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On a collision course? The large diversity of birds killed by wind turbines in South Africa

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Wind energy is a clean, renewable alternative to fossil fuel-derived energy sources, but many birds are at risk from collisions with wind turbines. We summarise the diversity of birds killed by turbine collisions at 20 wind energy facilities (WEFs) across southwest South Africa. Monitoring from 2014 to 2018 recovered 848 bird carcasses across all WEFs, at a crude rate of 1.0 ± 0.6 birds turbine^{-1} y^{-1} at 16 WEFs with at least 12 months of postconstruction monitoring. However, mortality estimates adjusted for detection and scavenger bias were appreciably higher: 4.6 ± 2.9 birds turbine^{-1} y^{-1} or 2.0 ± 1.3 birds MW^{-1} y^{-1} (n = 14 WEFs with site-specific bias correction factors), which is slightly lower than mean rates reported in the northern hemisphere, but still well within range. A striking result was the high diversity of birds killed: 130 species from 46 families, totalling 30% of bird species recorded at and around WEFs, including some species not recorded by specialist surveys at WEF sites (e.g. flufftails Sarothruridae). Species accumulation models suggest that 184 (±22) species will be killed at these facilities, some 42% of species found in the vicinity of WEFs. This is despite the smaller number of migrants in the study region, compared with the north temperate zone. Diurnal raptors were killed most often (36% of carcasses, 23 species) followed by passerines (30%, 49 species), waterbirds (11%, 24 species), swifts (9%, six species), large terrestrial birds (5%, 10 species), pigeons (4%, six species) and other near passerines (1%, seven species). Species of conservation concern killed include endangered Cape Vultures *Gyps coprotheres* and Black Harriers *Circus maurus*, both of which are endemic to southern Africa. Every effort must be made to site wind energy facilities away from important areas for birds, particularly raptors.

Sur une trajectoire de collision ? La grande diversité des oiseaux tués par les éoliennes en Afrique du Sud

L'énergie éolienne est une alternative propre et renouvelable aux sources d'énergie dérivées des combustibles fossiles, mais de nombreux oiseaux sont menacés par les collisions avec les éoliennes. Nous résumons la diversité des oiseaux tués par les collisions avec les turbines dans 20 installations éoliennes (WEF) du sud-ouest de l'Afrique du Sud. Le suivi de 2014 à 2018 a permis de récupérer 848 carcasses d'oiseaux dans tous les WEF, à un taux brut de 1.0 ± 0.6 oiseaux turbine^{-1} an^{-1} dans 16 WEF avec au moins 12 mois de surveillance postconstruction. Cependant, les estimations de mortalité ajustées pour tenir compte des biais de détection et de récupération étaient sensiblement plus élevées: 4.6 ± 2.9 oiseaux turbine^{-1} an^{-1} ou 2.0 ± 1.3 oiseaux MW^{-1} an^{-1} (*n* = 14 WEF avec des facteurs de correction des biais spécifiques au site), ce qui est légèrement inférieur aux taux moyens rapportés dans l'hémisphère nord, mais reste bien dans la fourchette. Un résultat frappant a été la grande diversité des oiseaux tués: 130 espèces de 46 familles, soit 30% des espèces d'oiseaux recensées aux WEF et aux alentours, y compris certaines espèces non recensées par des études spécialisées sur les sites des WEFs (par exemple les râles-nains de la famille des Sarothruridae). Les modèles d'accumulation des espèces suggèrent que 184 (±22) espèces seront tuées dans ces installations, soit environ 42% des espèces trouvées à proximité des WEF. Ceci malgré le nombre plus faible de migrateurs dans la région étudiée par rapport à la zone tempérée du nord. Les rapaces diurnes ont été tués le plus souvent (36% des carcasses, 23 espèces), suivis par les passereaux (30%, 49 espèces), les oiseaux aquatiques (11%, 24 espèces), les martinets (9%, 6 espèces), les grands oiseaux terrestres (5%, 10 espèces), les pigeons (4%, 6 espèces) et autres passereaux proches (1%, 7 espèces). Les espèces dont la conservation est préoccupante et qui ont été tuées sont notamment les Vautours chassefiente (*Gyps coprotheres*) et les Busards maures (*Circus maurus*), deux espèces endémiques d'Afrique australe. Tous les efforts doivent être faits pour placer les installations d'énergie éolienne loin des zones importantes pour les oiseaux, en particulier les rapaces.

Keywords: bird diversity, bird fatality rates, bird turbine collisions, postconstruction monitoring, wind energy

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Introduction

In many countries, wind energy is a key component of the strategy to reduce carbon emissions by decreasing dependence on fossil fuel-derived energy sources (Leung and Yang 2012; Dai et al. 2015). However, renewable energy generation can also have environmental impacts (Gasparatos et al. 2017). For wind energy, the main concern is collision mortality of birds and bats with turbines and associated powerlines (Smallwood and Thelander 2008; Loss et al. 2013; Erickson et al. 2014; Marques et al. 2014; Dai et al. 2015), although there may also be sublethal impacts on these organisms, as a result of behavioural changes linked to displacement and habitat loss (Drewitt and Langston 2006; Dahl et al. 2012; Schuster et al. 2015; Shaffer and Buhl 2016; Farfán et al. 2017; Gómez-Catasús et al. 2018; May et al. 2019). Other environmental impacts of large wind energy facilities (WEFs) include disturbance (visual and noise) and local climate change (Leung and Yang 2012; Dai et al. 2015).

Numerous studies have reported the diversity of birds killed at terrestrial WEFs globally (e.g. Erickson et al. 2014; Thaxter et al. 2017; Bose et al. 2018; Sebastián-González et al. 2018). Wind energy generating capacity is increasing worldwide (International Renewable Energy Association, IRENA 2019), but data on collision mortality is strongly biased towards Europe and North America (Schuster et al. 2015). A recent meta-analysis of 93 terrestrial WEFs only included two WEFs in Asia, two in Australasia and one each in South America and Africa (Thaxter et al. 2017). Almost half (46%) of bird species potentially exposed to wind turbines in the USA have been found killed (American Wind Wildlife Institute, AWWI 2019). This proportion was lower (18–21%) at two WEFs in Tasmania, Australia (Hull et al. 2013), the only comparable study from the southern hemisphere, despite monitoring for 10 years at these sites. One possible reason for this difference is the greater proportion of migrant species among bird communities in the north temperate region, compared with the south (Hull et al. 2013), given the high risk faced by migrating birds (e.g. Desholm 2009; Erickson et al. 2014).

