Cape Vultures (*Gyps coprotheres*) and the threat of wind farms: a race to extinction?

Francis Rae Brooke

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Advisors
Professor J.A. Venter
Dr M.B. Pfeiffer
Professor C.T. Downs

DECLARATION

I, FRANCIS RAE BROOKE (212258001), hereby declare that the thesis for *Doctor of Philosophy* in the Faculty of Science is my own work and that it has not previously been submitted for assessment or completion of any postgraduate qualification to another University or for another qualification.

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PREFACE

The work described in this dissertation was carried out in the School of Natural Resource Management, Nelson Mandela University, George Campus, George, South Africa. This study took place from January 2018 until December 2021 under the supervision of Prof Jan A. Venter (Department of Conservation Management, Nelson Mandela University), Dr Morgan B. Pfeiffer (U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Center) and Prof Colleen T. Downs (School of Life Sciences, University of KwaZulu-Natal).

This overall study represents original work by the author and has not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others, it is duly acknowledged in the text.

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Francis R. Brooke

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ABSTRACT

The development of wind energy is increasing globally and is often considered more environmentally friendly when compared to fossil fuel technologies. However, one of the ecological drawbacks of wind energy are the collisions of wildlife with turbine blades. In addition, the resulting anthropogenic landscape transformation can negatively impact populations. The Cape Vulture (*Gyps coprotheres*), a large endangered southern African endemic species, thus may be at risk from turbine development. The species has decreased dramatically in the past 50 years and understanding how additional mortalities from wind turbine impacts affect the population is needed to ensure effective conservation efforts. This study aimed to determine the population response to this emerging threat.

This study first reviewed the species-, site- and wind farm- specific traits that make *Gyps* species vulnerable to collision with wind energy infrastructure. It examined the monitoring practices employed during the pre- and post-construction phase and mitigation measures in South Africa and compared it with international standards. Furthermore, wind energy development may disrupt landscape connectivity and understanding which, and how habitat patches are used is needed. Using network theory combined with telemetry data from tagged individuals across three age classes, habitat patch use was identified. Further, environmental variables associated with identified habitat patches were identified. Additionally, considering the wind energy industry is expanding in South Africa, exploring how the Cape Vulture population will respond to this novel and emerging threat may aid future conservation management plans. Therefore, using a population viability analysis approach, the study explored how present and future wind turbine mortality scenarios impact the Cape Vulture

population and how the population will respond to increased wind turbine development.

The study results show that whilst South African monitoring methods are on a par with international studies, such methods are known to exhibit observer bias, and employing automated monitoring methods should be explored to reduce such biases. Furthermore, international studies revealed that curtailment methods are effective at reducing collisions, and such methods could prove useful in a South African context. This study further revealed through network analysis that Cape Vultures exhibit areas of intense use that are located close to established and proposed wind farms. This could present a hazardous situation, as poor placement of wind farms could lead to high collision probability. Should high numbers of collisions occur as a result of increased wind energy development, this study found that populations that overlap with wind energy development will experience a decline, which will lead to an overall population decline.

As South Africa is in the early stage of wind energy development, limiting the impacts of wind turbines on Cape Vultures should be considered a priority. Appropriate locational planning and the use of automated monitoring systems needs to be explored to limit observation biases and mitigation measures at operational wind farms is necessary to decrease collision mortalities. Furthermore, the decline of the Cape Vulture should be halted as it can have far reaching ecological implications. Whilst renewable energy development is necessary, it should not come at the cost of an endemic and ecologically significant species.

THESIS LAYOUT

This study sought to improve the knowledge on Cape Vultures (*Gyps coprotheres*) susceptibility to an emerging threat, namely wind energy development and determine the population's viability with this increasing threat. Chapters have been written as independent papers for publication in accredited journals, dictating some replication and non-uniform formatting. Each chapter nonetheless contributes to the central theme of the thesis.

Chapter 1 provides a general introduction to vultures and provides a descriptive detail of the study species. A broad overview of the study area is provided, and the problem is stated. The main study aim and objectives are provided, and the significance and research impact of the study highlighted.

Chapter 2 provides an overall review of traits that contribute to wind turbine collisions and examines how South African methods in determining collision risk prior to wind farm construction as well as monitoring and mitigation techniques at operational wind farms compared with international standards.

Chapter 3 identifies how juvenile, immature and adult age classes of Cape Vulture use habitat patches in the landscape and further explores the environmental variables associated with identified patches.

Chapter 4 establishes a spatially implicit population viability analysis examining how the Cape Vulture population responds to present mortalities from wind turbine collisions and how the population will respond to future, increased wind turbine mortalities.

Chapter 5 examines the flight height of Cape Vultures at a supplementary feeding site using a novel method.

Chapter 6 concludes the thesis, highlighting the main research findings and how these addressed the research aim. Further, areas of future research to improve Cape Vulture conservation management are provided.

PUBLICATION AND PRESENTATIONS RELATED TO THIS RESEARCH

Details of present and future publications and presentations that form part of the research presented in this thesis.

Scientific articles to be published

Chapter 2: Martens-Brooke, FR, Pfeiffer, MB, Downs, CT and Venter, JA. Implications of wind energy development on the Cape Vulture (*Gyps coprotheres*): a review. This paper has been completed, but an appropriate journal still needs to be decided.

Chapter 3: Martens-Brooke, FR, Brooke, CF, Prima, C-M, Schabo, DG, Farwig, N, Rösner, S, Pfeiffer, MB, Downs, CT and Venter, JA. Connectivity of priority areas of Cape Vultures (*Gyps coprotheres*) from the south-east population of South Africa. Submitted to Emu- Austral Ornithology.

Chapter 4: Martens-Brooke, FR, Bessa-Gomes, C, Duriez, O, Sarrazin, F, Mihoub, JB, Pfeiffer, MB, Downs, CT and Venter, JA. Population viability assessment of the Cape Vulture considering the emerging threat of wind energy infrastructure development in South Africa. Formatted for Animal Conservation.

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Conference presentations

South African Wildlife Management Association Symposium. Berg-en-Dal, Kruger National Park, 5-10 September 2021. Oral presentation: "*Connectivity of priority areas of Cape Vultures (Gyps coprotheres) from the south-east population of South Africa*" by Martens-Brooke, FR, Brooke, CF, Prima, C-M, Schabo, DG, Farwig, N, Rösner, S, Pfeiffer, MB, Downs, CT and Venter, JA.

Symposium on Wind Power. Land Use Competition - Power Generation – Avian Mortality. Vienna, Austria, 29 October 2019. Oral presentation: "*Cape Vulture Research in the Eastern Cape: A reflection on the last ten years"* by Martens, FR, Pfeiffer, MB, Downs, CT and Venter, JA.

The European Vulture Conference. Algarve, Portugal, 1-4 October 2019. Oral presentation: "*A comparative study of bird flight height: man vs photogrammetry"* by Martens, FR, Pfeiffer, MB, Downs, CT and Venter, JA.

South African Wildlife Management Association Symposium. Wilderness, Western Cape, 1-5 September 2019. Oral presentation: "*A comparative study of bird flight height: man vs photogrammetry"* by Martens, FR, Pfeiffer, MB, Downs, CT and Venter, JA.

AUTHOR CONTRIBUTIONS

I, Francis Brooke conceptualised the research, collected, processed, and analysed the data as well as designed and wrote the manuscripts. Prof J.A. Venter, Dr M.B. Pfeiffer and Prof C.T. Downs conceptualised the research, assisted with data analysis and provided valuable comments on the contents of the chapters. In addition, C.F. Brooke, MC. Prima, D.G. Schabo, N. Farwig, S. Rösner assisted with data analyses and provided valuable comments on the contents of Chapter 3. For Chapter 4, C. Bessa-Gomes, O. Duriez, F. Sarrazin and JB. Mihoub assisted with data analyses and provided valuable comments. In Chapter 5, M. Postma, N.D. Prinsloo and P.J.N. de Bruyn assisted with data analyses and provided valuable comments on the contents. Although this work is my own, I refer to the pronouns "we" and "I" interchangeably to include accreditation of my co-authors.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Globally, there are 23 species of vultures, of which 16 are found within Africa, Asia and Europe in the order Accipitriformes (considered Old World Vultures), whilst the remaining seven belonging to the family Cathartiformes are found within the America's (Mundy *et al.* 1992; McClure *et al.* 2019). Vultures are a functionally important group as terrestrial scavengers, which provide important ecological, economic as well as cultural services (Ogada *et al.* 2012a). As nature's most successful scavengers, vultures provide sanitation services in the form of carrion disposal and other organic use, preventing possible mammalian disease transmission as well as aiding in nutrient cycling (Ogada *et al.* 2012a; Ogada *et al.* 2012b; Dupont *et al.* 2012; Aresu *et al.* 2020).

Yet despite their significance, vultures remain some of the most underappreciated and threatened avian guilds worldwide (Ogada *et al.* 2012a), with 16 of the 23 species globally classified as threatened on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Buechley and Şekercioğlu 2016). Asia and Africa, areas considered to be vulture rich, have experienced catastrophic declines in vulture numbers over the past few decades, with Africa experiencing an 80% decline over three generations in seven vulture species (Ogada *et al.* 2012a; Ogada *et al.* 2016). Vultures are particularly susceptible to high mortality rates given their life history traits of delayed maturity and low reproductive rates (Mundy *et al.* 1992; Ogada *et al.* 2012a; Buechley and Şekercioğlu 2016). The decline of vulture species can have dramatic and devastating consequences in ecosystem services and processes (Loss *et al.* 2015).

The "Asian Vulture Crisis" in the late 1990's saw a decline of *Gyps* species by ~96% over 10 years as a result of diclofenac poisoning (Markandya *et al.* 2008). With the decline of vultures, carcasses persist in the system for longer, which act as reservoirs for infectious diseases such as anthrax and Ebola and may facilitate the spread of rabies through competing for mammalian scavengers (Lembo *et al.* 2008; Markandya *et al.* 2008). Facilitative mammalian scavengers like feral dogs increase the potential for disease transmission, as was witnessed in India, where an estimated 48 000 people were killed by rabid dog bites, costing the Indian government $34 billion in health care costs and efforts to curb disease transmission (Markandya *et al.* 2008; Buechley and Şekercioğlu 2016).

Whilst the decline of Asian vultures at the start of the 21st century was largely attributed to Diclofenac poisoning, the decline of African vulture species is a result of numerous anthropogenic causes (Ogada *et al.* 2012a; Loss *et al.* 2015; Botha *et al.* 2017). Poison and persecution appear to be prominent factors contributing to their decline, as well as negative interactions with electrical infrastructure (collisions or electrocution with power lines) and the illegal trade of body parts for belief-based medicine (Ogada *et al.* 2012a; Botha *et al.* 2017; Gore *et al.* 2020). Recent demand for renewable energy through wind turbine development is also a concern for declining populations.

1.2 Study species

The Cape Vulture (*Gyps coprotheres* – Forster 1789) is a large bird with an expansive wingspan of ~2.55 m, weighing between 7.5 - 9.5 kg and has a body length of 1.0 - 1.2 m (Mundy *et al.* 1992; Piper 2005). Adults (>5 years old) are monomorphic and characterised in appearance by a bluish, bare head, straw yellow eyes, black bill, a near-naked neck, and feathers creamy-buff or off-white (Piper *et al.* 1989; Piper 2005; Allan 2015). Juvenile (<2 years) and immature birds (2 -5 years old) are overall more streaked and darker with a brown to orange eye and a red neck (Piper 2005).

The Cape Vulture is a colonial, cliff-nesting species that reaches sexual maturity at five years of age and is considered to be monogamous (Mundy *et al.* 1992). The breeding period begins with the egg-laying period, which extends from May to June, whilst during July and August, chicks begin to hatch (Mundy *et al.* 1992; Piper 1994). Fledglings are reliant on their parents until October or November (Mundy *et al.* 1992; Piper 1994), after which time they exhibit a post-fledging dependence period (Mundy *et al.* 1992; Martens *et al.* 2018).

The Cape Vulture is considered a southern African endemic as 90% of the population is restricted to South Africa and Lesotho. The most recent global estimate indicates ~9400 mature individuals, of which 8800 are located within the South African region. Recent studies indicate that over the past 50 years, the population has experienced a decline between 66 – 81% (Ogada *et al.* 2015; BirdLife International 2015). Major threats to the population include electrocution and collision with energy infrastructure, poisoning incidents and the trade in body parts for belief-based medicine (Botha *et al.* 2017). As such, the species is classified both regionally and globally as “Endangered” on the International Union for Conservation of Nature’s (IUCN) Red List (Allan 2015; BirdLife International 2015).

1.2.2 Use of the environment and foraging range

The temporal and spatial use of the landscape and the foraging range of Cape Vultures is influenced by age (Piper *et al.* 1989; Mundy *et al.* 1992). Adult Cape Vultures have limited home range sizes, being restricted to areas centred around breeding colonies (Boshoff and Minnie 2011; Phipps *et al.* 2013; Pfeiffer *et al.* 2015a; Venter *et al.* 2019). This restriction is often associated with the care of nestlings or encountering potential breeding partners (Boshoff *et al.* 2009b; Phipps *et al.* 2013b; Pfeiffer *et al.* 2015a).

Core foraging ranges, as determined through Kernel Density Estimates (KDEs) indicated that during the breeding season (May to October) foraging range extended to a radius of 46 – 49 km (Pfeiffer *et al.* 2015a; Venter *et al.* 2019), whilst during the non-breeding season (November to April) the core range varied between 48 -52 km (Pfeiffer *et al.* 2015a; Venter *et al.* 2019). Adult Cape Vultures are thus considered as central place foragers, as they forage around a central point – the colony, returning to the colony every night (Boshoff and Minnie 2011). Juvenile and immature Cape Vultures have been shown to have far larger home ranges than adults (Phipps *et al.* 2013b; Kane *et al.* 2016; Martens *et al.* 2018), often covering extensive areas of the landscape and crossing international boundaries (Mundy *et al.* 1992; Phipps *et al.* 2013b; Kane *et al.* 2016; Martens *et al.* 2018). It is speculated that larger home ranges result from more competent adults outcompeting inexperienced juveniles at resources (Yamaç and Bilgin 2012; Bosé *et al.* 2012; Krüger *et al.* 2014).

Foraging ranges are also influenced by sparse and ephemeral food sources located within surrounding land use practices in the landscape mosaic (Pfeiffer *et al.* 2015a; Kane *et al.* 2016). In the Eastern Cape Province, South Africa, the former Transkei, which is dominated by subsistence land use practices, contains the most Cape Vulture breeding colonies. (Pfeiffer *et al.* 2015a). There is a profusion of tick-borne diseases and poor animal husbandry within this area, resulting in high livestock losses and a prevalence of carrion available for vultures (Pfeiffer *et al.* 2015a). Cape Vultures located in the north of South Africa typically use private and communal farmland, where domestic livestock carcasses are consumed (Phipps *et al.* 2013b). Additionally, tracking data from Cape Vultures tagged at a colony in the northern distribution of Cape Vultures showed that the birds moved into the Limpopo Province, where game farming is common, and wild ungulates are likely to be consumed (Phipps *et al.* 2013b).

As different ages require different resources in the landscape, a variety of habitat patches and their accessibility may be required for the species to persist in the landscape (Welbergen *et al.* 2020). However, anthropogenic landscape transformation may inhibit species ability to access certain habitat patches (Rayfield *et al.* 2011; Bastille-Rousseau and Wittemyer 2020), and the loss of landscape connectivity is deemed a major threat to conservation biodiversity.

1.3 Threats

1.3.1 Poisoning

The gregarious and scavenging nature of Cape Vultures magnifies the detrimental effects of carcasses laced with toxins. Given that vultures are highly specialised as obligate scavengers, consuming carcasses rapidly and in large numbers, there is an increased probability of exposure to contaminants such as poisons (Ogada *et al.* 2012a). Poisons can unintentionally impact vultures, where the deliberate poisoning of mammalian carnivores such as lions *Panthera leo*, hyenas *Crocuta crocuta* or jackals *Lupulella mesomelas* are targeted in retaliation of livestock losses. This results in poisoned food sources for vultures and, subsequently the unintentional poisoning of vultures (Buechley and Şekercioğlu 2016; Ogada *et al.* 2016). Additionally, deliberate poisoning is often witnessed at poached elephant *Loxodonta africana* or rhinoceros *Ceratotherium simum* or *Diceros bicornis* carcasses, where circling vultures serve as sentries for law enforcement agencies, providing the locality of the illicit activity (Buechley and Şekercioğlu 2016; Gore *et al.* 2020). This sentinel-type poisoning is believed to account for one third of all vulture poisoning incidents since the 1970s (Gore *et al.* 2020), and Ogada *et al.* (2015) reported over 1500 individuals affected in a span of two years (2012 – 2014) from sentinel-type poisoning. Given the continued demand for ivory, such incidents are likely to continue to increase. However, this type of poisoning mainly occurs in fenced reserves, representing a small percentage of the Cape Vulture's distribution. Whilst the exact number of Cape Vulture mortalities as a result of poisoning is unknown, 387 Cape Vultures have been recorded in the African Wildlife Poisoning Database from 1981 to 2017 (Endangered Wildlife Trust and the Peregrine Fund, Unpublished data). This is likely to be an under-representation, as often Cape Vultures are misidentified as African White-backed Vultures (*G. africanus*) (Ogada *et al.* 2016). Poisoning is also a prominent method used to obtain vulture body parts for belief-based use although other methods include trapping or shooting birds (Ogada *et al.* 2012a; McKean *et al.* 2013; Pfeiffer *et al.* 2015a).

1.3.2 Trade of vulture body parts

The use of herbal, animal and mineral material for treatments of physiological, symbolic or psychological ailments is common practice in Africa (McKean and Mander 2007; Mashele *et al.* 2021a). The use of vulture body parts in the belief-based trade is used in diverse ways for an array of purposes (McKean *et al.* 2013; Mashele *et al.* 2021a). Vulture brains and hearts are believed to provide clairvoyant properties or to increase intelligence (McKean and Mander 2007; Mashele *et al.* 2021a), whilst powdered vulture can be smeared into cuts on the body to protect from witches or mixed with other earthly components to appease ancestors (Mashele *et al.* 2021a). The methods of obtaining vulture species vary, with trapping, hunting, shooting or poisoning being reported (McKean *et al.* 2013; Pfeiffer *et al.* 2015b; Mashele *et al.*

2021a). The number of vultures harvested for this trade contrasts greatly between studies, ranging from an extreme of 160 birds per year (McKean *et al.* 2013) to one or two birds a year (Beilis and Esterhuizen 2006; Mashele *et al.* 2021a). Given vultures low population recruitment and replacement, this trade may be unsustainable for vulture populations in the long term. McKean *et al.* (2013) further stated that should this trade within the Eastern Cape, KwaZulu-Natal and Lesotho region continue to be unsustainable, the Cape Vulture population could experience local extinction within the next 44-53 years.

1.3.3 Power line infrastructure

Anthropogenic electrical infrastructure is a global contributor to bird mortalities (Loss *et al.* 2015). Vultures, given their morphological traits and behaviours, are susceptible to electrocutions and collisions with power lines (Jenkins *et al.* 2010a). With regards to electrocution, vultures have expansive wing spans, which can easily touch live electrical components when perched on pylons, causing a fatal current to flow through the bird and subsequently electrocuting them (Van Rooyen 2003; Chevallier *et al.* 2015). Additionally, electrical pylons are often used as perches or roosts (Phipps *et al.* 2013b; Chevallier *et al.* 2015), particularly when flying conditions are challenging in inclement weather (Boshoff *et al.* 2009b). Across Africa, the demand for energy is increasing, leading to an expansion of power line construction to areas previously undeveloped. With this comes the associated increase in possible electrocution incidents (Botha *et al.* 2017).

Vulture collisions with overhead power line cables or high-tension wires result from their morphological traits. Several factors, including large body size, weight and wing structure, all influence wing load and play a role in vultures flight manoeuvrability

(Drewitt and Langston 2008; Jenkins *et al.* 2010a; Martin *et al.* 2012; Hernández-Matias *et al.* 2015). With poor flight manoeuvrability, vultures are unlikely to avoid wires by changing flight paths, even when obstacles are detected timeously. Additionally, Gyps vultures' head position in flight and their binocular vision that focus on the terrain below them renders them blind in the direction of travel and moving their head in a position to see in that direction for obstacles is evolutionarily novel (Martin *et al.* 2012). Collision probability is further dependent on flight height, with low flight height often observed around colonies, roost sites or feeding sites, bringing individuals into the "zone" that contains power line infrastructure (Drewitt and Langston 2008). High risk areas where collision is prevalent may threaten local populations with local extinction (Phipps *et al.* 2013b). Boshoff *et al.* (2011) estimated an average of 14 Cape Vultures per annum are killed from powerline-related incidents in the Eastern Cape Province, South Africa, based on data collected from a national database. However, this number had a 5.7 fold increase when Boshoff *et al.* (2011) conducted landowner surveys, totalling approximately 80 Cape Vultures per annum. Further Howard *et al.* (2020) reported that between 2007 – 2018, 229 Cape Vultures were admitted to a rehabilitation centre within the North-West Province of South Africa as a result of powerline related incidents.

1.3.4 Wind energy

In a global effort to reduce carbon emissions and meet increasing energy demands, wind energy is increasing as it is considered environmentally friendly when compared with traditional fossil fuel energy methods (Carrete *et al.* 2009; Leung and Yang 2012; Martínez-Abraín *et al.* 2012; Marques *et al.* 2014). However, this renewable technology is not without drawbacks, as bird collisions with turbine blades are considered to impact species directly, whilst habitat displacement and disturbance are less obvious effects (Marques *et al.* 2014; Zwart *et al.* 2015).

South Africa is increasing wind energy development to diversify its energy supply and reduce greenhouse gas emissions (Szewczuk 2014). The then Department of Environmental Affairs (DEA) (now the Department of Environment, Forestry and Fisheries (DEFF)) identified the top three provinces for the development of wind energy. These were the Western Cape (35% development potential), the Eastern Cape (25% development potential) and the Northern Cape (15% development potential) (DEA 2013). Subsequently, operational wind farms have nearly tripled since the DEA rollout of wind energy, beginning with 253 wind turbines in 2014 and expanding to 825 wind turbines in 2018 (Perold *et al.* 2020). At operational wind farms in South Africa, Ralston Paton *et al.* (2017) examined mortality rates from post-construction monitoring from eight wind farms, indicated that 271 birds from 82 species had been killed. Perold, Ralston-Paton and Ryan (2020) extended this and collated avian turbine mortalities recorded up until 2018 at 20 wind farms and found that wind turbines killed 848 birds from 130 species. Raptors were reported as fatalities most frequently found (36%), aligning with studies elsewhere (Barrios and Rodríguez 2004; de Lucas *et al.* 2012a; Marques *et al.* 2014; Watson *et al.* 2018). It is a concern that, of the 130 species mortality recorded, 13 species are classified as regionally threatened (endangered = 5; vulnerable = 5, near-threatened = 3). The Cape Vulture (*Gyps coprotheres*) is one such species, and 10 fatalities have been recorded at wind farms to date (Perold *et al.* 2020).

The development of wind farms is likely to present a threat to South African vultures (Rushworth and Krüger 2014) if findings from international studies are to be examined (Drewitt and Langston 2008; Marques *et al.* 2014; Thaxter *et al.* 2017;

Watson *et al.* 2018). Whilst studies from Europe and North America indicate that collision risk with turbine blades is complex and involves interactions between species-specific, site-specific and wind farm specific traits (Drewitt and Langston 2008; Martin 2011; Martin *et al.* 2012; Marques *et al.* 2014; Rushworth and Krüger 2014; Zwart *et al.* 2015; Thaxter *et al.* 2017; Watson *et al.* 2018), the knowledge base of this threat in South Africa is limited.

1.3.5 Other threats

Human activities such as recreational or tourism related activities at breeding colonies cause a disturbance to breeding vultures, which subsequently has an impact on breeding success (Borello and Borello 2002; Botha *et al.* 2017; Hirschauer *et al.* 2020). Habitat loss and degradation are also considered a threat to vultures, with bush encroachment being the primary cause (Bamford *et al.* 2009; Botha *et al.* 2017). Given that vultures rely on their keen eyesight to detect food sources, although see Jackson *et al.* (2020) on vulture hearing, dense vegetation as a result of bush encroachment decreases the probability of vultures detecting carcasses (Bamford *et al.* 2009). Additionally, given vultures heavy wing load and unsuitability for powered flight (i.e., flapping flight), they may not land in confined areas where there is insufficient space to take off (Schultz 2007; Bamford *et al.* 2009).

Historically, between the 1970's and late 1990's, drowning in high walled reservoirs in southern Africa was considered a threat to vulture species (Monadjem *et al.* 2004; Boshoff and Anderson 2006; Ogada *et al.* 2012a). Subsequently, modifications were made, and whether this remains a threat is unclear (Monadjem *et al.* 2004; Boshoff and Anderson 2006).

Climate change is also considered to be a threat to vulture species (Simmons and Jenkins 2007; Botha *et al.* 2017). Distribution range contractions for vulture species that breed at higher latitudes are expected because of increased temperatures (Phipps *et al.* 2017).

1.4 Study area

The population of Cape Vultures in South Africa is distributed between three primary "nodes", namely a north-eastern, south-eastern and south-western node (Allan 2015). The north-eastern node contains 56% of the population and is located in the South African provinces of Mpumalanga and Limpopo (Allan 2015). The southeastern node is situated within the high lying regions of KwaZulu-Natal and Eastern Cape Provinces, and holds 42% of the population (Allan 2015). The remaining two percent of the population is located in the Western Cape Province at a small, partially isolated population (Allan 2015).

The Eastern Cape Province is dominated by grasslands, which historically supported wild herbivores and provided a reliant food source for the vulture population (Boshoff and Vernon 1980; Boshoff *et al.* 2009b). Wild herbivores were replaced with commercial or communal domestic stock, which now serves as the principal food source for vultures in the area (Boshoff *et al.* 2009b). The eastern portion of the Eastern Cape contains the former Transkei, one of three homelands in South Africa that gained self-rule in the 1970's, but now forms part of the Eastern Cape after its constitutional return to South Africa in 1994 (Porter and Phillips-Howard 1997; Kepe 1997). Due to an abundance of tick-borne diseases and insufficient animal husbandry, there is an abundance of carrion availability because of poor livestock management (Vernon 1999; Ainslie 2002; Pfeiffer *et al.* 2015a; Benson 2015). Consequently, most active Cape Vulture breeding colonies are located within or close to the former Transkei (Mundy *et al.* 1992; Boshoff *et al.* 2009b) and contain 20% of the global population (Boshoff *et al.* 2011; BirdLife International 2015). Two of the largest colonies within the area are the Colleywobbles Cape Vulture Colony and Msikaba Cape Vulture Colony.

The Colleywobbles Cape Vulture Colony (32°0'S, 28°35'E; Figure 1.1) is considered a globally important bird area (IBA SA088), supporting approximately 200 breeding pairs (Botha *et al.* 2012; Marnewick *et al.* 2015). Located above the Mbashe River in the Idutywa District, 13 separate cliffs form the breeding colony (Marnewick *et al.* 2015). This colony is considered an ancestral colony, having been in existence since the 1890's (Barnes *et al.* 2001; Marnewick *et al.* 2015). Approximately 150 km north-east of Colleywobbles lies the Msikaba Cape Vulture Colony (31°18'S, 29°55E; Figure 1.1). With the lowest elevation in the subcontinent, this colony is located on the periphery of the Mkambati Nature Reserve, a formally protected IBA (IBA SA087) (Piper and Ruddle 1986; BirdLife South Africa 2015; Pfeiffer *et al.* 2016). The colony is only two km from the Indian Ocean, located on Table Mountain sandstone above the Msikaba River (Piper and Ruddle 1986; Marnewick *et al.* 2015). Whilst these colonies are located in the subsistence farmland of the Eastern Cape, the Mzimkhulu Colony (30°39'S, 30°14'E) is located in commercial farmland ~70km north of the Msikaba colony (Figure 1.1) (Schabo *et al.* 2017). It is one of the few colonies located in the south of KwaZulu-Natal Province and is located on private land. The colony is situated above the Mzimkhulu River on sandstone cliffs (Marnewick *et al.* 2015; Schabo *et al.* 2017), and in 2012, the colony comprised 49 active breeding pairs. These colonies located within the so-called south-eastern node, were the focus of Chapter 3 in this study. Cape Vultures located in this node are believed to be a high priority species in risk assessments for wind turbine development as much of these developments are located within the Eastern Cape. Individuals tagged with tracking devices from these colonies provided the opportunity to examine individual's movement within the landscape and the proximity of movements within developed or proposed wind farms.

The north-eastern node is considered to be the stronghold of the Cape Vulture population (Allan 2015). Breeding colonies within this node often support high numbers of individuals but at relatively few colonies (Allan 2015; Hirschauer *et al.* 2020). Whilst no colony was explicitly studied in isolation, the population figures within this node were considered in order to understand the overall population dynamics (in conjunction with the southeastern node) conducted in Chapter 4 and used to conduct a population viability analysis (PVA). PVA's explore population trends (through modelling techniques) and make predictions on the persistence of a population, such as population growth or time to extinction (Carrete *et al.* 2009; García-Ripollés and López-López 2011; Hernández-Matias *et al.* 2013; Tsiakiris *et al.* 2021). Taking into consideration demographic or environmental parameters, PVA's are beneficial in risk assessments to assess the influence of these parameters on the persistence of a population (García-Ripollés *et al.* 2011; Murn and Botha 2018). Demographic parameters may be influenced by intrinsic factors, such as longevity, age at first breeding or dispersal of the study species, as well as extrinsic factors relating to environmental conditions (Tauler *et al.* 2015). Environmental conditions are being severely altered by anthropogenic impacts and understanding how these alterations affect threatened species is required to make informed conservation decisions. Given the extent of threats that species face, understanding how all threats contribute to the persistence of a population is necessary. While it is challenging to make predictions that are likely to reflect future populations' exact and precise trends, providing a crude outline of the extent that threats could have on populations could be beneficial (Carrete *et al.* 2009; Monadjem *et al.* 2018; Leepile *et al.* 2020). PVA outcomes should be considered by managers and policymakers and be used to guide management actions whilst considering the precautionary principle (Carrete *et al.* 2009).

The south-western node exists in the Overberg region of the Western Cape Province (Allan 2015), at a single colony located on the Potberg Mountains of the De Hoop Nature Reserve (34° 22'S, 20°33'E, Figure 1.1) (Barnes *et al.* 2001; Marnewick *et al.* 2015). This colony, a formally protected IBA (ZA098), is the most southerly breeding colony and is the last remaining colony in the winter rainfall region of South Africa (Boshoff and Currie 1981). Vultures here forage predominately on sheep carcasses from surrounding agricultural activities (Boshoff and Currie 1981), and 100 breeding pairs and 316 free-flying vultures were recorded during the 2017/2018 breeding season (K. Shaw 2019 pers. comm.). To the west of the colony lies a privately owned vulture restaurant that has been in existence for ~5 years and is intermittently replenished with sheep or cattle carcasses (N. Neethling, 2019 pers. comm.; Brink *et al.* 2020). A bird hide is located 200 m northeast of the vulture restaurant. This provided a feasible location to examine vulture flight height observations conducted in Chapter 5.

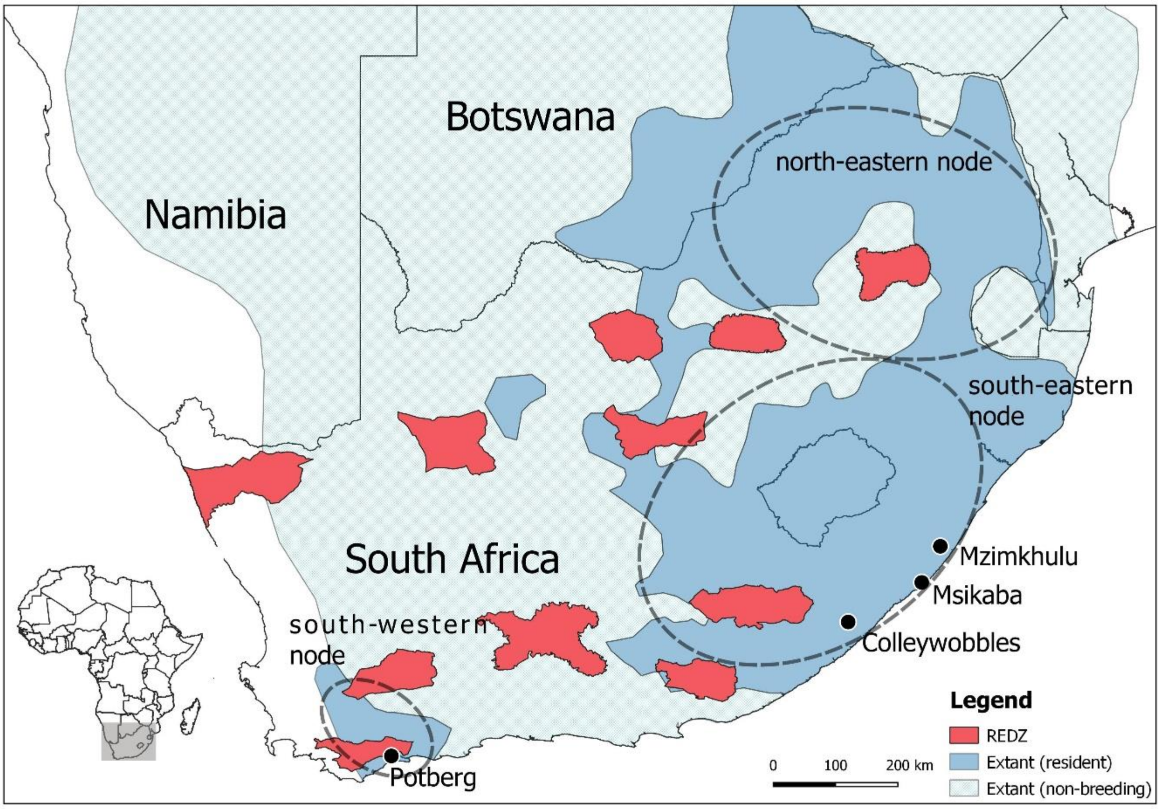

Figure 1.1: Distribution of Cape Vultures indicating the three nodes of the population. The overlap between Renewable Energy Development Zones (REDZ) and Cape Vulture distribution is also illustrated (adapted from BirdLife International (2017); Kleinhans and Willows-Munro (2019)).

