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Spatial overlap in powerline collisions and vehicle strikes obscures the primary cause of avian mortality

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ABSTRACT

Anthropogenic threats to Hawaii's birds have resulted in numerous extinctions with many additional species now listed as threatened or endangered. Implementing conservation recovery plans for these birds requires identifying a comprehensive list of threats. Research from outside of Hawaii has shown that avian powerline collisions are one of the greatest anthropogenic causes of mortality. To date, with the exception of endangered seabirds, powerline collisions have not been considered a major threat to most native and endangered birds in Hawaii. This may be because Hawaiian species face a multitude of already identified threats with the clearest causes of mortality (e.g., vehicle collisions) often obscuring evidence of powerline collisions. We report a strong spatial correlation between roads and powerlines which increases the likelihood that birds colliding with powerlines are grounded on roads, where secondary vehicle collisions can confound the primary grounding cause. We recorded flight heights of all birds at powerlines and roads, as well as the frequency of flights directly at powerline and vehicle height. We observed 162 powerline collisions across ten native and endemic birds. We also collected a further 251 grounded native and endangered birds. For each of the grounded birds we evaluated the injuries the bird sustained and the grounding location itself using multiple factors to attribute the primary cause of grounding. Using this system, we classified these birds as follows - powerline collision (69.3%), vehicle strike (9.2%), and uncertain cause of grounding (21.5%). Overall, we confirm that 13 native and endangered species collided with powerlines, including all native and endemic waterbirds, and vehicle collisions were confirmed for three species. Our study clearly demonstrates that birds hitting powerlines can be grounded in roads and then secondarily run over by vehicles, which can obscure the primary cause of grounding. The obfuscation of powerline collision by secondary vehicle strike has previously prevented researchers and managers from identifying powerline collisions as a threat to native and endemic waterbirds. By using the data reported here, the local power company has implemented 170 km of bird-friendly powerline modifications including the removal of static lines, attachment of bird diverters and reconfigurations. These bird-friendly powerline modifications are the first of their kind in the state of Hawaii.

1. Introduction

Anthropogenic threats to wildlife are 12 times more likely to cause extinctions on islands than on continents (Fernández-Palacios et al., 2021). The Hawaiian Islands, as an isolated archipelago in the middle of the Pacific Ocean, have been particularly vulnerable with numerous avian extinctions (Atkinson and LaPointe, 2009), and many additional species are listed as threatened or endangered by the International Union for the Conservation of Nature (IUCN). Threats to Hawaii's remaining birds have resulted in significant population reductions and range contractions, restricting some birds to a few islands in the archipelago or limited locations within a single island (Paxton et al., 2021, 2016). Implementing conservation recovery plans for these birds requires identifying a comprehensive list of threats (Reed et al., 2012; Work et al., 2015). The most cited threats to Hawaii's birds vary by species and island, but include introduced predators, introduced plants,

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introduced diseases, habitat modification, artificial lighting (which causes grounding for nocturnal seabirds), and collisions with vehicles (Friswold et al., 2020; Lepczyk et al., 2019; Paxton et al., 2021, 2018; Raine et al., 2020; Reed et al., 1985; Rees et al., 2018).

Powerline collisions are one of the top anthropogenic causes of mortality in birds (Erickson et al., 2005; Loss et al., 2015) and have been estimated to kill tens of millions of birds each year in Canada and the continental USA (Loss et al., 2015, 2014; Rioux et al., 2013). To date, powerline collisions have not been considered as a potential threat to Hawaii's threatened and endangered waterbirds (Lepczyk et al., 2019; Paxton et al., 2021; Reed et al., 2012; Underwood et al., 2013; Work et al., 2015) even though numerous continental congeners of Hawaiian waterbirds experience high collision risks (Baasch et al., 2022; Bevanger, 1998). Powerline collision risk may have been overlooked in Hawaii due to the difficulty of searching for grounded birds. Hawaii has rugged terrain and thick, lush vegetation under and near powerlines. Through environmental bias and crippling bias, these conditions can effectively obscure the occurrence of thousands of avian powerline collisions if researchers only use traditional carcass search methods (Travers, 2022; Travers et al., 2021).

Obfuscation of powerline collisions may also occur because Hawaii's threatened and endangered birds face a multitude of already identified threats with the clearest causes of mortality often obscuring others. Collisions with vehicles are a well-known cause of mortality for Hawaiian waterbirds as these species have behaviors that increase fatal vehicle interactions, such as foraging on road shoulders or walking across roads that bisect two water sources (Lepczyk et al., 2019; Rave et al., 2005; Rees et al., 2018; Work et al., 2015). Grounded waterbirds found on roads with injuries consistent with car collisions are typically assumed to have been hit by vehicles. However, if these birds initially collided with a powerline, which brought them into the road (as previously documented for endangered Hawaiian seabirds (Travers et al., 2021)), the primary cause of grounding will be obscured when the birds are then secondarily hit by a vehicle. The clear signs and devastating trauma of a vehicle strike on a bird has been well documented for Hawaiian waterbirds (Work et al., 2015). However, if powerlines are also present alongside or near the roads, powerline collision and subsequent grounding needs to be considered as a potential primary cause for grounded birds found on roads and subsequently run over (Morelli et al., 2020).

Correctly identifying the primary cause of mortality is necessary for implementation of effective mitigation measures (Loss et al., 2015). The Hawaiian Islands have five endangered waterbird species. The ʻalae ʻula (Hawaiian Common Gallinule *Gallinula galeata sandvicensis*) is restricted to Kauaʻi and Oʻahu, with a minimum population estimate of 927 (Paxton et al., 2021). The koloa maoli (Hawaiian Duck, *Anas wyvilliana*) has a minimum population estimate of 947 with 'pure-bred' birds (i.e. those that have not hybridized with feral mallards) only present on Kauaʻi (Paxton et al., 2021). The ʻalae keʻokeʻo (Hawaiian Coot, *Fulica alai*), the ʻaeʻo (Hawaiian Stilt, *Himantopus mexicanus knudseni*), and nēnē (Hawaiian Goose, *Branta sandvicensis*) are less restricted in range but have low minimum population estimates of 1815, 1932, and 3000, respectively (Paxton et al., 2021; Lepczyk et al., 2019). With such small population sizes and restricted distributions, it is critical that we understand all causes of mortality, as this allows for focused management actions. Threats such as powerline collisions can be reduced through avian-specific powerline modifications (Baasch et al., 2022; Dwyer et al., 2019; Ferrer et al., 2020; Shaw et al., 2021), but only if they are recognized as being a problem (for reviews see Bernardino et al., 2018; Jenkins et al., 2010; Silva et al., 2022; Travers, 2022).

In this paper we report observed avian powerline collisions and vehicle strikes along with birds that were found grounded under powerlines and or on roadways. We examine if both powerline collisions and vehicle strikes are a conservation threat for the endemic waterbirds on Kauaʻi. In addition we consider powerline collision and vehicle strikes in other native Hawaiian birds including owls, shorebirds, and native seabirds and we update powerline collision numbers for the endemic endangered seabirds previously identified to collide with powerlines (Travers et al., 2021). In locations where both collision hazards are present, we evaluate the relative collision risk with vehicles and powerlines for grounded birds and we examine if the spatial overlap between roads and powerlines can obscure the primary cause of grounding. The data presented can be used to prioritize areas on Kauaʻi for both road and powerline modifications and highlight the potential impacts of the previously unidentified powerline collision threat for these species across the Hawaiian Islands chain.