Species-specific abundance and behaviour, and WEF location in relation to local topography can affect the risk of collisions (De Lucas et al. 2008). Collision risk is not evenly spread among species and a few species usually account for a large proportion of carcasses found (Erickson et al. 2014; Sebastián-González et al. 2018; AWWI 2019). Overall, raptors and other large soaring species, as well as some migrating birds, are typically identified as the main bird groups at risk at terrestrial WEFs (e.g. Gove et al. 2013; Thaxter et al. 2017). It is critical to understand not only which species are at risk of wind turbine collisions, but are also likely to be vulnerable to population declines as a result (Loss et al. 2013, Beston et al. 2016; Thaxter et al. 2017). Diurnal raptors (Accipitriformes and Falconiformes) tend to attract most attention, because as top predators they occur at low densities, yet are killed in relatively large numbers (Barrios and Rodriquez 2004; Smallwood and Thelander 2008; Beston et al. 2016; Watson et al. 2018). Species at risk should become a key focus of Environmental Impact Assessments (EIA) and Strategic Environmental Assessments, which are important tools to reduce the impacts of wind energy developments (Gove et al. 2013).

South Africa has an energy intensive economy with among the highest per capita carbon emission rates globally (Fant et al. 2016). The country also has the greatest installed wind energy generating capacity in Africa (IRENA 2019), with the number of operational turbines increasing more than threefold from 253 in 2014 to 825 in 2017. Despite this, there is little published information on bird collision risk in South Africa. The meta-analysis by Thaxter et al. (2017) included data from only one South African WEF, based on one year of monitoring of a single turbine. Watson et al. (2018) summarised information on raptors impacted in South Africa, where most concern has focused on threatened vultures (Rushworth and Krüger 2014; Reid et al. 2015).

BirdLife South Africa and the Endangered Wildlife Trust worked with the wind energy industry to develop best practice guidelines for monitoring the impacts of WEFs on birds in South Africa (Jenkins et al. 2015). Ralston-Paton et al. (2017) summarised initial reports from postconstruction monitoring and reported 271 birds from 82 species killed at eight WEFs. We extend their study by collating all available information on birds killed by turbine collisions in South Africa at 20 WEFs up to 2018. This is by far the most comprehensive survey of wind energy impacts on birds in the southern hemisphere, and unlike most northern hemisphere studies, is from a region where there is limited migration of terrestrial birds. We extrapolate the number of species susceptible to collision risk at each WEF from the species accumulation curves observed to date and relate these numbers to the diversity of birds potentially at risk at each site. We also assess whether the paucity of migratory species results in a reduced collision risk at the community level. Our findings contribute to the global body of data on wind turbine collision fatalities, and help to inform ongoing conservation actions and monitoring and mitigation requirements.

Materials and methods

Study sites and data collection

Most wind energy facilities (WEFs) in South Africa are required to conduct postconstruction monitoring programmes that include searching for bird carcasses under turbines, as a condition of their environmental authorisation. We obtained copies of monitoring reports from WEF operators (Supplementary Information (SI) Appendix 1), sometimes by resorting to applications through the Promotion to Access to Information Act (Act No 2 of 2000). Postconstruction bird monitoring reports, compiled by specialist consultants, were obtained for 20 of 23 operational WEFs in South Africa, monitored from 2014 to 2018 (SI Appendix 1, Table S1). These WEFs are spread over three provinces and five biomes (Mucina and Rutherford 2006; Figure 1): five in the Western Cape (Fynbos), 11 in the Eastern Cape (Thicket, Fynbos, Grassland and Savannah), and four in the Northern Cape (Nama Karoo). However, most WEFs on the