1.5 Problem statement

South Africa is increasing its investments in wind energy development, presenting a novel threat to the Cape Vulture. The species has behavioural and morphological traits that make it susceptible to collision. This, combined with its range distribution overlap with present and proposed wind farms and conservation status of “Endangered”, make it a high priority species (and first on the list of the top 100 collision prone species in South Africa (Ralston Paton *et al.* 2017) where wind energy development is concerned. Understanding factors that cause wind turbine collisions are necessary to allow for the successful implementation of pre- and post- construction monitoring and mitigation measures, yet comprehensive literature on this matter with regards to the Cape Vulture is fairly limited (but see Pfeiffer & Ralston-Paton (2018)). The siting of wind farms in the landscape needs careful consideration to minimise impacts to Cape Vultures. Conservation priority areas of Cape Vultures and the environmental variables associated with the use of these areas, therefore, need to be identified to allow for the safe and sustainable development of wind farms. Furthermore, with the increase of wind farms in the near future comes the associated increase in possible wind turbine collisions. Understanding how the Cape Vulture responds to increased mortality rates will need to be made clear to guide future conservation management plans in their species protection efforts. The decline of an endemic species should be halted, especially considering that extensive international literature is available to make informed decisions.

1.6 Aims and objectives

1.6.1 Aims

This study aimed to (i) determine the susceptibility of Cape Vultures to wind farm development and (ii) to assess the species response to the emerging threat of wind farms through population viability.

1.6.2 Objectives

1. Provide a review of available knowledge on Cape Vulture vulnerability to wind energy development and review the effectiveness of wind farm monitoring and mitigation practices.
2. Identify connectivity of the landscape for Cape Vultures across different age classes and its relation to wind farms.

3. To examine the Cape Vulture population response to current and future wind farm mortality in combination with present threats.
4. Examine the accuracy of Cape Vulture flight height estimates of observers and explore a cost-effective alternative method.

1.7 Significance and research impact

Conducting this research will add to the body of literature, improving our understanding of Cape Vulture vulnerability to increasing wind turbine development within South Africa. Wind energy development within South Africa is relatively new. By reviewing the present knowledge base of wind turbine collisions on vulture species internationally, effectiveness of monitoring and mitigation methods employed can be assessed. These findings can identify shortcomings in currently proposed methods and to inform future management guidelines in a South African context.

Much of the proposed wind farms sites overlap with a portion of the Cape Vulture distribution in the Eastern Cape Province, South Africa. Through this study, identifying areas used by different age classes of Cape Vultures, the connectivity of these utilised areas as well as the environmental variables associated within these areas, could allow for conservation management authorities to aid in establishing "avoidance areas" for wind energy development. The study may further demonstrate areas that could be considered for future conservation management that move beyond small scale conservation measures of protecting colonies and feeding sites.

Lastly, understanding how the Cape Vulture population within the Eastern Cape is likely to respond to wind turbine developments is essential. This will allow us not only to understand how wind energy is likely to impact the Cape Vultures in the Eastern Cape but also, understand the implications of its effect on the overall Cape Vulture population in South Africa. Additionally, understanding the likely impact of wind turbines on different age classes of Cape Vultures may inform where conservation efforts should be prioritised. To the best of my knowledge, there are limited recent studies (Pfeiffer & Ralston-Paton (2018)) that assess the impacts that future wind farms could have on the South African population of Cape Vultures, and these results can be used for future conservation management decisions.

CHAPTER 2

IMPLICATIONS OF WIND ENERGY DEVELOPMENT ON THE CAPE VULTURE (*GYPS COPROTHERES*): A REVIEW

Francis R. Martens-Brooke[1], Morgan B. Pfeiffer[1,2], Colleen T. Downs[3], Jan A. Venter[1,4,5]

[1]*Department of Conservation Management, Faculty of Science, George Campus, Nelson Mandela University, George, South Africa*

[2]*U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Center, Ohio Field Station, 6100 Columbus Avenue, Sandusky, OH 44870, USA*

[3]*Centre for Functional Biodiversity, School of Life Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, KwaZulu-Natal, South Africa*

[4]*REHABS International Research Laboratory, CNRS-Université Lyon 1-Nelson Mandela University, George Campus, Madiba drive 6531, George, South Africa*

[5]*Centre for African Conservation Ecology, Nelson Mandela University, PO Box 77000, Gqeberha, 6031, South Africa*

2.1 Abstract

Globally, wind energy generation is increasing as an environmentally friendly alternative to traditional fossil-fuel power generation. However, wildlife collision with turbine blades is a concern. There is a need to identify species vulnerability to wind farm development by understanding the causes of wind farm collisions, assessing monitoring methods used to establish wind farms as well as the effectiveness of mitigation strategies. International studies illustrate that the Eurasian Griffon Vulture (*Gyps fulvus*) is severely impacted by wind farm development, and research on this presents a unique opportunity to gain insight into a similar southern African endemic, the Cape Vulture (*Gyps coprotheres*). Collision with turbine blades is a complex, interconnected relationship between species-specific, site-specific and wind farm specific traits and includes aspects of vulture sensory and behavioural ecology. *Gyps* species are susceptible to collision because of their high wing loading and poor manoeuvrability, their head position in flight which focuses their attention on the terrain below them and their need for orographic or thermal lift for flight, which overlaps with areas ear-marked for wind farm development. Pre-construction monitoring needs to provide a clear understanding of bird behaviour in proposed sites, and observer-based vantage point (VP) surveys are used within South Africa. Data obtained via VP surveys are often spatially inaccurate and observer bias is present as observer accuracy decreases with distance. VP surveys with radar, GPS tracking units or photogrammetry may reduce such biases. Collision risk models further provide guidance on wind farm placement for minimal impacts, and whilst there are many advantages, the shortfalls need to be addressed to improve these models to ensure their accuracy and effectiveness. South Africa is in a unique position whereby it can still limit the impact of wind farms on vultures with careful consideration of locational planning away from high vulture use areas. A suite of mitigation measures can be implemented to reduce collisions, and turbine shut down on demand appears to be most successful at international wind farms Importantly, the advent of green energy should not be at the cost of an endangered endemic species that plats an ecologically significant role in eco-system functioning.

Keywords: collision risks, pre-construction monitoring, post-construction monitoring, mitigation techniques

2.2 Introduction

Globally, wind energy generation has developed rapidly as it is considered environmentally friendly compared with fossil fuel technologies (Leung and Yang 2012; Marques *et al.* 2014). In the European Union and the United States of America, the installation of wind farms increased significantly between 2005 and 2009, by 45% and 74%, respectively (Martínez-Abraín *et al.* 2012), and continues to increase. In 2018, the European Union produced onshore energy of 160 Gigawatts (GW), and together with offshore capacity of 19GW, was able to account for 14% of the energy demand (European Commission 2020). Although wind energy is often considered to be “green energy”, it is not without its own ecological drawbacks.

Wildlife collisions with turbines blades are considered direct threats, whilst indirect threats such as habitat disturbance or displacement of wildlife also pose a risk (Marques *et al.* 2014; Zwart *et al.* 2015). Mortality rates due to collisions with wind farms are highest for raptor species (Drewitt and Langston 2008; Carrete *et al.* 2009; Watson *et al.* 2018; Vignali *et al.* 2021). Raptors appear to be most vulnerable because of their life history of being long-lived, having delayed maturity and slow reproduction, and consequently being unable to compensate for an increased mortality rate of individuals, particularly adults (Drewitt and Langston 2006; Drewitt and Langston 2008; Carrete *et al.* 2009; Thaxter *et al.* 2017). If collision mortalities caused by wind farms are an additional threat to already threatened species, this may cause population declines (Drewitt and Langston 2006; Drewitt and Langston 2008; Thaxter *et al.* 2017; Watson *et al.* 2018). Drewitt and Langston (2008) highlight that although collision mortalities affecting individual species may not necessarily be the cause of population declines, the risk of cumulative impacts across several wind farms causing elevated mortality should not be excluded. A few deaths of endangered species occurring in small, remnant populations could also potentially have significant impacts (Watson *et al.* 2018). Therefore, mortalities caused by wind farms should be considered as a factor potentially threatening conservation of wildlife worldwide (Carrete *et al.* 2009). There is thus a need to identify species vulnerability to wind farm development by understanding the causes of wind farm collisions, assessing pre-construction monitoring methods use to survey potential sites prior to development, and the effectiveness of mitigation measures. Lastly, understanding how populations are likely to respond to additional mortalities caused by collisions with wind turbines can guide conservation management in future decisions.

Much of the research focusing on the interaction between wind farms and wildlife has been biased towards North America and Europe (Thaxter *et al.* 2017; Perold *et al.* 2020), yet valuable lessons can be gleaned from this literature when wind farms are being proposed in new areas. South Africa is experiencing an increase in wind energy developments to meet the government's objectives of diversifying the supply of energy and reducing the emissions of greenhouse gases (Szewczuk 2014). Many current and proposed development sites of wind farms fall within the Eastern Cape Province of South Africa (Figure 2.1), with 25% of the province suitable for wind energy development as suggested by the presence of two Renewable Energy Development Zones (REDZ) (Figure 2.1) (DEA 2013). These sites overlap with the distribution of the endemic Cape Vulture (*Gyps coprotheres*), a species that is listed on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species as “Endangered” (BirdLife International 2015). Thus, the development of wind farms is likely to be a novel threat to vultures within South Africa (Rushworth and Krüger 2014) and likely to present a major threat (Vignali *et al.* 2021) judging by international research (Table 2.1). The Eurasian Griffon Vulture (*Gyps fulvus*) is a species severely impacted by wind turbine collisions within south-western Europe with high numbers of individuals being killed (Martínez-Abraín *et al.* 2012) (Table 2.1). This presents a unique opportunity for South Africa to gain insights into understanding collision probabilities (Pfeiffer and Ralston Paton 2018). The Cape Vulture and Griffon Vulture are similar in their life histories, being long-lived, exhibiting delayed maturity and low fecundity (Mundy *et al.* 1992). However, it is important to remember that whilst drawing parallels, there are differences between Cape Vultures and Griffon Vultures, such as population size, the land use practices utilised by the two species as well as food sources and their supply (Pfeiffer and Ralston Paton 2018). Griffon vultures are susceptible to several threats, with major threats considered to be poison baits, electrocution from energy infrastructure, a decline in food availability as a result of livestock farming practice changes, as well as the collision with energy infrastructure, particularly wind turbines. Similar trends from similar threats are likely to apply to Cape Vultures without appropriate mitigation and careful planning. The Cape Vulture is limited to southern Africa with the current population numbers around 9 400 mature individuals, having experienced a 50% decline over the last three generations (Allan 2015; Botha *et al.* 2017). The Cape Vulture experiences similar threats to the Griffon Vulture, although wind farm development in the species range distribution is new (Rushworth and Krüger 2014). Additional mortality rates from wind turbine collisions to an already threatened species may be unsustainable, and thus a clear understanding of what factors make the species vulnerable to collision is needed. Furthermore, given that wind energy development is relatively new in South Africa, understanding what methods are employed before wind farm establishment at an international level may inform South African guidelines on successful or unsuccessful processes. Moreover, as several wind farms are operational in South Africa, mitigation measures may be needed to limit negative interactions between Cape Vultures and wind farms, and drawing parallels from international studies can provide valuable insights.

This review examines the attributes of species-specific, site-specific and wind farm-specific traits that contribute to vulture collision with wind turbines. It further examines the effectiveness of pre-construction monitoring and post-construction monitoring, and mitigation measures of South Africa compared with international standards and identifies areas where future work can be focused.

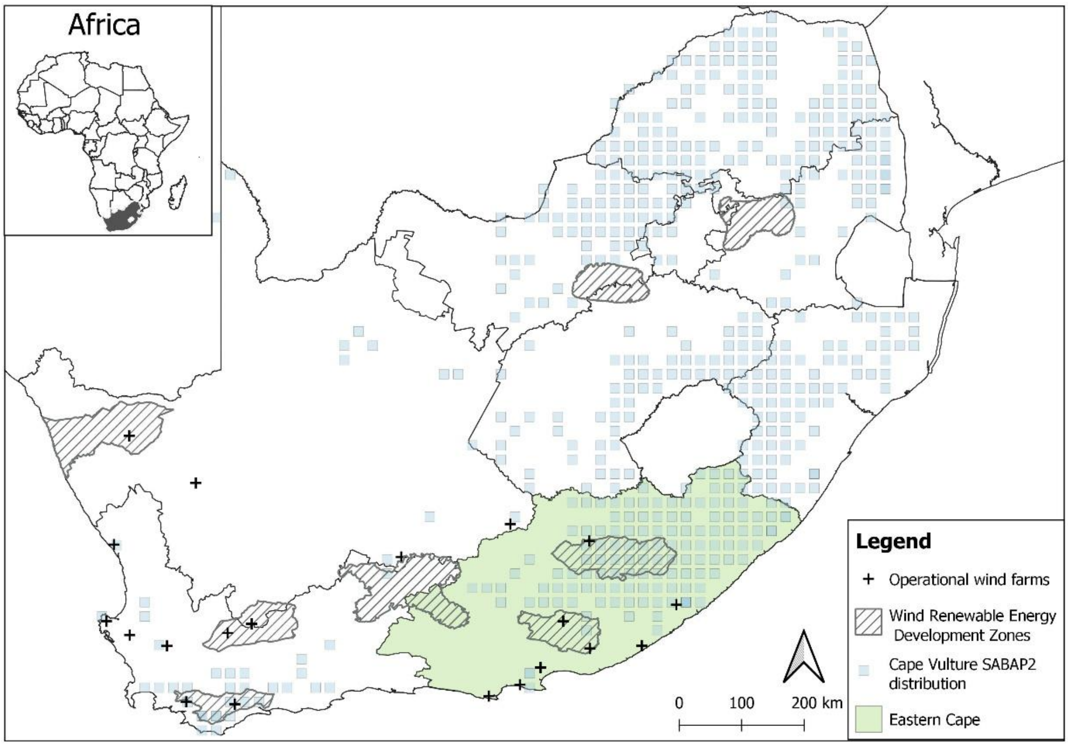

Figure 2.2: The spatial distribution of Cape Vultures as indicated by South African Bird Atlas Project 2 (SABAP2) overlayed with operational wind farms and proposed wind farms as indicated by the Renewable Energy Development Zones (REDZ).

Table 2.1: Mortality rates of Eurasian Griffon Vultures (*Gyps fulvus*) from Spain, 1993-2016. Wind farm output is in kilowatts (kW) or megawatts (MW).

Country	Study area	Wind farm	Study date	Number of turbines	Wind farm output	*Gyps fulvus* killed	Vulture/MW/Year mortality rate	Reference
Spain	Iberian Peninsula	PESUR	1993-1994	190	250 kW	28	0.15	(Barrios and Rodríguez 2004)
Spain	Iberian Peninsula	E3	1993-1994	66	320 kW	3	0.03	(Barrios and Rodríguez 2004)
Spain	Iberian Peninsula	Multiple (n=27)	1993-2016	897	-	1772	-	(Sebastián-González *et al.* 2018)
Spain	Castellón	Multiple (n=12)	2006-2015	320	-	672	-	(Sebastián-González *et al.* 2018)
Spain	Iberian Peninsula	PESUR	2002	33*	-	28	0.088	(de Lucas *et al.* 2012b)
Spain	Iberian Peninsula	EEE	1993-2003	66*	330kW	20	0.0313	(de Lucas *et al.* 2008)
Spain	Iberian Peninsula	PESUR	1993-2003	190	250kW	91	0.0495	(de Lucas *et al.* 2008)
Spain	Iberian Peninsula	Multiple (n=34)	1998-2008	799	-	342	-	(Carrete *et al.* 2012)
Spain	Iberian Peninsula	Undisclosed WEF1	2006-2007	16	1.5MW	5	0.156	(de Lucas *et al.* 2012a)
Spain	Iberian Peninsula	Undisclosed WEF2	2006-2007	11	1.9MW	19	0.863†	(de Lucas *et al.* 2012a)
Spain	Iberian Peninsula	Undisclosed WEF3	2006-2007	15	1.7MW	6	0.2	(de Lucas *et al.* 2012a)
Spain	Iberian Peninsula	Undisclosed WEF4	2006-2007	11	1.9MW	18	0.818†	(de Lucas *et al.* 2012a)
Spain	Iberian Peninsula	Undisclosed WEF5	2006-2007	17	0.8MW	6	0.176†	(de Lucas *et al.* 2012a)

Table 2.1: Mortality rates of Eurasian Griffon Vultures (*Gyps fulvus*) from Spain, 1993-2016 continued. Wind farm output is in kilowatts (kW) or megawatts (MW).

Country	**Study area**	**Wind farm**	**Study date**	**Number of turbines**	**Wind farm output**	***Gyps fulvus* killed**	**Vulture/MW/Year mortality rate**	**Reference**
Spain	Iberian Peninsula	Undisclosed WEF6	2006-2007	30	0.8MW	8	0.133†	(de Lucas *et al.* 2012a)
Spain	Iberian Peninsula	Undisclosed WEF7	2006-2007	11	2.2MW	10	0.454	(de Lucas *et al.* 2012a)
Spain	Iberian Peninsula	Undisclosed WEF8	2006-2007	20	0.8MW	7	0.175†	(de Lucas *et al.* 2012a)
Spain	Iberian Peninsula	Undisclosed WEF9	2006-2007	28	1.6MW	21	0.375†	(de Lucas *et al.* 2012a)
Spain	Iberian Peninsula	Undisclosed WEF10	2006-2007	15	0.8MW	5	0.166†	(de Lucas *et al.* 2012a)
Spain	Iberian Peninsula	Undisclosed WEF11	2006-2007	6	1.6MW	2	0.166†	(de Lucas *et al.* 2012a)
Spain	Iberian Peninsula	Undisclosed WEF12	2006-2007	16	0.8MW	5	0.156†	(de Lucas *et al.* 2012a)
Spain	Iberian Peninsula	Undisclosed WEF13	2006-2007	100	0.3MW	23	0.155†	(de Lucas *et al.* 2012a)
Spain	Castellón	Multiple (n=10)	2006-2010	267	-	393	-	(Camiña 2011)

- Data not provided; * number of turbines studied and not necessarily the total number of turbines within the wind farm; † mortality rate prior to curtailment methods

2.3 Causes of wind turbine collisions

To gain better insight into how best mitigation measures can be implemented it is first necessary to understand the factors that are likely to influence collision risk (Hull *et al.* 2013). Collision probability is complex and depends on the interaction of a number of species-specific, site-specific and wind farm-specific traits (Figure 2.2) (Drewitt and Langston 2008; Marques *et al.* 2014; Watson *et al.* 2018).

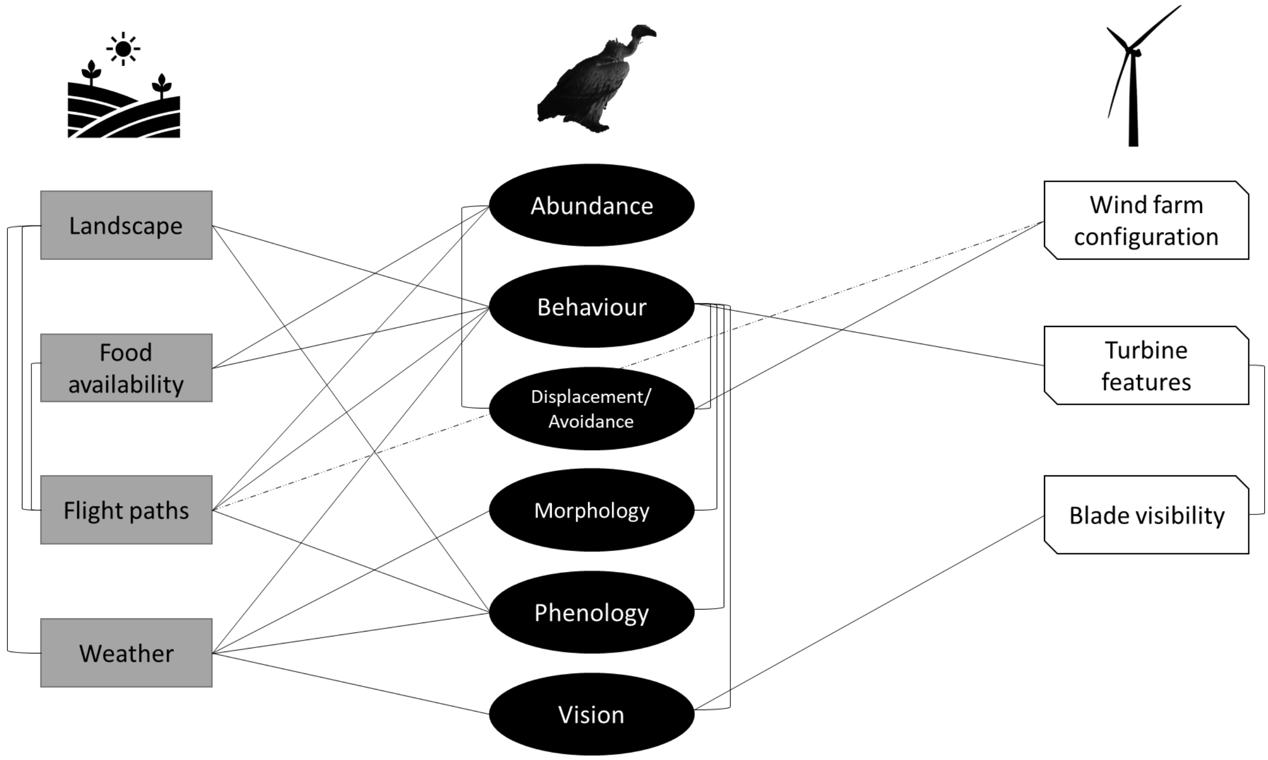

Figure 2.3: Site-specific, species-specific and wind farm-specific traits and the relationship between them that need to be considered in wind turbine collision probability (adapted from Marques *et al.* (2014)). (Dotted line for illustrative purposes to indicate the connection between wind farm specific traits and wind turbine specific traits).

2.3.1 Species-specific traits

The morphology of large birds (Accipitridae family) makes them susceptible to collisions (Drewitt and Langston 2008). *Gyps* species exhibit heavy wing loads (the ratio between body weight and wing area), influencing their manoeuvrability (Marques *et al.* 2014). With poor manoeuvrability, quick evasive action is not possible, and should individuals detect obstacles at the last minute, they are unlikely to avoid collision (Carrete *et al.* 2012; Marques *et al.* 2014; Scacco *et al.* 2020). The high wing loading of large, bodied birds also influences their flight type, as flapping is often an energy-expensive process, and thus dependence on updrafts caused by thermal or orographic conditions leading to soaring flight is a preferred method of flight (Marques *et al.* 2014; Rushworth and Krüger 2014). Additionally, individual experience with avoiding obstacles and flight manoeuvrability may contribute to collision probability. Young birds are inexperienced in flight (Harel *et al.* 2016), and DeVault *et al.* (2017) showed that inexperienced individuals were more likely to be killed than experienced individuals.

Collision vulnerability may further be influenced by bird vision in flight. *Gyps* species have been recorded as having frontal vision of a poor resolution, whilst the lateral fields of view, which allow for conspecific detection, predator detection and foraging opportunities, are of far greater resolution (Martin *et al.* 2012). This, combined with their head position in flight, focuses their attention on the terrain below as opposed to in the direction of flight (Martin 2011); thus, obstacles placed in what would otherwise be a clear flight path are not detected, and a collision may occur. This is evident with the number of birds that collide with electrical infrastructure (pylons and wires) (Boshoff *et al.* 2011; Howard *et al.* 2020). Further, wind turbine blades spinning at high speeds may appear safe to fly through as a result of motion smear (Hodos

2003; Marques *et al.* 2014), and subsequently, birds collide with the undetected blade. Motion smear is the result of the brain being unable to process images of objects moving to quickly, such that the object appears blurred or transparent (Hodos 2003, Marques *et al.* 2014). Mortalities because of turbine collisions may also be related to species phenology, such as age or life stage (Drewitt and Langston 2008; Hunt and Watson 2016; Watson *et al.* 2018; May *et al.* 2019). A small portion of the Griffon Vulture is said to overwinter in Africa during migration (Botha *et al.* 2017), during which time they cross the Strait of Gibraltar. Several wind farms located in this area (Table 2.1) has caused the deaths of numerous migrating species, with 221 Griffon vulture mortalities recorded at 13 wind farms (de Lucas *et al.* 2012a). Furthermore, evidence from the south of Spain indicates that the majority of Griffon vultures killed were juvenile birds (Camiña 2011), whilst the northern parts of Spain indicate the contrary with 75% of fatalities recorded as adult birds. Drewitt and Langston (2008) further highlight that certain species may experience greater rates of mortality during the post-breeding period because of the increase in numbers of young, inexperienced birds.

Juvenile Cape Vultures exhibit a post-fledgling dependence period (PFDP), during which time they cover expansive areas of the landscape (Mundy *et al.* 1992; Martens *et al.* 2018). During this time (predominantly around December), they are inexperienced in flight (Harel *et al.* 2016) as well as lacking knowledge of the landscape, and this may cause higher numbers of juveniles to come into contact with wind energy facilities. Adult Cape Vultures have fairly restricted home ranges, particularly during the breeding season, where foraging is mostly limited to 50 km around colonies (Pfeiffer *et al.* 2015a; Venter *et al.* 2019). Although Cape Vultures do not exhibit migratory behaviours such as the Griffon Vulture, there is evidence of partial migration during the non-breeding season (Boshoff *et al.* 2009a). Tellería

(2009) highlighted the overlap between breeding sites of Griffon Vultures and wind farms in Spain as a crude estimate of collision risk and found that over half of the vulture colonies were located within a 30 km buffer around wind farms. At the time of the study, data on the number of vultures killed yearly in Spain was not available. Later studies indicated that adult individuals made up 75% of mortalities in northern Spain, which could be detrimental to the population (Camiña 2011).

In terms of species abundance in the vicinity of wind farm developments, the assumption is that the higher the species abundance, the greater the chance of species mortality. There are many discrepancies between these findings, as some authors indicate that bird abundance is likely to increase collision risk as there is simply a higher abundance of birds to collide with turbine blades (Barrios and Rodríguez 2004). Other studies state that it is overly simplistic to assume a linear relationship, and additional factors such as species behaviour and site-specific traits may be influential in causing collisions (de Lucas *et al.* 2008; Ferrer *et al.* 2012).

2.3.2 Site-specific traits

Collision susceptibility can be influenced by site-specific traits, such as landscape features at wind farms. Wind energy developers select areas of high wind potential, often around ridges or steep slopes, where they arrange wind turbines in rows (Barrios and Rodríguez 2004). Orographic updrafts are caused by wind being deflected up by obstacles, such as mountain slopes or ridges. Subsequently, there is an overlap of these preferred wind conditions, leading to high collision probability (Marques *et al.* 2014; Zwart *et al.* 2015). Additionally, thermal conditions vary between seasons, given the difference in solar radiation, resulting in poor thermal conditions in winter (Zwart *et al.* 2015). Barrios and Rodríguez (2004) found that in the south of Spain a higher number of Griffon Vultures occurred during the winter months, during which time thermals are not as prevalent. This forced birds to make use of orographic conditions, and subsequently, lead to interactions with wind turbines located within these areas. Additionally, results from southern Spain indicate that the highest number of mortalities were reported in the European winter months (September to February), further supporting evidence that thermals are poor, causing birds to use the orographic lift instead (Camiña 2011). In the north of Spain, Camiña (2011) reported that vulture mortalities peaked in March but decreased until September. Weather conditions around sites may also influence collision probability, with strong headwinds or low cloud ceilings causing individuals to lower their flight height and subsequently bringing them into rotor swept zones of wind turbines (Drewitt and Langston 2008). Poor thermals caused by weak solar radiation result in poor uplift can cause birds to enter into the rotor swept zone of turbines and subsequently cause collisions (Drewitt and Langston 2008). Furthermore, low flight height may be caused by individuals' flight paths with local movements, namely between foraging sites and nesting or roosting sites (Drewitt and Langston 2008; Hunt and Watson 2016). Cape Vultures exhibit low flight height when in close proximity to colonies and roosts, and placing wind turbines in close proximity (<6 km) to these sites could increase collision probability exponentially (Venter *et al.* 2015). Given that Cape Vultures depend on carrion as a food source and the unpredictability of this source in the landscape, they need to gain altitude quickly to make use of thermal conditions, and thus, risky flight height is more prevalent in the morning hours rather than in the late afternoon (Venter *et al.* 2015).

Additionally, food availability in the landscape is a factor considered in collision probability with wind turbines, often drawing species to specific sites (Carrete *et al.* 2012; Marques *et al.* 2014). Not only should food availability at the proposed or developed site be considered, but surrounding land use and food provisioning should also be carefully considered. A study by Martínez-Abraín *et al.* (2012) in eastern Spain examined how the survival and fecundity of Griffon Vultures were impacted by wind turbines and food scarcity in the early 2000's. Food scarcity was caused by the closure of vulture supplementary feeding sites following an outbreak of bovine spongiform encephalopathy whilst concurrently wind turbine development became operational in the area. The closure of the feeding sites altered the foraging behaviour of vultures, leading to birds feeding at lower quality food sources at landfills, with flight paths crossing directly through a wind farm. This resulted in a population crash, with the collision with turbines being the leading cause of vulture mortality. With both factors acting simultaneously, wind farms had a rapid and strong impact leading to a decreased population in the short term (Martínez-Abraín *et al.* 2012). Following this, management actions at the wind farm included halting of turbines causing the highest mortality and conservation management opened new supplementary feeding sites a few years later, which allowed for vulture population growth. The use of supplementary feeding sites is a method used by conservation agencies in South Africa, and it has been proven to increase the survival rates of first-year birds (Piper *et al.* 1999). Long-term studies from KwaZulu-Natal suggest that supplementary feeding sites have a significant, positive effect on the number of breeding pairs (Schabo *et al.* 2017). However, the locality of feeding sites needs careful consideration, and it is strongly recommended that feeding sites are not placed in close proximity to wind farms, or that wind farms are not developed close to feeding sites (Pfeiffer and Ralston Paton 2018).

2.3.3 Wind farm-specific traits

Lastly, particular wind farm-specific traits are also influential when it comes to collision probability. Topography, the location of turbines within the landscape as well as the configuration of the wind farm and the design of the turbines all play a role in the possibility of collision (Drewitt and Langston 2008). Although considered separately, topography and wind farm location are interconnected in avifauna conservation and need to be considered together in the broader picture. Regarding the configuration of wind farms, research has shown that perpendicular arrangements of wind farms to main flight paths cause higher collision risk (Marques *et al.* 2014). General patterns observed indicate that the distribution of mortalities spatially is not uniform when examined at a large scale (i.e., among wind farms) or among turbines at a smaller scale (Sebastián-González *et al.* 2018). Thus, fatalities reported at wind farms appear to occur at a few "problem turbines" (Péron *et al.* 2013), with Barrios and Rodríguez (2004) demonstrating that only 15% of turbines in a particular wind farm were responsible for 57% of collisions. Some turbine features have been highlighted to increase collision probability, such as turbine size. Large turbines have increased rotor swept zones and subsequently an increased collision risk area (Marques *et al.* 2014; Zwart *et al.* 2015), and subsequently it has been found that collision rate increases were associated with larger turbine size (Thaxter *et al.* 2017). Rotor speed is a further consideration of turbine features, as faster rotor speeds have recorded higher fatalities (Marques *et al.* 2014). Additionally, blade visibility may influence collision probability. Turbine blades spinning at high speeds cause motion smear, causing the blades to appear blurred or transparent and possibly causing the rotor swept area to appear safe to fly through (Marques *et al.* 2014).

It is evident that bird collisions with wind turbines may not result from a single factor, but rather a combination of species-, site- and wind farm-specific traits. Given *Gyps* species dependence on orographic or thermal flights, combined with their morphological traits of large body size and subsequent heavy wing load making flight manoeuvrability poor, and the inability to either visually detect or behaviourally avoid anthropogenic structures, it is clear why these species are highly susceptible to collisions with wind turbines (Carrete *et al.* 2012; Rushworth and Krüger 2014). Given the Cape Vultures high collision risk (it is ranked first in the top 100 collision-prone species in southern Africa by Birdlife South Africa (Ralston-Paton *et al.* 2017) as a result of its morphology and behaviour, its poor conservation status and its distribution overlap of proposed and operational wind farms, the species is considered to be a high priority when conducting impact assessments prior to wind farm development, as well as when considering mitigation measures for operational wind farms in South Africa (Pfeiffer and Ralston Paton 2018).

2.4 Pre-construction monitoring techniques

To ensure that the wind energy industry is developed in a sustainable way, it is pertinent that the negative impacts on wildlife be understood, considered and ultimately mitigated (Murgatroyd *et al.* 2020). Given the proposed expansion of wind energy in South Africa, careful consideration of the spatial layout of wind farms in the landscape needs to be considered (Murgatroyd *et al.* 2020; Vignali *et al.* 2021). Therefore, mitigation measures should start at the planning phase of wind farms, as the aspect of wind farm design and layout can ensure that wind farms are designed to limit collisions with birds (Drewitt and Langston 2008). Hence, the first step in the mitigation hierarchy is locational planning (Murgatroyd *et al.* 2020; Scacco *et al.* 2020).