2. Methods

2.1. Observations at powerlines

Visual observations at powerlines were conducted to directly observe powerline collisions by species and to determine species-specific flight height (see Methods 2.2. for height measurement details). During daylight hours, observations were conducted with the naked eye. After dark, observers used unmagnified night vision goggles (Model PVS-7 m Generation 3, 40^0 field of view, 1x magnification, U.S. Night Vision, Roseville, California, USA). We used near-infrared illuminators (NIRI, Raymax-300-Platinum 50-180°; Raytec, Ashington, Northumberland, UK) to enhance night vision capabilities and ensure consistent nocturnal detection capabilities across sites with differing ambient light conditions. All observations occurred between 30 min prior to sunset to 30 min after sunrise. 97% of observations occurred between May 1 and October 1, although observations occurred in all months. We report observed powerline collisions that occurred from 2012 to 2023. We also report opportunistic observations of avian powerline collisions recorded outside of these standardized surveys. Overall, we report birds identified to species. However, apart from Cattle Egret, for the purposes of analysis all introduced species (including doves, parakeets and passerines) are combined into a single category; 'Introduced species'.

2.2. Evaluating bird flight heights at powerlines, roads, and the role of tall vegetation in preventing birds from flying at collision risk height.

2.2.1. Observed flight heights

Observers were positioned at discrete powerline sections between two power poles, with observers maintaining a view of powerlines and poles throughout the survey. We estimated bird flight height relative to wires and roads by comparing the bird's height to an object in the observer's field of view, which we refer to as a scaler. Using lidar (Light Detection and Ranging), we pre-measured the height of the scaler, which was most often a power pole or the vertical space between powerlines. To quantify bird crossing height, the observer reported the bird's height as a fraction or multiple of the scaler (e.g., 1.2 power poles) which was then converted to meters above or below powerlines, by using the scaler's height in meters as determined from lidar measurements. Each observer was extensively trained by estimating height and distance in conjunction with senior observers and by practicing estimates using a drone (DGI Mavic Pro 2) to simulate 'bird' powerline crossings at randomly selected heights and distances from the observers. Error in height estimates increase with increased above ground height (ABG) of the simulated bird crossings. We grouped simulated powerline crossings into low (<40 m ABG), mid (40–80 m ABG), and high (>80 m ABG) with a maximum drone height of 120 m. Mean error in our flight height estimates for the low, mid, and high groups were: 1.2 ± 7.2 m, −3.3 ± 13.0 m, and −11.7 ± 19.5 m, respectively compared to the true drone height. For accuracy reasons, we do not report birds that flew out of our monitoring span and/or above our standard field of view, as tests showed a considerable reduction in height estimate accuracy. Close higher birds forced observers to adjust their field of view upwards, thus losing good perspective on the scaler and decreasing overall accuracy in drone tests from −3.3 ± 13.7 m to −18.4 ± 17.7 m. For reference, our typical maximum upper field of view when conducting surveys ranged from 72 to 175 m above the ground while maintaining a view of the scaler (i.e. powerlines and poles), with the upper boundary determined by the length of the span monitored. The flight height surveys covered 1.5- to 3-hour time windows totaling 6,689 h of avian powerline monitoring at 49.9 km of powerlines from 2012 to 2021.

2.2.2. Powerline infrastructure

On Kauaʻi, there are 205.5 km of what we are referring to as major long-distance powerlines, which includes 178.5 km of transmission lines (69 kV) and 28.0 km of long-distance distribution lines (13 kV which extend up the Waimea Canyon and Kahili mountain (see Fig. 1)). There is an additional 1,331.0 km of local distribution powerlines, which transport low voltage electricity (13 kV) within and near communities. Transmission powerlines on Kauai are mounted on poles that typically range in height from 17 to 34 m, while distribution powerlines are typically mounted on power poles that are 10–14 m in height. Observations were conducted at the major long-distance powerlines, while grounded birds were collected at all powerline types if detected (see Fig. 1).

2.2.3. Simulated evaluation of lowest possible flight at powerlines and roads

We compared powerline height to all potential flight obstructions which included vegetation, topography, buildings, etc. to evaluate the likelihood that these obstructions would prevent birds from flying at powerline height. We used the same methodology to evaluate how low birds could potentially fly over roads. We measured powerline heights and the corresponding vegetation (or other obstruction) height using aerial lidar data, or in some location's aerial photogrammetry data, due to cost constraints with lidar sampling. Digital Surface Models (with powerlines and poles excluded) were interpolated from each dataset at 1 m resolution. Maximum wire heights were calculated at 10-m intervals along the powerlines.

To evaluate if powerlines extended into avian airspace, such that birds could fly directly at powerlines, we conducted the following spatial simulation: at each 10-m interval along the powerlines, a series of 125-m-long theoretical flight paths were digitally generated radiating out in 360 degrees at every 10-degree increment from the powerlines. Along every theoretical flight path, surface elevations (indicating the height of objects along the flight paths) were assessed at 1 m intervals. For every flight path, the maximum surface elevation was summarized. The maximum surface elevation classified the tallest obstruction for a bird flying at powerlines along each of the 125-m flight paths, to estimate the lowest height at which a transiting bird could fly while maintaining level flight. The difference between the lowest flight height and the maximum powerline height on that flight path represents the vertical extension of powerlines into the air space above the local flight barriers (i.e., the vertical height of powerlines that birds are exposed to above flight obstructions). We report the mean exposure of powerlines above vegetation or other obstructions per span (wires extending between two power poles) and road section (length of road between two power poles) by averaging the exposure at each 10-m section. For max powerline exposure we report the highest powerlines extend above vegetation at any one 10-m point.

For vehicle collision risk height, we considered the Hawaii Revised Statute, Chapter 291–34, Traffic Violations, tallest allowable vehicle height of 4.26 m (14 feet; https://www.capitol.hawaii.gov/hrscurrent/Vol05_Ch0261-0319/HRS0291/HRS_0291-0034.htm).

2.3. Grounded birds

Most grounded birds were detected opportunistically by biologists while driving (i.e., not during standardized surveys) and occasionally while hiking near powerlines. Members of the public also reported grounded native birds (predominantly live birds) to the local rehabilitation program called Save Our Shearwaters (SOS) or to State and Federal agencies. Grounded birds were collected between fall of 2011 and 2023. We have tested staff detection rates and carcass removal rates along specific transects identifying that these two biases, if not accounted for, will result in significant under detection of grounded birds (Travers et al., 2012). However, because most grounded birds were opportunistically detected, detection rates cannot be applied to non-standardized searches or searchers from outside our organization or the public in general. Carcass removal rates cannot be applied to areas outside our transects as we found considerable local variation in carcass scavenging and significant variation in removal of carcasses by industrial grass mowing which regularly occurs alongside highways on the island. Therefore, the grounded birds reported within this paper should be considered as minimums, which does not impact the primary focus of this paper. We did not collect data on grounded non-native birds, such as Cattle Egrets (*Bubulcus ibis)*, feral chickens (*Gallus gallus domesticus)*, dove species, or non-native songbirds.