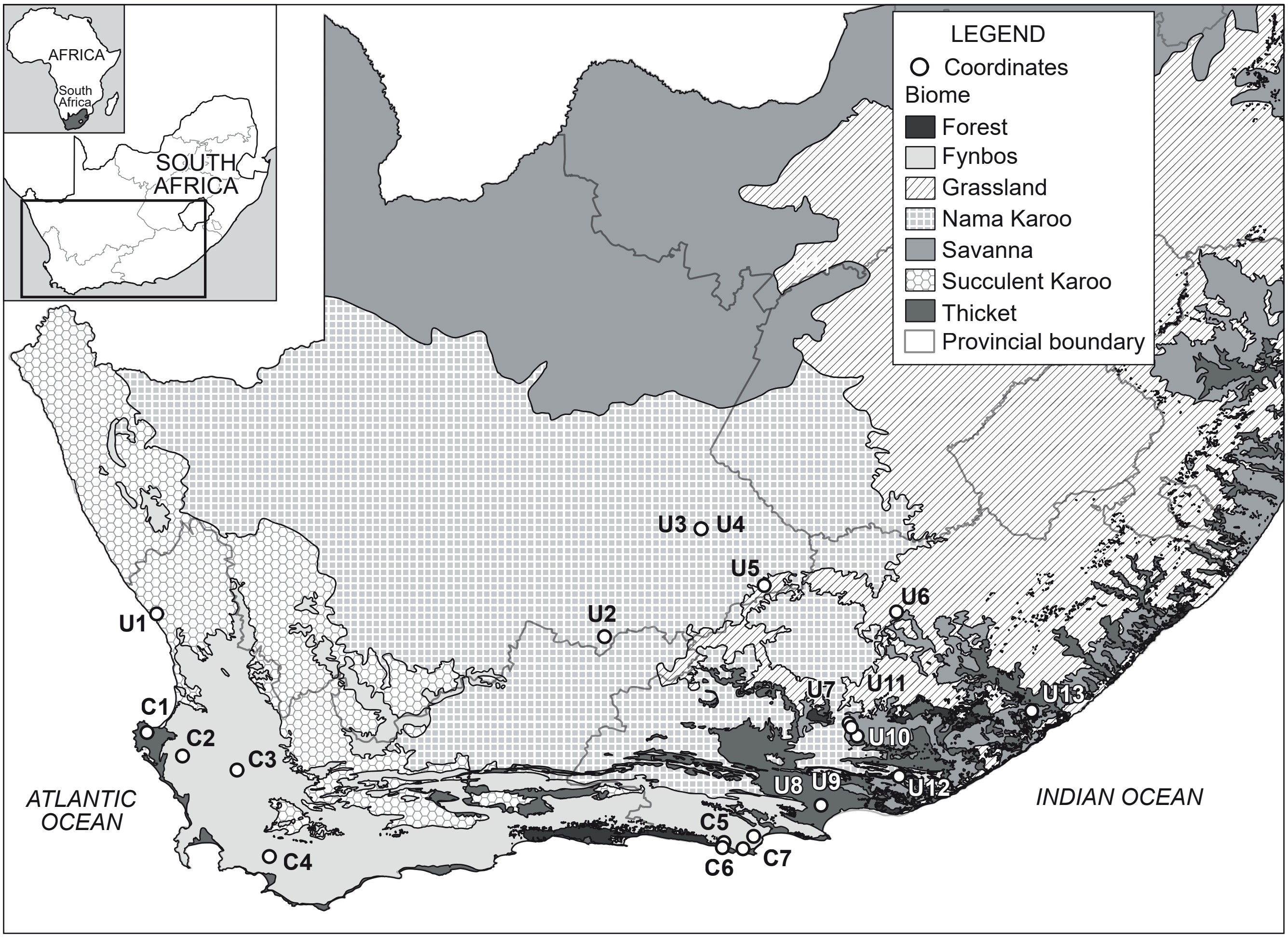

Figure 1: The locations of the 20 wind energy facilities (C1–7; U1–13) in relation to the major biomes (from Mucina and Rutherford 2006) in southwest South Africa. C = cultivated land; U = uncultivated land

coastal plain were in cultivated areas dominated by cereal crops and pastures. We accordingly categorised WEFs based on whether the surrounding land use was cultivated land (n = 7) or largely untransformed vegetation (typically used as rangelands, n = 13; Figure 1, Supplementary Table S1). Classification was based on the Department of Environmental Affair's 2013–2014 National Land Cover Data for South Africa (GEOTERRAIMAGE 2015).

The specialist consultants mostly followed the recommended guidelines for assessing and monitoring the impact of wind energy facilities on birds (Jenkins et al. 2015). Their reports provided the following information for most WEFs: survey interval, area searched, number of turbines searched, number of carcasses recorded (unadjusted for searcher efficiency and carcass persistence), species name (if identified), date recorded, turbine(s) responsible for collision, distance of carcass from turbine, carcass persistence rates, searcher efficiency estimates and adjusted fatality estimates.

The number of carcasses recorded typically underestimates the number of birds killed, because the probability of finding a collision victim depends on the search effort (extent and frequency), the likelihood of the carcass falling within the search area, searcher efficiency (detection rate), and carcass persistence (Smallwood 2007, 2013). These factors are influenced by site-specific characteristics, such as topography, vegetation type and height, and the types and abundance of scavengers present at a site (Smallwood 2007; Huso 2011; Korner-Nievergelt et al. 2013; Aschwanden et al. 2018). Large bird carcasses are easier to detect than smaller carcasses, and small carcasses are more likely to be removed by scavenging predators, further reducing their detection rate (Krijgsveld et al. 2009; Erickson et al. 2014; Welcker et al. 2017). Searcher efficiency is calculated by performing experimental trials within the search area around wind turbines. Trial carcasses are deployed by one individual, then searched for by uninformed searchers. The proportion of carcasses recorded provides an estimate of searcher efficiency. Carcass persistence is a measure of how many carcasses are missed, because of removal by scavengers. Carcasses placed within the search area are monitored until removal to provide a persistence rate. Together, these estimates are used to correct for these factors at each facility and consequently provide a more realistic estimate of the actual numbers of fatalities (Huso 2011; Korner-Nievergelt et al. 2013; Smallwood 2013).

Estimates of carcass persistence, searcher efficiency and the resultant adjusted fatality rates (calculated using Huso's (2011) estimator) were provided in monitoring reports (SI Appendix 1). At most WEFs, detection and scavenger bias estimates failed to control for bird size, as a result of the inability to source sufficient carcasses from different bird size classes. Only one WEF (C6) provided separate fatality estimates for small, medium and large birds; the correction factor for this WEF was taken as the average estimate across the three size classes for comparability with the other WEFs. Because most studies only provided an overall fatality estimate across all groups, we were limited for data analyses options at group level.

Species killed were identified by the specialist consultants; we had to assume that their identifications were accurate, although some reports included images of birds killed that could be used to confirm their identifications (the identity of one out-of-range species was corrected in this way; no other species reported killed were out of their known range). Nomenclature and taxonomic order follows the IOC World Bird List v. 9.1 (www.worldbirdnames.org).

Data analysis

The number of dead birds at WEFs were collated, including incidental finds, as well as fatalities recorded by systematic searches during postconstruction monitoring. Species were categorised into six broad groupings to assess the types of birds most affected by turbine collisions: diurnal raptors (Accipitridae and Falconidae), swifts (Apodidae), passerines (songbirds), waterbirds (ducks, grebes, flamingos, herons, ibises, rails, flufftails, cormorants, darters, shorebirds, gulls and terns), large terrestrial species (e.g. cranes, bustards, storks and gamebirds), pigeons and doves (Columbidae) and other 'near-passerines' (cuckoos, mousebirds, kingfishers, barbets and honeyguides). Migratory status was taken from Hockey et al. (2005), and included intra-African migrants and partial migrants, as well as long-distance migrants. Not all species could be identified to species level, because of dismemberment, scavenger and/or insect activity or carcass age. Species of conservation concern were identified on global (www.iucnredlist.org) and regional (Taylor et al. 2015) IUCN red-list status. These results present the actual number and diversity of carcasses recorded. We summarised the annual fatality estimates per turbine and per MW per year for each WEF (all estimates reported by specialists were calculated only using fatalities recorded at systematically searched turbines).

In order to calculate the proportion of species affected by turbine collisions in relation to the suite of species present at each WEF, we compared the list of birds killed with species lists recorded by avifaunal specialists during pre- and postconstruction monitoring programmes during walked transects, vehicle-based transects, focal site surveys, vantage point surveys and incidental observations of target species (Jenkins et al. 2015). Postconstruction lists were available for all 20 sites, but preconstruction lists were only available for 12 WEFs. These lists were further augmented with data from the Southern African Bird Atlas Project (SABAP, sabap2.adu.org.za), at a quarter-degree grid cell resolution. Combining the pre- and postconstruction species lists with SABAP data, allowed us to compile comprehensive area lists of the potential range of species that could be killed at each WEF (cf. Herrera-Alsina et al. 2013). We removed vagrants and out of range species recorded from the area lists, as well as seabirds (all WEFs were at least 5 km inland).