European countries apply the precautionary principle when wind farm development is considered in areas of protected or endangered species (Vignali *et al.* 2021). Environmental Impact Assessments (EIA) are conducted before the establishment of wind farms, which examines the potential environmental impacts the wind farm is likely to have (Oloo *et al.* 2018). Such assessments need to consider collision risks at a landscape level and a wind farm scale (Murgatroyd *et al.* 2020). At a landscape level, avoiding sensitive and important areas for birds, such as nesting sites, is often recommended, and sensitivity mapping is often used to ensure that wind farms are located away from such areas as a method to reduce possible collision risk (Carrete *et al.* 2009; Carrete *et al.* 2012; Oloo *et al.* 2018; Murgatroyd *et al.* 2020; Vignali *et al.* 2021). At the wind farm scale, there needs to be a clear understanding of the behaviour of species in the proposed site in relation to wind conditions and landscape topography to assist in turbine placement to minimise the effects of wind turbines on bird communities (Barrios and Rodríguez 2004; Drewitt and Langston 2008; Murgatroyd *et al.* 2020). This information is often obtained via vantage point surveys to understand bird movement within the landscape and through focal point surveys. These findings are often used as baseline data to compare with monitoring data collected post-construction (Jenkins *et al.* 2015). Further, information obtained from these monitoring activities need be sufficient to produce a collision risk model, indicating the potential mortality rates of species considered to be a high priority.

Encouragingly, Birdlife South Africa has developed both “Birds and Wind Energy Best-Practice Guidelines” and “Avian Wind Farm Sensitivity Map for South Africa” in response to the emerging wind energy industry (Retief *et al.* 2011; Jenkins *et al.* 2015). Additionally, a specific guideline for Cape Vultures has been developed to outline measures to be taken during impact assessments and monitoring (Pfeiffer and Ralston Paton 2018).

At the landscape level, the avoidance of important and sensitive areas is often implemented through buffers centred around breeding or nesting areas. Buffer size is often determined by species home range (usually obtained via global positioning systems (GPS) tracking units) or expert knowledge (Vignali *et al.* 2021). This method is frequently used for planning within South Africa and is presently employed in the case of Cape Vultures (Pfeiffer and Ralston Paton 2018; Murgatroyd *et al.* 2020). A buffer size of 50 km around colonies or roost sites (Venter *et al.* 2019) is presently identified as high or very high sensitivity, and the development of wind farms within these areas is strongly discouraged, particularly within 18 km around breeding colonies (Pfeiffer and Ralston Paton 2018). The use of circular buffers is, however, is not without its limitations. Circular buffers are temporally static, which often does not reflect the true nature of the potential impact (Pfeiffer and Ralston Paton 2018; Vignali *et al.* 2021). Parameters driving these core areas, such as food, which subsequently affect foraging areas, differ between years, and this, in turn, may alter the behaviour and range of movement surrounding colonies. Additionally, buffers are often established based on the premise of areas used only during a particular season, such as the breeding season, although behaviour and habitat alter during different life stages or times of year (Pfeiffer and Ralston Paton 2018; Vignali *et al.* 2021).

Whilst buffers are recommended around breeding and roosting sites, breeding colonies often contain a higher number of individuals, which is likely to influence collision risk (Pfeiffer and Ralston Paton 2018; Vignali *et al.* 2021). Breeding individuals are needed to ensure the persistence of the species, and thus higher protection of these sites is required; however, buffers are not able to take into account the density of birds located within colonies or roosts (Pfeiffer and Ralston Paton 2018). Whilst there are several issues that need to be considered, this is presently one of the few methods that afford some level of protection to breeding and roosting sites of Cape Vultures with the aim of limiting collision interactions.

Vantage point surveys are recommended to understand bird behaviour better in relation to landscape topography and wind conditions (Jenkins *et al.* 2015). The South African guidelines recommend an observer-based approach to determine the movements of birds through the proposed sites as this approach is low cost and relatively simple (Jenkins *et al.* 2015). The guidelines stipulate that complete coverage of the site during vantage point surveys are beneficial but that a minimum coverage of 75% of the proposed wind farm needs to be surveyed (Jenkins *et al.* 2015). Further, a minimum of 72 h of preconstruction monitoring needs to be conducted over 12 months. These observations require a dawn, midday and dusk observation period to take into consideration the range of environmental conditions that the site experiences and to account for different frequency of flights at different times of the day by different species (Jenkins *et al.* 2015; Pfeiffer and Ralston Paton 2018). However, it is highlighted that data obtained via this method is often spatially inaccurate and observer bias is often prevalent (Band *et al.* 2007; McClure *et al.* 2018). Species detectability by observers is influenced by species size, with larger species often being detected more often than smaller species (Berthiaume *et al.* 2009; Nolte *et al.* 2016), whilst the accuracy of detecting species decreases with increasing altitude and distance (Sattler and Bart 1984; Berthiaume *et al.* 2009; McClure *et al.* 2018). Prinsloo *et al.* (2021) further stated that underestimation by fatigued observers is further exacerbated given that there are no comparative reference heights before infrastructure construction. Alternative methods have been suggested and include the use of radar or tracking data (Pfeiffer and Ralston Paton 2018) and recently photogrammetry (Prinsloo *et al.* 2021). Automated monitoring systems such as radar allow for bird tracking whilst assessing the risk of collision (McClure *et al.* 2018), with the added benefit of collecting vast amounts of data relatively easily. The use of radar has been reported in two studies in South Africa (Jenkins *et al.* 2018; Becker *et al.* 2020), with Becker, Milikin and Leslie (2020) focusing their study area in proposed wind farm areas in the Eastern Cape in close proximity to a Cape Vulture breeding colony. Cape Vultures, given their size, foraging and flight behaviour, were easily detectable in the study area. Vantage point surveys were conducted in conjunction with radar surveys, and observations were synchronised, recording flight details (i.e., height, behaviour, direction etc.) of individuals moving through the landscape. Results indicated that Cape Vulture median flight height was repeatedly within the proposed rotor swept area. Furthermore, the study demonstrated discrepancies between observations and radar recorded flight height, and the distance from the vantage point observation to the recorded flight height accuracy also decreased with distance. Radar thus provides accurate spatial information often of multiple targets simultaneously. Although photogrammetry is new for use in preconstruction surveys, a recent study demonstrated that it was accurate while relatively simple to implement whilst still being cost-effective (Prinsloo *et al.* 2021). The importance of obtaining accurate collision risk information for species of conservation significance is imperative, with margins for error ever decreasing (Becker *et al.* 2020). However, Pfeiffer and Ralston Paton (2018) clearly stated that the use of radar does not replace the need for vantage points but should be used in conjunction with vantage point monitoring to aid in reducing human biases.

The use of tracking data obtained from GPS units attached to individuals may also allow for the collection of data to understand individual flight behaviour, as well as gain insight into habitat preferences (Pfeiffer and Ralston Paton 2018) and can also further provide information on areas that are highly utilised such as roost sites (Martens *et al.* 2020). High resolution tracking data from eight Griffon Vultures in France combined with available weather data made predictions possible of individuals flying into the rotor swept zone (Péron *et al.* 2017). Tracking data on Bearded Vultures (*Gypaetus barbatus*) from southern Africa was used to develop habitat use models, which indicated that adults and non-adults spent 55% and 66% respectively of their flight time within heights which place them at risk of collision (Reid *et al.* 2015). While tracking data can provide valuable information on species movements, these units are costly and require the capturing and handling of the species, which needs to be done by experienced individuals.

Information obtained from baseline monitoring is used to determine the abundance of species and the density of species crossing the proposed wind farm site (Watson *et al.* 2018), which is used to create a collision risk model. However, there is some scrutiny about the use of abundance and passage rates to inform collision rates (Carrete *et al.* 2012). Whilst some studies suggest that there is a poor relationship between bird abundance and collision risk (de Lucas *et al.* 2008), other studies suggest that the abundance of birds is likely to play a role in collision mortality at wind farms (Barrios and Rodríguez 2004; Carrete *et al.* 2012). Pfeiffer and Ralston Paton (2018) reported results from five wind farms located within the Eastern Cape where Cape Vultures were present (Table 2.2). Whilst the results reported are purely for comparative purposes and are from survey efforts below recommended guidelines (Pfeiffer and Ralston Paton 2018), there appear to be no uniform findings. Wind farm

2 and wind farm 5 appear to report similar pre-construction vulture passage rates, and distance to the nearest known colony or roost are also comparable.

Differences arise at the post-construction vulture passage rate, with zero recorded passage rates for wind farm 2, whilst a relatively high vulture passage rate was reported for the first year of monitoring and an even higher rate in the second year of monitoring. Yet, the predicted collision rate of vultures per turbine per year hardly varied between the two wind farms. It is worth exploring whether the change in passage rate for wind farm 5 was because of a change in monitoring protocols such as observer efficiency. Additionally, wind farm 3 and wind farm 4 report the same pre-construction vulture passage rates, and the distance to the nearest colony or roost site are once again comparable. However, whilst there was no value of post-construction monitoring for wind farm 3 (because of monitoring only occurring for three months), relatively different collision rates were reported. It may be worthwhile re-examining these values to determine whether these collision risk estimates were accurate, and how the models can be improved if need be.

Table 2.2: Average passage rates of Cape Vultures from five wind farms with 222 wind turbines in the Eastern Cape Province, South Africa. Pre-construction and post-construction values are displayed as passage rates of vulture per hour (adapted from Pfeiffer and Ralston Paton (2018)).

	Wind farm 1	**Wind farm 2**	**Wind farm 3**	**Wind farm 4**	**Wind farm 5**
Pre-construction	0.02	0.31	0.13	0.13	0.34
Post-construction year 1 (year 2)	0.23	0	-	0.11	0.64 (0.84)
Distance to nearest known colony or roost (km)	24	17	22	28	12

Collision rate (vultures/turbine/year)	0	0	0.45	0.07	0.03

The information obtained via vantage point surveys in conjunction with details of the proposed wind farms are used to develop predictive tools, such as collision risk models (May *et al.* 2017; Scacco *et al.* 2020). Collision risk models provide a prediction of collision risk for proposed wind farms (Kleyheeg-Hartman *et al.* 2018) and can be useful in advising developers and planners about where potential risks are likely to be highest (i.e., high sensitivity areas) and thus areas that are unsuitable for turbine development (Carrete *et al.* 2012; Scacco *et al.* 2020). The basics of collision risk models generally include four components, namely 1) consideration of the number of birds at risk; 2) the likely avoidance behaviour exhibited by particular species; 3) the probability of an encounter occurring between the turbine blades and an individual and 4) the likely collision of an individual with the turbine blade (Kleyheeg-Hartman *et al.* 2018). Collision probability is considered (with a mathematical probability) that a bird flying through the rotor swept zone of a specific turbine will be hit by one of the rotating turbine blades. Several collision risk models have been developed ((Willmot *et al.* (2012) identify 10 models), although the Band Model is a widely used and accepted model (Whitfield and Madders 2006; Band *et al.* 2007; Willmot *et al.* 2012; Kleyheeg-Hartman *et al.* 2018). The Band Model has many advantages, namely that it's openly available to use and the calculations are relatively simple and can be done in a spreadsheet (Willmot *et al.* 2012), which make it desirable for practitioners. Additionally, an array of environmental and structural parameters are incorporated and upwind and downwind results can be reported separately (Willmot *et al.* 2012). However, the shortfalls of the model include the fact that it is heavily data dependant, considers the assumption that individual bird flight speed is constant, there is an exclusion of habitat, and ultimately a crude avoidance rate estimation is considered. Whilst macro avoidance (avoidance of wind farms) and micro avoidance (avoidance of individual turbines) are called for in the model; these values are combined to give an overall and crude avoidance estimation rate (Kleyheeg-Hartman *et al.* 2018). This is considered a substantial constraint, as often the avoidance factor at both scales is unknown, and small changes in avoidance rate within the Band model led to high collision rate estimations (Kleyheeg-Hartman *et al.* 2018).

Further considerations for the use of collision risk models are the value of the input data. Considerable quantities and high quality data are needed to inform the model accurately, and obtaining data to such a degree is often challenging (Jenkins *et al.* 2018). Spatially accurate information is also a prerequisite (Jenkins *et al.* 2018), and studies show that there is an inherent human bias in estimating flight behaviour (Jenkins *et al.* 2018; McClure *et al.* 2018; Becker *et al.* 2020). Given the minimum vantage point hours required before wind farm construction, combined with the biased flight height information, may bring into question the validity of the outputs of such collision risk models.

Whilst collision risk models are likely to report estimated mortalities per turbine; such estimates should be examined across the landscape as opposed to in isolation of the studied wind farm, thus considering the cumulative impact of wind farms across the landscape (Drewitt and Langston 2006; Drewitt and Langston 2008).

2.5 Operational wind farm mitigation techniques and their success

Appropriate avoidance measures should be the first step when developing wind farms; nevertheless, certain impact risks may persist, and establishing mitigation measures should be considered (Watson *et al.* 2018). Post-construction surveys are undertaken to determine how many birds are killed and where these mortalities are occurring within the wind farm, and possibly under what conditions. These findings can be used to determine which mitigation measures may need to be implemented (Carrete *et al.* 2012). A suite of mitigation measures can be implemented to reduce collision risks with wind turbines and include turbine shut down on demand, the restriction of turbine operation during certain periods, habitat modification techniques and increasing the visibility of turbines (Marques *et al.* 2014; May *et al.* 2017).

Post-construction mortality surveys are conducted to detect both short- and long-term effects of wind farms on wildlife to allow wind farm developers to take the necessary actions to reduce impacts (Drewitt and Langston 2006). Additionally, the collection of these data can allow for a better understanding of the spatial and temporal rate of collisions at particular wind turbines (Willmot *et al.* 2012; Watson *et al.* 2018). These can be further used to validate the accuracy of preconstruction collision risk models, which can ultimately improve the implementation of such models. Post-construction mortality surveys involve searching for carcasses within the vicinity of wind turbines, considering scavenger- and search efficiency biases and determining the bird fatality rate of the wind farm (Willmot *et al.* 2012; Thaxter *et al.* 2017). Detection bias and detection rate between large and small carcasses are likely to differ, as larger carcasses are easier to detect and are less likely to be removed than smaller carcasses (such as passerines) (Krijgsveld *et al.* 2009; Péron *et al.* 2013; Perold *et al.* 2020). Searcher efficiency may also alter between different land use practices as the type of vegetation as well as density and height are known to play a role (Smallwood 2007). These measures may ultimately lead to underestimating mortalities occurring at wind farms (Thaxter *et al.* 2017).

A possible solution in limiting detection bias is the use of specially trained dogs to detect collision victims (Drewitt and Langston 2008; Smallwood *et al.* 2020). A study conducted at a wind farm in south-east Spain illustrated that dogs had a higher success rate of carcass detection than humans (Domínguez del Valle *et al.* 2020). Humans performed poorly at finding all but large carcasses and only in open habitat, whilst dogs had an ~80% detection rate for any carcass size in any vegetation type (Domínguez del Valle *et al.* 2020). Similarly, a study conducted in California, USA found that a higher number of birds (and bats) were detected by dogs, locating most of the carcasses during trials (Smallwood *et al.* 2020). Additionally, dog carcass detection rates remained unchanged when considering the distance from wind turbines, with dogs locating more carcasses than humans as the distance from the turbines increased (Smallwood *et al.* 2020). Whilst the cost associated with detection dogs is higher than that of human observers, the higher detection rates should be weighed against the cost (Domínguez del Valle *et al.* 2020). It is important that carcass detection trials are also carried out to assess how effective searchers are, and these are to be done under different seasons and weather conditions to account for variation. The extended benefits of post-construction monitoring, particularly from a sociological perspective, are opportunities for employment and skills development (Ralston Paton *et al.* 2017). South Africa has a high percentage of unemployed individuals (2020 states indicated a 29.22% unemployment rate (World Bank 2020)), and the development of wind farms may benefit the local communities through employment for carcass surveys, as training could be provided.

Europe standards recommend that three years of monitoring is sufficient to detect all species impacted (Hull *et al.* 2013). South African recommendations require, as a minimum, that two years of post-construction monitoring be conducted using the same survey protocols as in the pre-construction surveys, whilst carcass searches must be repeated on a five-year rotation basis (Jenkins *et al.* 2015). Interestingly, Perold, Ralston-Paton and Ryan (2020) indicated that at some wind farms, a decrease in annual fatality rates was detected, perhaps suggesting some level of adaptation to wind farms in the landscape, whilst at other wind farms, there appeared to be an increase in collision fatalities. Furthermore, the only other study examining wind farm interactions in the southern hemisphere indicated that only after seven years of monitoring were all species being detected (Hull *et al.* 2013). Therefore, long-term monitoring by wind energy developers is needed to ensure that long-term effects are understood.

The results from post-construction monitoring must be used to inform wind farm developers of the most appropriate mitigation measures. Turbine shut down on demand requires the turbine presenting the greatest risk of causing a collision fatality from an approaching bird to stop spinning. Such surveillance programs can make use of human observers, automated monitoring systems or a combination of the two, but importantly needs real-time surveillance (Marques *et al.* 2014; McClure *et al.* 2018; Watson *et al.* 2018). Curtailment techniques have proven to be particularly successful for reducing collision risks of Griffon Vultures in Europe. A wind farm in northern Spain identified that only 12% of turbines had a high collision rate, and when curtailment mitigation measures were employed, it reduced collision mortality by 36% (Camiña 2011). A further study conducted at a wind farm in Tarifa illustrated that through post-construction monitoring, researchers were able to identify the wind turbines causing the highest Griffon Vulture mortalities (de Lucas *et al.* 2012a). These identified wind turbines were then the focus of curtailment exercises. Turbine shut down was only deployed during conditions considered to be high risk, namely a high-risk season from

October to November (during the migration period) and high-risk wind conditions, where wind speed conditions were much higher than average days. By deploying this method, a 55% Griffon Vulture mortality reduction was observed with minimal loss to electricity generation (0.07%) (de Lucas *et al.* 2012a). A more recent study conducted at the largest wind farm in the Algarve region of southern Portugal examined the effectiveness of radar assisted shut down on demand (Tomé *et al.* 2017). Monitoring was conducted from two vantage points within the wind farm, whilst additional vantage points were located ~1.4-4.5km from the central point of the wind farm, constituting a "security perimeter". At one of the vantage points, a radar system was used to increase the detection probability whilst simultaneously allowing for approaching soaring birds at a distance to be followed. During the migration, observations were conducted from all vantage points, whilst during the non-migratory period, the active vantage point surveys varied. A fieldwork coordinator was responsible for determining whether turbines should be halted based on specific criteria and when the turbines could be restarted. The number of turbines shutdowns only occurred at 33% of the days over the years 2010, 2011, and 2013. At the start of the survey, the time of the shutdown took 4.5 min. but decreased to 24 s following a change in shut down protocol. This study further found that radar triggered the most detections and resulted in shutdowns with no mortalities of soaring birds, whilst there were negligible losses in wind generation capacity because of shutdown (0.2%) (Tomé *et al.* 2017).

Additionally, another study (McClure *et al.* 2018) tested a camera-based monitoring system, IdentiFlight, at a wind farm in the United States of America as a method of employing wind turbine curtailment. The IdentiFlight system determines in real-time whether turbines need to be shut down or prevented from starting up, based on the ability to detect raptors, specifically eagles, at a considerable distance from the turbine. The results again indicated that observer accuracy in detecting and identifying species decreased with distance, while IdentiFlight, at well over a distance of 500 m, was able to identify birds within split seconds. The system also produced low false negatives across a range of distances, although the authors recommend that additional testing be conducted under various scenarios. An added benefit of such a system may also allow for an increase in data collection and an increase in the quality of data collected.

The creation of alternative feeding sites is a habitat modification technique that has been explored to limit collision risks. Decreasing and reducing food availability in the landscape close to wind farms and creating foraging areas away from wind farms is a proposed method (Marques *et al.* 2014). For example, locating and removing carcasses from a wind farm in Spain uses this preventative method to limit the attractiveness of the landscape close to wind farms (Marques *et al.* 2014).

Increasing turbine blade visibility is an additional method explored to reduce avian collision risks (Marques *et al.* 2014). Using conspicuous colours and patterns painted on turbine blades are methods proposed to increase blade visibility and aid in reducing motion smear (Marques *et al.* 2014; May *et al.* 2020). A study conducted in Norway tested the efficacy of single blade painted black using long term data (seven years pre-treatment and three and a half years post-treatment) to reduce collision mortalities with the aid of passive markings (May *et al.* 2020). Although the sample size was small, and fairly limited (only four painted turbines with four control turbines), the results indicate it was an effective technique and reduced fatality rates of up to 70% were observed at treated turbines. Further studies are, however, recommended to test whether this method can be employed across several varying sites and conditions. The plausibility of this method in preventing Cape Vultures collisions remains unknown.

Although several proposed mitigation measures are available, the efficacy of such measures may vary across taxonomic groups and across geographical regions (Marques *et al.* 2014; May *et al.* 2017; Thaxter *et al.* 2017), and only a few have been tested in-situ. Additionally, in planning and mitigating the impacts of wind farms, different physical environments may present a challenge in transferring knowledge from one wind farm to the next (May *et al.* 2017). Priority should, however, be at the planning stage where wind farm layout can be carefully considered. This may reduce costs in the long run as wind farm developers may not need to employ costly mitigation measures at a later stage in the life span of the project.

2.6 Future work and considerations

While this study does not cover the full extent of pre-construction-, post-construction monitoring and mitigation measures, it highlights gaps in our knowledge and highlights where future work needs to be considered, especially for African vulture species. A continued challenge appears to be collecting behavioural and flight data during preconstruction monitoring that is cost-effective and practical and that can be implemented across a range of sites that can be used to accurately inform collision risk models (May *et al.* 2020). Continued assessment of automated monitoring systems in conjunction with human observers thus needs to be explored. The validation of collision risk also needs to be assessed to identify areas of improvement and strengths. Post-construction monitoring can infer the accuracy of collision risk models and thus highlights the importance of accurately collecting information on collision fatalities. Furthermore, long term monitoring data needs to be collected post-construction. This can be used to identify whether collision risks are changing over time and whether habituation to the wind farm is observed for particular species. It is also important to consider whether the population structure around wind farms is changing, and thus monitoring data from surrounding colonies needs to be collected. Benson and McClure (2019) highlighted that if more than two years of monitoring are skipped, fluctuations in the population might be missed. This highlights the importance of monitoring colonies in the Eastern Cape, which has only been conducted intermittently at various colonies since 2012 (Botha *et al.* 2012). If the effects of wind farms are to be determined, a clear understanding of the base population is needed to infer meaningful conservation objectives. Additionally, the long-term effects of wind turbines need to be considered, and population modelling may be an effective method to assess which management recommendations may be most meaningful to ensure the conservation of the species.

A systematic method of reporting collision rates needs to be implemented within South Africa. This information also needs to be available to relevant stakeholders (i.e., researchers, land managers and developers) if future collision mortalities are to be minimised. May *et al.* (2017) stated that all stakeholders invested in wind energy development need to effectively share their data and results as transdisciplinary co-learning will aid in preventing a "science-policy-practice" gap. Additionally, the balance between the population impacts of sensitive species such as the Cape Vulture and the socio-economic benefits of wind development needs to be considered by decision-makers (May *et al.* 2019).

The development of "Birds and Wind Energy Best-Practice Guidelines", the "Avian Wind Farm Sensitivity Map for South Africa" as well as the "Cape Vulture and Wind Farms. Guidelines for impact assessment, monitoring and mitigation" bodes well for present and future developments of wind farms and the guidance of their development. These documents can be updated as new information becomes available to continue the guidance of wind farm developers in the future.

2.7 Conclusions

It is evident that collision risk is impacted by a host of species specific, site specific and wind farm specific attributes (Drewitt and Langston 2008; Marques *et al.* 2014; Watson *et al.* 2018). Understanding the interaction between these traits is important if wind energy is to be developed sustainably whilst limiting and mitigating impacts to bird communities (Péron *et al.* 2013; Watson *et al.* 2018). Wind energy development is increasing within South Africa to meet the government's needs of diversifying energy development while reducing carbon emissions. This is likely to threaten vulnerable species such as the endemic Cape Vulture given its behaviour and morphology, poor conservation status and overlapping distribution with proposed and developed wind farms. Thus, adequate steps need to be considered when developing wind farms, and mitigation measures should be employed at operational wind farms.

The biggest constraint of preconstruction monitoring is obtaining accurate information about bird behaviour in the proposed site whilst keeping economic costs low. Vantage point surveys used in preconstruction monitoring have human bias, and minimising this through cost-effective automated monitoring systems needs further exploration. Whilst collision risk models may provide estimates of collision mortalities, such models need to be continually assessed and compared with post-construction monitoring results to improve their use for future developments.

For operational wind farms that experience collisions of high priority species, mitigation measures need to be explored and implemented. Turbine shut down on demand has proven successful for Griffon Vultures in south-western Europe with minimal loss of power generation to wind farm developers, and such methods need to be considered in a South African context. Whilst the development of wind farms continue to grow in South Africa, priority must be given to minimising impacts before development as opposed to taking a reactive approach of trying to reduce impacts of operational wind farms, and that impacts be considered in a broader, cumulative picture (Drewitt and Langston 2008). The increase of green energy is without a doubt necessary but should not come at the cost of biodiversity loss.

CHAPTER 3

CONNECTIVITY OF PRIORITY AREAS OF CAPE VULTURES (*GYPS COPROTHERES*) FROM THE SOUTH-EAST POPULATION OF SOUTH AFRICA.

Francis R. Martens-Brooke[1], Christopher F. Brooke[1,2], Marie-Caroline Prima[3], Dana G. Schabo[4], Nina Farwig[4], Sascha Rösner[4,5], Morgan B. Pfeiffer[1,6, 7], Colleen T. Downs[7], Jan A. Venter[1,2*]

[1]*Department of Conservation Management, Faculty of Science, George Campus, Nelson Mandela University, George, South Africa*

[2]*REHABS International Research Laboratory, CNRS-Université Lyon 1-Nelson Mandela University, George Campus, Madiba drive 6531, George, South Africa*

[3] *UMS Patrimoine Naturel (PATRINAT), OFB-CNRS-MNHN, 36 rue Geoffroy-Saint-Hilaire CP41, 75005 Paris, France*

[4]*Conservation Ecology, Department of Biology, Philipps-Universität Marburg, Karl-von-Frisch Str. 8, 35043, Marburg, Germany*

[5] *pixeldiversity GmbH, Kirchweg 2, 35043 Marburg, Germany*

[6]*U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Center, Ohio Field Station, 6100 Columbus Avenue, Sandusky, OH 44870, USA*

[7]*Centre for Functional Biodiversity, School of Life Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, KwaZulu-Natal, South Africa*

3.1 Abstract

Understanding the connectivity of ecological systems and animal movement between patches is important to ensure ecological processes and guide conservation management practices. Species that exhibit long-range movements often use different resources at different stages of their life cycle, requiring a multitude of habitats to meet their needs. Anthropogenic landscape transformation can disrupt landscape connectivity and is a major threat to biodiversity conservation. Network theory can be applied to quantify connectivity within a landscape, identifying habitat patches and corridors needed for mobile species such as the Cape Vulture (*Gyps coprotheres*). Using telemetry data and network theory principles, we identified areas used (e.g., as corridors) by three age classes of Cape Vultures (juvenile, immature and adult) and extracted environmental variables related to vulture movement to determine if these influence use of areas. Using network theory on telemetry metrics, areas of high use, low use and corridors (fast and slow corridors based on speed values and linear movement) were identified. High use areas were displayed by all age classes and were associated with land use practices, distance to roosts for immature and juveniles, distance to wind farms and distance to areas ear-marked for wind farms (Renewable Energy Development Zones- REDZ). Concerningly, fast and slow corridors were close to established wind farms and REDZ locations, presenting a potentially hazardous situation for collision probability. Conventional conservation may not be suitable for a mobile species like the Cape Vulture and may require innovative ways to limit impacts to this threatened species.

Keywords: animal movement, movement ecology, connectivity, GPS telemetry, movement corridor

3.2 Introduction

The degree of landscape connectivity is a critical component to ensure dispersal between habitat patches to maintain the dynamics of metapopulations and population persistence, such as juvenile dispersal, habitat recolonisation and allowing necessary range shifts in response to climate change (Pascual-Hortal and Saura 2006; Fortuna *et al.* 2006; Rayfield *et al.* 2011; Ehlers Smith *et al.* 2019; Matos *et al.* 2019). Understanding the physical, biological, and environmental stimuli of ranging animals may provide insight into the temporal and spatial structure of movement cycles (Jacoby *et al.* 2012). Highly mobile species or species that exhibit long-range movements, such as birds, often use different resources at different stages of their life cycle, requiring a multitude of habitats to meet these requirements (Welbergen *et al.* 2020). For example, to reduce resource competition, long-lived raptor species often display some level of dispersal, such as juveniles who move away from their natal areas to limit competition with adult breeding birds but may gather at communal roost sites to facilitate resource detection (Eiserer 1984; Dermody *et al.* 2011).

Environmental stimuli such as spatial or temporal ephemeral food sources, often a consequence of land use practices (Pfeiffer *et al.* 2015a), may require different age classes of species to use different habitat patches in the landscape. Further use of the landscape may be driven by behavioural adaptations, such as energy preservation in soaring-gliding flight, by using thermal air currents or orographic lift (Duriez *et al.* 2014) to navigate across the landscape. Movement patterns of long-lived mobile species may therefore be influenced by territorial status, food availability and intra- or inter-specific interactions (Jiménez *et al.* 2018). Thus, species persistence in the landscape may depend on the accessibility and availability of a range of habitats (Welbergen *et al.* 2020). Identifying and understanding how patches are used and either connect or impede movements of individual species or communities across the landscape is essential for informing conservation management decisions (Cumming *et al.* 2010; Rayfield *et al.* 2011; Bastille-Rousseau *et al.* 2018).

The movement of animals between habitat patches and subpopulations is often disrupted by anthropogenic landscape transformation (Rayfield *et al.* 2011; Bastille-Rousseau and Wittemyer 2020), which can impede animal fitness and can adversely affect ecosystem functioning (Rayfield *et al.* 2011; Bastille-Rousseau and Wittemyer 2020). Disrupted dispersal between fragmented landscapes may cause localised extinction of some species (Bergsten and Zetterberg 2013). The loss of landscape connectivity is therefore considered a major threat to biodiversity conservation (Pascual-Hortal and Saura 2006; Matos *et al.* 2019; Bastille-Rousseau and Wittemyer 2020). Ensuring areas critical for preserving wildlife should be the primary step for mitigating the increased human footprint (Bastille-Rousseau and Wittemyer 2020). Hence, understanding how species disperse between patches can provide insights into using limited conservation resources to ensure that appropriate conservation measures are implemented (Pascual-Hortal and Saura 2006; Rayfield *et al.* 2011; Jacoby *et al.* 2012; Knight *et al.* 2018).

However, contemporary conservation practises often view species as organised around discrete, localised populations (Welbergen *et al.* 2020) (except for migratory bird legislation and policies), following a segregation conservation approach. This contemporary approach may be inappropriate for threatened species considered mobile (Cumming *et al.* 2010). A solution to understanding and analysing spatial dynamics and connectivity of ecological systems of vulnerable, mobile species is that of network theory (Shimazaki *et al.* 2004; Cumming *et al.* 2010). Network theory is based on the concept that complex systems can be broken down into nodes that are connected by edges (Jacoby *et al.* 2012; Jacoby and Freeman 2016), such as regions or populations (nodes) being connected by migration (edges) (Knight *et al.* 2018). Network theory can provide insight into the functional role of locations in the landscape by linking information on their structural aspects, the intensity of use as well as movement path properties (Bastille-Rousseau and Wittemyer 2020). Network theory applied in an ecological context has real-world application potential for conservation planning (Cumming *et al.* 2010; Xu *et al.* 2019). The relative importance of habitat patches is the primary advantage of network theory and can be used to identify and maintain habitat connectivity (Pascual-Hortal and Saura 2006; Knight *et al.* 2018). Network theory can also discriminate between hospitable and inhospitable habitat patches (Cumming *et al.* 2010) and may even be as efficient as biologically complex metapopulation models in identifying habitat patches and connectivity (Bodin and Saura 2010).

The mobile Cape Vulture (*Gyps coprotheres*) uses varying resources at different ages, requiring multiple habitat patches to meet its resource needs. This endangered, southern African endemic species (Mundy *et al.* 1992; BirdLife International 2015) faces numerous anthropogenic threats, including poisoning incidents, use of body parts for belief-based medicine and the electrocution and collision with energy infrastructure (Allan 2015; Botha *et al.* 2017; Mashele *et al.* 2021b). Additionally, the emerging threat of wind turbine collisions of African vultures is a concern (Phipps *et al.* 2013b). It can negatively affect soaring, heavy-bodied birds through habitat displacement and collisions with wind turbine blades and infrastructure (Rushworth and Krüger 2014). The flight behaviours of soaring vultures (who select upper slopes and ridges during foraging trips) often overlap with the placement of proposed and developed wind farms, given similar preference for topographic and climatic features (Martin *et al.* 2012; Rushworth and Krüger 2014; Pfeiffer *et al.* 2016). Wind farm developers in South Africa are encouraged to place their projects away from Cape Vulture breeding and roosting areas, as well as areas of intense foraging, to limit potential collisions (Reid *et al.* 2015; Pfeiffer and Ralston Paton 2018; Venter *et al.* 2019). In addition, the spatial and temporal use between Cape Vulture age classes differs (Piper *et al.* 1989), potentially resulting in each age class facing different risk probabilities from wind turbine blades. Adult birds are often restricted to areas around colonies for breeding and foraging (Boshoff *et al.* 2009b; Boshoff and Minnie 2011; Phipps *et al.* 2013a; Pfeiffer *et al.* 2015a), whilst juveniles display far greater home ranges than adult birds (Piper *et al.* 1981; Phipps *et al.* 2013a; Kane *et al.* 2016; Martens *et al.* 2018) and use roosting sites further away from their natal colonies. Covering extensive home ranges requires sites for birds to rest and recover, and roosting sites often contain high concentrations of young, inexperienced birds (Moleón *et al.* 2011) as juvenile and immature birds are known to be nomadic until they reach maturity (Mundy *et al.* 1992). Roost sites can be identified by the presence of whitewash on cliffs but can also include power line infrastructure (Martens *et al.* 2020). Land use practices also influence the movement of vultures in the landscape, with the selection of certain land use practices appearing to be influenced by the availability of food as well as the selection of cliff sites for breeding and roosting (Pfeiffer *et al.* 2015a; Martens *et al.* 2018). Given the various factors associated with vulture space-use and the extensive areas covered by young vultures, conventional conservation measures (presently small-scale conservation actions concerning the protection of colonies and supplementary feeding sites) may not be sufficient in protecting this endangered species.

