Travers et al., 2021). Within that time period, population trend monitoring using radar (Day and Cooper, 1995; Day et al., 2003) showed declines of 78% and 94% for Hawaiian Petrels and Newell's Shearwaters, respectively (Raine et al., 2017a). Decades later, Travers et al. (2021) used alternative collision monitoring methods that demonstrated that seabird ground searches on Kauai failed to detect most collisions and thus vastly underestimated the seabird collision problem. The authors concluded that decades of ongoing and unmitigated powerline collisions were the greatest anthropogenic contributor to the decline of both endangered seabird species.

In collision research, the most common method used for quantifying avian powerline collisions is conducting searches for grounded birds under or near powerlines (Jenkins et al., 2010; Rioux et al., 2013). Between 2012 and 2020, Travers et al. (2021) conducted concurrent grounded seabird searches at powerlines and direct observations of Hawaiian Petrel and Newell's Shearwater powerline collisions. Based on the observed collision rates, the authors reported that at least 6513 endangered seabird collisions occurred at just 3% of the powerlines by length. Critically, only a small minority of seabirds (13%) observed hitting powerlines became grounded immediately within typical search distances while many others became grounded out to distances of more than a kilometer from powerlines, making them undetectable by standard searches (30 m on either side of the lines; Savereno et al., 1996). Furthermore, the majority of observed collisions occurred in areas that were effectively unsearchable, due to steep, unsafe terrain and thick vegetation. These factors meant that grounded seabird searches could not detect the frequency or geographic extent of seabird powerline collisions across the landscape. This was further evident when contrasting the observed collisions with the findings of the three independent grounded seabird searches conducted on Kauai (Cooper and Day, 1998; Podolsky et al., 1998; Travers et al., 2021) as all three searches had missed thousands of seabird powerline collisions that were occurring away from roads, the primary search space by area. The findings by Travers et al. (2021) that search studies can miss thousands of collisions are of general concern for seabird conservation but particularly for critically endangered species in which powerline mortality of a small number of individuals is unlikely to be detected and can be devastating to the population.

Seabird powerline collisions documented on Reunion Island in the Indian Ocean provide an additional case study into the risks of undocumented powerline collisions, particularly for rare species. When researchers on Reunion reviewed the results from Kauai, they determined that similar powerline collision risk factors existed for the Tropical Shearwater and the endemic Barau's Petrel (*Pterodroma baraui*) and Mascarene Petrel (*Pseudobulweria aterrima*). On Reunion, a rapid assessment was conducted in 2019 using information on collision risk provided from Kauai (discussed in "Identifying factors that impact seabird collision risk" section), to prioritize sections of powerlines for initial monitoring. Collision monitoring at select high-risk powerline sections resulted in the immediate documentation of Tropical Shearwaters collisions, with seabird flight heights and passage rates indicating collision risk was also present for Barau's Petrels and likely for Mascarene Petrels (Verbeke et al., 2020). At the most dangerous powerline section detected on Reunion, more than one collision occurred on average every night of monitoring, with documented collisions as high as nine birds in a single night (Verbeke et al., 2020). Despite a very high rate of collisions and mortality of Tropical Shearwaters, this location was not previously known to have powerline collisions. Of most concern is that the powerline section with the highest documented collisions is positioned on the flyway for one of only two known Mascarene Petrel colonies in the world, of which there is a global estimate of 100–200 mature individuals and a total estimated population of 1200 (Birdlife International, 2021; Lopez et al., 2021; Verbeke et al., 2020). Furthermore, one Mascarene Petrel has been found in this colony alive but with a bifurcated and chipped lower mandible (Dubos, 2018), an injury consistent with powerline collisions (Travers et al., 2021). The research on Reunion provides a clear example of the threat posed from ongoing undocumented powerline collisions.