In order to estimate the cumulative number of species that are likely to be impacted at WEFs per site and for the region as a whole, we used the iNEXT package (R package for rarefaction and extrapolation of species diversity, Hsieh et al. 2016). We compared species richness with the cumulative number of individuals killed per WEF for facilities with at least 12 months of postconstruction monitoring, and combined data from WEFs (where iNEXT estimated sample completeness was $\geq$50%) to estimate the total number of species likely to be killed at a regional scale. We used the area species list per WEF as reference species and the cumulative species list for the overall analysis. Analyses were performed in R (R Core Team 2018). Results are given as mean ± SD and confidence intervals are 95% unless otherwise indicated.

Results

Species killed by turbine collisions in South Africa

The 20 WEFs had a combined installed capacity of 1 811.5 MW (91 ± 37.4 MW per WEF) from 825 turbines (Supplementary Table S1). Turbine hub height was 88 ± 9.8 m (range 80–115 m), rotor diameter 103 ± 10.7 m (range 86–119 m) and height of blades above the ground 36.0 ± 8.8 m (range 25–60 m; Supplementary Table S1). The postconstruction reports monitored periods from three months to four years, representing 1 101 turbine years (Supplementary Table S1). Areas searched around each turbine ranged between 11 664 and 52 900 m^2 (Supplementary Table S1), equivalent to a mean search radius of 187 ± 32 m (range 108–230 m). Only 4 of 20 studies had search radii <175 m (cf. Smallwood 2013). Most WEFs (n = 15) were searched weekly, although turbine search intervals ranged from 4 to 14 days (Supplementary Table S1).

In total, 848 bird collision fatalities were recorded (Table 1), of which 83% (n = 707) were identified to species level and 95% (n = 804) to broad taxonomic or functional groups (Table 1, Supplementary Table S2). Of these carcasses, 24 were found outside of systematic postconstruction monitoring surveys: four during turbine construction and 20 during initial carcass sweeps or as incidental finds between systematic searches. Overall, 130 species were recorded killed, of which 16 were migrants (Table 1, Supplementary Table S2). Most carcasses found were of raptors (36%; of which 2% were owls), followed by passerines (30%), waterbirds (11%, of which 3% were waterfowl), swifts (9%), large terrestrial species (5%), pigeons and doves (4%) and other near-passerines (1%) (Table 1). Interestingly, although large numbers of swifts were killed, swallows and martins, which are if anything more abundant aerial insectivores, made up only 1% of all casualties.

The 130 species recorded belonged to 46 families (Table 1). At a family level, most birds found dead were Accipitridae (20.6%), which had the greatest number of species killed (n = 16) and were the only family recorded

Table 1: The diversity of birds killed by turbine collisions at order and family level, reporting the number of birds killed per family (# killed), the contribution of each family to the total (%), number of species killed per family (# species), the proportion of species at risk killed (% species), and the assigned group. # WEFs indicates the number of facilities at which fatalities were recorded (total *n* = 20). See Supplementary Table S1 for full species list; taxonomy follows the IOC list

Order / Family	# killed	%	# species	% species	Group	# WEFs
Anseriformes						
Anatidae	24	2.8	6	40%	Waterfowl (waterbirds)	6
Galliformes	23	2.7	5	71%		
Numididae	7	0.8	1	100%	Large terrestrial birds	4
Phasianidae	16	1.9	4	67%	Large terrestrial birds	7
Podicipediformes						
Podicipedidae	2	0.2	1	33%	Waterbirds	2
Phoenicopteriformes						
Phoenicopteridae	1	0.1	1	50%	Waterbirds	1
Ciconiiformes						
Ciconiidae	6	0.7	1	25%	Large terrestrial species	2
Pelecaniformes	19	2.3	5	28%		
Threskiornithidae	5	0.6	2	50%	Waterbirds	5
Ardeidae	14	1.7	3	25%	Waterbirds	5
Suliformes				50%		
Phalacrocoracidae	6	0.7	2	67%	Waterbirds	3
Accipitriformes	176	20.7	17	55%		
Sagittariidae	1	0.1	1	100%	Raptors (diurnal)	1
Accipitridae	175	20.6	16	55%	Raptors (diurnal)	20
Otidiformes						
Otididae	8	0.9	3	38%	Large terrestrial birds	2
Gruiformes	20	2.4	6	50%		
Sarothruridae	9	1.1	3	100%	Waterbirds	5
Rallidae	3	0.4	2	33%	Waterbirds	3
Gruidae	8	0.9	1	50%	Large terrestrial birds	4
Charadriiformes	23	2.7	7	15%		
Burhinidae	2	0.2	1	50%	Waterbirds	1
Charadriidae	15	1.8	3	27%	Waterbirds	8
Laridae	6	0.7	3	38%	Waterbirds	5
Columbiformes						
Columbidae	31	3.7	6	55%	Pigeons and doves	12
Cuculiformes						
Cuculidae	2	0.2	2	20%	Other near-passerines	2
Strigiformes	13	1.6	2	33%		
Tytonidae	9	1.1	1	100%	Raptors (owls)	7
Strigidae	4	0.5	1	20%	Raptors (owls)	3
Apodiformes						
Apodidae	73	8.6	6	86%	Swifts	15
Coliiformes						
Coliidae	4	0.5	2	67%	Other near-passerines	4
Coraciiformes				9%		
Alcedinidae	1	0.1	1	17%	Other near-passerines	1
Piciformes	2	0.2	2	14%		
Lybiidae	1	0.1	1	20%	Other near-passerines	1
Indicatoridae	1	0.1	1	25%	Other near-passerines	1
Falconiformes						
Falconidae	95	11.2	6	86%	Raptors (diurnal)	15
Passeriformes	212	25.0	49	24%		
Malaconotidae	28	3.3	1	13%	Passerines	8
Laniidae	4	0.5	1	33%	Passerines	2
Monarchidae	2	0.2	1	50%	Passerines	2
Corvidae	6	0.7	2	67%	Passerines	3
Alaudidae	51	6.0	8	50%	Passerines	12
Pycnonotidae	3	0.4	2	40%	Passerines	3
Hirundinidae	8	0.9	3	25%	Passerines	7
Cisticolidae	14	1.7	3	13%	Passerines	7
Zosteropidae	2	0.2	1	100%	Passerines	2
Sturnidae	4	0.5	3	33%	Passerines	3
Muscicapidae	13	1.5	6	25%	Passerines	10
Nectariniidae	4	0.5	4	44%	Passerines	**3**

Table 1: (cont.)