In situations where birds were grounded from a collision and found under powerlines with no roads and no other species-specific causes for grounding, the cause of grounding was designated as a powerline collision. Conversely, when birds were grounded on a road from a collision (or next to a road) with no powerlines present, the cause of grounding was designated as a vehicle strike. In cases where the grounded bird was on a road (or next to a road) with a powerline overhead, we evaluated the bird and grounding location using multiple factors to assess the cause of grounding. We do not report birds grounded from depredation, common at colony sites.

If the bird did not have significant trauma from a vehicle strike that would have obliterated signs of a prior mortality event, we carefully examined the bird for visible signs of injuries consistent with powerline collisions. These included injuries to the bill (including fractures and bifurcation) and feather removal on forehead, crown, cheek, or neck caused by collision with the wire (Travers et al 2021). Following this, we assessed each event as follows: 1) would it have been possible for a transiting bird to collide with the powerlines (i.e., were the powerlines taller than local vegetation and topography such that a transiting bird could fly low enough to collide with the wires), 2) could a low transiting bird hit a vehicle (i.e., is the vegetation on the side of the road low enough for birds to fly at traffic height), 3) is the location a known or suitable site for the species to forage on the side of the road, 4) would the bird be prevented from walking into the road by fences or topographic/vegetative barriers, 5) does the road pass through a seabird colony where birds are nesting on either side of the road, and 6) was the location a known or possible road crossing site due to favorable habitat on either side of the road (e.g. water and good foraging sites on both sides).

Using the above factors, we classified each grounded bird into five collision risk categories, as follows: (i) "powerline collision" when all available evidence indicated that powerlines were the cause of grounding, (ii) "probable powerline collision" when species and site details indicate that powerline collision is more likely than a vehicle collision, (iii) "undetermined", when both hazards are present with no evidence specific details to determine between the two hazards, (iv) "probable vehicle collision" when species and site details indicate that vehicle collision is more likely than powerline collision (i.e. location where birds are likely to walk into roads), and (v) "vehicle collisions" when a bird is hit by a car in an area without powerlines or the bird was observed being hit by a car.

We report only grounded birds that had accurate location information. For specific seabirds we only report birds grounded after-hatch-year (i.e., both subadults and breeding adults). The seabird species are ʻaʻo (Newell's Shearwater, *Puffinus newelli*), ʻuaʻu (Hawaiian Petrel, *Pterodroma sandwichensis*), and ʻuaʻu kane (Wedge-tailed Shearwater, *Ardenna pacifica*). We do not report fledgling seabirds, because fledglings of these species are predominantly grounded due to light attraction or collisions that result initially from light attraction (Friswold et al., 2020; Reed et al., 1985), a significant issue annually for Newell's

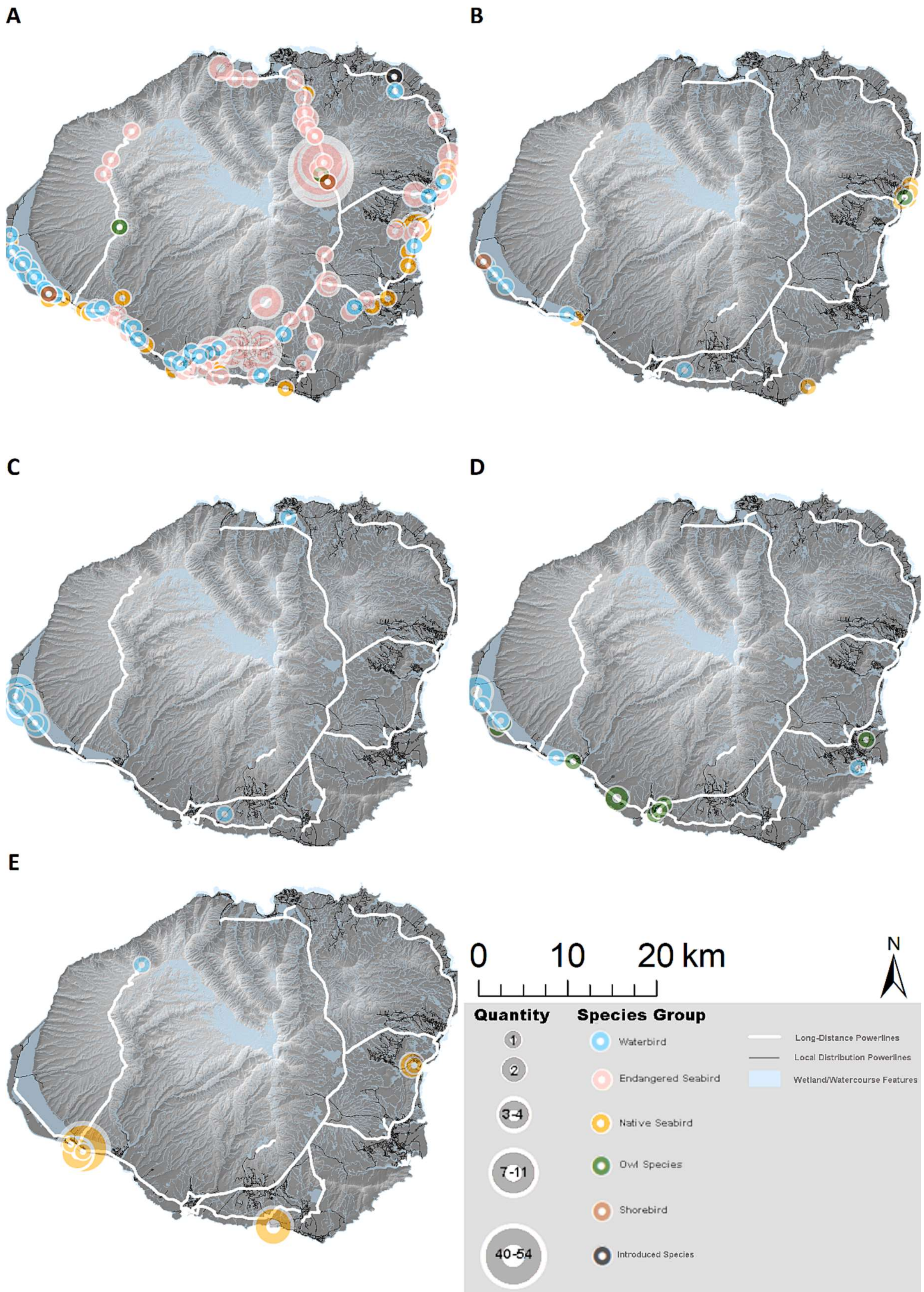

Fig. 1. Island of Kauai, Hawaii. Long-distance Powerlines are marked in white (transmission and long-distance distribution powerlines), while local distribution powerlines are marked in black. Data in the figure is both observed collisions and grounded birds. Panels indicate cause of grounding and colored symbols indicated species classes (e.g. waterbirds). Panels: A) Powerline collisions, B) Probable powerline collisions, C) undetermined, D) Probable vehicle collision, E) vehicle Collision. Although not obvious from the scale of the map, there are no powerlines at the roads where the definitive vehicle collisions were documented in map 1E.

Shearwater in particular (Podolsky et al., 1998; Raine et al., 2017). We differentiated between fledglings and older birds based on plumage wear, sun damage to feathers, and time of year (fledglings were only found from late September to December; Raine et al., 2022).