Many of the powerline collision risk factors present on Kauai, Reunion, and the Canary Islands occur across the globe wherever seabird flyways, breeding, and roosting locations overlap with powerlines. Similarly, many of the challenges associated with detecting collisions, and the associated underestimation of risk exists in these locations. In "Identifying factors that impact seabird collision risk" section, we identify the seabird species and the powerline locations that are most in need of collision examinations through a discussion of the general life history, morphology, environmental, and powerline construction variables that contribute to elevated powerline collision risk. In "Infrastructure with similar collision risk characteristics to powerlines" section, we consider collision risk from infrastructure that has similar properties as powerlines. In "Methods for reducing seabird collisions with powerlines and similar infrastructure" section, we review the available solutions for reducing powerline collisions. In "Knowledge gaps and future research" section, we discuss the current knowledge gaps and conclude with "Conclusions" section.

Identifying factors that impact seabird collision risk

Understanding the major collision risk factors and how they are mediated by species-specific biology (life history and morphology), environment, and powerline type will aid in rapidly assessing risk and prioritizing collision examinations to focus on the species and locations with the greatest need for monitoring (Bevanger, 1994). Powerline collision risk is a function of three overall factors: (1) the frequency of seabirds flying at powerlines, (2) the detectability of the wires, and (3) the likelihood of avoidance if the wires are detected. Within each of the three factors, collision risk is mediated by (1) the life history traits and morphology of the animals, (2) environment at the powerlines, and (3) the construction characteristics of the powerlines.

Collision risk factor 1—The frequency of seabirds flying at powerlines

For seabirds to collide with or be electrocuted by powerlines, the primary risk factor to consider is the frequency of birds flying directly at wires. The frequency of direct flights at powerlines is simultaneously a function of the seabird passage rate across powerlines and the flight height of those passages. For example, on the extremes, high passage rates over powerlines can occur with low collision risk if birds fly well above powerline height, and vice versa, high risk can exist in areas of low passage rate if most birds fly at wire height. Here, we examine (1) life history/morphology, (2) environmental, and (3) powerline construction characteristics that influence the frequency of seabirds flying directly at powerlines.

Life history/morphology

Birds that transit past powerlines more often will have elevated collision risk through increased exposure. The location of the breeding or roosting sites relative to local powerlines plays a role in increasing exposure to powerlines. Seabirds that breed inland of powerlines will have to transit past powerlines each visit to their breeding colony and when they return to the sea (Cooper and Day, 1998; Travers et al., 2021; Verbeke et al., 2020). For example, inland seabird breeding species select montane, forested, or desert environments. In contrast, species that breed immediately adjacent to the ocean typically would not have to cross powerlines to gain access to their colony or roosting site. Some coastal breeding species, however, may occasionally (Red-footed Boobies) or regularly (Wedge-tailed Shearwaters) wander inland (Travers et al., n.d.) or cut across land when transiting to foraging grounds (Anchundia et al., 2017), resulting in a powerline interaction potential greater than expected based on their coastal breeding and roosting sites (Travers et al., n.d.). Powerline exposure is increased for seabirds with long breeding seasons and shorter foraging trip durations, as breeding colony visitation rates are influenced by season length and foraging trip duration (Bolton et al., 2019; Shoji et al., 2015). Age of subadult return and age-specific colony visitation rates (Halley et al., 1995) will similarly play a role in exposure to powerlines, and younger, naive birds may have elevated powerline collision risk above that expected by their visitation rates (Cooper and Day, 1998). If species differ in their overland flight height (Cooper and Day, 1998), this would be expected to influence the species-specific frequency of flying at powerlines.