Order / Family	# killed	%	# species	% species	Group	# WEFs
Passeridae	15	1.8	3	75%	Passerines	11
Ploceidae	7	0.8	2	12%	Passerines	4
Estrildidae	1	0.1	1	13%	Passerines	1
Viduidae	1	0.1	1	50%	Passerines	1
Motacillidae	29	3.4	4	36%	Passerines	8
Fringillidae	20	2.4	3	27%	Passerines	8
Unidentified birds						
Unidentified passerines	39	4.6			Passerines	11
Unidentified raptors	20	2.4			Raptors (diurnal)	8
Unidentified waterbirds	4	0.5			Waterbirds	3
Unidentified birds	44	5.2			Unidentified	10
Total	848		130			

killed at all 20 WEFs. They were followed by another group of diurnal raptors, the Falconidae (six species accounting for 11.2% of birds found dead; Table 1). Other frequently killed families were the swifts Apodidae (8.6%), larks Alaudidae (6.0%), pigeons Columbidae (3.7%), Malaconotidae (3.3%, represented by a single species, the Bokmakierie *Telophorus zeylonus*) and ducks and geese Anatidae (2.8%, Table 1). The remaining families all contributed <2.5% of identified fatalities, with 27 families contributing <1% (Table 1).

Of the 707 birds identified to species level, seven species were represented by 20 or more individuals, which together accounted for 39% of mortalities, and ten species were represented by 10–19 individuals (which accounted for an additional 16% of mortalities; Supplementary Table S2). The Jackal Buzzard *Buteo rufofuscus* was the species most frequently found dead (n = 81), making up nearly half of all Accipitridae fatalities and 10% of all carcasses (Supplementary Table S2). The next most abundant species was the Rock Kestrel *Falco rupicolus* (n = 48, half of all Falconidae found dead), followed by Amur Falcons *F. amurensis* (n = 35) (Supplementary Table S2). However, it must be stressed that these are crude collision rates, unadjusted for searcher efficiency and carcass persistence, and therefore likely to be biased towards larger birds that are easier to detect and harder for scavengers to remove (Smallwood 2007; Urquhart et al. 2015). It is likely that even more passerines and other small birds were killed than reported in Supplementary Table S2.

The proportion of species occurring in the area of the WEFs (Supplementary Table S3) recorded as killed varied considerably among orders and families (Table 1). Among the more speciose groups with high proportions of species killed were the Falconidae, Apodidae, Galliformes, Columbidae, Accipitriformes and Alaudidae. The Sarothruridae were the largest family with all species recorded killed. In addition to the 46 families with fatalities recorded (Table 1), an additional 40 families occurred in the vicinity of the WEFs without having any casualties recorded (Supplementary Table S3). Most of these families were represented by only one (n = 20) or two (n = 10) species, but five families had four species (Glareolidae, Caprimulgidae, Meropidae, Locustellidae, Emberizidae), two had five species (Picidae, Acrocephalidae) and the Scolopacidae had 16 species without a single collision victim. Migrant species comprised 19% of fatalities, but were not more likely to be killed than resident species: migrants comprised 12% of species killed, compared with 17% of species not killed (Supplementary Tables S2 and S3; χ^2 = 1.86, DF = 1, p = 0.12). Of the 130 species killed, five are regionally Endangered, five Vulnerable and three Near-threatened (Table 2). At a global level, three are listed as Endangered and five as Vulnerable (Table 2).

Collision mortality rates

Unadjusted fatality rates per turbine for 16 WEFs with at least one year of postconstruction monitoring averaged 1.0 ± 0.6 birds turbine^{-1} y^{-1} (n = 16, range 0.1–2.0; Supplementary Table S4), but estimates adjusted for searcher efficiency and carcass persistence were almost five times higher at 4.6 ± 2.9 birds turbine^{-1} y^{-1} (n = 14, range 0.5–13.2; Supplementary Table S4). Unadjusted fatality rates per MW averaged 0.3 birds MW^{-1} y^{-1} (n = 16, range 0.0–0.7; Supplementary Table S5) whereas adjusted estimated were higher at 2.0 ± 1.3 birds MW^{-1} y^{-1} (n = 14, range 0.0–4.0; Supplementary Table S5). Annual fatality rates decreased over time at some WEFs, suggesting some level of accommodation among the local bird community (e.g. U1, U2 and U6), but increased at others (e.g. C4 and U8) (Figure 2; Supplementary Table S4). Unadjusted bird fatalities per turbine per year were greater closer to the coast ($F_{1,18}$ = 13.23, p = 0.02, R^2 = 0.42), but this relationship was not significant using the adjusted turbine fatality rates ($F_{1,12}$ = 1.50, p = 0.25; R^2 = 0.11). The main groups of birds killed varied between WEFs. Some WEFs had fatalities from all major groups (e.g. C1, C7, U1, U6, U7, U8), whereas others had fatalities from a subset of groups (e.g. C4, C7, U2, U9, U13; Figure 2). Raptors dominated fatalities at some WEFs (C1, C2, C3, U6, U9), whereas passerines accounted for most fatalities at other facilities (C4, C7, U1, U7, U13).

Site species lists (pre- and postconstruction monitoring) recorded at WEF sites ranged from 81 to 264 species, whereas area lists (site monitoring plus SABAP2) were more diverse (164–350 species, Table 3). The percentage of species killed per site ranged from 1 to 37% (Table 3). Altogether 29 species killed were not recorded on site and five not in the area, mainly as a result of secretive species

Table 2: Species of conservation concern killed across 20 WEFs in South Africa, listing conservation status (global, regional), level of endemism to South Africa, number of fatalities (including incidental finds, as well as carcasses from systematic searches) and the number of WEFs and land use area where the fatalities were recorded. EN – endangered; VU – vulnerable; NT – near threatened; LC – least concern; NR – not recognised. Land use: C = cultivated; U = uncultivated

Common name	Scientific name	Status	Endemic	# killed	# WEF	Land use
Cape Vulture	*Gyps coprotheres*	EN, EN	*	10	2	U
Cape Cormorant	*Phalacrocorax capensis*	EN, EN	*	1	1	C
Ludwig's Bustard	*Neotis ludwigii*	EN, EN	*	1	1	U
Black Harrier	*Circus maurus*	VU, EN	*	6	2	C, U
Martial Eagle	*Polemaetus bellicosus*	VU, EN		4	4	C, U
Southern Black Korhaan	*Afrotis afra*	VU, VU	**	5	1	U
Secretarybird	*Sagittarius serpentarius*	VU, VU		1	1	U
Blue Crane	*Grus paradiseaus*	VU, NT	*	8	4	C, U
Verreaux's Eagle	*Aquila verreauxii*	LC, VU		6	3	U
Lanner Falcon	*Falco biarmicus*	LC, VU		6	4	C, U
Striped Flufftail	*Sarothrura affini*	LC, VU		1	1	U
Greater Flamingo	*Phoenicopterus roseus*	LC, NT		1	1	U
Agulhas Long-billed Lark	*Certhilauda brevirostris*	NR, NT	**	1	1	C
Total				51		