Therefore, a better understanding of how habitat patches are used and connected in the landscape would be beneficial to Cape Vulture conservation efforts. Our study aimed at identifying how areas are connected and being used by juvenile, immature and adult age classes of Cape Vultures. Specifically, we identified areas of high use, low use and fast and slow corridors (based on flight speed) and evaluated environmental variables within areas used. Environmental variables that were considered included distance to colony, distance to roost site, habitat use, elevation, distance to established wind farms as well as distance to Renewable Energy Development Zones (REDZ – proposed wind farm sites). We predicted areas of high use would be located near colonies for adult birds and around roost sites for immature birds. For immature and juvenile birds, we predicted that slow flight corridors would be identified given their spatial movement in the landscape with the prediction that slow flight speed corridors are associated with slopes suitable for soaring as well as areas where land use type could provide adequate food. On the other hand, we predicted that fast corridors could be areas used for movement between colonies and foraging areas. These areas would be across the landscape in areas where vegetation type might not be suitable in finding adequate food sources and/or with slopes unsuitable for sufficient thermal air activity for efficient flight.

3.3 Methods

3.3.1 Study area

The Cape Vulture is restricted to southern Africa and has the most limited distribution of Old-World Vultures (Mundy *et al.* 1992; Allan 2015). The Eastern Cape and Kwa-Zulu Natal Provinces of South Africa, as well as Lesotho, is one of three subpopulations defined within the regional population (Allan 2015; Kleinhans and

Willows-Munro 2019). This south-eastern region contains ~40% of the global breeding population and is primarily limited to areas within or adjacent to the former Transkei in the Eastern Cape (Allan 2015; Pfeiffer *et al.* 2015a). Subsistence or communal livestock production forms the largest agricultural sector in the Eastern Cape (Ainslie 2002), which supplies a profusion of carrion given an abundance of tick-borne diseases and insufficient animal husbandry (Vernon 1999; Pfeiffer *et al.* 2015a). Additionally, numerous cliffs are suitable for breeding and roosting, and subsequently, a vast majority of breeding colonies are located within the former Transkei (Mundy *et al.* 1992; Vernon 1999; Pfeiffer *et al.* 2015a). Colleywobbles Cape Vulture Colony (32°0'S; 28°35'E, Figure 3.1) is one such colony, located above the Mbashe River, and is considered one of the largest colonies located in the Eastern Cape, supporting approximately 200 Cape Vulture breeding pairs (Botha *et al.* 2012; Marnewick *et al.* 2015). It is considered a globally important bird area (IBA SA088), although not formally protected (Marnewick *et al.* 2015). About 150 km north-east of Colleywobbles, located on the margins of the formally protected IBA of the Mkambati Nature Reserve (IBA SA087), lies the Msikaba Cape Vulture Colony (31°18'S; 29°55'E; Figure 3.1). The colony is home to approximately 180 breeding pairs, located above the Msikaba River on Table Mountain sandstone, only two km from the Indian Ocean (Pfeiffer *et al.* 2016). Additionally, a colony within close proximity (~ 70 km) to the Msikaba Colony, yet outside the former Transkei and within the KwaZulu-Natal Province, is the MzimKhulu Colony (30°39'S; 30°14'E; Figure 3.1). This colony is unique in that it is located on private land surrounded by commercial farmland, primarily sugar-cane farming (Schabo *et al.* 2017). The 2012 colony figures indicated that there were approximately 120 birds of which 49 were breeding pairs (Schabo *et al.* 2017).

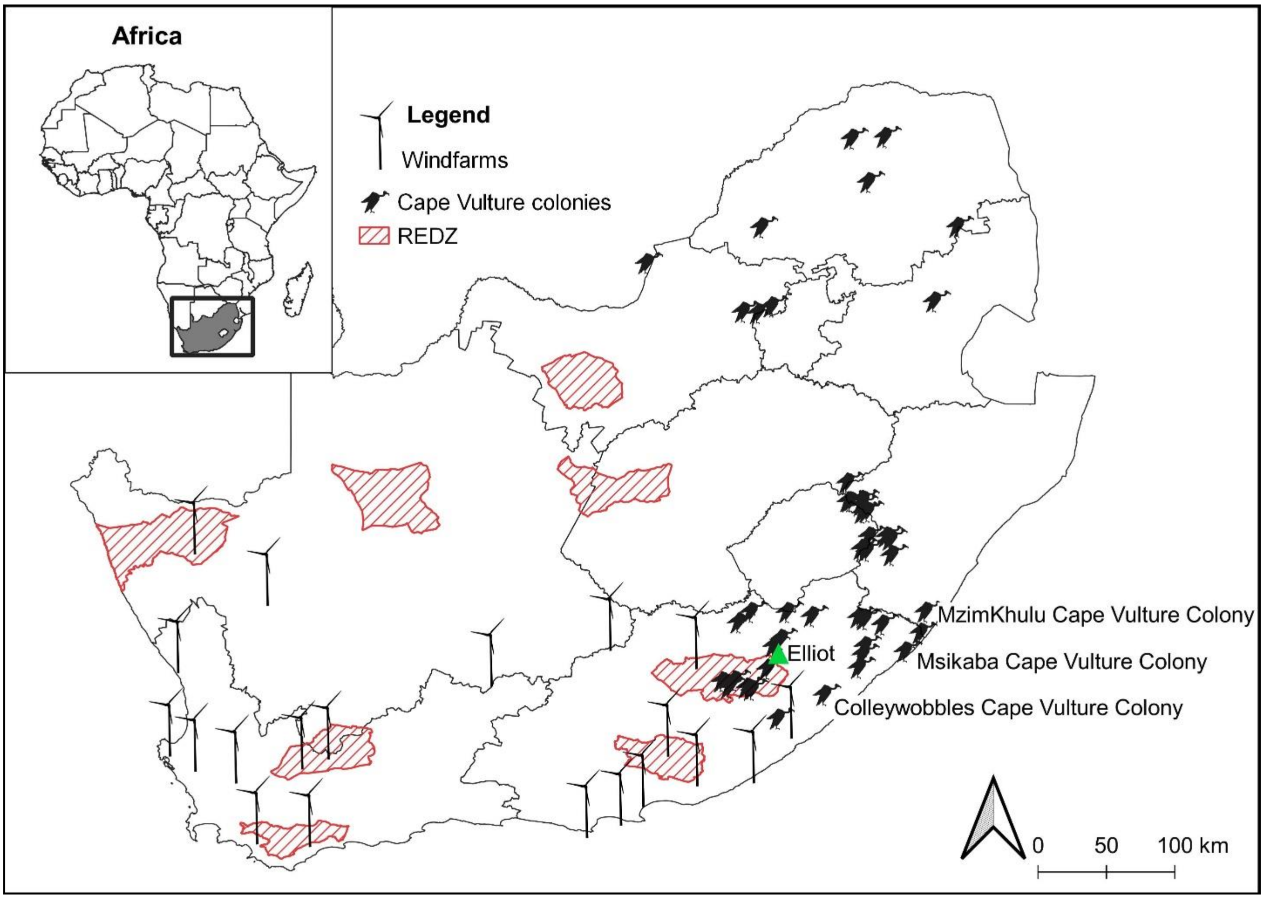

Figure 3.1: Study colonies of Cape vultures and the Elliot supplementary feeding site in relation to established wind farms and Renewable Energy Development Zones (REDZ).

3.3.2 Data collection

We used geographical location data collected from 2012 to 2021 from 29 Cape Vultures fitted with GPS/GSM trackers from the three study colonies for the analyses. The study colonies are likely to represent a gradient of land uses in South Africa (from commercial to communal to private nature reserves) and therefore could be considered a good representation of vulture activities within this subpopulation. Cape Vultures were classified into three distinct age classes, namely juveniles (<1 years old), immatures (2-4 years old) and adults (>5 years old). Six nestlings from Colleywobbles were fitted with Global Positioning Systems (GPS)/ Global Systems for

Mobile (GSM) communication transmitters (Cellular Tracking Technologies, Rio Grande, NJ) in September 2015. Nestlings were temporally extracted from their nests along the cliff face, placed in a secure bag and lifted to the top of the cliff where processing occurred. Each nestling was fitted with a transmitter attached as a pelvic mount, a metal South African Bird Ringing Unit (SAFRING) ring and a yellow patagial tag. Seven adult birds from the Msikaba Colony were captured with a wooden-framed walk-in cage trap at the Mkambati Nature Reserve feeding site (Pfeiffer *et al.* 2015a). Each adult was fitted with either an Avi-Track GPS/GSM transmitter or a Cellular Tracking Technologies (CTT) GPS/GSM transmitter as a backpack or pelvic mount, a SAFRING ring and patagial tags (Pfeiffer *et al.* 2015a). Three adults and 11 immature birds from the MzimKhulu Colony were captured with walk-in cage traps at the MzimKhulu feeding site. The birds were fitted with e-obs GPS transmitters attached using a backpack or pelvic harness (Pfeiffer 2016; Anderson *et al.* 2020). Additionally, an independent study conducted by environmental practitioners fitted tracking units on two adult birds. These birds were captured in the Eastern Cape town of Elliot (Figure 3.1). All tracking details are displayed in Supplementary Table 3.1. All procedures were approved by the University of KwaZulu-Natal Ethics committee (ethical clearance numbers 019/14/animal and 020/15/animal) as well as Nelson Mandela University Ethics committee (ethical clearance number A21-SCI-NRM-001) for the use of animal data. Permits for the capturing and handling of vultures and the fitting of tracking devices was granted by the Department of Environmental Affairs via the Threatened and Protected Species (TOPS) permit (permit numbers; 29551;05052;27273) and Ezemvelo KZN Wildlife (permit numbers OP4786-2012; OP304-2015; OP4622-2015).

GPS tracking units recorded GPS locations at varying time intervals (from 15 min. to 1 h), therefore requiring all trajectories to be resampled to one hour in order to accommodate the varying timing schedules of the tracking units. Resampling was done using the *tidyverse* package (Wickham *et al.* 2019) in R (R Core Team 2020). Juvenile trajectories began once the bird had fledged the nest (Martens *et al.* 2018), given that juveniles remained on the nest for a considerable time post tagging.

Data were grouped together per age class for further analysis given that Cape Vulture foraging strategy, spatial distribution and behaviour is related to its age (Piper *et al.* 1989). Adult birds are restricted to home ranges centred around breeding colonies (Boshoff *et al.* 2009b; Boshoff and Minnie 2011; Phipps *et al.* 2013b; Pfeiffer *et al.* 2015a), and as such, analysis for adult birds was conducted per colony to identify key areas per colony rather than generalised areas across the three colonies. Juveniles and immatures were separated from adults, given that they are known to exhibit wide-ranging exploratory behaviours (Piper *et al.* 1981; Phipps *et al.* 2013b; Kane *et al.* 2016; Martens *et al.* 2018). Juveniles and immatures were further separated, given that juveniles exhibit a post-fledging dependence period (PFDP) whereby they remain close to the natal colony for the first few months, and are partially or wholly dependent on parental care for food and then disperse (Piper *et al.* 1989; Martens *et al.* 2018). Immatures were considered independent free-flying birds, not yet in adult plumage which exhibit far greater home ranges than adults (Piper *et al.* 1989).

3.3.3 Estimation of movement metrics

We calculated the movement tracks of each individual using the approach of Bastille-Rousseau *et al.* (2018), which entailed several steps. Firstly, we overlaid GPS tracking data onto a grid, creating a mosaic of pixels. The median step length determined pixel size for each individual (Bastille-Rousseau *et al.* 2018). Using this pixel grid, we calculated the number of connections between pixels and entered these into an adjacency matrix, where several network metrics could then be calculated (Bastille-Rousseau *et al.* 2018; Bastille-Rousseau and Wittemyer 2020). Network metrics calculated were weight (locations within a pixel), degree (number of pixels any given pixel is connected to), betweenness (how important access to the rest of the network is through a given pixel), speed and dot production (*dotP,* cosine of the mean turning angle within a pixel). Weight and degree are indicators of intensive use areas, while betweenness illustrates areas that are important for connectivity in the landscape. *DotP* is an indicator of turning angles, which can represent non-linear and linear movements. The combination of speed, *dotP* and betweenness values can be used to identify corridors in the landscape (Bastille-Rousseau and Wittemyer 2020).

Using the network movements, we used machine learning (unsupervised classification (Bastille-Rousseau and Wittemyer 2020)) to determine various comparable types of movement (clusters) and then assign individual locations within the animal's movement range into specific movement classes and subsequently the different clusters. These individual clusters were then grouped together to make up population-level clustering using Gaussian mixture modelling (Bastille-Rousseau and Wittemyer 2020). Population clusters were limited to four clusters to represent areas of high use (areas frequently observed in), low use, fast corridors and slow corridors (corridors where separated due to possible flight behaviour differences e.g., direct flight versus thermalling flight). It should be noted that flight height was not considered in the analysis as not all telemetry units recorded this. For analysis of population clusters, we used the *moveNT* package (Bastille-Rousseau 2020) in R (R Core Team 2020). Thereafter, we extracted environmental variables for pixels within each population cluster to determine the environmental variables associated with the particular movement class within the landscape.

3.3.4 Environmental variables

We compiled spatial covariates relating to vulture movement in the landscape. These covariates included straight line distances to Cape Vulture colony locations, straight line distances to roost site locations (based on Martens *et al.* (2020)) and a habitat use map using the South African National Land Cover Database (Department of Environmental Affairs 2018). We merged the latter with the protected areas of South Africa (UNEP-WCMC and IUCN 2021) and reclassified it into nine land use classes (protected areas, commercial farmland, subsistence farmland, urban areas, villages, plantations, natural woody vegetation, rocks and water). Additionally, we included the straight-line distances to established wind farms and Renewable Energy Development Zones (REDZ, Department of Environmental Affairs 2015). Although the development of wind farms is relatively new in South Africa, recent monitoring data over four years, covering 20 wind farms, showed that ten Cape Vultures had been killed at two wind farms (Perold *et al.* 2020). Regarding REDZ, these are geographical areas identified by the South African government which are considered priority areas for the expansion of the countries “alternative energy mix” and for the reduction of reliance on coal energy (Department: Forestry Fisheries and the Environment 2021) and are therefore areas identified for renewable energy expansion. Both solar and wind energy REDZ are available, although only wind energy REDZ were included given the potential threat that such developments present to vultures. Further, whilst Cape Vultures and wind development occurs in Lesotho, these areas were excluded due to differing management practices and conservation agencies. Lastly, we obtained elevation data at a 30 m resolution from the Shuttle Radar Topography Mission (http://opendatacommons.org/licenses/odbl/1.0/) and reclassified these into six landform types (i.e., valley, lower slope, flat slope, middle slope, upper slope, ridge) using the R packages *raster* (Hijmans 2020) and S*patialEco* (Evans 2020). We then extracted each environmental variable for each pixel centroid in Quantum GIS (QGIS) 3.10.10 (QGIS 2020) to use in the principal component analysis.

3.3.5 Estimation of environmental variables

Following the identification of population clusters and the extraction of environmental variables for each cluster pixel, we conducted a correlation matrix principal component analysis (PCA) using the built-in *stats* package in R (R Core Team 2020). We conducted a PCA per age class and per cluster to determine which environmental variables were associated with the different clusters used. Data were standardised between 0 and 1 for use in the PCA given the different scales of variables.

3.4 Results

3.4.1 Individual and population-level clustering

Juvenile birds

Four clusters were identified for juvenile Cape Vultures (n = 6) from Colleywobbles Colony at the population level. Cluster one was identified as areas of high use given the relative high weight and degree values (Table 3.1), whilst comparatively low weight, degree and betweenness values of cluster two were indicative of areas not extensively used nor well connected (Figure 3.2a). Cluster three illustrated relative betweenness, slow speed and non-linear movement (Table 3.1), indicating an area likely being a slow-moving corridor (Figure 3.2a), whilst cluster four displayed fast speed and linear movements and high connectivity (high betweenness value), thus being classified as an area that is a fast corridor (Figure 3.2a).

Immature birds

Three clusters were identified for immature Cape Vultures (n = 11) from the MzimKhulu Colony at the population level. Cluster one was identified as an area of high use and important for connectivity (Figure 3.2b), given the high weight and degree values as well as high betweenness value (Table 3.1). Although the betweenness value of cluster two was lower than cluster one, cluster two was identified as a slow corridor (Figure 3.2b) given the slow speed and relatively high use values (when compared with cluster three, Table 3.1). Cluster three was identified as an area of low use (Figure 3.2b), given the poor weight and degree values.

Msikaba adult birds

Four clusters were identified from seven adult Cape Vultures from the Msikaba Colony. Cluster four displayed high weight, degree and betweenness values (Table 3.1), indicating areas of high use and landscape connectivity (Figure 3.3a). Contrastingly, cluster one displayed areas of little use and poor connectivity, and although it indicated areas of slow and non-linear movement, the cluster was identified as low use (Table 3.1). Cluster two was identified as a slow corridor (Figure 3.3a) given its relative betweenness and slow, non-linear movement, whilst cluster three was considered a fast corridor.

Table 3.1: Summary of various network metrics from movement data of Cape Vultures in South Africa between 2012 and 2021. Network analysis was performed separately for each age class and colony: Colleywobbles Cape Vulture (6 juveniles), MzimKhulu Colony (11 immatures; 3 adults), Msikaba Cape Vulture Colony (7 adults) and Elliot supplementary feeding site (2 adults). Movement type was defined for each cluster according to the combined values of weight, degree, betweenness, speed and DotP*.

	Colleywobbles juvenile birds			
	Cluster 1	*Cluster 2*	*Cluster 3*	*Cluster 4*
Weight	4.8646	-0.2471	1.0969	-0.2593
Degree	1.8853	-0.3102	1.5003	-0.4164
Betweenness	-0.4394	-0.5459	0.0058	1.2689
Speed	-0.1757	-0.0021	-0.7292	0.5126
DotP	0.0630	-0.0423	-0.0697	0.0565
Movement type	High use	Low use	Slow corridor	Fast corridor
	MzimKhulu immature birds			
	Cluster 1	*Cluster 2*	*Cluster 3*	*Cluster 4*
Weight	1.4088	0.9829	-0.2285	-
Degree	1.0485	1.3612	-0.2956	-
Betweenness	1.9260	0.2302	0.0614	-
Speed	0.2677	-0.8000	0.1933	-
DotP	-0.136	-0.0077	-0.0308	-
Movement type	High use	Slow corridor	Low use	-
	Msikaba adult birds			
	Cluster 1	*Cluster 2*	*Cluster 3*	*Cluster 4*
Weight	-0.1891	0.5627	-0.2484	4.8536
Degree	-0.0308	0.9019	-0.5452	2.0397
Betweenness	-0.2028	0.2845	-0.1402	1.6795
Speed	-0.1060	-0.7633	0.5218	-0.2808
DotP	-0.5853	-0.1055	0.5204	-1.2620
Movement type	Low use	Slow corridor	Fast corridor	High Use
	MzimKhulu adult birds			
	Cluster 1	*Cluster 2*	*Cluster 3*	*Cluster 4*
Weight	0.3994	14.4208	-0.1184	-
Degree	1.2992	6.0218	-0.6072	-
Betweenness	0.9459	5.9268	-0.3600	-
Speed	-0.4767	-1.2382	0.6160	-
DotP	0.0490	0.2391	0.1576	-
Movement type	Slow corridor	High use	Low use	-

Table 3.1 continued

	Elliot adult birds			
	Cluster 1	*Cluster 2*	*Cluster 3*	*Cluster 4*
Weight	-0.1966	2.2041	-	-
Degree	-0.1428	2.2059	-	-
Betweenness	-0.1685	1.9676	-	-
Speed	-0.0702	-0.6053	-	-
DotP	-0.0988	-0.0383	-	-
Movement type	Low use	High use	-	-

**Higher mean values are indicated by positive values and lower values are indicated by negative mean values. Lower means illustrate lower movement property in the specified cluster when compared with other clusters.*

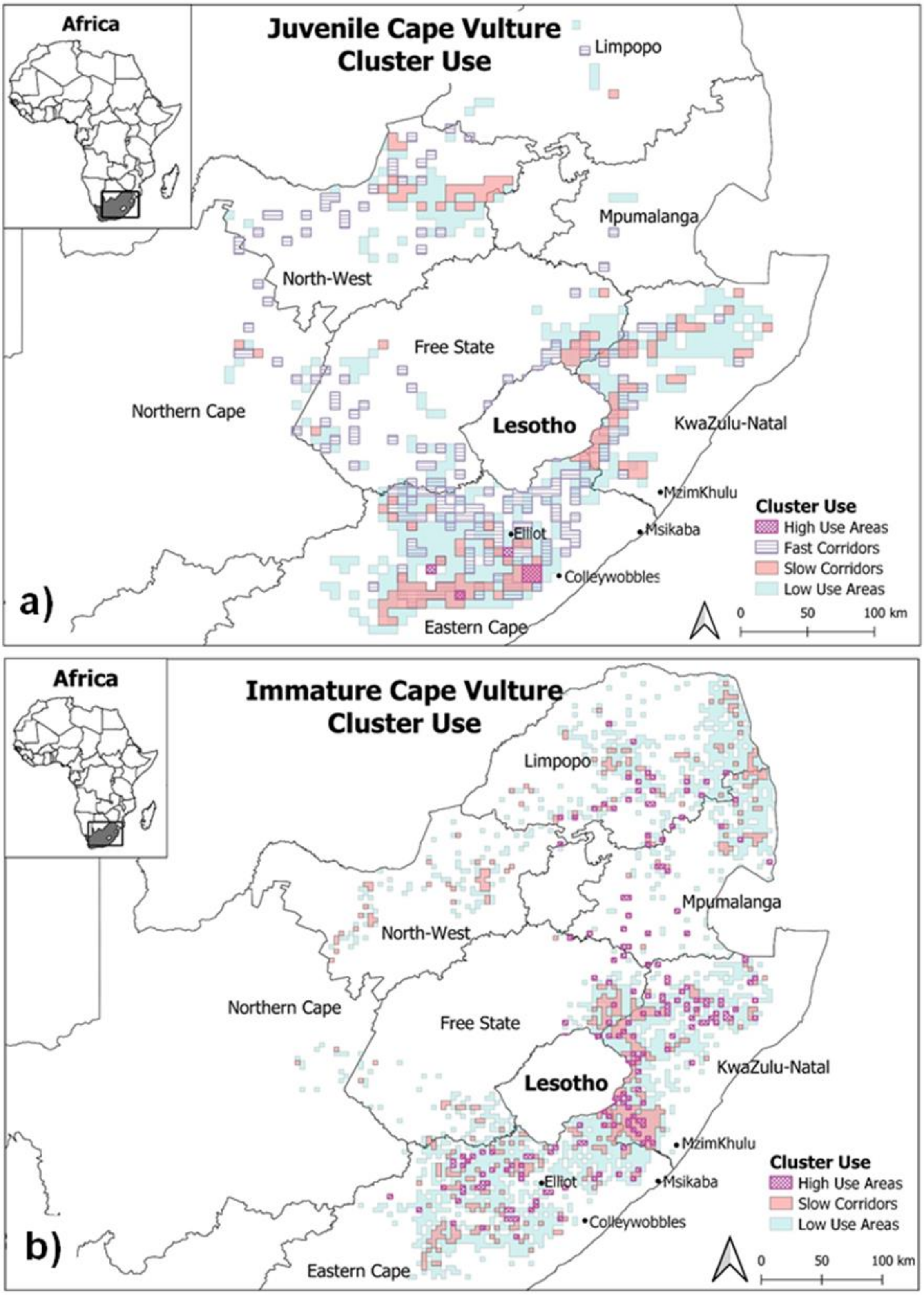

Figure 3.2: Identification of cluster use areas by a) juvenile from Colleywobbles Cape Vulture Colony and b) immature Cape Vultures from MzimKhulu Colony in South Africa between 2012 and 2021 based on network metrics from movement data.

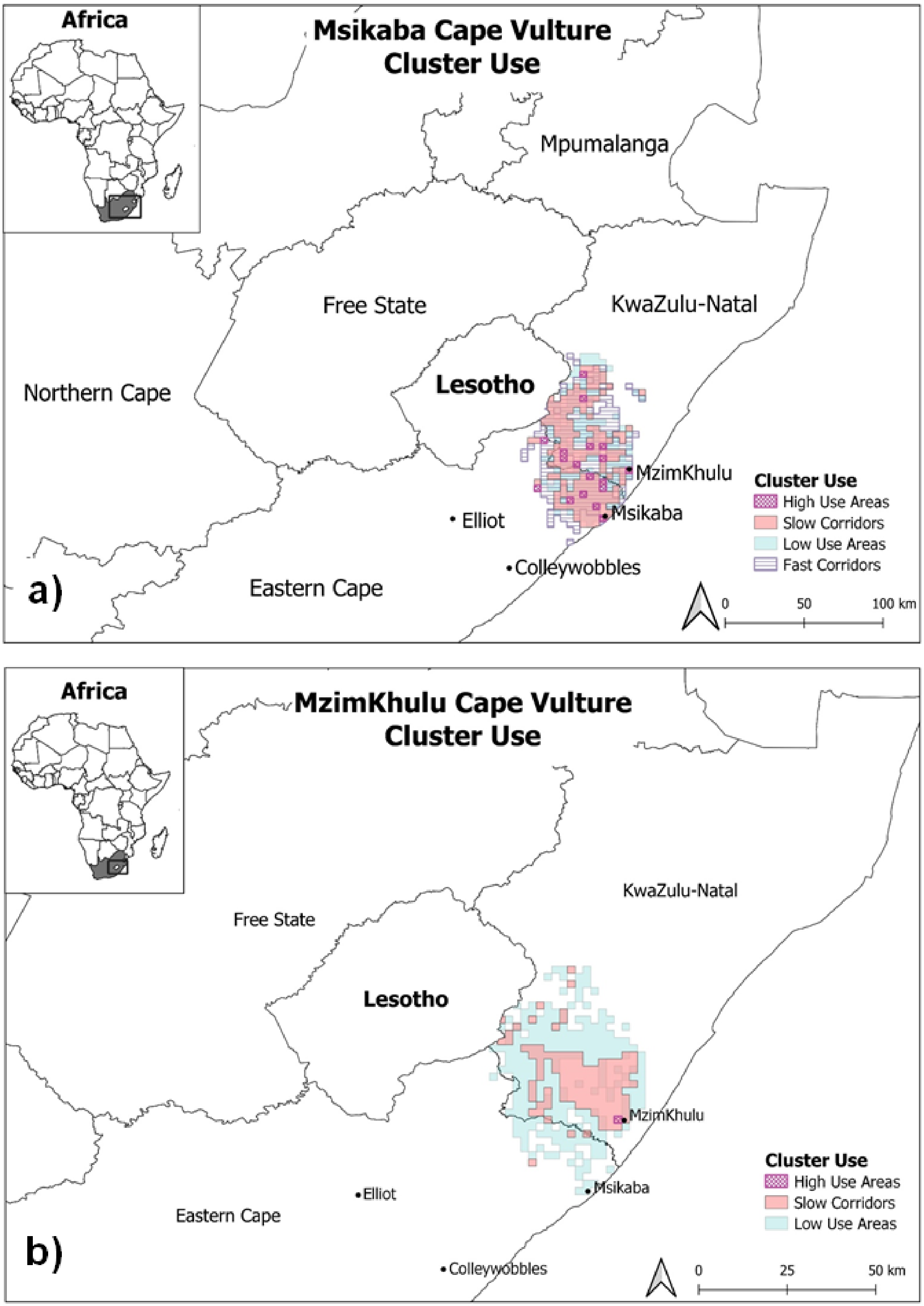

Figure 3.3: Identification of cluster use areas by adult Cape Vultures from a) Msikaba Colony in the Eastern Cape Province and b) MzimKhulu Colony in KwaZulu-Natal Province, South Africa between 2012 and 2021 based on network metrics from movement data.

MzimKhulu adult birds

Three clusters were identified from three adult Cape Vultures from the MzimKhulu Colony. Cluster two was identified as areas of high use (Figure 3.3b), given the exceptionally high values of weight and degree (Table 3.1). Cluster two was also important for connectivity in the landscape illustrated by its high betweenness value. Given the slow speed and relative betweenness value cluster one was identified as slow corridor areas. Cluster three was considered an area of low use (Figure 3.3b), given the low weight, degree and betweenness values.

Elliot adult birds

The two adult Cape Vultures tagged at Elliot feeding site resulted in only two clusters being identified and used. Cluster two was associated with areas of high use (Figure 3.4), given by the high weight, degree and betweenness values (Table 3.1). Slow speed and non-linear movement also indicated that vultures were likely moving in a thermalling manner or foraging within this cluster. Cluster two indicated areas of low use (Figure 3.4).

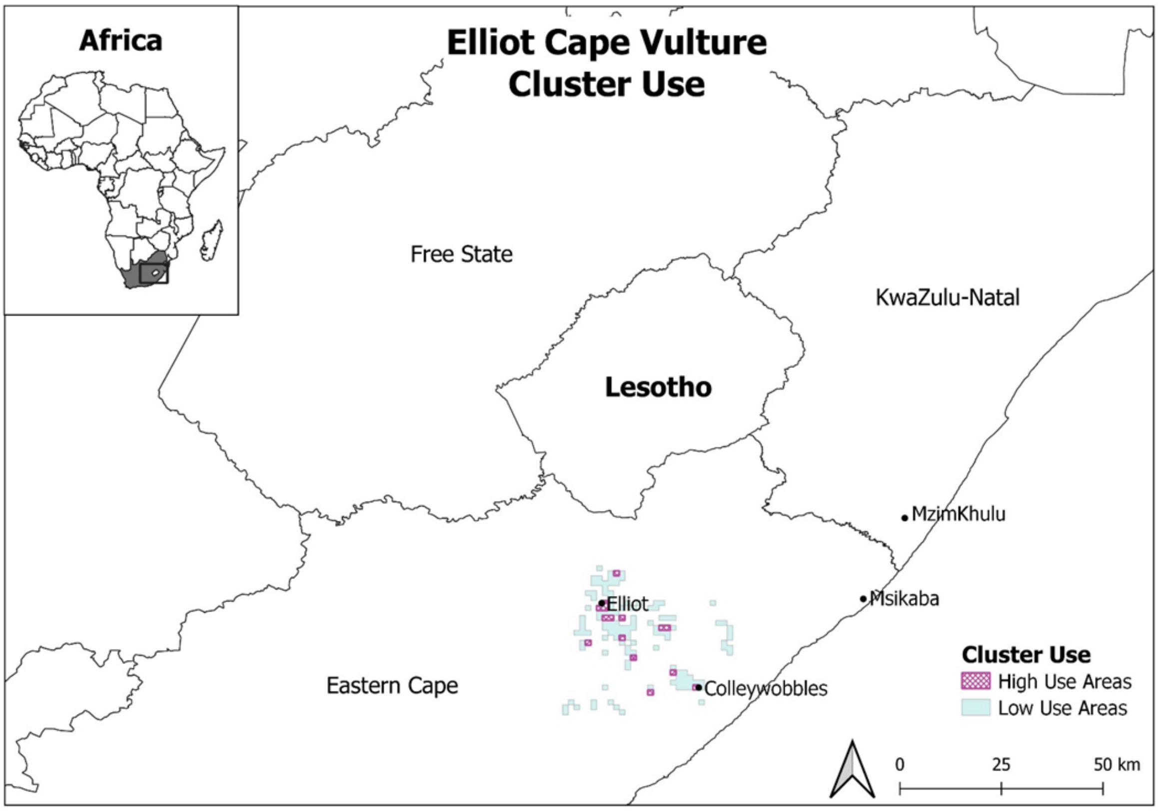

Figure 3.4: Identification of cluster use areas by adult Cape Vultures from a supplementary feeding site in Eastern Cape Province, South Africa between 2012 and 2021 based on network metrics from movement data.

3.4.2 Cluster environmental variables

Juvenile birds

Areas of high use (cluster one) explained 70.8 % of the variation between the first two principal components (PC; Supplementary Figure 3.1.a). PC one explained 46.9 % of the variation, with elevation class of flat slope, distance to colony and roost having strong positive associations, whilst elevation class middle slope and distance to wind farm displayed negative associations (Supplementary Figure 3.1.a). PC two was positively associated with distance to REDZ and elevation class ridge. Since each pixel of this cluster was classified as the land use type of subsistence farmland, we could not include it in the PCA given the limited variation.

Areas of low use (cluster two) only explain 23% of the variation between the first two PC (Supplementary Figure 3.1.b). Distance to windfarms and REDZ were associated positively with PC one, whilst subsistence farmland had a negative association. PC two displayed a positive association with middle slope and woody vegetation and a negative association with flat slope.