Environmental

The environment at or near the powerlines can have localized influence on both passage rates and flight height of seabirds. Least cost flyways (energetically easiest route) to suitable and productive breeding habitat can result in dramatic increases in localized seabird transits over powerlines (Cooper and Day, 1998; Day and Cooper, 1995; Raine et al., 2017a,b; Travers et al., 2014). On some islands, seabirds appear to preferentially enter land at select large topographic features such as drainages (Cooper and Day, 2003). The overall terrain gradient along the flight path can influence seabird flight height relative to powerlines. Seabirds that access higher elevation breeding sites in terrain with consistent steep slope will often gain elevation before crossing onto land, particularly if there is a tailwind, and maintain high aboveground flight height when heading to sea, reducing collision risk in both flight directions (Raine et al., 2017b; Travers et al., 2014; Verbeke et al., 2020). If trees are taller than powerlines, transiting birds in general will be forced to fly above both the trees and the powerlines, whereas in areas with short vegetation or where tree removal has occurred, birds will have increased risk of flying directly at powerlines (Bevanger, 1994; Bevanger and Brøseth, 2001, 2004; Jenkins et al., 2010). Tree and vegetation removal following tropical storms, as occurred on Kauai following Hurricane Iniki in 1992 (Harrington et al., 1997), is a natural and stochastic event that could lead to dramatic increase in powerline exposure on the landscape following the rebuilding of powerlines poststorm. Wind can influence the number of seabirds flying at powerlines through effects on seabird flight height. Seabirds are known to fly lower into headwinds to gain flight efficiency (Ainley et al., 2015). On land, seabirds flying into headwinds have similarly been observed flying lower which resulted in a subsequent increase in powerline interactions (Travers et al., 2014). Artificial lights are increasingly a part of the environment where seabirds transit and are well-known to confuse and attract mostly juvenile seabirds (Podolsky et al., 1998; Reed et al., 1985; Rodríguez et al., 2012, 2017). Lights are spatially correlated with powerlines, and thus, light attraction is a special case in which an unnatural attractant puts seabirds at risk of powerline collisions (Friswold et al., 2020). We consider powerlines a secondary risk factor in these situations as the removal of the lights would greatly reduce or eliminate the collision risk.

Powerline configuration

Interactions between the environment and powerline location can increase the frequency of seabirds flying at powerlines. When constructing powerlines in terrain with deep valleys and ridges, the most efficient powerline configuration is often to place the poles on ridges and string the wires across the open airspace above the valleys or drainages (Bagli et al., 2011). This configuration maximizes the aboveground height of the wires over the middle of the valleys and drainages (see Fig. 14.1), which in turn maximizes the frequency of seabirds flying directly at powerlines (Travers et al., 2021; Verbeke et al., 2020). Constructing powerlines on top of ridges increases the likelihood that powerlines are the highest feature on the local landscape (D'Amico et al., 2018) and is particularly dangerous when seabird flight is perpendicular to the ridge and powerlines. When seabirds are flying inland on a set trajectory, their flight height above ground varies as the terrain below their flight path undulates and changes in elevation. As a result, bird flight trajectories can be closest to the ground when their trajectory aims just above ridgelines. This is a commonly

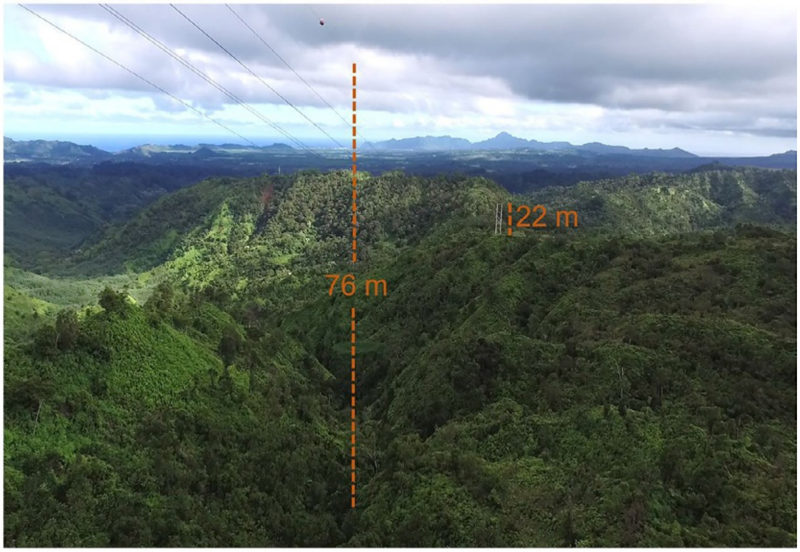

FIG. 14.1

Powerlines in rugged terrain constructed high over a valley. Construction of power poles on ridge points with wires across valleys results in a substantial increase in the height of wires above the ground at mid-valley. Due to the terrain these wires are much higher above ground and further into avian airspace at mid-valley than at the poles where wires are closest to the ground. The powerline array in the figure has seven total wires and is 340 m long from ridge to ridge. The top wire is a nonelectrified lightening grounding wire with an aviation marker ball mid-span. There are six transmission wires in three paired vertical layers below the grounding wire. This span would be described as having four layers of hazards a bird could fly directly.