** Endemic to South Africa
*Endemic or near-endemic to the southern Africa subregion

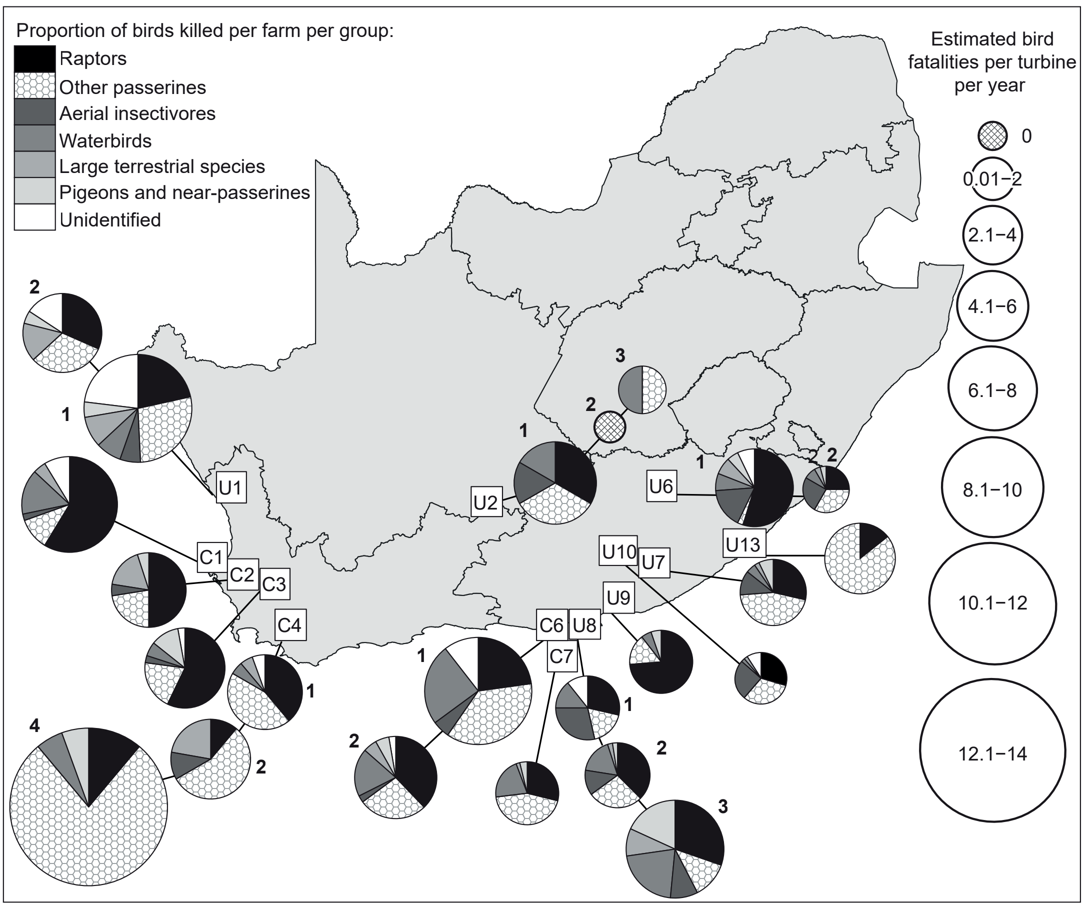

Figure 2: Bird fatality estimates at 14 South African WEFs using graduated symbol sizes to indicate the fatality rate per turbine per year (adjusted for searcher efficiency and carcass persistence). Shaded areas indicate the proportion of raptors, passerines, swifts, waterbirds, large terrestrial species, pigeons and near passerines (pigeons, doves and other near passerines grouped together), and unidentified birds that made up the actual number of carcasses recorded (not adjusted for searcher efficiency or carcass persistence). Fatality data up to second year of monitoring were included for six farms [U6, U8, C4, C7, U2 (no carcasses recorded) and U1], up to third year for two farms (U8 and U2) and up to fourth year for one farm (C4 – no fatality estimate was available for 3rd year of monitoring). Number adjacent to symbols depicts monitoring year (only indicated if monitored for more than one year)

Table 3: The total monitoring period in months, number of species reported killed at each windfarm in relation to the number of species reported at each site by specialist consultants (species on site), and the total bird diversity in the area (species in area) based on a combination of consultant lists and SABAP2 data. Superscript number indicates species (in footnote) that were killed, but not recorded at the site. Only WEFs with at least one full year of monitoring data were included in analyses (sites listed in order of decreasing monitoring period)

WEF	Period (months)	Species killed (%)	Species on site	Species in area
C4	48	21 (18%)	116 (1)[1]	222 (0)
U8	36	43 (20%)	216 (4)[2, 3, 4, 5]	334 (0)
U2	36	8 (3%)	247 (0)	258 (0)
U6	24	23 (14%)	169 (3)[5, 6, 7]	198 (3)[5, 6, 7]
U9	24	13 (9%)	151 (2)[4, 5]	292 (1)[4]
C7	24	30 (16%)	183 (5)[4, 8, 9, 10, 11]	301 (1)[4]
U1	24	30 (37%)	81*(7)[6, 12, 13, 14, 15, 16, 17]	203 (1)[6]
C1	14	22 (16%)	138(1)[14]	201 (0)
U10	12	24 (12%)	206 (1)[18]	265 (0)
U13	12	7 (4%)	161 (0)	251 (0)
U7	12	20 (20%)	99*(9)[6, 12, 19, 20, 21, 22, 23, 24, 25]	198 (1)[25]
C3	12	16 (7%)	214 (0)	241 (0)
C2	12	13 (14%)	95*(0)	187 (0)
U5	12	14 (15%)	91*(4)[26, 27, 28, 6]	164 (1)[6]
U12	12	1 (1%)	183 (0)	284 (0)
C6	12	24 (9%)	264 (1)[29]	350 (0)