2.4. Spatial overlap in powerlines and roads

Road distances from powerlines were identified using county road shapefiles accessed from the Hawaii Statewide GIS Program (geoportal.hawaii.gov, accessed 2021), which were sampled in 10-m intervals along all public paved roads on Kauaʻi. Powerlines were located spatially by Lidar sampling mentioned above. The searchable terrain within 60 m of powerlines (30 m on either side of the wires) was evaluated following the methods described in Travers et al. (2021). Spatial overlap of powerline searchable space provided by roads was evaluated using GIS tools quantifying the road and road shoulder proximity to powerlines as described in Travers et al.(2021).

3. Results

3.1. Observations

3.1.1. Powerline collisions

We observed 162 avian powerline collisions during systematic surveys and opportunistic observations (see Fig. 1A & Table 1). Among the native and endangered Hawaiian birds, we visually confirmed powerline collisions for Newell's Shearwater, Hawaiian Petrel, Hawaiian Duck, Hawaiian Stilt, Hawaiian Common Gallinule, Hawaiian Goose, ʻaukuʻu (Black-crowned Night Heron, *Nycticorax nycticorax hoactli*), Wedge-tailed Shearwater, ʻā (Red-footed Booby, *Sula sula)*, and pueo (Hawaiian Short-eared Owl, *Asio flammeus sandwichensis*; Table 1).

Most collisions observed during the standardized surveys (94%) were Newell's Shearwaters or Hawaiian Petrels. The opportunistically observed Red-footed Booby collision resulted in the bird being electrocuted when its wings made simultaneous contact with two separate distribution lines (it had a clear electrical exit wound and the smell of burnt feathers). All other collisions were the result of a direct impact with a single wire. The Short-eared Owl collided with a powerline over a remote mountain valley at midday. The owl was soaring, scanning the forest below it when the collision occurred. The Hawaiian Goose collisions involved geese in flocks. In four cases, the leading birds barely cleared the hazard with each successive bird clearing the wires by less distance, while the last or second to last bird in the flock collided with the powerline. The fifth Hawaiian Goose collision was observed by a member of the public and details on the bird's position in the flock were not provided. Three of the five Hawaiian Goose collisions resulted in the bird crashing into the roadway post collision.

3.1.2. Vehicle strikes

During systematic observation surveys, we did not observe any vehicle strikes or birds walking on roads. Opportunistically, we directly observed a koaʻe kea (White-tailed Tropicbird, *Phaethon lepturus)* struck by a car in an area where presumed breeding cliffs are immediately next to a highway on the east side of the island (see east side of Fig. 1E). Although no collision occurred, we observed two adult Hawaiian Geese with a gosling between them run into the road directly in front of our vehicle, in full darkness, narrowly avoiding a direct vehicle collision at highway speed.

Table 1
Species specific observed powerline collisions and detected grounded birds organized by grounding cause.

			Observed powerline collisions		Grounded bird collision risk categories					
Hawaiian Name	**English Name**	**Species Group**	**Survey**	**Opportunistic**	**Powerline collision**	**Probable powerline**	**Un-determined**	**Probable vehicle**	**Vehicle collision**	**Total**
ʻAʻo	Newell's Shearwater	Endangered Seabird	75	0	91 (68)	0	0	0	0	166
ʻUʻau	Hawaiian Petrel	Endangered Seabird	32	0	14 (4)	0	0	0	0	46
ʻAʻo /ʻUʻau	Newell's/Hawaiian Petrel Incomplete identification	Endangered Seabird	37	0	NA	NA	NA	NA	NA	37
ʻUaʻu kani	Wedge-tailed shearwater	Native Seabird	3	0	20 (15)	4	0	0	19	46
koaʻe kea	White-tailed tropicbird	Native Seabird	0	0	8 (2)	2	0	0	3	13
ʻA	Red-footed Booby	Native Seabird	0	1	6 (6)	1	0	0	0	8
Nēnē	Hawaiian Goose	Waterbird	2	3	8 (6)	1	8	6	1	29
ʻAlae ʻula	Hawaiian Common Moorhen	Waterbird	0	1	8 (6)	0	7	2	0	18
ʻAukuʻu	Black-crowned Night Heron	Waterbird	3	1	7 (6)	5	0	0	0	16
ʻAlae keʻokeʻo	Hawaiian Coot	Waterbird	0	0	1 (1)	1	3	1	0	6
Aeʻo	Hawaiian Stilt	Waterbird	1	1	4 (3)	0	0	0	0	6
Koloa maoli	Hawaii Duck	Waterbird	1	0	4 (2)	0	0	0	0	5
Kōlea	Pacific Golden-plover	Shorebird	0	0	2 (1)	1	0	0	0	3
Pueo	Hawaiian Short-eared Owl	Owl Species	0	1	0	1	0	11	0	13
	Black Brant	Vagrant Waterbird	0	0	1 (1)	0	0	0	0	1
Total		–	154	8	174 (121)	16	18	20	23	413

In the grounded bird collision risk category "Powerline collision", we report the total number of detected powerline grounded birds and, in brackets, the number of those birds found in roadways. Most grounded birds were found in roadways because roadways provide the majority of search space near powerlines. By definition, all other grounded bird collision risk categories indicate the bird was found in the roadway. The bracketed numbers can be used to compare species specific relative risk of powerlines vs vehicle collisions at study sites with both hazards present.

3.2. Vegetative shielding of roads and powerlines preventing hazardous flights

Vegetation height along most road sections with powerlines was taller than the highest allowable vehicles (4.26 m) but shorter than most powerlines, resulting in most transiting birds being forced to fly above vehicle height but not powerline height. Overall, 95.6% of road sections (length of road between two power poles) had vegetation > 4.26 m, with a median height of 10.7 m (mean ± sd = 12.3 ± 6.2 m). At the remaining 4.4% of road sections with vegetation < 4.26 m, the median vegetation height was 3.7 m (3.6 ± 0.4 m)(see Fig. 2). In contrast, 86.5% or 178 km of 205.5 km of major long-distance powerline spans (length of wires between two poles) had vegetation that was shorter than powerline height, leaving powerlines extended into transiting bird airspace. Overall, the median height that powerlines extend above all transiting bird flight obstacles was 9.0 m (10.2 ± 5.8 m)(see Fig. 2). If we reduce the scale of examination from powerline span means to 10 m sections, then only 0.7 km or 0.3% of the 205.5 km of long-distance powerline spans on Kauaʻi are fully shielded by vegetation (thus preventing collisions by transiting birds), while 99.7% of powerline spans on Kauaʻi have some portion of wires above the local vegetation or other flight barriers. The maximum height a 10 m section of powerline extends above vegetation or other obstruction was 100.3 m, located in mountainous terrain where wires cross over a drainage.

3.3. Flight heights of birds transiting powerlines and roads

3.3.1. Roads with major powerlines

During systematic surveys, all species except White-tailed Tropicbirds were observed flying directly at the wire zone (i.e. powerline array height) indicating that flight heights can put these species at risk of powerline collisions. Black-crowned Night Herons had the highest ratio of flights directly at powerlines (24%), while at 5% Newell's Shearwaters had the lowest ratio of flights directly at powerlines (Fig. 3). Relative to roads, the highest above-ground flight heights of transiting birds were recorded for White-tailed Tropicbirds, Hawaiian Petrels, and Newell's Shearwaters (see Fig. 4).