Photo by Marc S. Travers.

observed behavior for Newell's Shearwaters and Hawaiian Petrels, which puts bird flight paths directly at powerlines present on the ridgeline (Raine et al., 2017b; Travers et al., 2019a,b, 2021).

Powerline configuration can also influence the number of seabirds flying at powerlines when powerline engineering and regulatory standards maximize aboveground height of wires. Powerline engineering is constrained by public utility regulations that primarily focus on the safety and reliability of powerlines for consumers and the people who work on or near powerlines, which in the United States is National Electrical Safety Code (National Electrical Safety Code® (NESC®) C2-2017, 2017). These regulations influence the spacing, vertical height, and number of vertical wire layers. For example, the higher the voltage of electricity, the greater the wire spacing requirements and the greater the clearance required above the ground, buildings, or vehicles (National Electrical Safety Code® (NESC®) C2-2017, 2017). Therefore, high-voltage transmission powerlines that carry electricity long distances are the tallest powerlines constructed. All else being equal, the increased above-ground height makes transmission powerlines the most dangerous to birds from a collision perspective (Bernardino et al., 2018; Ward and Anderson, 1988) including seabirds (Travers et al., 2021). Engineers often meet the spacing requirements by building powerline arrays vertically rather than horizontally, as it can reduce the lateral footprint of powerlines. This type of powerline construction maximizes top powerline height and increases the number of powerlines that birds in general (Bernardino et al., 2018; Bevanger and Brøseth, 2001; Drewitt and Langston, 2008; Jenkins et al., 2010) and seabirds specifically can fly at directly (Podolsky et al., 1998). For example, many powerline circuits are constructed with three electrified wires (many utility poles carry multiple groupings of 3). When built vertically, this results in three wire layers each extending further into avian airspace (see Fig. 14.2). When built horizontally, all

FIG. 14.2

Horizontal reconfiguration of powerlines. Powerlines modified from a vertical design (distant pole) to a horizontal design (close pole). The first phase of the modification was the removal of the lightening shield wire. Position (A) in the figure shows the lightening shield wire and its subsequent removal in the modified section. The second phase of the modification was configuring the vertically arrayed wires horizontally. Position (B) in the figure shows six transmission powerlines in three vertically paired layers modified to two vertical layers of three wires. Position (C) in the figure shows three distribution powerlines and a neutral wire in four vertical layers modified to a single layer of four wires. These modifications lowered the upper wire profile by 8.5 m and reduced nine vertical hazard layers a bird could fly directly down to four vertical hazards. For additional protection, reflective diverters have also been added to the top two layers post reconfiguration. Each of these modifications will improve bird safety. Lastly, position (D) in the figure shows a fiber-optic cable for communication which is unmodified.

Photo by Marc S. Travers.

three wires are constructed at the height of the lowest wire in the vertical design and represent a reduction to a single collision hazard that a bird could fly at directly (see Fig. 14.2). Land use under powerlines can also influence wire height and collision risk. For example, powerlines constructed over agricultural land are often designed with taller power poles to ensure that large machinery cannot come in contact with the powerlines, increasing human safety while inadvertently increasing landbird and seabird collision risk from the taller more exposed powerlines (Demerdzhiev, 2014; Travers et al., 2021).

Collision risk factor 2—The detectability of powerlines

Once a seabird is on a collision course with powerlines, the detection of the hazard by the seabird is the first requirement for actively avoiding a collision. Powerline detection is therefore a major factor in powerline collision risk as well as an important consideration when developing collision reduction solutions. Most observed Newell's Shearwaters and Hawaiian Petrel powerline interactions, for example, resulted in successful detection of the hazard but with varying collision avoidance outcomes depending on the conditions (Travers et al., 2019a,b, 2021).