*Only postconstruction species lists available for site
[1]Red-chested Flufftail, [2]Black-necked Grebe, [3]Yellow-breasted Apalis, [4]Buff-spotted Flufftail, [5]Western Barn Owl, [6]Common Swift, [7]Great Spotted Cuckoo, [8]Ant-eating Chat, [9]Cape Cormorant, [10]Cape Long-billed Lark, [11]Yellow-billed Egret, [12]White-rumped Swift, [13]Cape Weaver, [14]Common Tern, [15]Greater Flamingo, [16]Laughing Dove, [17]Little Swift, [18]Horus Swift, [19]African Quail Finch, [20]Black-collared Barbet, [21]Common Quail, [22]Greater Striped Swallow, [23]Lesser Kestrel, [24]Spike-heeled Lark, [25]Striped Flufftail, [26]Lesser Honeyguide, [27]Black-headed Heron, [28]Alpine Swift, [29]Southern Pochard

that travel at night (e.g. flufftails Sarothruridae) and hard to identify species (e.g. Common Swifts *Apus apus*, which are often confused with African Black Swifts *A. barbatus*; Table 3). Overall, some 440 species (excluding seabirds) were potentially at risk of colliding with turbines at the 20 WEFs (Supplementary Table S3), 30% of which have been killed to date. Species accumulation curves predict that 27–112 bird species will be killed at individual WEFs with lower- and upper 95% confidence levels of 15–311 species. The estimated number of species killed at all WEFs combined was 184 ± 22 (SE; 95% confidence interval 154–246 birds; Figure 3), 42% of species potentially at risk. The number of species recorded per site (R^2 = 0.02, $F_{1,13}$ = 0.33, p = 0.58) and in the vicinity (R^2 = 0.10, $F_{1,13}$ = 1.43, p = 0.25) were both poor predictors of the estimated number of species likely to be killed at each WEF. The number of species detected during carcass surveys, compared with sampling effort (turbines x monitoring months) showed a strong relationship whereby greater sampling effort delivered a higher species count (R^2 = 0.40, $F_{1,18}$ = 11.70, p = 0.003).

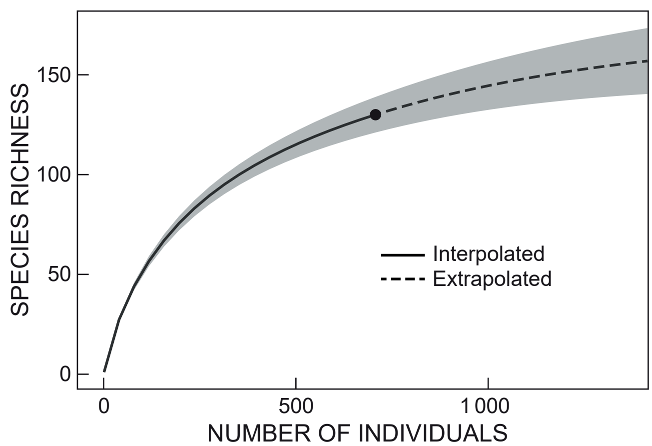

Figure 3: Asymptotic model estimate (solid line = interpolated; dashed line = extrapolated) of the number of species killed (species richness) in relation to the number of individuals killed at WEFs in southwest South Africa. The shaded grey area indicates 95% confidence interval (based on iNEXT; Hsieh et al. 2016)

Discussion

This is the first study to provide a comprehensive summary of the range of birds impacted by turbine collisions at a national scale in the southern hemisphere. As is the case in the northern hemisphere (e.g. Loss et al. 2013; Thaxter et al. 2017; Sebastián-González et al. 2018; Watson et al. 2018), a wide variety of birds was killed, including species from 46 out of 86 families.

At least 30% of species recorded in the vicinity of WEFs have been killed within the first few years of operation, and species accumulation curves suggest that this is likely to rise to more than 40% of all birds. As expected, more species are recorded killed at WEFs with greater sampling effort (cf. Beston et al. 2015). Northern hemisphere studies suggest that at least three years of carcass surveys are required for most affected species to be detected (Smallwood and Thelander 2008; Beston et al. 2015), whereas Hull et al. (2013), in one of the few other southern hemisphere studies, found that species accumulation curves only started to level out after seven years. It is therefore premature to identify any species or group as 'non-colliders'.

The proportion of bird species in the vicinity of WEFs expected to be killed is similar to that recorded in North America (46%; AWWI 2019), despite a much greater proportion of resident species in South Africa. Most northern hemisphere studies have been conducted in areas where there is extensive migration of terrestrial birds (Loss et al. 2013; Thaxter et al. 2017; Sebastián-González et al. 2018; Watson et al. 2018). The importance of migration-linked mortality is evident in species accumulation curves at some American WEFs, where most changes in the diversity of birds killed occur during spring and fall (Beston et al. 2015). Relatively few migrant birds occur at WEFs in South Africa, and our study sites are all close to the southern tip of Africa so there is little passage of birds migrating through the area. The slightly lower proportion of migrants killed, relative to resident species, probably reflects this lack of passage through the region, coupled with the shorter risk period for migrants, which are only present in South Africa for part of the year, compared with resident species.

Although a large number of species are killed by collisions in South Africa, a few species account for the bulk of fatalities, as has been found elsewhere (Erickson et al. 2014; Sebastián-González et al. 2018; AWWI 2019). Direct comparisons of collision rates among species are difficult, as a result of the limited suite of species found in both hemispheres, but similarities in the kinds of birds impacted by turbine collisions were observed at higher taxonomic levels. Raptors were the group most frequently found dead, confirming their susceptibility to turbine collisions, which has been attributed to their foraging behaviour, morphology and aerodynamics (Barrios and Rodriguez 2004; de Lucas et al. 2008; Garvin et al. 2011; Marques et al. 2014; Watson et al. 2018). The Jackal Buzzard was the species most often killed, reflecting its widespread distribution and relatively high abundance among resident raptors. Thaxter et al. (2017) predicted high fatality rates for *Buteo* species and turbine collisions have been reported for other members of the genus in the northern hemisphere (Ferrer et al. 2012; Welcker et al. 2017). Indeed, Red-tailed Hawks *B. jamaicensis* were the most commonly killed bird at the large Altamont Pass facility in California, accounting for 18% of carcasses recovered (Smallwood and Thelander 2008). Although not threatened, Jackal Buzzards are endemic to southern Africa (Taylor et al. 2015), with a population estimated in the tens of thousands (BirdLife International 2019). Population level impacts may not be significant at this stage, but continued monitoring and additional research is recommended to help ensure that this common species remains common, and that the ecological implications of any losses are understood. The Rock Kestrel is another widespread, common raptor in South Africa, and high fatality rates have been reported for closely-related kestrels at turbines in Spain (Common Kestrel *Falco tinnunculus*, Sebastián-González et al. 2018) and the USA (American Kestrel *F. sparverius*, Smallwood and Thelander 2008). The Amur Falcon was the migrant species most often killed; they are abundant non-breeding migrants from east Asia that spend the southern summer in South Africa.