Cluster three (slow corridors) could explain 25% of the variation between the first two PC (Supplementary Figure 3.1.c). Distance to wind farms and REDZ was positively associated with PC one, and subsistence farmland was a negative association. For PC two, the middle slope indicated a positive association whilst distance to colony indicated a negative association. Fast corridors (cluster four) displayed a low variation of 24% between the first two PC (Supplementary Figure 3.1.d). PC one was positively associated with distances to colonies, roosts and wind farms, and negatively associated with middle slope. PC two was negatively associated with subsistence farmland.

Immature birds

Areas of high use (cluster one) explained 26% of the variation between the first two PC (Supplementary Figure 3.2.a). PC one was positively associated with distance to roosts, REDZ and wind farms, whilst PC two was positively associated with flat slope and negatively associated with middle slope.

Areas of slow corridors (cluster two) displayed a low variation of 26%, with distance to roosts, REDZ, wind farms and protected areas being negative associations, whilst subsistence farmland was a positive association in the first PC (Supplementary Figure 3.2.c). Flat slope indicated a positive association, whilst middle slope indicated a negative association in the second PC.

Areas of low use (cluster three) only explained 28.7 % of the variation between the first two PC (Supplementary Figure 3.2.b). PC one was positively associated with subsistence farmland and negatively associated with distance to roosts, REDZ, windfarms and protected areas. PC two was positively associated with middle slope and negatively associated with flat slope.

Msikaba adult birds

Areas of high use (cluster four) explained 42.1 % of the variation between the first two PC (Supplementary Figure 3.3.a). PC one had a positive association with protected areas, distance to wind farms and REDZ, and a negative association with distance to roosts. PC two was negatively associated with distance to REDZ, subsistence farmland and flat slope, whilst the middle slope indicated a positive association.

Areas of low use (cluster one) explained 29% of the variation between the first two PC (Supplementary Figure 3.3.b). PC one had a positive association with distance to REDZ and wind farms and a negative association with distance to roosts. The middle slope indicated a negative association in PC two.

Slow corridors and fast corridors only explained 24.6% and 25% of the variation, respectively (Supplementary Figure 3.3.c and Figure 3.3.d). Slow corridors PC one was positively associated with distance to REDZ and wind farms and negatively associated with distance to roost and middle slope. Slow corridor PC two was negatively associated with flat slope yet positively associated with middle slope. Fast corridor PC one was positively associated with distance to REDZ and windfarms and negatively associated with middle slope, while PC two was positively associated with middle slope and protected areas and negatively associated with flat slope.

MzimKhulu adult birds

Areas of slow corridors (cluster one) only explained 23.8% of the variation (Supplementary Figure 3.4.b). PC one was positively associated with distance to REDZ and windfarms and negatively associated with distance to roosts. PC two was negatively associated with the middle slope and positively associated with flat slope.

Low use areas (cluster three) explained 24.3 % of the variation (Supplementary Figure 3.4.a). PC one was positively associated with distance to REDZ and windfarms, while PC two was positively associated with middle slope and negatively associated with flat slope. Cluster two contained a single pixel, and a principle component could not be conducted.

Elliot adult birds

Areas of high use (cluster two) explained 55.7 % of the variation, with distance to REDZ, woody vegetation and middle slope indicating a positive association, whilst distance to roosts, wind farms and flat slope indicating a negative association in PC one (Supplementary Figure 3.5.a). PC two had a positive association with middle slope and a negative association with flat slope.

Low use areas (cluster one) explained 32.8 % of the variation, with PC one indicating a positive association with distance to colony, roost and wind farm, whilst PC two had a positive association with flat slope and a negative association with middle slope (Supplementary Figure 3.5.b).

3.5 Discussion

Present conservation measures for the endangered Cape Vulture focus on small scale conservation actions, mainly protecting colonies and supplementary feeding sites. Such actions may not be sufficient in protecting this far-ranging species, given the extensive areas covered by young vultures and the various factors associated with vulture space use. This study provides a better understanding of how different age classes of Cape Vultures use habitat patches, the environmental variables potentially associated with this use, and the connectivity of the habitat patches in the landscape. These can be beneficial for driving future Cape Vulture conservation efforts.

Low use areas were identified for all age classes of Cape Vultures, and environmental variables associated with each age class showed great variation. This would be expected, as although the birds are making use of these areas, there could be a lack of suitable conditions for use in these areas. On the other hand, all age classes of Cape Vultures showed areas of high use, with similar environmental variables associated with such areas. Although all age classes had a positive association with distance to colony, juveniles predominated with the strongest positive association, possibly because of their dependence of parental care and poor flight ability in the first few months (Robertson 1985; Boshoff and Robertson 1985; Martens *et al.* 2018), hence the dependence of areas surrounding the colony. Juveniles and immature birds further indicated strong positive associations with roost sites (cliffs and power lines situated away from breeding colonies), while adults displayed the opposite. Juvenile and immature birds are known to move extensively across the landscape (Kane *et al.* 2016; Martens *et al.* 2018), requiring sites to rest and recover, which may explain the high roost site use among juveniles and immature birds when compared with adult birds. Adult Cape Vultures may have limited need for roost sites, given their nest locality at colonies and their restricted home range allow them to return to the colony daily (Boshoff *et al.* 2009b; Boshoff and Minnie 2011; Pfeiffer *et al.* 2015a), therefore not requiring the use of roost sites. Present conservation recommendations suggest that buffer zones be established around colonies (Pfeiffer and Ralston Paton 2018; Venter *et al.* 2019), and this should be extended to extensively used roost sites where applicable. While juvenile birds are not limited to a single roost, the disturbance may be less as immature and juvenile birds are able to move, conservation consideration should ideally be given to areas considered high use areas (Figure 3.2). Ideally, protection of these roosts should aid in limiting the construction of wind farms in high use and potentially lethal areas.

Concerningly, juvenile birds and adults from Elliot used habitat close to operational wind farms as high use areas. The use of thermal and orographic conditions for soaring-flying often overlaps with preferable conditions for wind farms (Rushworth and Krüger 2014), presenting a challenge for conservation and renewable wind energy. More sustainable energy development is needed in South Africa to decrease emissions generated by coal-powered stations (the primary power generating method in South Africa) whilst still maintaining the ecological integrity of the landscape. Established wind farms should consider limiting the collision probability as a priority and use appropriate methods to detect, identify and track moving birds within the wind farm landscape (McClure *et al.* 2018). This is especially important in areas where vultures are flying at lower heights, such as in close proximity to colonies and roosts and in high use areas and slow corridors (Figures 3.2 – 3.4). One possible solution to limit the risks of sustainable energy development is to focus development in areas where birds are less likely to come into contact with turbines. Wind farm operators need to invest in methods (e.g., IdentiFlight, camera-based monitoring systems or turbine blade painting techniques (May *et al.* 2020; McClure *et al.* 2018)) to minimise collision probabilities for species to continue their ecological roles whilst still fulfilling their role as “green energy” suppliers, especially in slow corridors and high use areas. As an additional precautionary approach, limiting the future development of wind farms in high-use areas should be a priority.

High use areas appeared to have no uniform land use association between age classes. Protected areas were prevalent in Msikaba adult birds, as would be expected given the location of the colony within the formally protected Mkambati Nature Reserve (Pfeiffer *et al.* 2015a). Juvenile birds land use association was with subsistence farmland, which could be linked to the farmlands surrounding the colony. Interestingly, a single pixel for MzimKhulu Colony was determined as high use area, and whilst it could not be included in the PCA, it is worth noting the pixel was located at the colony, which is located in a commercial agricultural landscape (Schabo *et al.* 2017). Additionally, a vulture supplementary feeding site is located at the colony, which may further be driving the use of this area. The use of commercial and subsistence farmland by different age classes of vultures highlights the fact that protected areas may not be adequate in conserving this far-ranging species. Food resources may also be a driving factor for varied land use types, given that *Gyps* vultures are known to display a dominance hierarchy (Mundy *et al.* 1992; Bosé *et al.* 2012).

Various age classes of Cape Vultures used identified corridors. Slow corridors were used by all age classes of Cape Vultures, potentially displaying areas where thermalling in the landscape occurs or where birds actively forage in the landscape for ephemeral food sources. Juvenile and adults Cape Vultures (bar the Elliot birds) showed a positive association with distance to wind farms and REDZ. The overlap between wind farms and REDZ with that of slow corridors may be a result of similar climatic conditions needed by soaring birds and wind farm development (Martin *et al.* 2012; Rushworth and Krüger 2014). Juvenile bird movements within the first few months were predominately within the Eastern Cape interior (Figure 3.2a), where numerous wind farms are active and where various REDZ are planned, which coupled with the inexperienced flight ability of young birds, is likely to present a concern for conservation management. Additionally, juvenile birds and the Msikaba adults displayed fast corridors, which were positively associated with distance to wind farms and REDZ. This could present a potentially hazardous situation in terms of collision probability, given that birds are moving at high speeds in close proximity to wind farms. It would, however, be beneficial for future studies to consider flight height to determine the collision probability of birds moving within these fast corridors. Juvenile birds also positively associated fast corridors with roost sites, potentially moving to roost sites to settle for the night. This association once again should encourage the protection of roost sites, with buffers being established and wind farms limited within these buffers.

Power lines are often used as roost sites, and future research could examine which designs are favourable for roosting and which designs cause the most electrocutions, which could then inform future designs and recommendations. Given that both fast and slow corridors were associated with wind farms and REDZ, this once again highlights the need for established wind farms to launch shutdown on demand operations or increase the visibility of blades in order to avoid the probability of collision. Prior to the development of wind farms within REDZ, there should be a clear understanding of whether prevalent Cape Vulture movement occurs in the proposed site in order to follow a proactive approach rather than a reactive one.

Given species' vast and free-ranging movement, present conservation measures are often inadequate in conserving highly mobile species, such as the Cape Vulture. Understanding the dispersal behaviour between habitats in the landscape of far-ranging species is needed to ensure limited conservation resources are used adequately. High use areas within this study could be considered as “keystone” areas, requiring conventional conservation management practices. The identification of corridors could highlight areas where further conservation efforts should be focused. This may include limiting power line interactions, providing awareness campaigns and management strategies for poison-related incidents and harvesting vulture body parts for belief-based medicine. Furthermore, limiting the impact of wind farms on Cape Vultures is necessary, which, although challenging for conservation and renewable wind energy, requires innovative solutions. To further prioritise site-specific conservation efforts, future research may focus on a component of network theory known as rewiring. This theoretical process simulates the removal of components of the landscape and examines the response of the species to habitat alteration. Removing components of the landscape and identifying which removal causes the most disturbances to the species can further identify which landscape components require the most urgent conservation attention. This may be highly applicable for determining the influence of wind farms on the ranging behaviour of Cape Vultures. Maintaining important areas of connectivity may allow for range shifts in response to climate change (Phipps *et al.* 2017), which may be an important factor to consider ensuring the survival of this species. Using network theory, we have gleaned a better understanding of how Cape Vultures use the landscape. From this, we have identified areas where prioritisation of Cape Vulture conservation should be centred and what key elements in the landscape should be considered with limiting the construction of wind energy development.

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CHAPTER 4

POPULATION VIABILITY ASSESSMENT OF THE CAPE VULTURE CONSIDERING THE EMERGING WIND ENERGY INFRASTRUCTURE DEVELOPMENT IN SOUTH AFRICA

Francis R. Martens-Brooke[1], Carmen Bessa-Gomes[2], Olivier Duriez[3], François Sarrazin[4], Jean-Baptiste Mihoub[4], Morgan B. Pfeiffer[1,5,6], Colleen T. Downs[6], Jan A. Venter[1,7,8]

[1]Department of Conservation Management, Faculty of Science, George Campus, Nelson Mandela University, George, South Africa.

[2]Ecologie Systématique Evolution, Université Paris-Sud, CNRS, AgroParisTech, Université Paris Saclay, Orsay, France

[3]Centre of Evolutionary and Functional Ecology, Univ Montpellier, CNRS, EPHE, IRD, 1919 Route de Mende, 34293 Montpellier cedex 5, France

[4]Centre d'Écologie et des Sciences de la Conservation (CESCO), Muséum National d'Histoire Naturelle, Centre National de la Recherche Scientifique, Sorbonne Université, CP 135, 43 rue Buffon, 75005, Paris, France

[5]U.S Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Centre, Ohio Field Station, 6100 Columbus Avenue, Sandusky, OH 44870, USA

[6]Centre for Functional Biodiversity, School of Life Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, KwaZulu-Natal, South Africa

[7]REHABS International Research Laboratory, CNRS-Université Lyon 1 – Nelson Mandela University, George Campus, Madiba drive 6531, George, South Africa

[8]Centre for African Conservation Ecology, Nelson Mandela University, PO Box 77000, Gqeberha, 6031, South Africa

4.1 Abstract

Vultures are the most threatened avian guild worldwide as they are susceptible to anthropogenic pressures. African vultures have declined dramatically in the past few years due to consumption of poisoned carcasses, fatal interactions with electrical infrastructure, the illegal trade of body parts and, recently, wind energy infrastructure. The southern African endemic Cape Vulture (*Gyps coprotheres*) is considered at risk to wind turbine collisions given its overlap with proposed and developed wind farms and its international ranked conservation status as “Endangered”. Therefore, using a population viability modelling approach, our study examined how the present threats impact the Cape Vulture population and how the population will respond to potentially increased mortality rates from wind farm development at “worst-case scenarios”. Model simulations indicated that wind energy development will cause a decline in stochastic population growth in a portion of the population that overlaps with wind farms, and should large numbers of adult birds be killed in a “worst-case scenario”, the global population will begin to decline. Present population figures for breeding colonies are not available for the portion of Cape Vultures likely to be impacted by wind farms and obtaining clear population figures must be prioritised to ensure future effective management decisions. Measures to limit the impacts of wind turbines on Cape Vultures are imperative whilst South Africa is still in the early stages of renewable energy development. Appropriate locational planning for future proposed wind farms need to take priority, whilst mitigation measures at operational wind farms should be explored to ensure the species long term survival.

Keywords: wind farm, *Gyps coprotheres*, turbine mortality, population growth, endangered species

4.2 Introduction

The African continent is rich with vulture species and currently supports 11 out of 23 worldwide species, of which seven are classified as Critically Endangered or Endangered on the IUCN (International Union for Conservation of Nature) Red List of Threatened species (Ogada *et al.* 2012a; Ogada *et al.* 2015). Africa in recent decades has seen a dramatic decline in vulture populations, and as such, vultures are believed to be the most threatened avian guild worldwide (Ogada *et al.* 2012a; Ogada *et al.* 2015; Buechley and Şekercioğlu 2016; Aresu *et al.* 2020). Vultures are susceptible to direct anthropogenic mortalities given their sensory, movement and foraging ecology. These features, coupled with their delayed maturity and low reproductive rates (Mundy *et al.* 1992; Ogada *et al.* 2012a; Buechley and Şekercioğlu 2016), make the viability and stability of their population largely dependent on high survival rates of adult birds (Allan 2015). Conservation of African vultures, compared with other continents, is complex given the myriad of direct mortality factors from anthropogenic causes (Ogada *et al.* 2012a). Intentional and unintentional poisoning, collision or electrocutions on power lines and the illegal trade of body parts for belief-based use or bushmeat are prominent threats (Botha *et al.* 2017). Vultures are vital to socio-ecosystem functioning, and their decline can have far-reaching implications for both humans and non-humans (Markandya *et al.* 2008; Ogada *et al.* 2012b). Recent developments in "green energy" initiatives such as wind farms also present a serious concern to declining African vulture populations as is found in Europe (Drewitt and Langston 2006; Carrete *et al.* 2009; de Lucas *et al.* 2012a). A clear understanding of how the present threats are impacting vulture populations is needed to guide conservation management decisions and actions.

Wind energy is likely to impact bird species either through direct impacts such as collision with turbine blades, or indirectly through habitat disturbance or habitat displacement (Marques *et al.* 2014). Additionally, vultures make regular use of ridges or steep slopes to use orographic or thermal conditions for flight, areas also selected by wind farm developers because of the regular presence of strong winds (Marques *et al.* 2014; Zwart *et al.* 2015). Consequently, with little manoeuvrability and travel blindness when searching for carcasses below them in flight, vulture collisions with turbines are highly likely (Carrete *et al.* 2012; Martin *et al.* 2012). Wind farms created additional mortality that negatively impacted the Eurasian Griffon Vulture (*Gyps fulvus*), so it is the most severely affected residential species in southern Europe (Carrete *et al.* 2009; Martínez-Abraín *et al.* 2012; Sebastián-González *et al.* 2018). Such information should be considered with future wind energy facilities development, especially in Africa.

The Cape Vulture (*Gyps coprotheres*) is a species with a limited range distribution and is considered a southern African endemic species (Mundy *et al.* 1992; Allan 2015; BirdLife International 2015). It is presently listed on the IUCN Red List of Threatened Species as “Endangered” (BirdLife International 2015). The species has a small global population of 9400 mature individuals (2013 estimate), and within South Africa, the 8800 mature individuals are found primarily within three “nodes” (Allan 2015). The north-eastern population of Cape Vultures, situated in the Limpopo and Mpumalanga Provinces, has ~56% of the regional breeding population, whilst the south-eastern population constituting ~42% of the regional population is contained in the high lying regions of KwaZulu-Natal and Eastern Cape Provinces, as well as the country of Lesotho (Allan 2015; Kleinhans and Willows-Munro 2019). The remaining two percent of the South African population occurs within a small, partially isolated population in the Western Cape Province (Allan 2015; Kleinhans and Willows-Munro 2019). Movement of individuals between nodes has been reported (Kleinhans and Willows-Munro 2019), although the true extent of dispersal individuals between nodes remains unknown. The Eastern Cape Province, which contains ~20% of the global population, has a high wind energy development potential, with 25% of the province considered suitable for such development (DEA 2013; Venter *et al.* 2015). Kleinhans and Willows-Munro (2019) further suggest that the south-eastern node acts as a source population for the other regions, and understanding how this novel threat is likely to impact the population is critical for future conservation management decision support.

Therefore, in this study, we examined how the Cape Vulture population within the south- and north-eastern nodes of South Africa are being impacted by present threats and how the population is likely to perform under the potential increased mortalities from wind farm development. Furthermore, we examined how the population would respond if wind turbine mortalities were to impact resident individuals (i.e., predominantly adult birds that are constrained to the colony and its surrounds) and/or dispersing individuals (i.e., predominately young birds dispersing from their natal colony). In line with previous recommendations of Pfeiffer and Ralston Paton (2018) we used a PVA modelling approach to assess whether increased mortalities from wind turbines could impact Cape Vulture population viability by investigating a variety of wind farm development scenarios. Population viability analysis (PVA) is a widely used tool for assessing risks to populations (Caswell 2001; Carrete *et al.* 2009; García-Ripollés *et al.* 2011; Hernández-Matias *et al.* 2013). Population Viability analysis (PVAs) are useful to predict population trends such as extinction rates and population growth by determining which demographic or environmental parameters influence population persistence (Norris 2004; Carrete *et al.* 2009; García-Ripollés *et al.* 2011; Hernández-Matias *et al.* 2013; Velevski *et al.* 2014).

We predicted that dispersing individuals would suffer higher additional mortality caused by current wind farms as placement of developments are currently away from Cape Vulture breeding colonies, possibly limiting the impact on breeding individuals. We further predicted that a population crash will occur if wind farms are located close to breeding colonies, impacting breeding individuals at higher mortality rates similar to those observed in southwestern Europe. By understanding how different age classes (and subsequent dispersal status) of the population respond to additional threats and possibly influence the overall population, findings can be used to not only allow conservation management to identify areas of concern but also guide wind farm developers away from Cape Vulture priority and sensitive areas.

4.3 Methods

4.3.1 Population size and structure

Our study area was limited to the north-eastern (NE node) and south-eastern node (SE node; Figure 4.1), which together contribute to the largest proportion of the Cape Vulture population (Allan 2015). Although the remaining ~2% of the population occurs within the southwestern node, it is small and geographically isolated from the two eastern nodes with restricted gene flow (Kleinhans and Willows-Munro 2019), and therefore excluded from the PVA.

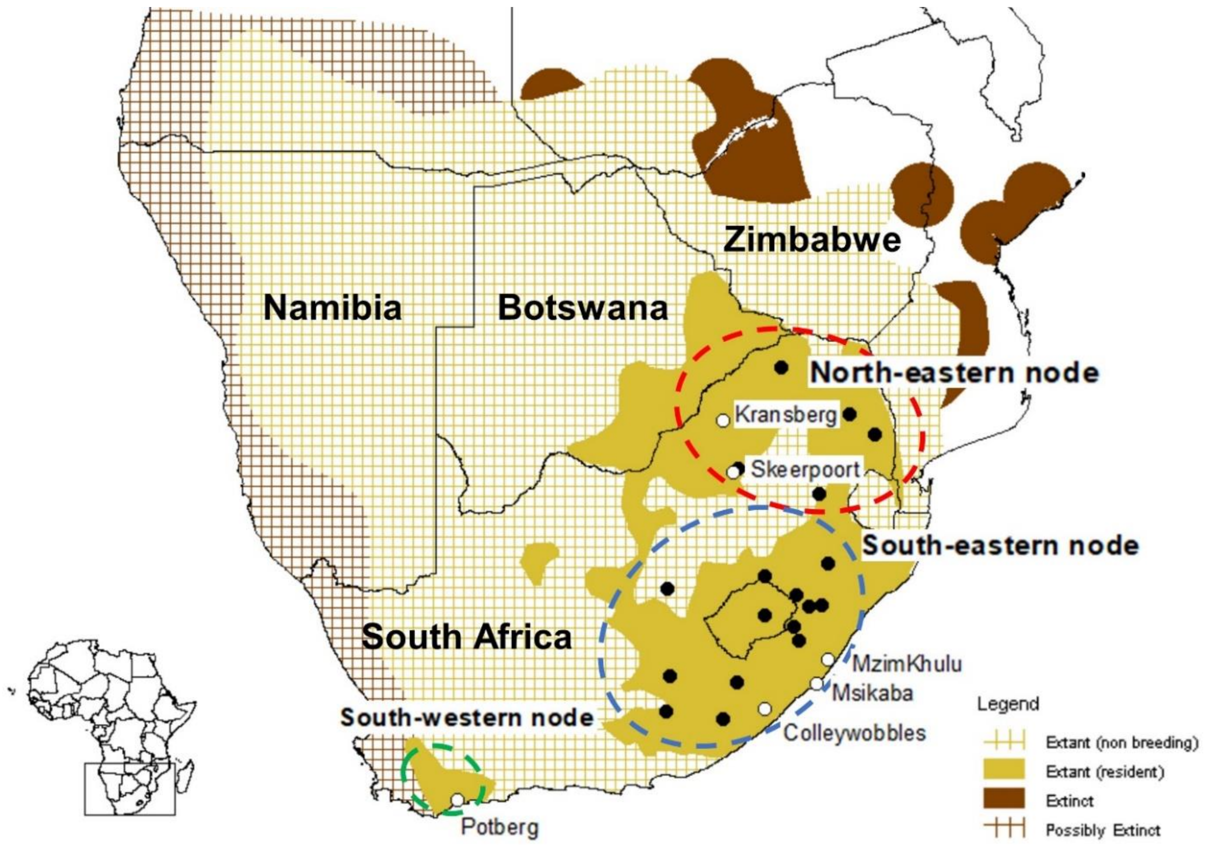

Figure 4.4: Map showing the Cape Vulture nodes within South Africa (Used with permission from: Kleinhans and Willows-Munro (2019)). The northern node (in red) and south-eastern node (in blue) are the focus of the study while the southwestern node (green) is geographically isolated from the eastern nodes and was excluded from the population viability analysis.

The Cape Vulture is a colonial, cliff-nesting species, and adult birds are often restricted to small home ranges centred around the colony (Boshoff *et al.* 2009b; Phipps *et al.* 2013b; Pfeiffer *et al.* 2015a) whilst young individuals are known to disperse extensively across the landscape. Colonies within the SE node have not been continuously monitored over the past years (Hirschauer *et al.* 2020) and present figures for this population are unclear. Therefore, we used existing contemporary literature to determine the starting population size. Allan (2015) estimated that the South African regional population contained 8800 mature individuals, of which 42%

(~3700 mature individuals) was within the SE node. Mature individuals (i.e., > 5 years old) make up 67% of the population (Botha *et al.* 2017), with the remaining 33% of the population being juveniles (i.e., < 1 years old), immatures (i.e., 2 -3 years old) and subadults (i.e., 4 – 5 years old), bringing the starting population for this region to just over 5500 birds. The starting population for the NE node, using Allan (2015), was just under 5000 mature individuals, combined with the additional 33% of the non-breeding birds, giving a total starting population of just over 7300 birds.

Young Cape Vultures are known to be highly mobile (Hirschauer *et al.* 2017; Martens *et al.* 2018) and are likely to disperse from their natal colony, and as such, an emigration component was included. Given that the SE node appears to be acting as a source population (Kleinhans and Willows-Munro 2019), a higher number of individuals from this population may move to the NE node, constituting higher dispersal rates for the SE node individuals when compared to the NE node. A lower rate between individuals from the NE node dispersing to the SE node is accounted for. Therefore, within each node, the population was made up of dispersing individuals as well as a resident individuals (Figure 4.2). Natal dispersal was only accounted for in juveniles, immatures and subadults, as once *Gyps* species start reproducing, breeding dispersal is limited (Sarrazin *et al.* 1994) and therefore, it is likely that adult Cape Vultures do not disperse from their breeding colonies. Both resident and dispersing birds experienced mortality from anthropogenic threats, as indicated below.

4.3.2 Threats

We treated power line electrocution incidents, power line collision incidents and poisoning events as pressures occurring within each of the nodes. Individuals from the SE node were modelled to experience an additional threat of wind turbine collisions.

We mapped locations of threats (based on available incident data) using QGIS (QGIS 2020) and threats located in high use areas (obtained from Chapter 3 for the SE node and Venter *et al.* (2019) for the NE node) impacted resident birds, whilst threats located outside of high use areas impacted dispersing individuals, informed the spatially implicit PVA.

Wind farms

The number of wind farms is increasing within the Eastern Cape Province (DEA 2013; Venter *et al.* 2015) presenting an additional threat to Cape Vultures located within the SE node. Wind farm development within the NE node is unlikely to occur because of poor wind resources (DEA 2013). Therefore we only included wind farm mortalities within the SE node. Perold *et al.* (2020) indicated that up until 2018, 10 Cape Vultures had been killed at two wind farms (from a possible 20), over a span of four years (2014-2018). As wind farms are a recent threat and the consequences of such development to Cape Vulture populations are unknown, we considered six scenarios to assess the potential impact on the population. Firstly, we examined the likely effects of present wind turbines impact only dispersing birds (potentially indicating the present situation). An alternative model examined the impact of wind turbine collisions on resident populations. This scenario is likely if wind farm development is located close to colonies (as such resident birds would be affected more (Venter *et al.* 2019)). Additionally, we simulated four worst-case scenarios. Griffon Vultures, a similar species to the Cape Vulture in terms of sensory ecology and physiology, are severely impacted by wind collisions in southwestern Europe, and Ferrer *et al.* (2012) indicated that within Spain 0.41 vultures are killed per turbine per year. This value was extrapolated as a worst-case scenario for Cape Vultures. Presently, there are 460 wind turbines fully operational within the Cape Vultures distribution range, and thus, 189 individuals could potentially be killed per year at this worst-case rate. This value was simulated in two models. Firstly, with only dispersing birds, and secondly simulating a worst-case scenario including resident birds. Given that wind farms are likely to increase, two further models were simulated at this worst-case rate where the current number of wind turbines were doubled. This would result in 920 wind turbines within the Cape Vulture distribution range, and a predicted 377 vultures per year would be killed at this worst-case rate. Once again, these figures were simulated for two models, firstly impacting dispersing individuals and secondly, impacting resident birds. It should be noted that whilst the values of wind farm collisions within each model varied, the values associated with other anthropogenic factors remained constant throughout each simulation.

Power line incidents

We obtained vulture mortality incidents from electrical infrastructures from the Endangered Wildlife Trust and ESKOM (South Africa's national and only power utility supplier) (unpublished data). This dataset included information on electrocution incidents as well as incidents involving collisions with power line infrastructure and spans across the years 1996 to 2019. We treated electrocution and collision incidents as individual threats within the models. We extracted the numbers of individuals killed per electrocution and collision separately for within and outside areas of high use, and calculated an average per threat to use in the models.

Poisoning

We obtained vulture poisoning incidents from the African Wildlife Poisoning Database, the Endangered Wildlife Trust and the Peregrine Fund (unpublished data). Whether a poisoning incident was likely to occur was determined by a binomial distribution. If an event did occur, we determined the number of individuals killed by this threat by a Poisson distribution. We modelled poisoning as catastrophic events as high numbers of individuals (e.g., > 50) are known to be killed at single incidents of reported poisonings (Ogada *et al.* 2016).

Belief-based medicine trade

The trade of vulture body parts in the belief-based medicine trade is known to impact the Cape Vulture population (Botha *et al.* 2017; Mashele *et al.* 2021a,b). However, the number of birds harvested contrasts greatly between studies, ranging from one or two birds a year (Mashele *et al.* 2021a) to 160 birds per year (McKean *et al.* 2013). An array of methods are used to capture vultures for this trade, including shooting, trapping, hunting or poisoning (Allan *et al.* 2013; McKean *et al.* 2013; Pfeiffer *et al.* 2015b). We assumed that birds harvested for this trade were likely to fall within the other categories of threats and, as such, did not treat this threat in isolation.

4.3.3 Population viability analyses

We used the population viability analysis software program Unified Life Models (ULM) (Legendre and Clobert 1995) to determine the persistence of Cape Vultures under a variety of scenarios with increased wind farm development. A demographically stochastic, two sex pre-breeding census with five age classes was programmed in ULM. The demographic parameters used in the simulations are summarised in Table 4.1. Six model scenarios were run (Table 4.2) and Monte-Carlo simulations were run at the default values of 1000 iterations over a 30-year time period. The relationship between dispersing birds between nodes, how resident and/or dispersing birds are likely to face threats and surviving individuals impact population nodes is demonstrated in Figure 4.2.

Table 4.1: Demographic parameters of Cape Vultures *Gyps coprotheres* used in a demographically stochastic, two sex pre-breeding census, five age class population viability analysis. Values are indicated separately for south-east (SE) and north-east (NE) nodes, or pooled for both nodes.

Parameter	Value SE node	Value NE node	Source
Population size	5514	7348	(Allan 2015)
Annual survival:			(Piper *et al.* 1999; Monadjem *et al.* 2014)
Juvenile	0.68		
Immature	0.88		
Sub-adult	0.78		
Adult	0.91		
Age at first breeding (years)	5		(Mundy *et al.* 1992)
Breeding proportion	0.8		(Allan 2015)
Age ratio:			(Murn and Botha 2018)
Juveniles	0.9		
Immatures	0.18		
Sub-adults	0.6		
Adults	0.67		
Emigration	0.31	0.02	(Kleinhans and Willows-Munro 2019)

Table 4.2: Wind turbine threats included within the six model simulations run for Cape Vultures, using a demographically stochastic PVA, with two sex pre-breeding census with five age classes. Additional threats remained constant in each model and are as follows: SE node powerline collision dispersers = 12; SE node powerline collision residents = 1; SE node powerline electrocution dispersers= 110; SE node powerline electrocution residents = 2, SE node poison dispersers and residents = Poisson distribution; NE node powerline collision dispersers = 1; NE node powerline collision residents = 8, NE node powerline electrocutions dispersers = 3; NE node powerline electrocutions residents = 70, NE node poison dispersers and residents = Poisson distribution.

	SE dispersers	**SE residents**
Current mortality rates	Model 1 (n = 2)	Model 2 (n = 2)
Worst case scenario mortality rates at current wind turbines (n=460)	Model 3 (n = 189)	Model 4 (n =189)
Worst case scenario mortality rates at increased wind turbines (n=920)	Model 5 (n = 377)	Model 6 (n = 377)

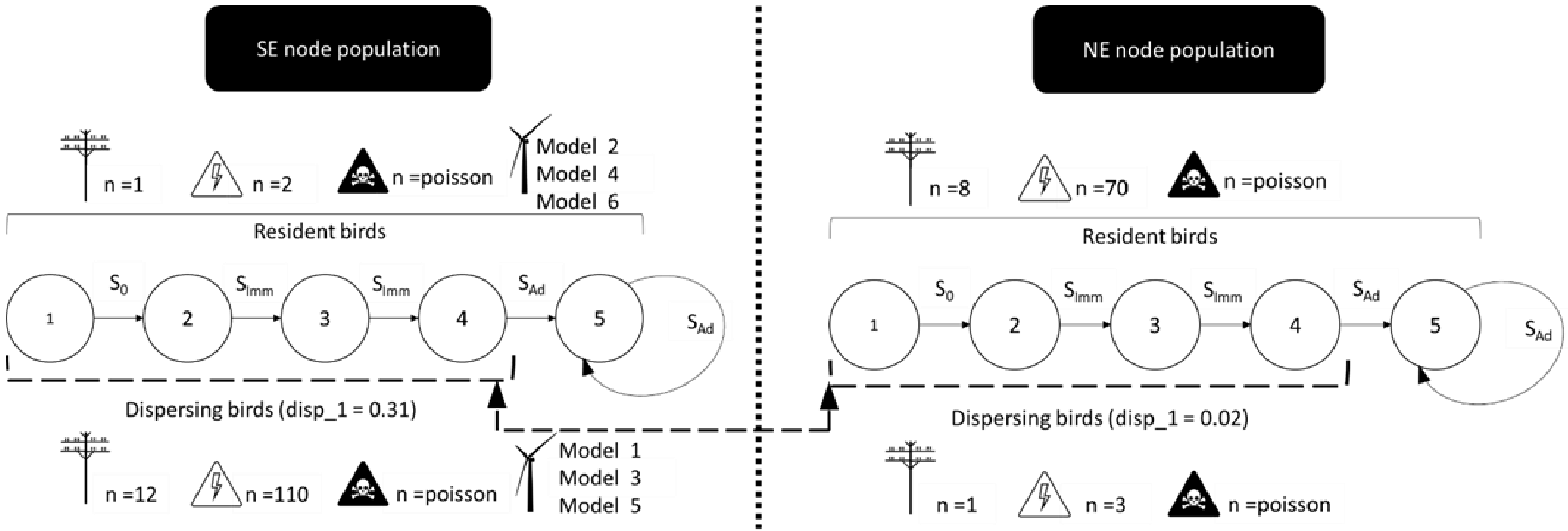

Figure 4.2*:* Relationship between movements of dispersing and resident Cape Vultures from the south-east (SE) node to the north-east (NE) node and vice versa. Dispersing and resident birds who survive the respective threats are likely to continue to contribute to the population dynamics.