Several species were observed flying as low as vehicle height (see Fig. 4 for median and variance). Owls (combined Short-eared owl and Barn Owl, *Tyto alba*) and introduced bird species were detected as low as 1.5 m and 1.9 m above the road, respectively, while Cattle Egrets and Black-crowned Night Herons flew as low as 3.1 m and 3.7 m above the road, respectively, in areas with short vegetation (see Fig. 4). Considering the inland-breeding seabirds, the lowest detected road crossing

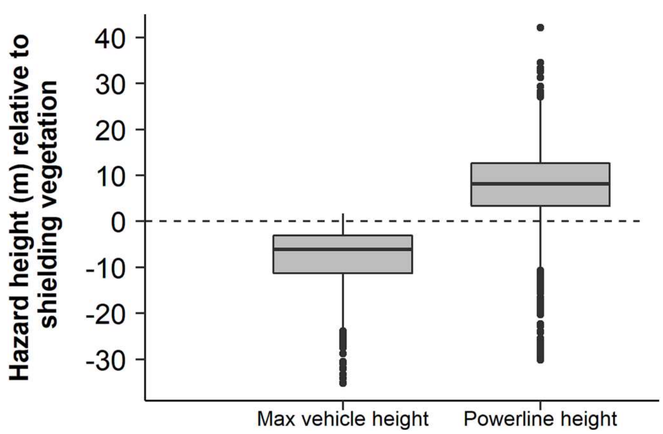

Fig. 2. Height of collision hazards relative to the protective shielding of vegetation. Vegetation that is taller than collision hazards force transiting birds to fly safely above hazards. Max vehicle height (4.26 m) subtracted by vegetation height at each powerline section. Mean top powerline height minus mean vegetation height at each powerline section.

heights for White-tailed Tropicbirds was 28.3 m, 12.7 m for Hawaiian Petrels, and 11.8 m for Newell's Shearwaters, which differs from the opportunistic detections of White-tailed Tropicbirds over roads close to colonies but without powerlines, mentioned above. For Hawaiian Petrels and Newell's Shearwaters, the lowest flight heights observed for birds crossing roads were detected on a high-elevation mountain road that transits along the ridge of Waimea Canyon (which is above the elevation of nearby colonies).

3.3.2. Road observations near Wedge-tailed Shearwater colonies

In two areas without powerlines, roads that extend to the coast pass near or directly through Wedge-tailed Shearwater colonies. On the west side of the island (see Fig. 1E), we observed Wedge-tailed Shearwaters regularly flying as low as 2.5 m above the road. On the south side of the island where a dead-end road transits through a coastal colony (with burrows on either side of the road; see Fig. 1E), we have observed Wedge-tailed Shearwaters flying at less than 1 m above the road and landing on the road. In both locations we have documented multiple dead Wedge-tailed Shearwaters on the roads (see Fig. 1E).

3.4. Classifying primary cause of grounding

Overall, we detected 251 grounded native or endemic birds, including endangered species (see Table 1). Based on species flight heights, species behavior, location, vegetation, and injuries we classified 69.3% as powerline-grounded birds (see Fig. 5 for examples of injuries), 6.4% as probable powerline collisions (but vehicle strike could not be eliminated), 7.2% as undetermined (both powerlines and vehicles collisions likely), 8.0% as probable vehicle (but powerline strike could not be eliminated), and 9.2% as unambiguously vehicle collisions.

This grounded bird dataset confirmed for the first time that an addition three species collide with powerlines: Hawaiian Coot, White-tailed Tropicbird, and Kōlea (Pacific Golden-Plover, Pluvialis fulva). For all species except the coot, we have found carcasses in situations where it would have been impossible for vehicles to hit the birds, such as under powerlines in agricultural fields away from water sources or under powerlines on remote hiking trails. In the case of the coot, the bird was found in the road 950 m from the nearest open water. At this location the bird would not have been able to walk into the road or fly at vehicle height due to a 3 m high vertical dirt berm with an additional 1.5 m of vegetation on top of the berm, suggesting the bird flew into powerlines and then was grounded in the road. We also detected a vagrant Black Brant (*Branta bernicla*) dead under powerlines with powerline-specific injuries. We reconfirmed native or endemic birds found grounded by powerlines, which have also previously been observed hitting powerlines, include the Newell's Shearwaters, Hawaiian Petrels, Wedge-tailed Shearwaters, Red-footed Boobies, Black-crowned Night Herons, Hawaiian Geese, Hawaiian Stilt, Hawaiian Common Gallinule, and Hawaiian Duck. The only evidence of electrocution (smell of burnt feathers and an electrical exit wound) was from three Red-footed Boobies and one Hawaiian Goose all found under distribution powerlines.

Three native or endangered species were unambiguously killed by vehicle strike: Wedge-tailed Shearwaters, White-tailed Tropicbirds, and Hawaiian Geese, which were all hit by vehicles in areas without powerlines (Fig. 1E Table 1).

3.5. Spatial overlap in powerline collisions and vehicle strikes

Overall, roads were spatially correlated with powerlines and available search space around powerlines was spatially correlated with roads. 79.8% of public paved roads on Kauaʻi are within 30 m of powerlines. Despite only 54.0% of the long-distance powerlines being located within 30 m of roads, 89.5 percent of all search space around the long-distance powerlines is provided by cleared space of the roadways (Travers et al., 2021). The local distribution powerlines were also associated with