Life history/morphology

The time of day birds transit past powerlines is an important factor in powerline detection. All else being equal, powerlines are most difficult to detect during flights in full darkness (Brown and Drewien, 1995; Deng and Frederick, 2001; Murphy et al., 2016a,b) than during crepuscular flights and easiest to detect in the daytime (Bernardino et al., 2018; Bevanger, 1998). This is a particularly salient point for seabirds as most petrels fly into their colonies nocturnally (Mougeot and Bretagnolle, 2000), and this group is one of those at highest risk for powerline collisions. Species-specific vision is important for powerline detection (Martin and Shaw, 2010), but interspecies differences in powerline detection among seabird remain unknown. Social behavior that distracts birds from detecting hazards in their flight path can increase collision risk (Bernardino et al., 2018; Drewitt and Langston, 2008). In seabirds, subadult or prebreeding aerial courtship is an example of behavior that could increase collision risk when it occurs near powerlines.

Environmental

Environmental conditions that reduce visibility will reduce powerline detection (Bernardino et al., 2018; Drewitt and Langston, 2008), and in seabirds, this is most likely to be fog, rain, and sea spray. Nocturnal ambient light levels will also influence powerline detection. Newell's Shearwater and Hawaiian Petrel powerline collisions were negatively correlated with ambient light levels from light pollution, presumably because light reflecting onto powerlines allowed birds to detect powerlines and avoid collisions (Travers et al., 2021). During bright moonlight seabirds have also been observed detecting powerlines early and thus clearing the powerline hazard early and with greater distance (Travers et al., 2014, 2016). Therefore, conditions that result in maximal darkness at powerlines or minimal visual contrast between the powerline and the background are expected to reduce seabird powerline detection and increase collision risk.

Powerline configuration

Powerlines configured with larger diameter wire are expected to increase avian detection of powerlines (Jenkins et al., 2010). Wire diameter is larger in higher voltage wires and often reduced in nonelectrified wires such as lightning grounding wires. Tall wires at risk for collision from helicopters and other aircraft have large marker balls to aid pilot detection of wires. Aviation marker balls may aid birds flying at or near the marker balls in detecting a hazard but are likely spaced too widely apart to indicate to a bird that there is a suspended obstacle between the markers (pers. Comm James F. Dwyer and Marc S. Travers). However, further research is required as objects that increase the diameter and visual contrast of powerlines, such as the more tightly spaced bird diverters (discussed in "Influence seabirds to alter their flight height to avoid powerline airspace" section), are expected to increase hazard detection for birds (Shaw et al., 2021) although limited research has focused on nocturnal bird movement.

Collision risk factor 3—Collision avoidance

Once a seabird is on a collision course and has detected a powerline, their collision avoidance response is the final factor determining seabird powerline collision risk. In addition, understanding the variables that determine collision avoidance after successful detection is a critical component in developing effective collision avoidance solutions.

Life history/morphology

A seabird's mass and wing morphology play a primary role in flight speed and maneuverability (Alerstam et al., 1993; Bevanger, 1998; Pennycuick, 1987) which is largely determined by foraging strategy (Brewer and Hertel, 2007; Hertel and Ballance, 1999). Flight speed determines the distance and time a bird has to execute an avoidance from the moment of detection, and maneuverability determines the extent to which a bird can alter its course within the distance–time window (Bevanger, 1998; Janss, 2000). Many seabirds have very rapid overland flight speeds, and combined with the nocturnal nature of these flights, this results in a narrow detection avoidance window. Marbled Murrelets have average overland flight speeds of 91–102 km/h (Cooper et al., 2001), and Newell's Shearwaters and Hawaiian Petrels in steep terrain on the northwest of Kauai had average inland flight speeds of 36 and 34 km/h, respectively, and outbound speeds of 43 km/h and 51 km/h, respectively (Raine et al., 2017b), leaving very little time or distance to make an avoidance maneuver if powerlines are detected late. The heavier body and smaller wing area of diving and pursuit-diving seabirds increase flight speed and reduce maneuverability, which overall reduces these seabirds' powerline collision avoidance capabilities relative to other seabirds (Bevanger, 1998). In contrast, seabirds that are surface-gleaning foragers and light on the wing, like gadfly petrels, have greater relative collision avoidance capabilities, if the powerlines are detected (Bevanger, 1998).