4.4 Results

In all six scenarios, the SE node population declined when faced with increased wind farm development, although without extinction within the timeframe considered. The NE node in each simulation experienced an increasing population (λ above 1), whilst the overall population retained a population growth (λ) just above 1 at current wind farm mortality rates but decreased when experienced "worst-case scenario" mortality rates at both operational and increased wind turbine numbers.

Model 1 demonstrated the population response to additional mortality rates to dispersing individuals from current wind turbine mortalities in the SE node. The SE node displayed a slight decline in population growth (λ = 0.951; Table 4.3; Figure 4.3), whilst the NE node continued to increase (λ = 1.022), and the overall population growth remained just above 1 (λ = 1.006). Similarly, model 2 illustrated that the SE node would decline to the same degree as model 1 should resident individuals be affected by current turbine mortalities (λ = 0.951; Table 4.3). The NE node (λ = 1.022) and overall population (λ = 1.006) for model 2 retained a similar degree of population growth as displayed in model 1.

Model 3 illustrated the population response given a "worst case mortality rate" similar to that experienced in Spain at current operational wind turbines within South Africa. With dispersing individuals from the SE node being impacted by additional wind turbine mortalities, the SE node experienced a greater population decline (λ = 0.947; Table 4.3) when compared with models 1 and 2. Additionally, whilst the NE node population still continued to increase (λ = 1.014), the overall population growth dropped below a stable population (λ = 0.998). A greater population decline was reported in response to resident individuals from the SE node (λ = 0.873, Figure 4.3) being impacted at a "worst case mortality rate" at present operational wind farms, as illustrated in model 4. The NE node continued to experience an increasing population (λ= 1.015) in model 4, yet the overall population, when compared with previous models, demonstrated a population decline (λ = 0.996).

Model 5 established that “worst case mortality rate” at increased wind turbine numbers (double the present operational wind turbine figures) impacting dispersing birds, caused the SE node to decline (λ = 0.944). Whilst the NE node continued to increase (λ = 1.009), this was the lowest reported stochastic growth rate for the node. Additionally, the lowest overall population stochastic growth rate was reported for model 5, with the overall population experiencing the greatest decline (λ = 0.993). The greatest population decline to the SE node (λ = 0.870, Figure 4.3) in response to resident individuals being impacted at a “worst case mortality rate” at increased wind turbine numbers was evident in model 6. Whilst the NE node continued to increase (λ = 1.012, Figure 4.3), the overall population experienced a decline (λ = 0.994).

Table 4.3: Stochastic population growth rate of Cape Vultures in response to different wind turbine mortality impacts.

	Stochastic population growth rate (λ)		
Model simulation	**SE node**	**NE node**	**Overall population**
Model 1[a]	0.951	1.022	1.006
Model 2[b]	0.951	1.022	1.006
Model 3[c]	0.947	1.014	0.998
Model 4[d]	0.873	1.015	0.996
Model 5[e]	0.944	1.009	0.993
Model 6[f]	0.870	1.012	0.994

[a] Current mortality rates of SE dispersers; [b] Current mortality rates of SE residents; [c] Worst case scenario mortality rates at current wind turbines for SE dispersers; [d] Worst case mortality rates at current wind turbines for SE residents; [e] Worst case scenario mortality

rates at increased wind turbines for SE dispersers; [f] Worst case scenario mortality rates at increased wind turbines for SE residents

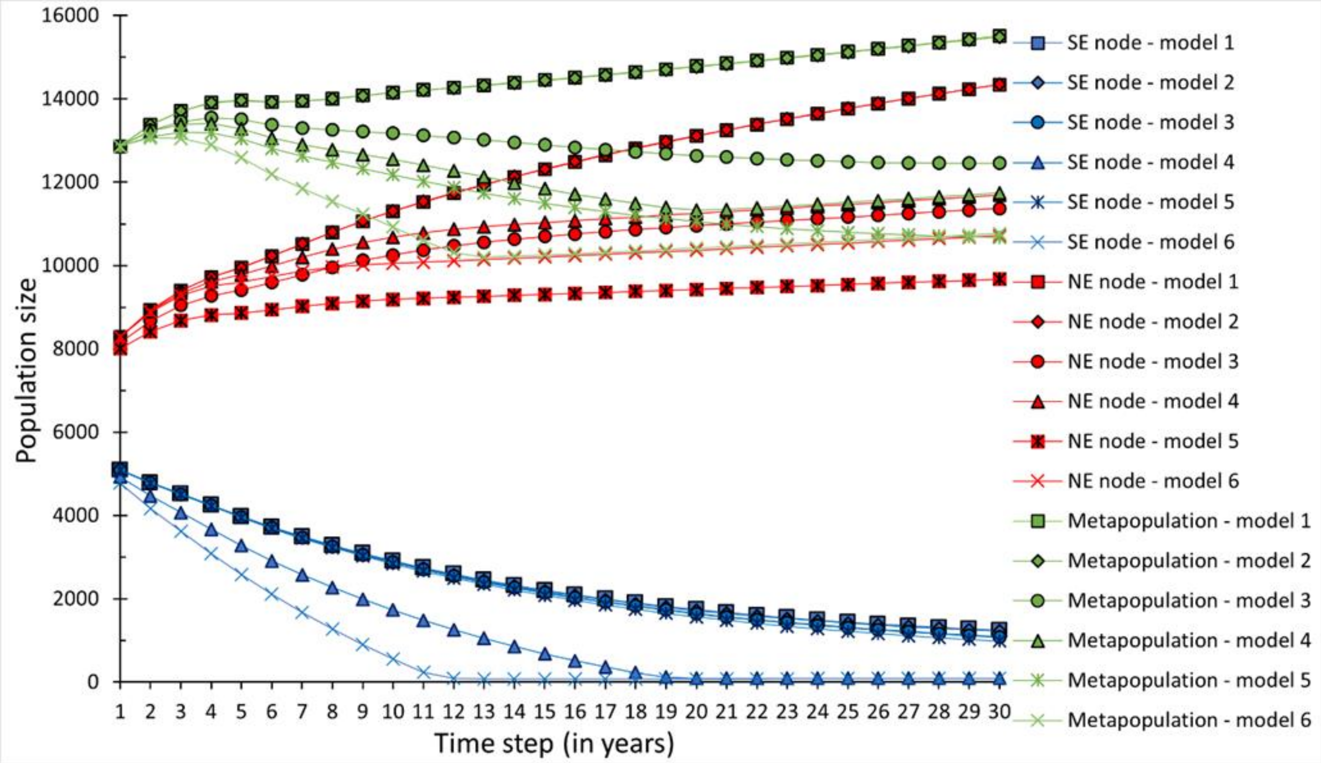

Figure 4.3: Output from the different models on the population trajectory of Cape Vultures over 30 years when the southeastern node (SE node) of the population experiences wind farm fatalities at different intensities.

4.5 Discussion

Our study aimed to assess how the Cape Vulture population within the north- and south-eastern node of the South African population is likely to fair under the novel and increasing threat of wind turbines in addition to the anthropogenic threats they already face. The SE node is likely to experience population declines due to wind turbine collisions, as much of the current and proposed sites fall within close proximity to this node. As such, PVA simulations run within this study focused mortalities because of wind turbine collisions on the SE node.

Under present threats and additional low wind turbine mortality, modelled results indicated that wind farms impact dispersing individuals or resident individuals within the SE node, the population experienced the same stochastic declining population growth rate ($\lambda = 0.951$). However, this should be interpreted with caution, as the present number of birds impacted by wind turbine collision is still comparatively low. Should turbine mortalities reach "worst case mortality rates", similar to mortality rates exhibited in Spain on the sister species *G. fulvus*, stochastic population growth indicated a more severe decline in the SE node when resident birds were impacted as opposed to when dispersing birds were impacted (Table 4.3).

Whilst dispersing birds represent young individuals, resident populations included adult birds that are constrained to colonies. It is well known that adult survival plays an important role in the population dynamics of long-lived species such as the Cape Vulture (Allan 2015). Studies conducted in northern Spain indicated that adult Griffon Vultures were the age class most frequently killed at wind farms (Camiña 2011) and a similar study concluded that the number of breeding pairs decreased by 24% and adult survival experienced a 30% decrease because of wind farm collisions (Martínez-Abraín *et al.* 2012). These collisions were driven by changes in food resources and subsequently foraging ranges, forcing individuals to fly across a newly established wind farm (Martínez-Abraín *et al.* 2012). This illustrates the point that although birds are able to alter their daily movements in response to changing environmental variables, movement around colonies remains prevalent (Carrete *et al.* 2012). As such, this should be used to consider future conservation management implications and spatial planning of wind farm developments in South Africa. Thus, proposed wind farm sites need to be established away from breeding colonies as well as areas of high vulture use in order to limit the number of probable collisions to resident individuals. Present recommendations indicate a 50 km buffer around colonies in order to protect breeding birds within their home range (Venter *et al.* 2019) and these should be adhered to prevent further declines of breeding individuals.

Further studies in the south of Spain indicated that young Griffon Vultures are often the casualties of turbine collisions (Barrios and Rodríguez 2004; de Lucas *et al.* 2012a), likely as a result of erraticism and migration, where they aggregate in large numbers to cross the Strait of Gibraltar, where a large number of poorly placed wind farms occur (Drewitt and Langston 2006; de Lucas *et al.* 2012a). The Cape Vulture does not exhibit migration like the Griffon Vulture (although suspected partial migration has been reported (Boshoff *et al.* 2009a)), the species, however, does experience a post-fledging dependence period (PFDP). During this time, young individuals are inexperienced in flight (Harel *et al.* 2016) and cover extensive areas of the landscape (Mundy *et al.* 1992; Martens *et al.* 2018). Their poor flight ability and lack of knowledge of the landscape may cause a higher number of juveniles to occupy areas of proposed or developed wind farms, resulting in turbine collisions. Our results show that when dispersing individuals from the SE node experienced a decline as a result of wind turbine mortalities, the NE node population growth decreased to the greatest extent (model 5). With more dispersing individual mortalities at a "worst case mortality rate" at increased wind farms, the NE node exhibited a reduced population growth (when compared to other models). This is likely explained by the fact that should a high number of dispersing individuals be killed by wind turbines; these individuals are not able to reach the NE node and supplement the nodes numbers.

Model simulations indicate that under "worst-case mortality rate" scenarios, the overall Cape Vulture population begins to suffer a population decline. Measures need to be taken to ensure that high numbers of birds are not removed; thus mitigation measures need to be considered at proposed and established wind farms. Locational planning is considered the first step in wind farm development. Careful consideration of wind farm location and design should take priority at this stage (Drewitt and Langston 2006; Murgatroyd *et al.* 2020; Scacco *et al.* 2020). This is particularly relevant in South Africa, as the threat to Cape Vultures is still novel, and the placement of wind farms can be selected away from sensitive areas. At established wind farms, shut down on demand has proven successful in reducing turbine mortality rates of Griffon Vultures by over 50% with minimal electricity generation loss (de Lucas *et al.* 2012a). Such methods need to be considered should mortality rates reach exceedingly high numbers for Cape Vultures at wind farms.

The decline of vultures can have serious implications, as they are not only ecologically important, but also economically and culturally significant (Ogada *et al.* 2012a; Mashele *et al.* 2021a,b). Vultures provide sanitation services by disposing of large portions of carrion as well as other organic refuse and contribute to nutrient cycling (Deygout *et al.* 2009; Dupont *et al.* 2011, 2012; Ogada *et al.* 2012a, b; Aresu *et al.* 2020). By consuming carcasses quickly, vultures also limit the spread of diseases such as anthrax or rabies whilst simultaneously controlling facultative scavenger numbers (Markandya *et al.* 2008; Ogada *et al.* 2012b, 2015; Buechley and Şekercioğlu 2016). The decline of vultures could lead to a change in ecosystem stability, as was witnessed in the 'Asian Vulture Crisis' (Markandya *et al.* 2008; Ogada *et al.* 2012a). Further, whilst extinction was not reached within the time frame considered for any model simulation, low individual numbers in the SE node could have other implications for the population. The SE node appears to act as a source population (Kleinhans and Willows-Munro 2019), and the loss of individuals within this node could lead to loss of genetic diversity. This loss may mean that changes in the population's ability to cope with environmental changes in the future may be compromised (Scribner *et al.* 2006; Wilson and Primack 2019). Whilst the genetic implications of population declines was not explored within our study, this should warrant further in-depth research.

Whilst this study indicated that the Cape Vulture population is likely to remain stable under present additional wind turbine mortalities, future “worst-case scenario” collisions could lead to population declines. There are several caveats of this study, however. Firstly, the number of threats from powerlines and poisoning incidents were treated as baseline threats, and these did not differ between models. These incidents may fluctuate in time, and this was not captured in the models. The number of baseline threats should further be considered a conservative estimate, as the number of reported incidents per threat is likely to be an underestimation of the total number, as many incidents go unreported (Boshoff *et al.* 2011). Additionally, the information used to create the starting population is dated (2013), but there is little up to date information available. The number of breeding individuals within the SE node is unknown. It, therefore, highlights the need to re-establish extensive colony monitoring within this area for conservation organisations to be informed of future management recommendations. Additionally, Hirschauer *et al.* (2020) indicated that colonies from the NE node have increased in numbers of breeding individuals, so much so that should the mature individuals of this node follow the population of Allan (2015), it is likely to represent 74% of the breeding population as opposed to the 56%. This raises the question of whether this trend is being reflected in the SE node, or numbers in the SE node are decreasing to supplement individuals in the north. This highlights the need to establish monitoring protocols, particularly if we are to accurately observe if the population is declining with the increase of wind farm development. Moreover, the demographic information used to establish the models is outdated. Whether these factors have changed in the last 20 years is likely, yet to what extent is uncertain. Generating present demographic information would certainly be beneficial to capture the current state of the population to allow for a clear and current understanding of how the species fairs. Lastly, the PVA models run in this study were not spatially explicit. Given that collision rates with wind turbines are known to be species-, site- and wind farm- specific, incorporating such information into future studies could allow for more accurate results, which could then be used to inform management recommendations.

4.6 Conclusions

Our findings indicate that Cape Vultures, should they experience high collision mortality rates similar to the Griffon Vulture, the population is likely to experience a decline. The fact that the current status of breeding colonies within the SE node is unknown highlights a significant shortcoming within Cape Vulture conservation. Given the proposed increase of wind farms within this area, obtaining clear population numbers is needed to ensure future management decisions can be based on empirical data. Further, ensuring that populations do not reach critically low numbers and cross a threshold where no population growth occurs should be avoided. Monadjem *et al.* (2014) demonstrated that although a considerable effort is being put into the rehabilitation of injured vultures, the survival rates of rehabilitated birds are far below those of non-injured wild birds. Thus, limiting the impacts of various threats on the Cape Vulture is pertinent to ensure this species' long-term survival.

4.7 Acknowledgements

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CHAPTER 5

A COMPARATIVE STUDY OF VULTURE FLIGHT HEIGHT: MAN VS PHOTOGRAMMETRY

Francis R. Martens-Brooke[1], Morgan B. Pfeiffer[1,2], Colleen T. Downs[3], Martin Postma[4], Nicolas D. Prinsloo[4], P.J. Nico de Bruyn[4], Jan A. Venter[1]

[1]*Department of Conservation Management, Faculty of Science, George Campus, Nelson Mandela University, George, South Africa.*

[2]*U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Center, Ohio Field Station, 6100 Columbus Avenue, Sandusky, OH 44870, USA*

[3]*Centre for Functional Biodiversity, School of Life Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, KwaZulu-Natal, South Africa*

[4]*Department of Zoology and Entomology, Mammal Research Institute, Private Bag X20, Hatfield 0028, University of Pretoria, Pretoria, South Africa*

5.1 Abstract

Wind energy is considered a clean and renewable energy source, but it can negatively impact avian species. Understanding movements of avian species prior to wind energy development is pertinent. Direct observations are considered a suitable method to understanding such movements, but such estimates are not quantified. A potentially comparative method to direct observations is photogrammetry, “measurement through the use of photographs”. Cape Vulture (*Gyps coprotheres*) flight height estimations from experienced and inexperienced observers were compared to photogrammetry measurements at a vulture restaurant in the Western Cape. Observers significantly underestimated higher flight heights when compared to photogrammetry. This could lead to poor placement of wind turbines in the landscape and, therefore, increased collision risks. Cumulative losses of individuals could be detrimental to a threatened population and developments should be established appropriately to limit such risks. Given the inaccuracy of human observed estimates, preliminary results indicate the use of alternative methods, i.e., photogrammetry, be considered for environmental impact assessments.

5.2 Significance

- Photogrammetric measurement of bird flight height is cheaper and easier than present supplementary remote sensing techniques (e.g., radar) and may be beneficial for species conservation and monitoring.
- Observers (experienced and inexperienced) are likely to underestimate flight heights of birds when compared with photogrammetry measurements. Underestimations could lead to inappropriate placement of wind turbines in the landscape, potentially leading to detrimental ecological and economic losses.

5.3 Introduction

The development of clean and renewable energy sources globally is pertinent (Leung and Yang 2012), with wind energy considered to be “environmentally benign” when compared with fossil fuel technologies (Carrete *et al.* 2009; Leung and Yang 2012; de Lucas *et al.* 2012a). However, it can negatively impact avian species through blade strikes, avoidance behaviour, displacement and habitat loss (Drewitt and Langston 2006; Carrete *et al.* 2009; Leung and Yang 2012; de Lucas *et al.* 2012a).

To address these potential threats to South African bird populations, policies were developed (Retief *et al.* 2011; Jenkins *et al.* 2015), which state that understanding the spatially explicit movements of birds in and around proposed wind energy sites is important for establishing project suitability (Jenkins *et al.* 2015). Such data is often obtained via direct observations (Jenkins *et al.* 2015). Remote sensing techniques, although valuable in detecting, monitoring and quantifying bird flight patterns, are costly and often a deterrent to clients (Jenkins *et al.* 2015; Becker *et al.* 2020). A comparatively cheaper method, photogrammetry, is being explored (Prinsloo *et al.* 2021). Photogrammetry, “measurement from photographs” (Linder 2009; Postma *et al.* 2015; Marchal *et al.* 2016), is well-established and allows for the replication of a 3D scene from at least two overlapping photographs. Its application to biological studies has been used extensively, from determining mass of terrestrial and marine mammals to estimating bird flight height (Prinsloo *et al.* 2021; Postma *et al.* 2013; Postma *et al.* 2015).

Direct observations are frequently used to estimate, but not quantify, bird flight height (Johnston *et al.* 2014). Flight heights indicate whether the bird is below, within or above the rotor swept area in 10 m bands (Jenkins *et al.* 2015; Pfeiffer and Ralston

Paton 2018). Inaccuracies in flight height observations could lead to increased collision risks with wind turbines, which could lead to population declines and local extinctions (Rushworth and Krüger 2014). The Cape Vulture (*Gyps coprotheres*) is currently under threat and is considered a high priority species for impact assessment and mitigation at wind farms within South Africa (Pfeiffer and Ralston Paton 2018). Cape Vulture size, lack of manoeuvrability, behaviour and habitat use increase their collision risk (Retief *et al.* 2011; Pfeiffer and Ralston Paton 2018). Furthermore, they require similar climatic (i.e., wind) conditions for orographic or thermal uplift to that targeted by wind energy development (Rushworth and Krüger 2014). Its vulnerability and detectability make it a suitable model for flight height assessment studies.

Given the uncertain accuracy of direct observations and recent research indicating significant differences in flight height estimates of Cape Vultures between radar and direct observations (Becker *et al.* 2020), we aimed to:

1. Compare the accuracy of experienced observers and inexperienced observers when estimating vulture flight height.
2. Compare observer accuracy to photogrammetry estimates.
3. Test whether observation estimates were categorised in the correct 10 m bands (Pfeiffer and Ralston Paton 2018) when compared with photogrammetry.

5.4 Methods

The Potberg Mountain (De Hoop Nature Reserve, Western Cape), a formally protected Important Bird Area (IBA, ZA098 (BirdLife International 2020)), contains an isolated subpopulation of the only breeding colony of Cape Vultures in the Western Cape

(Boshoff and Currie 1981; Allan 2015). The vultures forage predominately on sheep carcasses from agricultural activities (outside of the IBA) (Boshoff and Currie 1981), which raises concerns as a Renewable Energy Development Zone (REDZ) has been identified 20 km north of the colony (Marnewick *et al.* 2015).

We conducted vulture flight observations in July 2019 over three days from a bird hide located 200 m northeast of a vulture restaurant. Observations were conducted by experienced (n = 2) or inexperienced (n = 2) observers in clear weather conditions between 07:00 and 16:00. Experienced observers had previously estimated bird flight heights. Flight heights of Cape Vultures were estimated (in meters) by observers when vultures flew in the photogrammetry cameras' field of view (CFOV). When possible, flight height was recorded every 5 s from when the vulture entered the CFOV until it landed at the restaurant or flew out of the CFOV. Recorded observations were coordinated to correspond with photogrammetry photographs. For photogrammetry, three cameras (Canon EOS 1300D; Ultrasonic lenses (18 to 55 mm)) were set in triangular formation in front of the bird hide (Figure 5.1), within reach of a remote-controlled trigger (Prinsloo *et al.* 2021). Before camera deployment, cameras (set to 55 mm) were calibrated (see Photomodeler® Pro help file (EOS systems Inc., Vancouver)). Experienced and inexperienced observer estimates of flight heights were compared with photogrammetric measurements using a non-parametric Kruskal-Wallis test in R (R Core Team 2020).

Based on recommendations (Pfeiffer and Ralston Paton 2018), observed data was divided into 10 m bands. Observations were conducted at relatively low flight heights (< 30 m) based on the setup of the feeding site. We ran a Fischer's exact test in R to compare the accuracies of observation heights with benchmark photogrammetry heights.

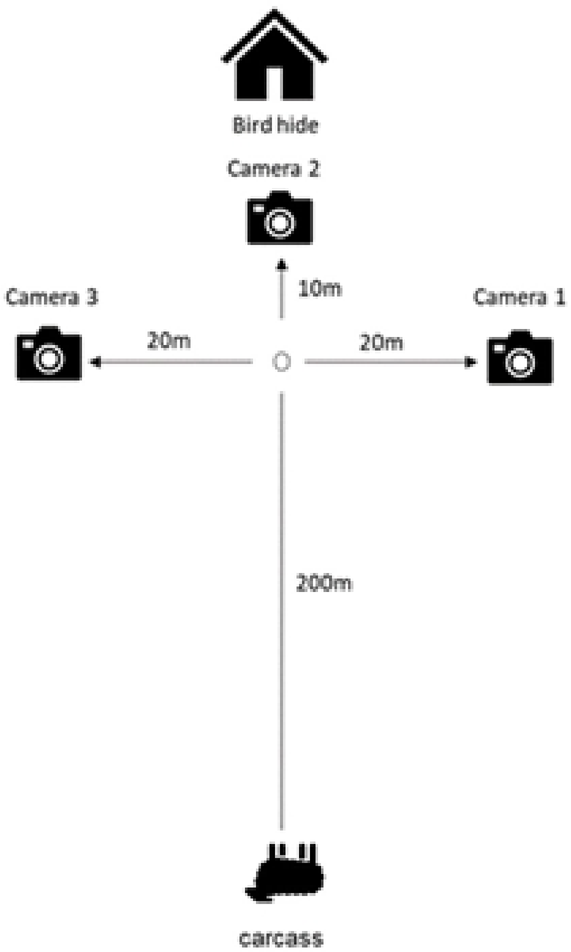

Figure. 5.1: Graphical representation of camera layout for photogrammetry at a vulture restaurant (Western Cape, South Africa).

5.5 Results

We collected 78 observations per observer over three days. Observer and photogrammetry height estimates differed significantly (Kruskal-Wallis test; H_2 = 34.629; $p < 0.001$), for both inexperienced observers (Post-hoc tests; $p < 0.001$) and experienced observers ($p < 0.001$).

Vulture flight heights assigned to bands differed significantly between observers and photogrammetry (Fisher's Exact Test, $p < 0.001$). Observers were more likely to classify flight heights in the correct bands at low flight heights (< 10 m), but underestimate and incorrectly classify flight height with increasing vulture flight heights (Figure 5.2).

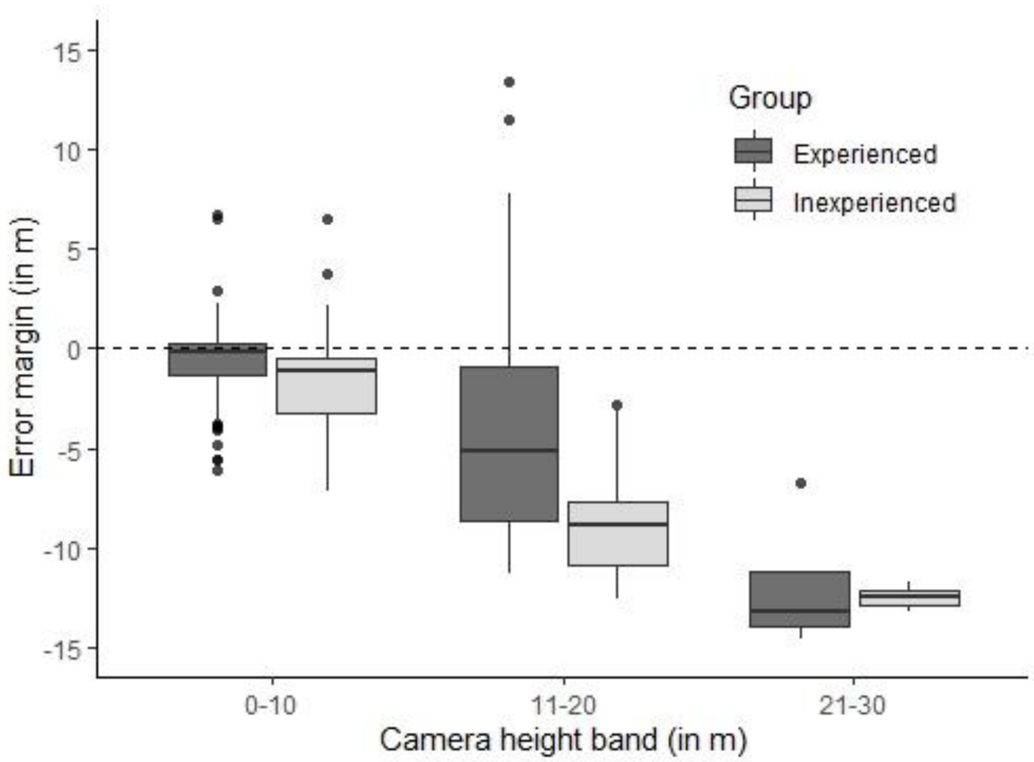

Figure. 5.2: Observational error margin (in meters) between experienced and inexperienced observers when calculating Cape Vulture flight height into 10 m bands at a vulture restaurant (Western Cape).

5.6 Discussion

Automated monitoring systems adequately determine bird flight heights (McClure *et al.* 2018; Becker *et al.* 2020), and estimations obtained via photogrammetry represent real flight heights (Prinsloo *et al.* 2021). Experienced observers were better at estimating flight heights of Cape Vultures than inexperienced observers. When height observations were compared with photogrammetry estimates, all observers generally underestimated flight height. Incorrect estimations could be detrimental to the outcomes of proposed wind farm development, leading to poor placement of wind turbines and increased collision risks.

Discrepancies in the accuracy of different methods of flight height determination were highlighted. Given the drive to develop green energy and the associated susceptibility of species to wind energy harnessing, appropriate methods are imperative. Determining accurate flight height of vultures in proposed wind farm sites should be prioritised given Cape Vultures already high collision rates (Pfeiffer and Ralston Paton 2018; Perold *et al.* 2020). With this species already facing numerous threats (Botha *et al.* 2017), combined with slow reproductive rates (Mundy *et al.* 1992), increased mortalities could accelerate the species' decline towards local extinction (Rushworth and Krüger 2014). Given that South African wind energy developments are relatively new, these developments must be appropriately established to limit additional risk to an already threatened species.

Several caveats require consideration. Few observers were used (n = 4), therefore sample size should be increased in future studies. Observations were conducted at relatively low flight heights (< 30 m). Quantifying flight height at higher elevations would be worthwhile to determine whether underestimation still occurs or is exaggerated. Observations were conducted over three days in one season, not reflecting the environmental impact assessment process, and seasonal variation in vulture flight heights should be assessed (Spiegel *et al.* 2015). Lastly, observations were conducted at a maximum horizontal distance of 200 m, necessitating further research to determine whether altering observation distance impacts the accuracy of observations (McClure *et al.* 2018; Becker *et al.* 2020).

Preliminary results indicate that photogrammetry may be an alternative method to measure bird flight height during wind energy development processes. Given the inaccuracy of human observed estimates, the alternative use of automated systems (i.e., photogrammetry or radar) be recommended for environmental impact assessments.

5.7 Acknowledgements:

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CHAPTER 6

CONCLUSIONS

6.1 Introduction

The main research findings are reported in this chapter, and how these findings address the study aims and objectives are discussed. Study constraints are highlighted, and areas of future research to improve Cape Vulture (*Gyps coprotheres*) conservation are presented.

The Cape Vulture is a southern African endemic species that faces numerous anthropogenic threats, noticeably from poisoning incidents and negative interactions with power lines (Boshoff *et al.* 2011; Ogada *et al.* 2012a; Botha *et al.* 2017). The development of renewable energy through wind turbines is likely to pose a novel, yet significant threat to a portion of the species distributed within the Eastern Cape Province of South Africa (Rushworth and Krüger 2014; Pfeiffer and Ralston Paton 2018). While international research indicates that *Gyps* species are vulnerable to mortalities from wind turbines, South Africa is in the unique position to gain insights into understanding collision probabilities and modelling predictions of the species response to increased threats from wind turbines to limit their decline. As vultures play a substantial ecological and economic role in the ecosystem (Ogada *et al.* 2012b; Ogada *et al.* 2012a; Dupont *et al.* 2012; Aresu *et al.* 2020), it is imperative that their decline be halted as the loss of these obligate scavengers can have far reaching implications. This was experienced first-hand in Asia, where the rapid decline of vultures (and subsequently their ecological role of limiting the spread of diseases) had substantial health and subsequent economic consequences (Markandya *et al.* 2008).

This study, therefore, first reviewed the traits that make vultures, notably *Gyps* species, vulnerable to collision with wind energy infrastructure (Chapter 2). This review further provided an overview of monitoring at wind farms during construction (pre – and post -) and examined the mitigation measures of limiting vulture collisions with wind turbines. Further, using telemetry data from individuals tagged at three colonies within the species' distribution threatened by wind farms, this study was able to identify, through network analysis, patches that were being used by different age classes of Cape Vultures (Chapter 3). How the patches were being used (i.e., as corridors) and the environmental variables associated with each patch was also determined. Considering the possibility of increasing wind energy and the current threats Cape Vultures face, a population viability analysis was conducted in Chapter 4. This allowed us to determine the likely response of the population to present, low wind turbine mortalities and consider the population response to increased mortality rates should the Cape Vulture experience similar mortalities to those of the Eurasian Griffon Vulture (*Gyps fulvus*). To conclude the thesis, a methodological approach evaluated the efficacy of a method to improve observer accuracy during the pre-construction monitoring phase.

Whilst the Cape Vulture is one of the most studied African vulture species (Mundy *et al.* 1992), wind energy is a new threat to this endangered species. This study, therefore, investigated the susceptibility of Cape Vultures to wind farm development, and as a result, each chapter provides information and recommendations that can be used to further the conservation of the species when considering the emerging threat of wind energy development.

6.2 Research findings

To address the overarching study aim of determining Cape Vulture population effects of wind farms, four separate research objectives were examined in this dissertation.

The first research objective (Chapter 2) aimed to review the knowledge base of Cape Vulture susceptibility to wind farms and review the effectiveness of pre- and post-construction monitoring and mitigation measures employed. As has been found in other studies, *Gyps* species are susceptible to collision with wind turbines as a result of species-, site- and wind farm-specific traits (Drewitt and Langston 2008; Marques *et al.* 2014; Watson *et al.* 2018). The large body size and heavy wing load of Cape Vultures result in poor flight manoeuvrability and combined with their inability to visually detect anthropogenic structures (as a result of their head position in flight and focus on terrain below them as opposed to in front of them in flight), makes this species highly susceptible to collisions with wind turbines (Martin 2011; Martin *et al.* 2012). Further, a reliance on orographic and thermal lift puts the species in conflict with wind energy developers who often select similar conditions for wind farms (Marques *et al.* 2014; Zwart *et al.* 2015).