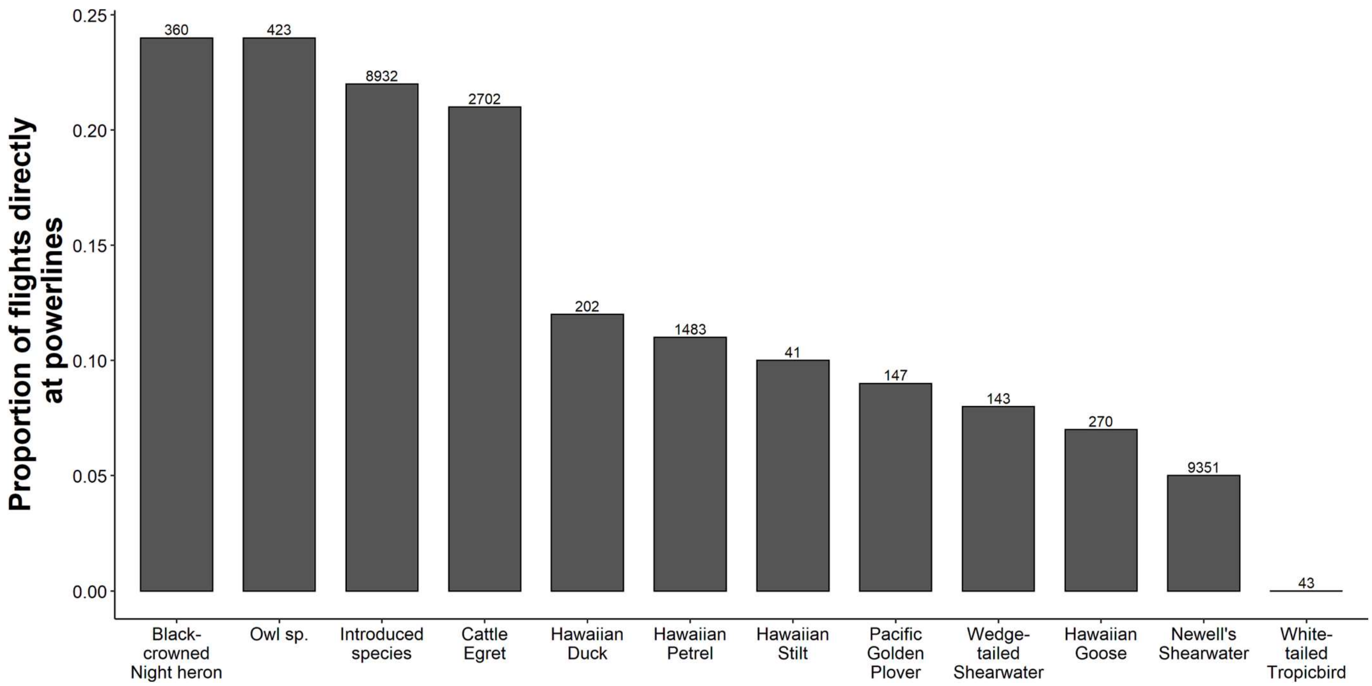

Fig. 3. Proportion of total flights directly at powerline wire zone (airspace from top wire to bottom wire) by species. Numeric value indicates total observed powerline crossings by species.

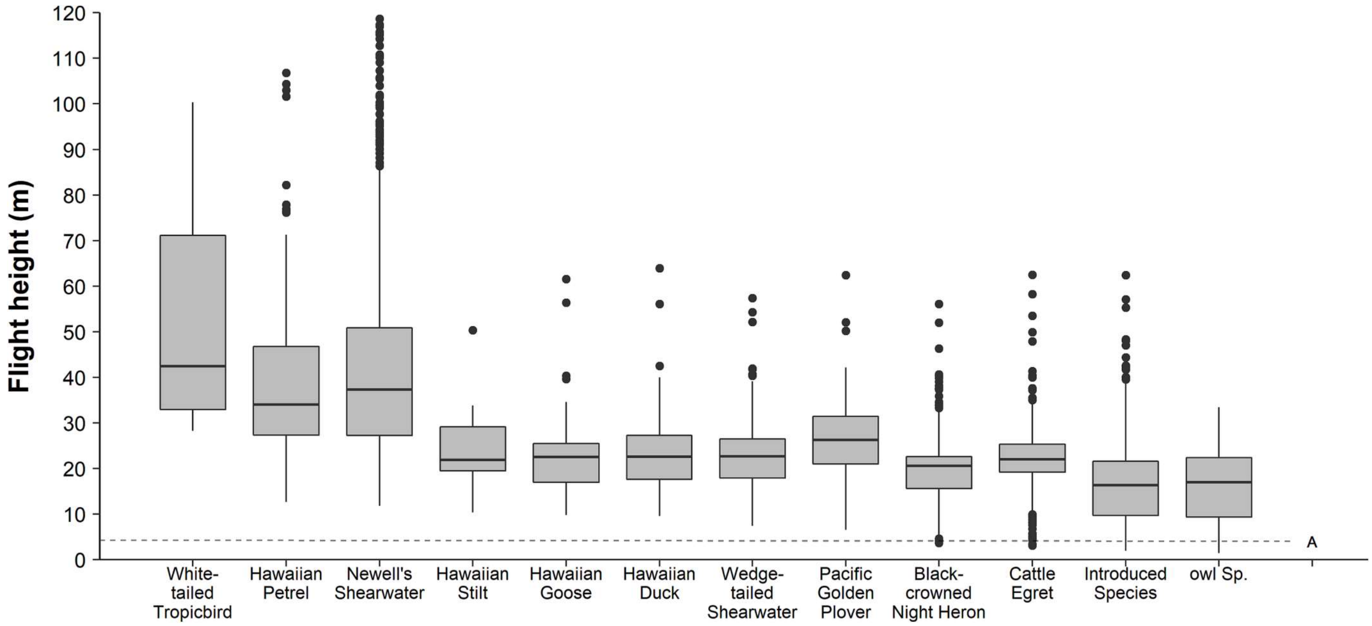

Fig. 4. Flight height of birds transiting across roads with powerlines present. (A) designates 4.26 m, the tallest permissible vehicle height in Hawaii.

roads. 83.9% of local distribution powerlines are located within 30 m of roads and 96.9 % of all search space around the local distribution powerlines is provided by cleared space of the roadways.

These spatial correlations resulted in grounded birds predominantly being detected in roadways with powerlines next to the road, regardless of the cause of grounding. Overall, 69.7 % of grounded birds were found in roadways with powerlines present, while 21.1 and 9.2 % of birds were found at powerlines without roads or roads without powerlines respectively. Of the birds found in roadways with both collision hazards present, the relative risk due to powerline or vehicles was species specific (see Table 1 for species ratios). For example, nearly all grounding risk for the Hawaiian Short-eared Owl was from vehicle strikes while for the endangered seabirds all risk was due to powerlines. Lastly, the Hawaiian Goose, the Hawaiian Common Moorhen, and the Hawaiian Coot had the highest proportion of undetermined cause of grounding (see Table 1).

Regardless of the assessed primary grounding cause, injuries detected on grounded birds in roads with powerlines present were skewed to vehicle collisions (see Fig. 5 for examples of vehicle and powerline injuries). Only 19.3% of birds were found on the pavement (i.e. driving surface) without vehicle injuries, and all were warm and clearly found just after the powerline collision and prior to a secondary vehicle strike or were past the white line and close to a guard rail or curb that drivers would actively avoiding driving near, thus preventing secondary vehicle