Environmental

Environmental conditions at or near the powerlines can affect a seabird's powerline avoidance capability. A seabird's flight path relative to the prevailing wind direction and wind speed can affect approach speed and maneuverability. Above, we mentioned that flying into a headwind can increase collision risk by reducing a seabird's aboveground flight height. Yet, in the case where powerlines are detected, a bird flying into a headwind will approach wires more slowly, increasing the time and distance available for avoidance, and also will have increased lift and thus maneuverability (Savereno et al., 1996; Ward and Anderson, 1988). Inland colony elevation can impact the avoidance distance-time window as birds leaving higher elevations gain speed while descending to the ocean (Cooper et al., 2001). Newell's Shearwaters and Hawaiian Petrels monitored with GPS tags travel to the sea at significantly higher flight speeds compared with inland flights (Raine et al., 2017b).

Powerline configuration

Powerline construction affects collision avoidance through the overall vertical wire profile in meters and the number of wires. The greater the exposed vertical profile of the powerline array, the greater the distance birds must maneuver to clear the array once wires are detected (Podolsky et al., 1998). Powerline construction varies greatly in the number of wires strung between power poles depending on the local needs and power supply. Powerline sections constructed with greater numbers of wires have a greater number of aerial hazards that could be flown at directly and which then need to be avoided, while wire density can increase the likelihood that one wire is avoided resulting in a collision with a nearby wire (Bevanger, 1994; Podolsky et al., 1998).

Summary of collision risk and seabird groups with elevated risk

For seabirds that are known to breed, roost, or transit across areas with powerlines, collision risk should be a consideration in their conservation. Any species that transits an area where powerlines extend into their airspace are at risk of collisions. Consideration of collision risk based on the biology of the birds, the environment, and powerline configuration can provide an initial assessment of collision risk and determination of whether collision monitoring is needed. At present, documented powerline collisions in seabirds most commonly map onto at least one or more of the following biological characteristics: breeding inland of powerlines, transiting past powerlines nocturnally (even if uncommonly, such as Red-footed Boobies), and a foraging strategy of diving/pursuit-diving. There are documented accounts of powerline collision risk for species within the nocturnal burrow nesting genera *Puffinus*, *Pterodroma*, *Ardenna*, *Bulweria*, *Calonectris*, *Pseudobulweria*, and the inland cliff breeding *Phaethon* which have multiple or all the biological risk factors. Based on their life history and morphology, several other seabird groups would be expected to have relatively elevated collision risk including the alcids (Alcidae), diving-petrels (genus *Pelecanoides*), and seaducks (Anatinae) if powerlines currently exist or in the future are constructed across their flight paths. Overall, the biology of the species interacts with the environment and powerline construction such that collision risk is elevated when (i) conditions reduce the aboveground flight height of seabirds, (ii) there is reduced visual detection of powerlines, (iii) increased flight speed, and (iv) there is increased height and number of wires in seabird airspace.

Infrastructure with similar collision risk characteristics to powerlines

We have focused on powerlines, but other infrastructure exists that has similar collision risk characteristics for seabirds. Fiber-optic cable and other lines used in communications can be constructed in a manner similar to powerlines and thus can have similar collision risk. Guy wires used to support communication towers (see Fig. 14.3) have been shown to have collision risk for landbirds (Gehring et al., 2011; Loss et al., 2012) and seabirds like the Newell's Shearwaters (Travers et al., n.d.) and the critically endangered Black-capped Petrel (*Pterodroma hasitata*) on the island of Hispaniola in the Caribbean (Brown et al., 2013). Light attraction likely played an exacerbating role in the documented collisions for the Black-capped Petrel, but regardless, observations from Hispaniola indicate tower guy wires should be considered a threat to seabirds. On a single night, five Black-capped Petrels were found grounded under a communication guy wire and dozens more were observed colliding

FIG. 14.3

Communication tower guy-wire collision hazard. Tall communication tower and guy-wire collision hazards above the local vegetation and topography.

Photo by Marc S. Travers.

with the wire but gliding or flapping beyond the searchable area and thus would not have been documented without the direct collision observation (Brown et al., 2013). Other forms of aerial cable also have collision risk including cables used in gondolas, chairlifts, and zip lines (Bech et al., 2012).