South Africa has been quick to develop “Best Practice Guidelines” and “Avian Sensitivity Mapping” to guide wind farm development and have further provided specialised guidelines targeted for Cape Vultures, which is encouraging. Present efforts across the landscape encourage 50 km buffers around Cape Vulture colonies, where wind farm development should be limited. Whilst this approach is not without its own limitations, it is one of the few methods that afford some protection to sensitive Cape Vulture areas. The greatest challenge of preconstruction monitoring appears to be the accurate assimilation of flight height data, which is cost-effective, practical and spatially accurate. Observer bias has been reported to be influenced by species size (i.e., detectability), species behaviour and distance between observer and study species (Smallwood 2007; Krijgsveld *et al.* 2009; Péron *et al.* 2013; Perold *et al.* 2020) and these biases are often compounded when this spatially inaccurate data are used to create collision risk models. Whilst collision risk models can aid developers and planners about probable collision mortalities in the landscape, spatially accurate, high quality (and quantity) data is needed to inform these models. This highlights the need to find appropriate, cost-effective methods of examining bird behaviour in proposed sites, which can then be used to inform the appropriate placement of sites in the landscape. Once wind farms are approved and become operational, post-construction monitoring is undertaken to detect mortalities and monitor the effects on wildlife. Carcass detection below wind turbines is common practice and allows for the spatial and temporal understanding of collisions at certain wind turbines (Willmot *et al.* 2012; Watson *et al.* 2018). Bias may also be prevalent in carcass detection as a result of searcher efficiency and scavenger removal rates (Willmot *et al.* 2012; Thaxter *et al.* 2017). The use of specially trained dogs has shown to significantly improve detection rates (Drewitt and Langston 2008; Domínguez del Valle *et al.* 2020; Smallwood *et al.* 2020) and warrants further investigation in a South African context. A sociological advantage of carcass monitoring surveys in South Africa is that they may provide local communities employment opportunities. Information gained from post-construction monitoring should be used to advise mitigation measures. Curtailment methods have been successful in reducing collision risks of Griffon Vultures in Europe. While present Cape Vulture casualties are low, developers need to keep in mind that as wind farms multiply, such methods (and their associated costs) may need to be implemented. Therefore, it is important that South Africa take a proactive approach in limiting collisions with priority species like the Cape Vulture through careful planning at all stages of the wind farm development cycle.

To further understand the likely interaction of Cape Vultures and wind farms in the landscape, understanding how Cape Vultures use and move between different patches in the landscape could benefit conservation efforts through focused management approaches. The spatial distribution and behaviour of Cape Vultures are age-related (Piper *et al.* 1981; Piper *et al.* 1989), which may be driven by different resources in the landscape. Consequently, age classes may face differing risk probabilities. With present and proposed wind energy development occurring in a portion of the Cape Vultures range distribution, the second research objective of the study aimed at identifying which and how areas in the landscape are being used by three age classes (juveniles <1 years old, immatures 2-4 years old and adults >5 years old) of Cape Vultures across three colonies and their overlap with current and proposed wind farms (Chapter 3). Additionally, environmental variables associated with each area was identified, as this may provide insight into which components of the landscape can be used for conservation efforts and which areas should be avoided for the placement of wind farms. Based on network metrics obtained via telemetry data, areas were classified into areas of high use, low use and fast or slow corridors.

All three age classes of Cape Vultures displayed areas of high use, and the environmental variables associated between the three age classes were similar. Distance to roost sites had strong associations for juvenile and immature Cape Vultures in high use areas, likely as a result of their extensive movement in the landscape (Piper *et al.* 1981; Phipps *et al.* 2013b; Kane *et al.* 2016; Martens *et al.* 2018) and requiring sites to rest and recover. This may give an indication of the importance of protecting roost sites and providing conservation efforts beyond the conventional conservation measures of protecting breeding colonies. Areas close to operational wind farms were also used extensively by juvenile Cape Vultures and a portion of the adults and is likely as a result of similar orographic and thermal conditions selected by vultures and wind farm developers. High use areas were indicative of high vulture activity and should be considered areas of sensitivity, where limiting the threats to Cape Vultures should be a priority. This includes the careful consideration of proposed wind farms within these areas and limiting the impact of established wind farms on Cape Vultures through active collision preventative measures. Further, corridors were identified and are thought to present areas where birds are moving across the landscape. Slow corridors, areas where vultures flew across the landscape at a relatively slow speed, were used by all age classes of Cape Vultures. Slow corridors are likely to represent areas where Cape Vultures are kettling in the landscape or actively foraging for food sources ephemerally located in the landscape. Concerningly, these slow corridors showed an association with distance to established wind farms and renewable energy development zones (REDZ), which may again be attributed to the overlap of similar orographic or thermal conditions. Birds thermalling in areas of rotating turbines could increase collision probability, and therefore active monitoring methods need to be employed to ensure that bird behaviour is understood in the landscape and can allow for the appropriate placement of wind turbines in the landscape or the appropriate monitoring within operational wind farms. Some of the Cape Vultures also used patches in the landscape as fast corridors (identified by birds moving at high speeds across the landscape). These areas had an association with distance to established wind farms and REDZ, which may present a collision concern. High speed movement across the landscape may cause birds to collide with wind turbines located within the airspace. Even if vultures make timeously detection of turbine blades, their high flight speed in these areas may not result in successful avoidance (Carrete *et al.* 2012; Marques *et al.* 2014; Scacco *et al.* 2020). However, direct movement between locations is often at higher altitudes (Péron *et al.* 2017), and further research on flight height within these areas is warranted. Knowledge of habitat patch use in the landscape may aid more appropriate placements of wind farms in the landscape, which may aid in limiting this threat to Cape Vultures.

Whilst the Cape Vulture faces numerous anthropogenic threats presently, reported mortalities from wind turbine collisions are still relatively low. It is, however, likely that the wind energy industry will continue to grow in South Africa, and mortalities as a result of turbine blade strikes will increase. Therefore, understanding how the Cape Vulture population is likely to respond to increased wind turbine mortalities may assist in guiding conservation management decisions. As such, Chapter 4 set out to examine the Cape Vulture population response to current and future wind farm mortalities in conjunction with the threats presently faced. As the spatial distribution of Cape Vultures is influenced by age, the study aimed to examine how mortalities affect resident individuals (mostly adult birds who are restricted to areas around the colony) and/or dispersing individuals (mainly young birds who disperse from their natal colony) would impact the population. Six spatially implicit Population Viability Analysis (PVA's) were conducted with wind turbine mortalities affecting only a portion of the Cape Vulture regional population (the south-east node; SE node), whilst the so called "stronghold" of the Cape Vulture population, the north-eastern node (NE node), is unlikely to encounter wind turbine blade strikes as a result of poor wind resource availability within the northern part of South Africa (DEA 2013). The results indicate that should dispersing or resident individuals experience current, low mortalities from turbines, in addition to other anthropogenic threats, the SE node population will decline. However, the NE node numbers will remain stable and ensure that the overall population (both SE and NE node) will continue to grow. On the contrary, if wind turbine collisions increase to the same extent as Griffon Vultures observed in Spain (0.41 vultures/turbine/year (Ferrer *et al.* 2012)), considering the current number of wind farms within the Cape Vulture distribution, the SE node is likely to experience a decline if both dispersing or resident individuals are to be impacted. With the decline of these individuals, the overall population growth rate drops below a stable population threshold (considered to be $\lambda = 1$). However, should wind turbine development double its current capacity and Cape Vultures experience collision mortalities to the same degree as Griffon Vultures, the greatest population decline within the SE node is to be as a result of resident individuals being impacted. This once again has a strong impact on the overall population of the Cape Vulture. Interestingly, the greatest overall population decline of Cape Vultures was as a result of dispersing individuals with the SE node being impacted at mortality rates similar to Griffon Vultures at double the present farm development capacity (i.e., 0.41 vultures killed at 920 turbines per annum). Whilst the SE node population size in four of the six models reached low numbers, no model led to the extinction of the species considered in the 30-year time frame. However, such low numbers are likely to have genetic implications for the Cape Vulture population, which this study did not consider. However, this study indicates that should wind farm mortalities increase to rates experienced in Europe on the sister species, the Cape Vulture population is likely to decrease, which can have far reaching implications.

The fifth chapter of the thesis was a methodological paper that examined the accuracy of observer estimates when determining Cape Vulture flight heights with the use of an alternative, cost-effective method. Obtaining spatially accurate movement data of avian species within proposed wind energy facilities is vital to ensuring a sustainable project with minimal collision mortalities recorded. Prior to wind turbine construction in the landscape, the collection of bird flight observations within proposed sites is mandatory (Jenkins *et al.* 2015). These observations are often collected via direct observations conducted by individuals located at vantage points within the landscape. However, observational bias has been reported in direct observations (Band *et al.* 2007; McClure *et al.* 2018; Becker *et al.* 2020) and these could have implications relating to the appropriate placement of wind turbines in the landscape. Exploring more cost-effective yet accurate methods of obtaining flight height is necessary, and this chapter aimed to explore the accuracy of observer experience (experience vs inexperience) and how it compared with that of a cheaper automated system of photogrammetry ("the science of measuring in photographs" (Linder 2009; Postma *et al.* 2015; Marchal *et al.* 2016)). This study found that whilst experienced observers were better at determining flight height when compared to inexperienced observers, flight height by observers was generally underestimated when compared to photogrammetry estimates. Inaccurate flight height estimates could negatively impact the population, as areas deemed safe for vulture flight may in actual fact, still fall within the rotor swept zone of turbines, creating additional mortalities to an already threatened species. Thus, establishing accurate methods of determining flight height should be a priority in order to become a valuable tool for monitoring and conservation of threatened species.

6.3 Discussion and recommendations

With the review of the literature in Chapter 2, we identified gaps concerning aspects of pre- and post-construction monitoring and mitigation measures. One of the biggest challenges to date entails the accurate assimilation of information on behavioural and flight data during monitoring. Whilst vantage point surveys conducted by observers are the most cost-effective method, the continued results found from studies concerning the spatial inaccuracy of data obtained (Band *et al.* 2007; McClure *et al.*

2018; Becker *et al.* 2020; Prinsloo *et al.* 2021) brings into question the validity of these results. Whilst monitoring activities (both pre- and post-construction) allow for socio-economic opportunities such as employment for local communities, methods that can verify flight height need to be considered. The consideration of automated monitoring systems in conjunction with human observers should be evaluated and continually assessed. Present automated monitoring methods employed within South Africa are few, however, as the development of wind energy is likely to increase, methods to accurately determine avian flight height and behaviour will become increasingly important. Additionally, given that pre-construction monitoring results are often used to create collision risk models, high quality data should be collected to ensure some level of accuracy within these models. Collision risk models also need to be carefully considered, and the validation of the models should be continually assessed and improved as more information becomes available.

Results from post-construction monitoring can be used to validate collision risk models, granted that consistent monitoring is conducted. Post-construction monitoring, namely carcass detection monitoring, can be improved with the employment of detection dogs, which have been shown to improve carcass detection significantly under variable conditions and target size (Drewitt and Langston 2008; Domínguez del Valle *et al.* 2020; Smallwood *et al.* 2020). Post-construction monitoring further needs to be collected over a long-term period to detect whether collision mortality changes over time and to consider species displacement or disturbance from the landscape. Importantly, there needs to be transparency between wind energy developers, researchers and consultants in sharing data and findings to ensure that no “science-policy-practice” gaps develop. Additionally, creating coherence across environmental impact assessment (EIA) reports and ensuring standardised reported between sites may allow for easier comparison of impacts. These reporting's may assist in updating present guidelines as more coherent information becomes available.

Cape Vultures spatial and temporal use of the environmental landscape is influenced by the species age (Piper *et al.* 1981; Piper *et al.* 1989) and as such, current conservation measures focusing on the protection of breeding colonies may not be sufficient to protect young birds that exhibit long range movements (Kane *et al.* 2016; Martens *et al.* 2018). Chapter 3, therefore, allowed for a clear understanding of the extent that different age classes use habitat patches in the landscape and the environmental variables associated with identified habitat patches. This study identified certain patches in the landscape as "high use areas", and these indicated areas where high vulture activity was present. These areas are likely to be areas of high sensitivity, and conservation efforts could focus on minimising threats within these areas as it is likely to afford protection to a number of individuals.

With wind energy development increasing in South Africa, the identification of these patches should be considered in the planning phase and treated as "no-go" areas for the establishment of wind turbines. The identification of these patches may further help refine buffers around colonies, a conservation measure currently employed to limit wind farm development in certain areas (Pfeiffer and Ralston Paton 2018; Venter *et al.* 2019). Further, high use areas displayed associations with roost sites, and this may indicate that the conservation and protection of roost sites should be considered. Identifying roost sites that are intensively used by Cape Vultures through further research may assist in refining the protection of these sites. Establishing relationships with community members and landowners who are located close to roost sites may aid in increasing the knowledge base and creating "conservation custodians" in these areas may aid in the monitoring of these sites.

Whilst high use areas may be concentrated areas in the landscape, corridor use by Cape Vultures may cover far more extensive areas of the landscape.

Cape Vultures within this study exhibited corridors considered to be “slow” or “fast” based on network metrics of speed and turning angle within pixels. Slow corridors were thought to be areas where birds were actively foraging or thermalling in the landscape, and as a result, flight height is speculated to be low within these areas. Therefore, it is advisable that should wind farm development be considered within these slow corridors, a precautionary approach is taken. Fast corridors within the landscape were also identified, and these may reflect areas where individuals are taking direct paths in the landscape to reach habitat patches. Fast corridors were associated with wind farms and renewable energy development zones (REDZ), and this could present a concern. If flight height within these identified areas is low, it could be possible that collision risk with wind turbines is likely. However, flight height was not included when determining habitat patches because not all telemetry units recorded this, and it would be warranted to investigate the flight height of birds to further examine the collision risk probability within areas. Identified corridors may become significant in the future as it is predicted that in response to climate change, the species may exhibit a range shift from their northern breeding territories to the more southerly distribution (Simmons and Jenkins 2007; Phipps *et al.* 2017). Thus, identified corridors may play a role in ensuring that movement between sites can occur with limited additional anthropogenic mortalities, and limiting the added threat of wind turbines within corridors needs to be carefully considered.

Understanding how Cape Vultures respond to anthropogenic mortalities could aid conservation management in identifying thresholds of concern. Wind farms may become a significant threat to Cape Vultures located within the south-eastern node

(SE node), in addition to the anthropogenic threats the species already face. The population viability analysis (PVA) in Chapter 5 indicated that current, low wind farm mortalities would cause a decline to the SE node, yet the overall population will remain stable. However, should wind farm mortality increase and the number of current wind farms double (currently 460 wind turbines within the species distribution would double to 920 wind turbines), the overall population will experience a decline. The decline of the south-eastern node is likely to have far reaching implications for the population. This node is said to be acting as a source population (Kleinhans and Willows-Munro 2019), and the decline of this node could have genetic implications in the long run. Whilst a genetic component was not included in the PVA's, this consideration should not be excluded when considering the future management plans for Cape Vultures. Furthermore, the PVA results should be considered a conservative estimate, as a number of caveats were identified, which could be addressed with future research. Anthropogenic threats (powerline interactions and poisoning incidents) within the models remained constant between years. This is unlikely to reflect the true nature of threats, which fluctuate between years. Additionally, the reported incidents of threats are considered to be an underestimation, as many incidents are believed to go unreported. Obtaining accurate mortality rates can be difficult for a species that exhibits extensive movement across the landscape and encouraging members of the public to be aware and report incidents of mortalities should be investigated. Perhaps the largest concern within the PVA, and a substantial shortfall in Cape Vulture conservation, is the number of breeding individuals within the SE node is currently unknown. As such, the information used to inform the models is dated. It is recommended that monitoring of colonies within this node should commence as soon as possible, mainly because if we are to understand the true extent that future wind farms are likely to have on the population, it is vital that we have an understanding of the present trend of the population. Further, whilst current guidelines recommend that 50 km buffers be established around breeding colonies, the results showed that while resident individuals in the SE node face a sharper decline when compared with dispersing individuals in the SE node (at mortality rates similar to Griffon Vultures from present numbers of operational turbines or at double the present operational turbine numbers), the overall population will continue to decline. This highlights the point that while buffers may protect resident individuals from wind turbine mortalities, the decline of dispersing individuals also needs to halt if the same population decline is to be minimised. Methods to protect dispersing individuals from turbine collisions requires further research. Wind farm developers also need to plan for curtailment methods if mortalities of Cape Vultures are experienced. The loss of electricity generation and financial costs should be factored in if wind farm developers continue to develop within the distribution of the Cape Vulture.

Lastly, Chapter 5 demonstrated that observer bias is prevalent when estimating bird flight heights, as has been found in other studies. Accurate flight height in proposed wind farms is vital to ensure that wind turbines are developed appropriately in the landscape and minimises collision risks. Methods of estimating flight height through automated systems such as radar is often costly, and photogrammetry may be an alternative, cost effective method that warrants further research. Additional studies should be conducted with this method to test its effectiveness across a range of proposed sites. Further, this study was limited to low flight heights (i.e., < 30 m) of Cape Vultures at supplementary feeding sites and not representative of all contexts and further research will need to focus on increased height to determine whether this method is appropriate and whether observer bias is still prevalent at higher observations.

6.4 Study constraints

To classify habitat use and identify clusters in Chapter 3, GPS tracking data was obtained from 29 individuals across three colonies. The tracking data was obtained from various sources for different vulture populations, and the data recording intervals varied from 15 min for juvenile individuals from Colleywobbles to two hours for adult individuals from Msikaba. Based on the variation in recording intervals, the tracking data were reset to one-hour intervals to create consistency throughout the study. Data that were recorded at less than hourly intervals were interpolated evenly to provide hourly fixes. This interval was considered a conservative choice, whilst other studies have demonstrated greater variation between intervals (Phipps *et al.* 2013b; Kane *et al.* 2016; Jobson *et al.* 2021). Future considerations going forward may include resetting data to more frequent intervals. However, it must be considered that if this is done, more intersected points along a straight line will be included. With this comes the associated risk of minimising turning angles between points and the subsequent influence of interpretation of results. Furthermore, the investigation of corridors using network theory could lead to the potential concern of small and scattered data. This concern stems from the use of the different age classes of Cape Vultures, where these age classes are centred around certain colonies (juveniles from Colleywobbles and immatures from MzimKhulu). Although these birds originate from these colonies, once they have fledged, they are no longer confined to foraging within a daily radius from the colony (Martens *et al.* 2018). For this reason, the necessity for having immature and juvenile birds tagged at different colonies should have minimal impact on the clusters used by these birds. However, we do not argue that incorporation of additional juvenile and immature birds in this analysis could only strengthen our understanding of Cape Vulture cluster use, and the additional areas that may be identified as important through a greater number of tracked birds in this study, should it become available. More data are likely to become available in the near future as GPS satellite trackers are fitted to these age classes and we acknowledge the fact that revision of these analyses when more data becomes available will benefit Cape Vulture conservation in the future. Additionally, whilst vultures are likely to use areas within Lesotho, these areas were excluded from the analysis as different management practices and conservation agencies occur between the two countries. However, the Cape Vulture population should be managed as a single population within the SE node (Kleinhans and Willows-Munro 2019), and conservation organisations between the two countries should establish collaborations for the protection of the Cape Vulture.

With the spatially implicit PVA, threats from power lines and poisoning did not differ between models because they were treated as baseline threats. These values are likely to fluctuate between years and areas, and this may not have been adequately captured by the models. The largest constraint of the PVA pertains to the available demographic and population values. Demographic values were extensively studied by Piper (1994), and whilst these figures are likely to have changed in the past 27 years, to what extent is unknown. Further, literature values were used to inform the starting population of the PVA. Whilst the values have changed, as demonstrated between the NE node colony monitoring figures between 2013 and 2019 (Allan 2015; Hirschauer *et al.* 2020), the extent within the SE node remains unknown. With the rapid development of wind farms expected to occur within the SE node, to assess the true impact of wind turbines on Cape Vulture populations, it is necessary to have a clear understanding of the current status of the species within this node. Therefore, it is critical that present colony monitoring figures are obtained to determine whether the population is experiencing a decline as wind farm development increases in the future. Furthermore, the SE node is considered to be acting as a source population, and the decline of this population could have crucial implications. As previously mentioned, the PVA's conducted were unable to incorporate genetic components within simulations, however, this should further be explored to assess the true extent of the likely population extinction and the genetic consequences. Lastly, a spatially explicit PVA may provide further guidance on where conservation management could focus their efforts on areas causing unusually high mortality rates.

Whilst Chapter 5 examined a relatively new method of obtaining vulture flight heights and compared with observer accuracy, the sample size used in the study was small. This sample size (two experienced and two inexperienced observers) was mostly constrained by the number of individuals that were able to fit in the bird hide. Future research could increase the sample size of observers used and examine the effectiveness of this method under a variety of conditions. A further constraint of this method that needs consideration is its limitation of use in fair weather conditions.

6.5 Areas of future research

Whilst certain knowledge aspects of Cape Vultures have been reported in this study, a number of further research questions have been raised.

Whilst Chapter 3 identified habitat patches and cluster use of Cape Vultures within the landscape, it may be necessary to consider the temporal use of the landscape. If certain behaviours are likely to occur during certain times of the day (i.e., fast corridors in the evening when individuals are returning to the breeding colony), or during certain seasons (post-fledging dependence period of juveniles) within close proximity to established wind farms, could this allow for the consideration of particular mitigation measures at specified times? A further examination of flight height in relation to the topography within identified areas may provide information on the likely collision probability risk of turbine blades. Given that flight height is often correlated with weather conditions (Duriez *et al.* 2014), it could be worthwhile examining the interaction of flight height and weather conditions extrapolated within identified areas, and whether conditions could be used to determine the likely flight behaviour of Cape Vultures. Additionally, with the increasing development of wind farms, habitat patches may become unavailable to birds, and how this is likely to affect bird movement in the landscape needs to be understood. A process known as rewiring is often conducted with network analysis, where theoretically, parts of the landscape become unavailable. Using this rewiring process, it may be possible to identify areas that should be considered “no-go” areas for wind farm development as it may have irreversible consequences on the population.

The Population Viability Analyses (PVA) conducted on Cape Vultures were spatially implicit and threats, other than wind farm mortalities, were treated as baseline threats. It may however be worthwhile to further examine the impact that each individual threat is having on the output of the PVA (i.e., which threat is causing the greatest decline), and this could be done through a sensitivity analysis. Additionally, conducting a spatially explicit PVA may also provide further information as to where the greatest number of threats are occurring in the landscape and how management organisations can address these issues.

The use of photogrammetry in determining flight height of birds is relatively new and warrants further exploration as potentially a more accurate and cost-effective method. In order to test the accuracy of photogrammetry in the landscape across different conditions, the identification of a drone may give an indication to the accuracy of flight height and distance measured on the device to that measured via photogrammetry. It would further be useful to have a comparison between automated monitoring systems such as radar, photogrammetry and IdentiFlight. The comparison can assess the economic viability of each system, the practicality of the system, and the accuracy between systems.

However, perhaps the most urgent of future research needs to be focused on obtaining current, up to date colony monitoring information if we are to understand the true impact that wind farms are likely to have on this population. Presently there is limited or no monitoring being conducted at colonies within the Eastern Cape, which presents a shortfall in the current conservation management of the species. Extensive colony monitoring is being conducted on species within the northern regions of this species distribution, and conservation agencies need to mirror these efforts. Monitoring protocols have been established (Wolter *et al.* 2011), and the relevant conservation and management organisations need to ensure that these are carried out systematically and timeously.

6.6 Concluding remarks

In this thesis, important baseline information for understanding Cape Vultures and wind farms is provided. South Africa is in a unique position in that it can establish wind farms that have limited impacts on Cape Vultures. A review of traits that make the Cape Vulture vulnerable to collision has been provided and highlighted methods that can be used to further improve pre- and post-construction monitoring at wind farms and limit collision risks at operational farms through proven mitigation measures.

Furthermore, area use within the landscape has been identified. This provided information on how patches in the landscape were being used, and this information can be used to inform the appropriate placement of wind turbines in the future. Importantly, this thesis gives an indication of the Cape Vulture population viability in the face of a novel threat. The results from this study should be used as a warning sign, and conservation actions should aim to prevent the decline of this species.

It is hoped that this thesis can significantly contribute to the future conservation of Cape Vultures should wind energy development continues to pose a threat to the species. While developing renewable energy is necessary, it is important that biodiversity loss, and notably an endemic species that is ecologically valuable, is not the cost.

7. REFERENCES

Ainslie, A. (2002). Cattle Ownership and production in the communal areas of the Eastern Cape, South Africa. Programme for Land and Agrarian Studies, Cape Town.

Allan, D. (2015). Cape Vulture *Gyps coprotheres*. In 'The Eskom Red Data Book of Birds of South Africa, Lesotho and Swaziland'. (Eds M. Taylor, F. Peacock, and R. Wanless.) (BirdLife South Africa: Johannesburg.) Available at: http://speciesstatus.sanbi.org/assessment/last-assessment/2766/

Allan, D., Benson, P., Pfeiffer, M., and Theron, N. (2013). Cape Vulture *Gyps coprotheres* caught in a gin trap. *Vulture News* **64**, 50–54.

Anderson, D., Arkumarev, V., Bildstein, K., Botha, A., Bowden, C., Davies, M., Duriez, O., Forbes, N., Godino, A., Green, R., Kruger, S., Lambertucci, S., Orr-Ewing, D., Parish, C., Parry-Jones, J., and Weston, E. (2020). A practical guide to methods for attaching research devices to vultures and condors. *Vulture News 78a*, 1–72.

Aresu, M., Rotta, A., Fozzi, A., Campus, A., Muzzeddu, M., Secci, D., Fozzi, I., De Rosa, D., and Berlinguer, F. (2020). Assessing the effects of different management scenarios on the conservation of small island vulture populations. *Bird Conservation International*. doi:10.1017/S0959270920000040

Bamford, A., Monadjem, A., and Hardy, I. (2009). An effect of vegetation structure on carcass exploitation by vultures in an African savanna. *Ostrich* **80**, 135–137.

Band, W., Madders, M., and Whitfield, D. P. (2007). Developing field and analytical methods to assess avian collision risk at wind farms. In 'Birds and Wind Farms Risk Assessment and Mitigation'. pp. 259–275 Available at: http://www.vliz.be/imis/imis.php?module=ref&refid=111981&request=1

22779

Barnes, K., Johnson, D., Anderson, M., and Taylor, P. (2001). South Africa. In 'Important Bird Areas in Africa and associateed islands: Priority sites for conservation'. (Eds D. Fishpool and M. Evans.) pp. 793–876. (Pisces Publications and BirdLife International: Newbury and Cambridge, UK.)

Barrios, L., and Rodríguez, A. (2004). Behavioural and environmental correlates of soaring-bird mortality at on-shore wind turbines. *Journal of Applied Ecology* **41**, 72–81. doi:10.1111/j.1365-2664.2004.00876.x

Bastille-Rousseau, G. (2020). moveNT: an R package for the analysis of movement data using network theory. Available at: https://github.com/BastilleRousseau/moveNT.

Bastille-Rousseau, G., Douglas-Hamilton, I., Blake, S., Northrup, J. M., and Wittemyer, G. (2018). Applying network theory to animal movements to identify properties of landscape space use. *Ecological Applications* **28**, 854–864. doi:10.1002/eap.1697

Bastille-Rousseau, G., and Wittemyer, G. (2020). Characterizing the landscape of movement to identify critical wildlife habitat and corridors. *Conservation Biology* **35**, 346–359. doi:10.1111/cobi.13519

Becker, F. K., Milikin, R. L., and Leslie, A. J. (2020). Using radar technology to assess visual monitoring accuracy of Cape Vulture movements. *Ostrich* **91**, 83–90. doi:10.2989/00306525.2019.1664673

Beilis, N., and Esterhuizen, J. (2006). The potential impact on Cape Griffon *Gyps coprotheres* populations due to the trade in traditional medicine in Maseru, Lesotho. *Vulture News* **53**, 15–19. doi:10.4314/vulnew.v53i1.37630

Benson, P. . (2015). A Survey of Cape Vulture Breeding Colonies in South Africa's

Northern Provinces (Transvaal Region)- an update 2013. *Ornithological observations* **6**, 31–36.

Benson, P., and McClure, C. J. (2019). The decline and rise of the Kransberg Cape Vulture colony over 35 years has implications for composite population indices and survey frequency. *Ibis*.**162, 863-872.** doi:https://doi.org/10.1111/ibi.1278

Bergsten, A., and Zetterberg, A. (2013). To model the landscape as a network: A practitioner's perspective. *Landscape and Urban Planning* **119**, 35–43. doi:https://doi.org/10.1016/j.landurbplan.2013.06.009

Berthiaume, E., Bélisle, M., and Savard, J. (2009). Incorporating detectability into analyses of population trends based on hawk counts: a double - observer approach. *The Condor* **111**, 43–58.

BirdLife International (2015). Gyps coprotheres. *The IUCN Red List of Threatened Species 2016*. Available at: http://dx.doi.org/10.2305/IUCN.UK.2015-

BirdLife International (2017). *Gyps coprotheres* (amended version of 2016 assessment). The IUCN Red List of Threatened Species 2017. doi:https://dx.doi.org/10.2305/IUCN.UK.2017-3.RLTS.T22695225A118592987.en.

BirdLife International (2020). Important Bird Areas factsheet: De Hoop Nature Reserve. Available at: http://www.birdlife.org

BirdLife South Africa (2015). Important Bird Areas of the Eastern Cape. Available at: http://www.birdlife.org.za/images/IBA/Brochures/IBA_Eastern_Cape.pdf

Bodin, Ö., and Saura, S. (2010). Ranking individual habitat patches as connectivity providers: Integrating network analysis and patch removal experiments. *Ecological Modelling* **221**, 2393–2405. doi:10.1016/j.ecolmodel.2010.06.017

Borello, W. D., and Borello, R. M. (2002). The breeding status and colony dynamics of Cape Vulture Gyps coprotheres in Botswana. *Bird Conservation International* **12**, 79–97. doi:10.1017/S0959270902002058

Bosé, M., Duriez, O., and Sarrazin, F. (2012). Intra-specific competition in foraging Griffon Vultures *Gyps fulvus*: 1. Dynamics of group feeding. *Bird Study* **59**, 189–192. doi:https://doi.org/10.1080/00063657.2012.658639

Boshoff, A., Barkhuysen, A., Brown, G., and Michael, M. (2009a). Evidence of partial migratory behaviour by the Cape Griffon *Gyps coprotheres*. *Ostrich* **80**, 129–133. doi:10.2989/OSTRICH.2009.80.3.1.964

Boshoff, A. F., and Anderson, M. D. (2006). Towards a conservation plan for the Cape Griffon *Gyps coprotheres*: identifying priorities for research and conservation action. Available at: http://ace.nmmu.ac.za/ace/media/Store/documents/Technical reports/ACE-Report-55-Conservation-plan-Cape-Griffon.pdf

Boshoff, A. F., and Currie, M. H. (1981). Notes on the Cape Vulture colony at Potberg, Bredasdorp. *Ostrich* **52**, 1–8. doi:10.1080/00306525.1981.9633575org/10.1080/00306525.1981.9633575

Boshoff, A. F., Minnie, J. C., Tambling, C. J., and Michael, M. D. (2011). The impact of power line-related mortality on the Cape Vulture Gyps coprotheres in a part of its range, with an emphasis on electrocution. *Bird Conservation International* **21**, 311–327. doi:10.1017/S095927091100013X

Boshoff, A. F., Piper, S. ., and Michael, M. (2009b). On the distribution and breeding status of the Cape Griffon *Gyps coprotheres* in the Eastern Cape province, South Africa. *Ostrich* **80**, 85–92. doi:10.2989/OSTRICH.2009.80.2.4.831

Boshoff, A. F., and Robertson, A. S. (1985). Post-nestling mortality in Cape Vultures. *Ostrich* **56**, 204–207. doi:10.1080/00306525.1985.9639589

Boshoff, A. F., and Vernon, C. J. (1980). The past and present distribution and status of the Cape Vulture in the Cape Province. *Ostrich* **51**, 230–250. doi:10.1080/00306525.1980.9633570

Boshoff, A., and Minnie, J. (2011). On the role of the shape and size of foraging area, and colony size, in selecting critical areas for Cape Griffon *Gyps coprotheres* conservation action. *Vulture News* **61**, 4–15. doi:10.4314/vulnew.v61i1.1

Botha, A., Allan, D., Krueger, S., Neethling, M., Neser, W., Pfeiffer, M., Ronaldson, S., Shaw, K., Webster, K., Uys, R., Wolter, K., van Wyk, J., and Venter, J. (2012). Cape Vulture Task Force Report 2012. Johannesburg.

Botha, A., Andevski, J., Bowden, C. G. R., Gudka, M., Safford, R. J., and Williams, N. (2017). Multi-species action plan to conserve African-Eurasian Vultures. CMS Raptors MOU Technical Publication No. 5 CMS Technical Series. Available at: https://www.cms.int/raptors/en/publication/multi-species-action-plan-conserve-african-eurasian-vultures-vulture-msap-1

Brink, C. W., Santangeli, A., Amar, A., Wolter, K., Tate, G., Krüger, S., Tucker, A. S., and Thomson, R. L. (2020). Quantifying the spatial distribution and trends of supplementary feeding sites in South Africa and their potential contribution to vulture energetic requirements. *Animal Conservation* **23**, 491–501. doi:10.1111/acv.12561

Buechley, E. R., and Şekercioğlu, Ç. H. (2016). The avian scavenger crisis: Looming extinctions, trophic cascades, and loss of critical ecosystem functions. *Biological Conservation* **198**, 220–228. doi:10.1016/j.biocon.2016.04.001

Camiña, A. (2011). The effect of wind farms on vultures in Northern Spain: fatalities, behaviour and correction measures. In ‘Proceedings on the Conference on wind energy and wildlife impacts'. (Eds R. May and K. Bevanger.) (Trondheim, Norway.)