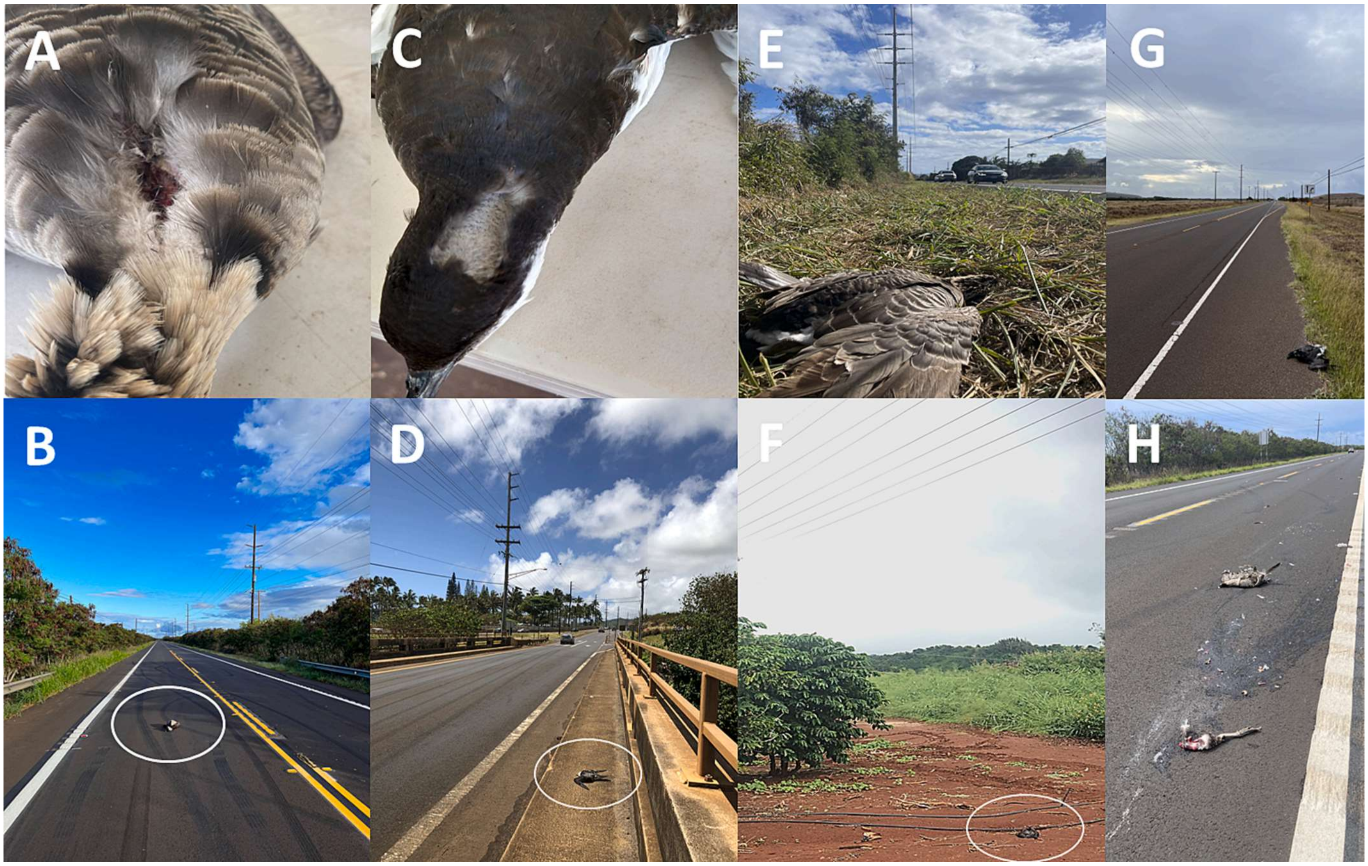

Fig. 5. A) Powerline feather scrape and wound on Hawaiian Goose. Feathers shaved in the direction of flight ending in wound at upper back. B) Hawaiian Goose found dead in road with powerline scrape but no other injuries, indicating it was found prior to being hit by a car. The goose was found at first light and was still warm, indicating it had not been grounded long. C) Powerline feather scrape on the head of Newell's Shearwater. Scrape larger than is typically found. D) Hawaiian Petrel dead from powerline collision, crash landed just onto the sidewalk preventing it from being secondarily run over by a vehicle. E) Hawaiian Goose observed hitting powerline and crashing dead into the road shoulder. The goose had a compound fracture of the left wing, just proximal to the wrist. F) Hawaiian Common Moorhen found dead under powerlines in an agricultural field away from freshwater. G) Black Brant was found dead with powerline scuff on neck. Also, a vehicle tire clearly rolled over this bird from left to right (direction of traffic) as the bird's intestines were coming out of right side. Bird appears to have been dead when run over, because despite clearly being run over, there are no vehicle contact injuries, just compression from tire (i.e. bird lying flat when hit) and no blood on pavement despite intestines coming out (i.e. heart not pumping when runover). H) Hawaiian Goose hit by vehicle. Large blood spatter over 3 m from point of contact and removal of one leg suggest that the bird was alive (blood spatter) and standing (not simply rolled over by tire) when struck.

collision. 2.5 percent of birds had clear powerline feather scrapes (patches of missing feathers scrapped head to tail in direction of flight, see Fig. 5 for examples) which occurred prior to the vehicle contact injuries that were also visible but not yet so catastrophic as to obscure the powerline injuries. The remainder of birds found on the pavement had clear vehicle injuries that could have obscured powerline injuries or were so catastrophic (often run over repeatedly or birds with missing limbs and disemboweled, see Fig. 5) that we would not have been able to detect powerline injuries if they had been present prior to vehicle injuries. Of the birds found grounded in roadways with powerlines present, 100% of owls, 58.6% of waterbirds, and 23.3% of native seabirds could not be given a definitive cause of grounding as this was obscured by the presence of both hazards. If being detected in the roadway (pavement and grassy shoulder) with vehicle collision injuries was the only criteria used to assess the cause of grounding, then 53.5% and 64.3% of powerline grounded and probable powerline grounded birds would have been classified as vehicle collisions.

4. Discussion

In this paper we confirmed that 13 native and endemic Hawaiian species collide with powerlines. Of these, nine are recorded for the first time as hitting powerlines. Overall, this includes all six waterbirds (including all five endemics and one native), five seabirds (including two endemics and three native), an endemic owl, and a migratory shorebird. The discovery of this hitherto undocumented threat has major ramifications for avian conservation in Hawaiʻi, and in particular for the recovery of threatened and endangered species. In addition, we found an uncommon vagrant goose killed by a powerline. We also confirmed vehicle strikes to Hawaiian Geese, White-tailed Tropicbirds, and Wedge-tailed Shearwaters.

Determining definitive vehicle strike risk for the waterbirds in our Kauaʻi dataset was challenging. Although the data is representative of most of Kauaʻi's roads, we may have detected additional conclusive waterbird vehicle collisions had we been able to expanded our search to the limited sections of private or restricted roads without powerlines. These roads are on golf courses and military properties where waterbirds are known to forage and walk across roads. Regardless, there was strong spatial overlap in the two causes of mortality considered here, with 79.8% of all public paved roads on Kauaʻi having powerlines nearby. Furthermore, powerlines are present at the roads transiting through Kauaʻi's most important waterbird sanctuaries such as Hanalei National Wildlife Refuge (NWR) and Kawaiʻele Waterbird Sanctuary. Given the spatial correlation of roads and powerlines, it is not surprising that we detected only a single waterbird specimen (a Hawaiian Goose) found grounded without powerlines present. A global development analysis has also found a strong spatial correlation between powerlines and roads (Arderne et al., 2020). Therefore, studies of avian vehicle strike risk in Hawaii and elsewhere clearly need to consider powerlines as an additional or primary source of mortality (Morelli et al., 2020).

Due to the presence of multiple hazards, we could not definitively classify the cause of mortality for more than half of all grounded waterbirds. The uncertainty in the cause of grounding arises because birds that collide with powerlines can crash into roads and be secondarily run over. More than half the Hawaiian Goose powerline collisions resulted in the birds dropping into the roadway or just missing the road and landing on the road shoulder. Therefore, even if there are clear signs of vehicle collision injuries or the bird was found dead in the road, it is not possible to definitively state that the cause of death was by vehicle collision if powerlines are present. In at least three instances, Hawaiian Goose injuries clearly indicated the bird was hit by a car while standing (i.e., alive). However, because powerlines were present, we could not definitively rule out the possibility that the birds hit the powerlines and crashed into the road but were still alive but injured (observed on one occasion for a Hawaiian Goose) and were subsequently standing at the time of vehicle collision. Further overlap of mortality between powerlines and vehicles can be observed in the common Hawaiian Goose behavior of standing for hours next to dead partners (often vocalizing; pers obs). Hawaiian Geese are occasionally found dead in pairs likely because of this behavior. As an example, in one instance a Hawaiian Goose was found dead with a clear powerline injury and a second Hawaiian Goose was found dead 50 m away with a clear indication that it was hit by a vehicle while alive. This suggests that the second goose was hit by a vehicle while standing near its partner, which had been killed by a powerline collision.