Methods for reducing seabird collisions with powerlines and similar infrastructure

Once seabird powerline collisions have been identified, it is critical that collision prevention solutions be implemented to ensure that power authorities can quickly and effectively prevent further impacts to seabirds. Overall, there are three broad strategies to reduce seabird collisions with powerlines: (1) Powerlines can be removed from avian airspace, (2) seabirds can be influenced to alter their flight height to avoid a collision with the powerlines, and (3) preconstruction planning can position powerlines on the landscape to avoid high-collision-risk locations. Many of the solutions mentioned below are directly applicable to other types of aerial cable infrastructure like communication tower guy wires.

Remove wires from seabird airspace

Having powerlines underground is clearly the preferred solution for seabirds as it is 100% effective at reducing seabird powerline collisions while increasing the safety and reliability of the powerlines for the human population (Glass and Glass, 2019; Larsen, 2016). However, undergrounding powerlines can cost a million dollars a mile and as such is not considered the most cost-effective solution (Freeman et al., 2019; Glass and Glass, 2019; Larsen et al., 2018). Incremental reconstruction of existing powerlines can be a more practical way for power authorities to reduce collisions. Lowering wires, even modest amounts, can reduce collisions particularly when only the lowest flying birds hit the uppermost powerlines. For example, collisions were reduced by 50% when removing a single nonelectrified wire, such as the lightning shield wire, from the highest position in the wire array (Bevanger and Brøseth, 2001) and replacing it with alternative grounding methods mounted at the power pole. Even larger collision reductions would be expected if powerlines were rebuilt from a vertical wire array (e.g., three vertically spaced wires) into a single layer of horizontal wires (see Fig. 14.2) because this lowers the collision profile of the wires to a height of the lowest wire in the vertical array and reduces the number of wires layers that birds can fly at directly (Bernardino et al., 2018; Bevanger, 1994). Existing exposed powerlines can be replaced with insulated aerial cable, which reduces electrocution potential and thus relaxes safety regulations allowing high voltage wires to be mounted significantly lower on existing power poles (Bevanger, 1994). The insulated powerlines also have a larger diameter and thus would likely increase their detectability by birds (Jenkins et al., 2010); however, the positive effect of the increased diameter may be counteracted at night by the black coloration of the outer coating on insulated wires.

Influence seabirds to alter their flight height to avoid powerline airspace

Planting, promoting, or maintaining tall trees (at a safe distance from powerlines) is the lowest tech solution available for reducing avian collision with powerlines (Bevanger, 1994; Bevanger and Brøseth, 2001, 2004; Jenkins et al., 2010). If trees are taller than powerlines (see Fig. 14.4), seabirds will maintain a minimum height above vegetation, preventing collisions by forcing seabirds to safely fly over the wires (Cooper and Day, 1998). Depending on nearby land use and land agreements, trees may also present the lowest cost solution if trees are at a safe horizontal distance that prevents any wire contact or damage to powerlines. Alternatively, several solutions focus on increasing the detectability of powerlines by seabirds with the intention of providing increased distance and time for birds to successfully make an evasive maneuver. Bird flight diverters are objects attached to powerlines (see

FIG. 14.4

Trees shielding powerlines from seabird collisions. Transiting seabirds are forced to fly above the tall trees and as a result above powerline height. One consideration of tree shielding is that trees can be removed for a variety of reasons. This would result in powerlines becoming the tallest object on the landscape and a clear collision hazard in a location that was previously safe for transiting birds. When planning tree removal or harvest, power authorities should attempt to negotiate that several lines of trees remain such that trees continue to shield wires for bird safety. Considering powerline safety and reliability, the remaining trees should be wind firmed (removing limbs of trees on the edge of the clear cut to reduce wind blow down of trees) and trees should be maintained only at a distance preventing any possible contact with powerlines.

Photo by Marc S. Travers.

FIG. 14.5

Bird flight diverters mounted on powerlines. Left image is of reflective diverters on a section of transmission wires (2 sets of 3 vertically configured transmission wires) and lightening shield wire. The right image is of three different types of reflective diverter. The diverters on the top left and bottom right are nonmoving reflective diverters. The diverters on the bottom left and top right are two types of swiveling reflective diverters.

Photo by Marc S. Travers.