Most species of conservation concern reported as turbine fatalities also were raptors. The Endangered Cape Vulture is the species of greatest concern, especially, because the closely related Griffon Vulture *Gyps fulvus* suffers very high mortality rates at WEFs in Spain (Ferrer et al. 2012; Sebastián-González et al. 2018). Cape Vulture populations are under severe pressure from a suite of anthropogenic impacts, resulting in a 92% decline over the past three decades (Boshoff et al. 2011; Ogada et al. 2016; Phipps et al. 2017). Ten Cape Vulture collision fatalities have already been reported, despite this species' small population and its limited spatial overlap with existing WEFs. Given the short monitoring period in our study, we anticipate more Cape Vulture fatalities in future, and this could become a very serious concern if additional WEFs are constructed in the vulture's core distribution. Without careful planning, other vulture species also are likely to be impacted as WEFs are built throughout Africa (Rushworth and Krüger 2014; Reid et al. 2015; Thaxter et al. 2017), further contributing to the continent's vulture 'crisis' (Ogada et al. 2016).

With a total population of only 500–1 000 breeding pairs, the endangered Black Harrier *Circus maurus* is the most range restricted continental raptor globally and has lost half its breeding habitat to land-use change (Taylor et al. 2015). Madders and Whitfield (2006) suggested that harriers are likely to have low mortality rates from wind turbines, because they tend to forage below the rotor swept area, but fatalities of at least four harrier species have been reported elsewhere (Thaxter et al. 2017) and six Black Harriers have already been killed at South African facilities (Table 2). If this trend continues, wind energy facilities could pose a significant threat to the survival of the species (Ralston-Paton et al. 2017). Verreaux's Eagles *Aquila verreauxii* also appear to be particularly susceptible to windfarms, with four birds killed at one wind farm in three months, and two other fatalities at different WEFs. Four nationally Endangered Martial Eagles *Polemaetus bellicosus* were also killed during the study period, as well as 21 other eagles from four species (Supplementary Table S2). Eagles are well known to be at risk from wind farms (e.g. Smallwood and Thelander 2008; Pagel et al. 2013; Smallwood 2013). The direct and indirect impacts of WEFs on eagles (e.g. Dahl et al. 2012) highlight the importance of properly siting WEFs outside eagle territories.

Passerines were the group affected most frequently after raptors, and their importance probably was underestimated, as a result of the lack of species- or group-specific detection and scavenger removal information, which results in a bias towards larger birds (Smallwood 2007; Urquhart et al. 2015). Erickson et al. (2014) estimated that 62.5% of all fatalities at WEFs in the USA and Canada were small passerines, with larks (Alaudidae) dominating. Larks also feature as a high-risk group in northern Europe (Bose et al. 2018), and wind farms have been directly implicated in the decline of a threatened lark species in Spain (Gómez-Catasús et al. 2018). The Red-capped Lark *Calandrella cinerea* was the passerine most frequently killed in South Africa. It is abundant and widely distributed, and therefore unlikely to be at-risk for any immediate population-level impacts. However, the susceptibility of larks to turbine collision could have larger impacts on other threatened or range-restricted species.

Among the aerial insectivores, surprisingly few swallows and martins (Hirundinidae) were killed, compared with swifts (Apodidae), which were the third most frequently killed family after the diurnal raptors (Accipitridae and Falconidae). One important point to consider when interpreting collision rates among passerines in south temperate and tropical regions is their more conservative life histories, characterised by high adult survival and low fecundity, compared with north temperate passerines (Martin et al. 2006, Lloyd et al. 2014). As a result, particular caution needs to be taken when wind energy developments are planned within habitats of range-restricted, threatened or endemic passerines, especially larks and other species with aerial displays (Ralston-Paton 2017; Watson et al. 2018).

The estimated collision rate of 4.6 (range 0.5–13.2) birds turbine^{-1} y^{-1} in our study is similar to the average mortality rate at most WEFs in the USA (5.25 (range 3.2–7.4) birds turbine^{-1} y^{-1} based on 44 577 turbines; Loss et al. 2013), and some European WEFs (e.g. 4.1 birds turbine^{-1} y^{-1} at Fehmarn Island, Germany; Welcker et al. 2017). However, Smallwood and Thelander (2008) estimated 0.5 birds turbine^{-1} y^{-1} at the Altamont Pass Wind Resource Area (APWRA) in California, USA, which is substantially lower than our estimate. Some European facilities also recorded substantially lower estimates (e.g. 0.03 birds turbine^{-1} y^{-1} in Spain; Farfán et al. 2017 and 1.3 birds turbine^{-1} y^{-1} in Turkey; Arikan and Turan 2017). However, other European studies reported substantially higher rates above 20 birds turbine^{-1} y^{-1} (Krijgsfeld et al. 2009; Everaert 2014; Aschwanden et al. 2018). Other studies report fatality rates as number of birds killed per MW per year. Erickson et al. (2014) reported 2.4 (0.3–11.0) birds MW^{-1} y^{-1} across all bird sizes and estimates whereas Loss et al. (2013) reported rates of 4.1 (2.5–5.8) birds MW^{-1} y^{-1}. Our adjusted estimate of 2.0 (0.0–4.0) birds MW^{-1} y^{-1} is only slightly lower. However, Smallwood (2013) estimated fatality rates across North America and calculated a mean of 13.1 (0.0–77.0) birds MW^{-1} y^{-1}, which is substantially higher than our estimates. The large variation in estimated fatality rates for WEFs both locally and in the northern hemisphere is likely, because of site specific factors, such as topography and species-specific abundance and behaviour (De Lucas et al. 2008).

The growing wind-energy industry is driven by the need for more environmentally friendly and sustainable energy sources, as well as economic incentives (Watson et al. 2018). It is long overdue in South Africa, which has one of the highest per capita carbon emission levels globally (Fant et al. 2016). However, it is important to ensure that alternative energy production technology does not have unsustainable impacts. Our study highlights the value of postconstruction monitoring at WEFs, particularly in areas with scant data on collision impacts. As the first comprehensive study of its kind in the region, our results generally agree with the findings from North America and Europe that suggest avoidance and mitigation strategies should prioritise raptors. However, a wide diversity of species is affected by collisions with wind turbines in South Africa, so other species of conservation concern should not be overlooked when assessing the suitability of potential development sites, and developing appropriate mitigation measures.

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