We do not present the powerline collision data to argue that vehicles are not a major threat to Hawaii's native and endangered birds. Vehicle strikes are considered a major cause of avian mortality (Jacek et al., 2020; Johnson et al., 2017; Loss et al., 2015; Møller et al., 2011; Morelli et al., 2020; Pagany, 2020) and there is no evidence to indicate that Hawaii is different. Our data indicate that multiple native species were exposed to vehicle collision risk while flying. The Hawaiian Short-eared Owl is vulnerable from flying low on foraging flights near and across roads, which is consistent with vehicle collision data for other owl species (Gagné et al., 2015; Gomes et al., 2009). Unlike other Hawaiian species where taller vegetation alongside roads can prevent low flight, owls tend to swoop down from or in between the trees to hunt in the roadway. In one instance a Short-eared Owl rescued after being hit by a car was rehabilitated and released by the Save Our Shearwaters program only to be run over and killed a few weeks later (AF Raine pers obs). Roads near seabird colonies exposed White-tailed Tropicbirds and Wedge-tailed Shearwaters to vehicle collisions and the very lowest-flying Black-crowned Night Herons could potentially be hit by tall vehicles or wind turbulence from fast-moving vehicles (Orłowski and siembieda, 2005), in areas where vegetation along the side of the road is sufficiently short to allow these birds to fly at vehicle height. A large Wedge-tailed Shearwater colony on the south side of the island has been heavily impacted by vehicular collision in addition to depredation by cats and dogs (MS Travers and AF Raine pers obs). Even for the species with clear risk of flying into vehicles, this was spatially isolated to a small section of roads on Kaua'i. For all other species, our data indicate that there is relatively low risk of flying into a vehicle. However, for multiple waterbirds, vehicle collision hazard appears to result predominantly from birds walking into roads. Three of Hawaii's endemic waterbirds are particularly prone to vehicle strike risk while walking because they regularly forage on mowed grass at the side of roads or transit across roads that bisect two water sources (Lepczyk et al., 2019; Rave et al., 2005). On Kaua'i, the Hawaiian Goose, Hawaiian Common Gallinule, and Hawaiian Coot are regularly observed foraging and walking near roads at Kawai'ele Waterbird Sanctuary on the west side of the island and at the Hanalei NWR in the north. This propensity of walking into the roads which also have exposed powerlines nearby, resulted in these three species having the highest proportion of individual carcasses classified as undetermined cause of grounding.

Results of powerline collision data collected from continental areas predicted high collision risk in several Hawaiian waterbirds. Rayner (1988) examined avian aerodynamic performance based on wing loading and wing aspect (shape), classifying bird groups into six classifications; 'poor' fliers, waterbirds, diving birds, marine soarers, aerial predators, and thermal soarers. Bevanger (1998), considering these flight classifications, reported that species with higher wing-loadings (mass per unit wing area), such as rails, coots, diving birds, ducks, and geese were frequent powerline collision victims, with gallinules and coots among the most commonly recorded. Hawaiian Common Gallinules and Hawaiian Coots are believed to conduct infrequent nocturnal dispersal flights (Rees et al., 2018) and indeed many Rallids conduct extensive nocturnal migrations elsewhere in the world, exposing them to infrastructure collision risk in low light (Taylor and Anderson, 1973). However, despite our extensive observational effort, we confirmed only a single Rallid collision visually and generally failed to directly observe additional risky flights. Nearly all powerline collisions in these species were documented by detecting grounded birds. The detection of powerline grounded birds without many observations suggests, as predicted by Bevanger and other grounded bird studies, that these species must have a high powerline collision risk per flight.

By examining the overlapping threats of vehicles and powerlines, we have identified a mechanism by which powerline collisions could be obscured by vehicle collisions, which has so far prevented the inclusion of powerlines as a threat in conservation recovery plans for the Hawaiian waterbirds (U.S. Fish and Wildlife Service, 2011, 2004). With a multitude of threats facing Hawaii's birds, obfuscation may not be limited just to vehicle strikes. Common powerline injuries may also be misinterpreted in the field. Head injuries were the most common reason for grounding in Newell's Shearwaters and Hawaiian Petrels (Day and Cooper, 1995; Travers et al., 2021). However, 20% of powerline grounded seabirds had no visible injury (Travers et al., 2021). A limited number of these birds were found alive and sometimes exhibited delayed-onset neurological issues, such as lethargy, tail-twitching, torticollis, head scanning, and/or ataxia. These symptoms overlap with and thus can be interpreted as the result of other conditions such as severe dehydration, emaciation, or toxicosis. Predators and scavengers can detect powerline-grounded birds (Barrientos et al., 2018) and leave distinctive bite marks, which may also obscure the primary cause of grounding.

On Kaua'i, underestimating endemic seabird powerline collisions due to challenges in detection of grounded birds delayed actions to reduce powerline collision by nearly three decades (Travers et al., 2021), contributing to a 94% decline in Newell's Shearwaters and 78% decline in Hawaiian Petrels (Raine et al., 2017). Lessons learned from Kaua'i's endemic seabirds have since accelerated waterbird powerline conservation actions on Kaua'i. Documenting waterbird powerline collisions and flight heights that put birds at risk has resulted in the expansion of conservation actions originally initiated just for seabirds to include waterbirds, leading to waterbird conservation actions not previously considered or implemented anywhere in Hawaii. The Kaua'i Island Utility Cooperative (KIUC) has responded to the powerline collision data by modifying 170 km of powerlines for the protection of birds, focusing on installing bird diverters, removing static lines, lowering wires, and consolidating lines to reduce collision risk (see Travers, 2022 for description and visual representation of powerline modifications). KIUC is also continuing to modify additional sections of powerlines and is funding research to determine the collision reduction efficacy for waterbirds and seabirds. In addition, the power company is funding the local avian rehabilitation program, Save Our Shearwaters, to now include all threatened and endangered birds confirmed hitting powerlines, including waterbirds.

Ironically, despite the previously documented threat from vehicle strikes, almost no action has been implemented to reduce vehicle mortality. We found most dead waterbirds on the stretch of highway that separates the Kawai'ele waterbird sanctuary from other nearby freshwater habitats. Although many dead waterbirds from this area were classified as "undetermined" because both powerlines and vehicles clearly pose a risk to these species at this location, road traffic clearly is a major factor. Road signs have been installed warning drivers of waterbirds but standard road signs are unlikely to reduce collisions (Huijser et al., 2015), and drivers may intentionally hit species viewed negatively (Ashley et al., 2007). This area would benefit from measures put in place to reduce the attractiveness of the roadside to foraging waterbirds, which could include modifying mowing regimens to reduce stretches of low-cut grass, changing the substrate to prevent growth of palatable vegetation, and adding barriers to prevent birds from walking across the road (Jacobson, 2005; Kociolek et al., 2015; Lepczyk et al., 2019). The collision problems on the west side of Kaua'i's highway exemplifies the need to identify all coexisting threats, as addressing just powerline collisions or just vehicle strikes would not have adequately addressed this risk of mortality to these endemic birds.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marc Simon Travers reports financial support was provided by Kauai Island Utility Cooperative.

Data availability

The data that has been used is confidential.

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