Fig. 14.5) at set intervals which are designed to increase the bird's detection of a hazard on its flight path. Two meta-analyses indicated considerable variability in collision reduction but reported between 50% and 78% reduction on average for studies of diverter efficacy for landbird and waterbirds (Barrientos et al., 2011; Bernardino et al., 2019). Many more types of bird flight diverters exist than have been tested for collision reduction efficacy, but when comparison tests are implemented, results indicate that diverter type, bird species (Brown and Drewien, 1995; Shaw et al., 2021), and environment (Jenkins et al., 2010) affect the collision reduction efficacy of these devices. Reflective diverters attempt to increase detection using materials that are bright and reflect light (sun, moon, and ambient light pollution). Spiral diverters are designed to increase the profile diameter of powerlines and may have a lower collision reduction rate compared to other diverters (Barrientos et al., 2012), while spinning diverters are designed to catch the attention of birds through movement. For nocturnally transiting birds, blinking LED or glow-in-the-dark material has been added to diverters (Murphy et al., 2016a). Dwyer et al. (2019) tested the use of UV lights to illuminate powerlines marked with diverters and reported that nocturnal powerline collisions were reduced by 98% in one landbird species. Any method that will increase a bird's detection of a hazard should be considered, including painting wires with a material that increases avian detection (Bevanger, 1994).

Preconstruction planning

Engineering plans for powerline construction focus on the most efficient construction pathway across a landscape (Bagli et al., 2011), which in some terrain can result in maximizing wire height above ground (e.g., when wires cross valleys) and above local vegetation (see Fig. 14.1), which increases seabird powerline collision risk

(Travers et al., 2021; Verbeke et al., 2020). Conservation-informed planning of powerline routing across the landscape is considered one of the most effective solutions for preventing avian collisions (Bernardino et al., 2018). Powerline development in seabird transit locations should attempt to maximize the powerline contouring of the landscape, to ensure the wires are shielded by the natural topographic features and local vegetation (D'Amico et al., 2018). Monitoring and modeling how birds move across a landscape can provide power companies the information they need to relocate powerlines in the planning stage, sometimes by only short distances with minimal financial impacts, to areas that reduce the extent that powerlines rise above existing landscape features (Bagli et al., 2011). Preconstruction surveys to locate areas where seabird flight height is locally maximized or minimized will aid in powerline location planning (Luzenski et al., 2016). Additionally, at the time of construction, power authorities should consider installing powerlines with the most effective collision reduction solution mentioned in "Remove wires from seabird airspace" and "Influence seabirds to alter their flight height to avoid powerline airspace" sections (see Figs. 14.2, 14.4, and 14.5).

Knowledge gaps and future research

In general, research on seabird powerline collisions lags behind that of landbirds. Globally, seabird powerline collision monitoring has largely been isolated to a handful of islands resulting in limited collision data across species and locations. Even less research has focused on towers and tower guy wires and other similar obstructions on seabird flyways and near seabird colonies. Special attention should initially focus on rare species that move past powerlines and similar infrastructure, while recognizing the fact that detection of collisions is especially challenging in rare seabirds. To date, almost no research has focused on testing the efficacy of collision reduction solution in seabirds. Particularly critical to seabirds are nocturnal collision avoidance solutions, but little research has yet focused specifically on nocturnal collision reduction. Across all bird groups, almost no research has been conducted on the optimization of collision reduction solutions like bird diverters. What is the optimal spacing along the wires? How many wires in an array require diverters? What is the optimal size and color? Do glow-in-the-dark, reflective, or moving elements on line markers minimize collisions? Additionally, R&D should focus on solutions that aid power companies in the safe deployment and installation of collision reduction solutions, for example, recent work developing drone application of bird diverters (Acklen et al., 2020).

Conclusions

Extensive research on avian powerline collision across 40 years has shown that collisions will occur when powerlines exist in avian airspace. Power authorities will inevitably consider the cost-benefit analysis between no action and that of planning for collisions and implementing collision reductions solutions, particularly when considering the geographic scope of powerlines on the landscape and the extent that modifications may be required. Just as collision risk varies by environment and type of powerline configuration, so too does the logistical and engineering considerations for implementing collision reduction solutions. Continuing research will benefit both seabirds and power authorities through the optimization of collision monitoring, modeling, and collision reduction solutions. Developing cost-effective, easily implemented, powerline-safe collision reduction methods will protect seabirds by providing power authorities implementable solutions.

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