Carrete, M., Sánchez-Zapata, J. A., Benítez, J. R., Lobón, M., and Donázar, J. A. (2009). Large scale risk-assessment of wind-farms on population viability of a globally endangered long-lived raptor. *Biological Conservation* **142**, 2954–2961. doi:10.1016/j.biocon.2009.07.027

Carrete, M., Sánchez-Zapata, J., Benítez, J., Lobón, M., Montoya, F., and Donázar, J. (2012). Mortality at wind-farms is positively related to large-scale distribution and aggregation in griffon vultures. *Biological Conservation* **145**, 102–108. doi:10.1016/j.biocon.2011.10.017

Caswell, H. (2001). 'Matrix population models'. (Sinauer Associates Inc: Sunderland.)

Chevallier, C., Hernández-Matias, A., Real, J., Vincent-Martin, N., Ravayrol, A., and Besnard, A. (2015). Retrofitting of power lines effectively reduces mortality by electrocution in large birds: an example with the endangered Bonelli's eagle. *Journal of Applied Ecology* **52**, 1465–1473.

Cumming, G. S., Bodin, Ö., Ernstson, H., and Elmqvist, T. (2010). Network analysis in conservation biogeography: challenges and opportunities. *Diversity and Distributions* **16**, 414–425. doi:10.1111/j.1472-4642.2010.00651.x

DEA (2013). National Stategic Environmental Assessment for the Efficient and Effective Rollout of Wind and Solar Photovoltaic Energy. Available at: http://www.savetheeaglesinternational.org.za/wp-content/uploads/docs/CSIR/DEA_Wind_and_Solar_PV_SEA_Study_Area_Metadata_and_Notes.pdf

Department: Forestry Fisheries and the Environment (2021). Geographical areas for the development of renewable energy development zones gazettes. Available at: https://www.environment.gov.za/mediarelease/geographicalzones_renewableenergydevelopmentzones

Department of Environmental Affairs (2018). South African National Land Cover (SANLC). Available at: https://egis.environment.gov.za/data_egis/data_download/current

Department of Environmental Affairs (2015). Wind and Solar PV Energy Strategic Environmental Assessments- REDZ database. Available at: https://egis.environment.gov.za/data_egis/data_download/current

Dermody, B. J., Tanner, C. J., and Jackson, A. L. (2011). The evolutionary pathway to obligate scavenging in *Gyps* vultures. *PloS one* **6**, e24635. doi:10.1371/journal.pone.0024635

DeVault, T. L., Seamans, T. W., Blackwell, B. F., Lima, S. L., Martinez, M. A., and Fernández-Juricic, E. (2017). Can experience reduce collisions between birds and vehicles? *Journal of Zoology* **301**, 17–22. doi:10.1111/jzo.12385

Deygout, C., Gault, A., Sarrazin, F., and Bessa-Gomes, C. (2009). Modeling the impact of feeding stations on vulture scavenging service efficiency. *Ecological Modelling* **220**, 1826–1835.

Domínguez del Valle, J., Cervantes Peralta, F., and Jaquero Arjona, M. I. (2020). Factors affecting carcass detection at wind farms using dogs and human searchers. *Journal of Applied Ecology* **57**, 1926–1935. doi:10.1111/1365-2664.13714

Drewitt, A. L., and Langston, R. H. W. (2006). Assessing the impacts of wind farms on birds. *Ibis* **148**, 29–42. doi:10.1111/j.1474-919X.2006.00516.x

Drewitt, A. L., and Langston, R. H. W. (2008). Collision effects of wind-power generators and other obstacles on birds. *Annals of the New York Academy of Sciences* **1134**, 233–66. doi:10.1196/annals.1439.015

Dupont, H., Mihoub, J. B., Becu, N., and Sarrazin, F. (2011). Modelling interactions between scavenger behaviour and farming practices: Impacts on scavenger population and ecosystem service efficiency. *Ecological Modelling* **222**, 982–992. doi:10.1016/J.ECOLMODEL.2010.11.029

Dupont, H., Mihoub, J. B., Bobbé, S., and Sarrazin, F. (2012). Modelling carcass disposal practices: Implications for the management of an ecological service provided by vultures. *Journal of Applied Ecology* **49**, 404–411. doi:10.1111/j.1365-2664.2012.02111.x

Duriez, O., Kato, A., Tromp, C., Dell'Omo, G., Vyssotski, A. L., Sarrazin, F., and Ropert-Coudert, Y. (2014). How cheap is soaring flight in raptors? A preliminary investigation in freely-flying vultures. *PloS one* **9**, e84887. doi:10.1371/journal.pone.0084887

Ehlers Smith, D. A., Ehlers Smith, Y. C., and Downs, C. T. (2019). Promoting functional connectivity of anthropogenically-fragmented forest patches for multiple taxa across a critically endangered biome. *Landscape and Urban Planning* **190**, 103579. doi:10.1016/j.landurbplan.2019.05.010

Eiserer, L. (1984). Communal Roosting in Birds. *Bird Behaviour* **5**, 61–80.

European Commission (2020). Guidance document on wind energy developments and EU nature legislation.

Evans, J. (2020). _spatialEco_. R package version 1.3-4. Available at: https://github.com/jeffreyevans/spatialEco

Ferrer, M., de Lucas, M., Janss, G. F. E., Casado, E., Muñoz, A. R., Bechard, M. J., and Calabuig, C. P. (2012). Weak relationship between risk assessment studies and recorded mortality in wind farms. *Journal of Applied Ecology* **49**, 38–46. doi:10.1111/j.1365-2664.2011.02054.x

Fortuna, M., Gómez-Rodríguez, C., and Bascompte, J. (2006). Spatial network structure and amphibian persistence in stochastic environments. *Proceedings of the Royal Society B* **273**, 1429–1434. doi:doi:10.1098/rspb.2005.3448

García-Ripollés, C., and López-López, P. (2011). Integrating effects of supplementary feeding, poisoning, pollutant ingestion and wind farms of two vulture species in Spain using a population viability analysis. *Journal of Ornithology* **152**, 879–888

García-Ripollés, C., López-López, P., and Urios, V. (2011). Ranging Behaviour of Non-Breeding Eurasian Griffon Vultures Gyps fulvus : A GPS-Telemetry Study. *Acta Ornithologica* **46**, 127–134. doi:10.3161/000164511X625892

Gore, M. L., Hübschle, A., Botha, A. J., Coverdale, B. M., Garbett, R., Harrell, R. M., Krüeger, S., Mullinax, J. M., Olson, L. J., Ottinger, M. A., Robinson, H. S., Shaffer, L. J., Thompson, L. J., van den Heever, L., and Bowerman, W. W. (2020). A conservation criminology-based desk assessment of vulture poisoning in the Great Limpopo Transfrontier Conservation Area. *Global Ecology and Conservation* **23**. doi:10.1016/j.gecco.2020.e01076

Harel, R., Horvitz, N., and Nathan, R. (2016). Adult vultures outperform juveniles in challenging thermal soaring conditions. *Scientific reports* **6**, 27865. doi:10.1038/srep27865

Hernández-Matias, A., Real, J., Moleón, M., Palma, L., Sánchez-Zapata, J., Pradel, R., Carrete, M., Gil-Sánchez, J., Beja, P., Balbontín, J., Vincent-Martin, N., Ravayrol, A., Benítez, J., Arroyo, B., Fernández, C., Ferreiro, E., and García, J.

(2013). From local monitoring to a broad-scale viability assessment: a case study for the Bonelli's Eagle in western Europe. *Ecological Monographs* **83**, 239–261.

Hernández-Matias, A., Real, J., Parés, F., and Pradel, R. (2015). Electrocution threatens the viability of populations of the endangered Bonelli's eagle (*Aquila fasciata*) in Southern Europe. *Biological Conservation* **191**, 110–116.

Hijmans, R. J. (2020). raster: Geographic Data Analysis and Modeling. R package version 3.4-5. Available at: https://cran.r-project.org/package=raster

Hirschauer, M. T., Wolter, K., Howard, A., Rolek, B. W., and McClure, C. J. W. (2020). Population growth rates in northern Cape Vulture Gyps coprotheres colonies between 2010 and 2019. *Bird Conservation International*, 1–10. doi:10.1017/S0959270920000465

Hirschauer, M. T., Wolter, K., and Neser, W. (2017). Natal philopatry in young Cape Vultures *Gyps coprotheres*. *Ostrich* **88**, 79–82. doi:10.2989/00306525.2017.1245683

Hodos, W. (2003). Minimization of Motion Smear: Reducing Avian Collisions with Wind Turbines: Period of Performance: July 12, 1999 – August 31, 2002. Available at: https://tethys.pnnl.gov/publications/minimization-motion-smear-reducing-avian-collisions-wind-turbines-period-performance

Howard, A., Hirschauer, M., Monadjem, A., Forbes, N., and Wolter, K. (2020). Injuries, mortality rates, and release rates of endangered vultures admitted to a rehabilitation center in South Africa. *Wildlife Rehabilitation* **40**, 15–23.

Hull, C., Stark, E., Peruzzo, S., and Sims, C. (2013). Avian collisions at two wind farms in Tasmania, Australia: taxonomic and ecological characteristics of colliders versus non-colliders. *New Zealand Journal of Zoology* **40**, 47–62.

Hunt, G. W., and Watson, J. W. (2016). Addressing the Factors that Juxtapose Raptors and Wind Turbines. *Journal of Raptor Research* **50**, 92–96. doi:10.3356/rapt-50-01-92-96.1

Jackson, C. R., Maddox, T., Mbise, F. P., Stokke, B. G., Belant, J. L., Bevanger, K., Durant, S. M., Fyumagwa, R., Ranke, P. S., Røskaft, E., May, R., and Fossøy, F. (2020). A dead giveaway: Foraging vultures and other avian scavengers respond to auditory cues. *Ecology and Evolution* **10**, 6769–6774. doi:10.1002/ECE3.6366

Jacoby, D., Brooks, E., Croft, D., and Sims, D. (2012). Developing a deeper understanding of animal movements and spatial dynamics through novel application of network analyses. *Methods in Ecology and Evolution* **3**, 574–583. doi:doi: 10.1111/j.2041-210X.2012.00187.x

Jacoby, D., and Freeman, R. (2016). Emerging network-based tools in movement ecology. *Trends in Ecology and Evolution* **31**, 301–314. doi:http://dx.doi.org/10.1016/j.tree.2016.01.011

Jenkins, A. R., Reid, T., Plessis, J. du, Colyn, R., Benn, G., and Millikin, R. (2018). Combining radar and direct observation to estimate pelican collision risk at a proposed wind farm on the Cape west coast, South Africa. *PLoS ONE* **13**. doi:10.1371/journal.pone.0192515

Jenkins, A. R., Van Rooyen, C. S., Smallie, J. J., Harrison, J. A., Diamond, M., Smit-Robinson, H. A., and Ralston, S. (2015). Birds and Wind-Energy Best-Practice Guidelines. Johannesburg. Available at: http://wildskies.co.za/wp-content/uploads/2015/04/BAWESG_Monitoring-guidelines_2nd-Revision-_16July14.pdf

Jenkins, A. R., Smallie, J. J., and Diamond, M. (2010a). Avian collisions with power lines: a global review of causes and mitigation with a South African perspective. *Bird Conservation International* **20**, 263–278. Available at: http://www.tandfonline.com/doi/abs/10.1080/00306525.1984.9634488

Jenkins, A. R., Smallie, J. J., and Diamond, M. (2010b). Avian collisions with power lines: a global review of causes and mitigation with a South African perspective. *Bird Conservation International* **20**, 263–278. doi:10.1017/S0959270910000122

Jiménez, R., Pérez-Garcia, J. and Margalida, A. (2018). Drivers of daily movement patterns affecting an endangered vulture flight activity. *BMC Ecology* **18**. Available at: https://doi.org/10.1186/s12898-018-0195-7

Jobson, B., Wolter, K., Jordan, L., Monadjem, A., and Rowcliffe, J. M. (2021). Home range and habitat selection of captive-bred and rehabilitated cape vultures *Gyps coprotheres* in southern Africa. *ORYX* **55**, 607–612. doi:10.1017/S0030605319000814

Johnston, A., Cook, A., Wright, L., Humphreys, E., and Burton, N. (2014). Modelling flight heights of marine birds to more accurately assess collision risk with offshore wind turbines. *Journal of Applied Ecology* **51**, 31–41.

Kane, A., Wolter, K., Neser, W., Kotze, A., Naidoo, V., and Monadjem, A. (2016). Home range and habitat selection of Cape Vultures *Gyps coprotheres* in relation to supplementary feeding. *Bird Study* **63**, 387–394. doi:10.1080/00063657.2016.1214105

Kepe, T. (1997). Communities, Entitlements and Nature Reserves: The Case of the Wild Coast, South Africa. *IDS Bulletin* **28**, 47–58. doi:10.1111/j.1759-5436.1997.mp28004006.x

Kleinhans, C., and Willows-Munro, S. (2019). Low genetic diversity and shallow population structure in the endangered vulture, Gyps coprotheres. *Scientific*

Reports **9**, 5536. doi:10.1038/s41598-019-41755-4

Kleyheeg-Hartman, J. ., Krijgsveld, K. L., Collier, M. P., Poot, M. J. M., Boon, A. R., Troost, T. A., and Dirksen, S. (2018). Predicting bird collisions with wind turbines: Comparison of new empirical Flux Collision Model with the SOSS Band model. *Ecological Modelling* **387**, 144–153.

Knight, S. M., Bradley, D. W., Clark, R. G., Gow, E. A., and Belisle, M. (2018). Constructing and evaluating a continent-wide migratory songbird network across the annual cycle. *Ecological Monographs* **88**, 445–460. doi:10.1002/ecm.1298

Krijgsveld, K. ., Akershoek, K., Schenk, F., Dijk, F., and Dirksen, S. (2009). Collision risks of birds with modern large wind turbines. *Ardea* **97**, 357–366.

Krüger, S., Reid, T., and Amar, A. (2014). Differential range use between age classes of southern African Bearded Vultures *Gypaetus barbatus*. *PloS ONE* **9**, e114920. doi:10.1371/journal.pone.0114920

Leepile, L. B. L., Maude, G., Hancock, P., Reading, R. P., Bridges, B., Hartley, R., and Amar, A. (2020). Changes in nesting numbers and breeding success of African White-backed Vulture *Gyps africanus* in north-central Botswana. *Bird Conservation International* **30**, 456–473. doi:10.1017/S0959270920000179

Legendre, S., and Clobert, J. (1995). ULM, a software for conservation and evolutionary biologists. *Journal of Applied Statistics* **22**, 817–834. doi:10.1080/02664769524649

Lembo, T., Hampson, K., Haydon, D. T., Craft, M., Dobson, A., Dushoff, J., Ernest, E., Hoare, R., Kaare, M., Mlengeya, T., Mentzel, C., and Cleaveland, S. (2008). Exploring reservoir dynamics: a case study of rabies in the Serengeti ecosystem. *Journal of Applied Ecology* **45**, 1246–1257. doi:10.1111/J.1365-2664.2008.01468.X

Leung, D. Y. C., and Yang, Y. (2012). Wind energy development and its environmental impact: A review. *Renewable and Sustainable Energy Reviews* **16**, 1031–1039. doi:10.1016/j.rser.2011.09.024

Linder, W. (2009). ‘Digital photogrammetry: A practical course’ 3rd ed. (Springer Berlin Heidelberg: Berlin.) doi:10.1007/978-3-540-92725-9

Loss, S. R., Will, T., and Marra, P. P. (2015). Direct Mortality of Birds from Anthropogenic Causes. *Annual Review of Ecology, Evolution, and Systematics* **46**, 99–120. doi:10.1146/annurev-ecolsys-112414-054133

de Lucas, M., Ferrer, M., Bechard, M. J., and Muñoz, A. R. (2012a). Griffon vulture mortality at wind farms in southern Spain: Distribution of fatalities and active mitigation measures. *Biological Conservation* **147**, 184–189. doi:10.1016/j.biocon.2011.12.029

de Lucas, M., Ferrer, M., and Janss, G. F. E. (2012b). Using wind tunnels to predict bird mortality in wind farms: the case of griffon vultures. *PloS one* **7**, e48092. doi:10.1371/journal.pone.0048092

de Lucas, M., Janss, G. E., Whitfield, D. P., and Ferrer, M. (2008). Collision fatality of raptors in wind farms does not depend on raptor abundance. *Journal of Applied Ecology* **45**, 1695–1703. doi:10.1111/j.1365-2664.2008.01549.x

Marchal, A. F. ., Lejeune, P., and de Bruyn, P. J. . (2016). Virtual plaster cast: digital 3D modelling of lion paws and tracks using close-range photogrammetry. *Journal of Zoology* **300**, 111–119. doi:10.1111/jzo.12342

Markandya, A., Taylor, T., Longo, A., Murty, M. ., Murty, S., and Dhavala, K. (2008). Counting the cost of vulture decline—An appraisal of the human health and other benefits of vultures in India. *Ecological Economics* **67**, 194–204. doi:10.1016/J.ECOLECON.2008.04.020

Marnewick, M., Retief, E., Theron, N., Wright, D., and Anderson, T. (2015). ‘Important Bird and Biodiversity Areas of South Africa’ second. (BirdLife South Africa: Johannesburg.) Available at: https://www.birdlife.org.za/images/IBA/Documents/IBA Version 2.pdf

Marques, A. T., Batalha, H., Rodrigues, S., Costa, H., Pereira, M. J. R., Fonseca, C., Mascarenhas, M., and Bernardino, J. (2014). Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies. *Biological Conservation* **179**, 40–52. doi:10.1016/j.biocon.2014.08.017

Martens, F. R., Pfeiffer, M. B., Downs, C. T., and Venter, J. A. (2020). Cliff roost site selection of the endangered Cape Vulture *Gyps coprotheres* in the Eastern Cape province, South Africa. *Ostrich* **91**, 25–34. doi:10.2989/00306525.2019.1651417

Martens, F. R., Pfeiffer, M. B., Downs, C. T., and Venter, J. A. (2018). Post-fledging movement and spatial ecology of the endangered Cape Vulture (Gyps coprotheres). *Journal of Ornithology* **159**, 913–922.

Martin, G. R. (2011). Understanding bird collisions with man-made objects: a sensory ecology approach. *Ibis* **153**, 239–254. doi:10.1111/j.1474-919X.2011.01117.x

Martin, G. R., Portugal, S. J., and Murn, C. P. (2012). Visual fields, foraging and collision vulnerability in *Gyps* vultures. *Ibis* **154**, 626–631. doi:10.1111/j.1474-919X.2012.01227.x

Martínez-Abraín, A., Tavecchia, G., Regan, H. M., Jiménez, J., Surroca, M., and Oro, D. (2012). Effects of wind farms and food scarcity on a large scavenging bird species following an epidemic of bovine spongiform encephalopathy. *Journal of Applied Ecology* **49**, 109–117. doi:10.1111/j.1365-2664.2011.02080.x

Mashele, N. M., Thompson, L. J., and Downs, C. T. (2021b). Traditional health practitioners' and other community members' perceptions of vultures in the Kruger to Canyons Biosphere Region, South Africa. *Journal of Raptor Research* **55**, 340–358.

Mashele, N. M., Thompson, L. J., and Downs, C. T. (2021a). Uses of Vultures In Traditional Medicines In the Kruger To Canyons Biosphere Region, South Africa. *Journal of Raptor Research*. doi:10.3356/JRR-20-36

Matos, C., Petrovan, S. O., Wheeler, P. M., and Ward, A. I. (2019). Landscape connectivity and spatial prioritization in an urbanising world: A network analysis approach for a threatened amphibian. *Biological Conservation* **237**, 238–247. doi:10.1016/j.biocon.2019.06.035

May, R., Gill, A. B., Köppel, J., Langston, R. H. W., Reichenbach, M., Scheidat, M., Smallwood, S., Voigt, C. C., Hüppop, O., and Portman, M. (2017). Future Research Directions to Reconcile Wind Turbine–Wildlife Interactions. In 'Wind Energy and Wildlife Interactions'. pp. 255–276 doi:10.1007/978-3-319-51272-3_15

May, R., Masden, E. ., Bennet, F., and Perron, M. (2019). Considerations for upscaling individual effects of wind energy development towards population-level impacts on wildlife. *Journal of Environmental Management* **230**, 94–93.

May, R., Nygård, T., Falkdalen, U., Åström, J., Hamre, Ø., and Stokke, B. G. (2020). Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. *Ecology and Evolution* **10**, 8927–8935. doi:10.1002/ece3.6592

McClure, C. J., Martinson, L., and Allison, T. (2018). Automated monitoring for birds in flight: Proof of concept with eagles at a wind power facility. *Biological Conservation* **224**, 26–33.

McClure, C. J. W., Schulwitz, S. E., Anderson, D. L., Robinson, B. W., Mojica, E. K., Therrien, J. F., Oleyar, M. D., and Johnson, J. (2019). Commentary: Defining Raptors and Birds of Prey. *Journal of Raptor Research* **53**, 419–430. doi:10.3356/0892-1016-53.4.419

McKean, S., and Mander, M. (2007). Traditional Medicine and the Vulture Trade. In 'South African Health Review'. (Eds S. Harrison, R. Bhana, and A. Ntuli.) pp. 197–199. (Health Systems Trust: Durban.)

McKean, S., Mander, M., Diederichs, N., Ntuli, L., Mavundla, K., Williams, V., and Wakelin, J. (2013). The impact of traditional use on vultures in South Africa. *Vulture News* **65**, 15–36. doi:10.4314/vulnew.v65i1.2

Moleón, M., Bautista, J., and Madero, A. (2011). Communal Roosting in Young Bonelli's Eagles (*Aquila fasciata*). *Journal of Raptor Research* **45**, 353–356. doi:10.3356/JRR-11-30.1

Monadjem, A., Anderson, M. D., Piper, S. E., and Boshoff, A. F. (2004). The Vultures of Southern Africa – Quo Vadis? Proceedings of a workshop on vulture research and conservation in southern Africa. Available at: https://www.researchgate.net/profile/Ian_Rushworth/publication/299668966_Status_and_conservation_of_vultures_in_KwaZulu-Natal_South_Africa/links/57040d6908ae74a08e245ec8/Status-and-conservation-of-vultures-in-KwaZulu-Natal-South-Africa.pdf#page=90

Monadjem, A., Kane, A., Botha, A., Kelly, C., and Murn, C. (2018). Spatially explicit poisoning risk affects survival rates of an obligate scavenger. *Scientific Reports* **8**. doi:10.1038/s41598-018-22632-y

Monadjem, A., Wolter, K., Neser, W., and Kane, A. (2014). Effect of rehabilitation on survival rates of endangered Cape vultures. *Animal Conservation* **17**, 52–60.

doi:10.1111/acv.12054

Mundy, P., Butchart, D., Ledger, J., and Piper, S. (1992). ‘The Vultures of Africa’. (Acorn Books: Randburg.)

Murgatroyd, M., Bouten, W., and Amar, A. (2020). A predictive model for improving placement of wind turbines to minimise collision risk potential for a large soaring raptor. *Journal of Applied Ecology*, 1–12. doi:10.1111/1365-2664.13799

Murn, C., and Botha, A. (2018). A clear and present danger: impacts of poisoning on a vulture population and the effect of poison response activities. *Oryx* **52**, 552–558. doi:10.1017/S0030605316001137

Nolte, E. G., Bart, J., Pauli, B. P., Kaltenecker, G. S., and Heath, J. A. (2016). Detectability of migrating raptors and its effect on bias and precision of trend estimates. *Avian Conservation and Ecology* **11**. doi:10.5751/ACE-00894-110209

Norris, K. (2004). Managing threatened species: the ecological toolbox, evolutionary theory and declining-population paradigm. *Journal of Applied Ecology* **41**, 413–426. doi:10.1111/j.0021-8901.2004.00910.x

Ogada, D., Botha, A., and Shaw, P. (2016). Ivory poachers and poison: drivers of Africa’s declining vulture populations. *Oryx* **50**, 593–596. doi:10.1017/S0030605315001209

Ogada, D. L., Keesing, F., and Virani, M. Z. (2012a). Dropping dead: causes and consequences of vulture population declines worldwide. *Annals of the New York Academy of Sciences* **1249**, 57–71. doi:10.1111/j.1749-6632.2011.06293.x

Ogada, D. L., Shaw, P., Beyers, R. L., Buij, R., Murn, C., Thiollay, J. M., Beale, C. M., Holdo, R. M., Pomeroy, D., Baker, N., Krüger, S. C., Botha, A., Virani, M. Z., Monadjem, A., and Sinclair, A. R. E. (2015). Another Continental Vulture Crisis: Africa’s Vultures Collapsing toward Extinction. *Conservation Letters* **9**, 89–97.

doi:10.1111/conl.12182

Ogada, D. L., Torchin, M. E., Kinnaird, M. F., and Ezenwa, V. O. (2012b). Effects of vulture declines on facultative scavengers and potential implications for mammalian disease transmission. *Conservation Biology* **26**, 453–60. doi:10.1111/j.1523-1739.2012.01827.x

Oloo, F., Safi, K., and Aryal, J. (2018). Predicting Migratory Corridors of White Storks, *Ciconia ciconia* , to enhance sustainable wind energy planning: a data-driven agent-based model. *Susitainability* **10**.

Pascual-Hortal, L., and Saura, S. (2006). Comparison and development of new graph-based landscape connectivity indices: Towards the priorization of habitat patches and corridors for conservation. *Landscape Ecology* **21**, 959–967. doi:10.1007/s10980-006-0013-z

Perold, V., Ralston-Paton, S., and Ryan, P. (2020). On a collision course? The large diversity of birds killed by wind turbines in South Africa. *Ostrich* **91**, 228–239. doi:10.2989/00306525.2020.1770889

Péron, G., Fleming, C. H., Duriez, O., Fluhr, J., Itty, C., Lambertucci, S. A., Safi, K., Shepard, E. L. C., and Calabrese, J. M. (2017). The energy landscape predicts flight height and wind turbine collision hazard in three species of large soaring raptor. *Journal of Applied Ecology*.

Péron, G., Hines, J. E., Nichols, J. D., Kendall, W. I., Peters, K. A., and Mizrahi, D. S. (2013). Estimation of bird and bat mortality at wind-power farms with superpopulation models Ed J. Matthiopoulos. *Journal of Applied Ecology* **50**, 902–911. doi:10.1111/1365-2664.12100

Pfeiffer, M. B. (2016). Ecology and Conservation of the Cape Vulture in the Eastern Cape Province, South Africa. University of KwaZulu-Natal.

Pfeiffer, M. B., and Ralston Paton, S. (2018). Cape Vulture and Wind Farms. Guidelines for impact assessment, monitoring and mitigation.

Pfeiffer, M. B., Venter, J. A., and Downs, C. T. (2016). Cliff characteristics, neighbour requirements and breeding success of the colonial Cape Vulture *Gyps coprotheres*. *Ibis* **159**, 26–37. doi:10.1111/ibi.12428

Pfeiffer, M. B., Venter, J. A., and Downs, C. T. (2015a). Foraging range and habitat use by Cape Vulture *Gyps coprotheres* from the Msikaba colony, Eastern Cape province, South Africa. *Koedoe* **57**, 1–11. doi:10.4102/koedoe.v57i1.1240

Pfeiffer, M. B., Venter, J. A., and Downs, C. T. (2015b). Identifying anthropogenic threats to Cape Vultures *Gyps coprotheres* using community perceptions in communal farmland, Eastern Cape Province, South Africa. *Bird Conservation International* **25**, 353–365. doi:10.1017/S0959270914000148

Phipps, W. L., Diekmann, M., MacTavish, L. M., Mendelsohn, J. M., Naidoo, V., Wolter, K., and Yarnell, R. W. (2017). Due South: A first assessment of the potential impacts of climate change on Cape vulture occurrence. *Biological Conservation* **210**, 16–25. doi:10.1016/j.biocon.2017.03.028

Phipps, W. L., Willis, S. G., Wolter, K., and Naidoo, V. (2013a). Foraging ranges of immature African white-backed vultures (*Gyps africanus*) and their use of protected areas in southern Africa. *PLoS ONE* **8**, e52813. doi:10.1371/journal.pone.0052813

Phipps, W. L., Wolter, K., Michael, M. D., MacTavish, L. M., and Yarnell, R. W. (2013b). Do Power Lines and Protected Areas Present a Catch-22 Situation for Cape Vultures (*Gyps coprotheres*)? *PLoS ONE* **8**, e76794. doi:10.1371/journal.pone.0076794

Piper, S. (2005). Cape Vulture *Gyps coprotheres*. In ‘Roberts Birds of Southern

Africa'. (Eds P. Hockey, W. Dean, and P. Ryan.) pp. 489–491. (The Trustees of the John Voelcker Bird Book Fund: Cape Town.)

Piper, S. (1994). Mathematical demography of the Cape Vulture. University of Cape Town.

Piper, S. E., Boshoff, A. F., and Scott, H. A. (1999). Modelling survival rates in the Cape Griffon *Gyps coprotheres*, with emphasis on the effects of supplementary feeding. *Bird Study* **46**, S230–S238. doi:10.1080/00063659909477249

Piper, S. E., Mundy, P. J., and Ledger, J. A. (1981). Estimates of Survival in the Cape Vulture, *Gyps coprotheres*. *Journal of Animal Ecology* **50**, 815–825. doi:10.2307/4139

Piper, S. E., Mundy, P. J., and Vernon, C. J. (1989). An ageing guide for the Cape Vulture. *Madoqua* **16**, 105–110. Available at: http://www.the-eis.com/data/literature/An ageing guide for the Cape Vulture.pdf

Piper, S., and Ruddle, P. (1986). An initial evaluation of the Cape Vulture colonies at Mkambati, Transkei. *Vulture News* **15**, 7–12.

Porter, G., and Phillips-Howard, K. (1997). Agricultural issues in the former homelands of South Africa: the Transkei. *Review of African Political Economy* **24**, 185–202. doi:10.1080/03056249708704252

Postma, M., Bester, M., and de Bruyn, P. J. (2013). Spatial variation in female southern elephant seal mass change assessed by an accurate non-invasive photogrammetry method. *Antartic Science* **25**, 731–740. doi:doi:10.1017/S0954102013000059

Postma, M., Tordiffe, A. S., Hofmeyr, M., Reisinger, R., Bester, L.., Buss, P., and de Bruyn, P. J. (2015). Terrestrial mammal three-dimensional photogrammetry: multispecies mass estimation. *Ecosphere* **6**, 293. doi:doi.org/10.1890/ES15-

00368.1

Prinsloo, N., Postma, M., Ryan, P., Coetzee, M., and de Bruyn, P. J. (2021). Estimating bird flight height using 3-D photogrammetry. *Journal of Zoology*. doi:doi:10.1111/jzo.12879

QGIS (2020). Quantum GIS geographic information system. Available at: http://www.qgis.org/

R Core Team (2020). R: A language and environment for statistical computing. Available at: https://www.r-project.org/.

Ralston Paton, S., Smallie, J., Pearson, A., and Ramalho, R. (2017). Wind energy's impacts on birds in South Africa: A preliminary review of the results of operational monitoring at the first wind farms of the Renewable Energy Independent Power Producer Procurement Programme in South South Africa. Johannesburg.

Rayfield, B., Fortin, M.-J., and Fall, A. (2011). Connectivity for conservation: a framework to classify network measures. *Ecology* **92**, 847–858.

Reid, T., Krüger, S. C., Whitfield, D. P., and Amar, A. (2015). Using spatial analyses of bearded vulture movements in southern Africa to inform wind turbine placement. *Journal of Applied Ecology* **52**, 881–892. doi:10.1111/1365-2664.12468

Retief, E., Diamond, M., Anderson, M. D., Smit, H., Jenkins, A., and Brooks, M. (2011). Avian Wind Farm Sensitivity Map for South Africa - Criteria and Procedures Used. Johannesburg. Available at: https://www.ewt.org.za/WEP/WindSensitivity/Wind Farm Species and Sensitivity Criteria Final.pdf

Robertson, A. S. (1985). Observations on the post-fledging dependence period of

Cape Vultures. *Ostrich* **56**, 58–66. doi:10.1080/00306525.1985.9639570

Van Rooyen, C. (2003). The Management of Wildlife Interactions with Overhead Power Lines. Available at: http://www.sapp.co.zw/documents/The Management of Wildlife Interactions with Overhead Powerlines.pdf

Rushworth, I., and Krüger, S. (2014). Wind farms threaten southern Africa's cliff-nesting vultures. *Ostrich* **85**, 13–23. doi:10.2989/00306525.2014.913211

Sarrazin, F., Bagnolini, C., Pinna, J. L., Danchin, E., and Clobert, J. (1994). High Survival Estimates of Griffon Vultures (*Gyps Fulvus Fulvus*) in a Reintroduced Population. *The Auk* **111**, 853–862.

Sattler, G., and Bart, J. (1984). Reliability of counts of migrating raptors: an experimental analysis. *Journal of Field Ornithology* **55**, 415–423.

Scacco, M., Arrondo, E., Donázar, J. A., Flack, A., Sanchez-Zapata, J. A., Duriez, O., Wikelski, M., and Safi, K. (2020). The species-specificity of energy landscapes for soaring birds and its consequences for the risk-assessment of anthropogenic infrastructures. *bioRxiv*, 2021.03.24.436775. doi:10.1101/2021.03.24.436775

Schabo, D. G., Heuner, S., Neethling, M. V, Rösner, S., Uys, R., and Farwig, N. (2017). Long-term data indicates that supplementary food enhances the number of breeding pairs in a Cape Vulture *Gyps coprotheres* colony. *Bird Conservation International* **27**, 140–152. doi:10.1111/aje.12178

Schultz, P. (2007). Does bush encroachment impact foraging success of the critically endangered Namibian population of the Cape Vulture *Gyps coprotheres*? University of Cape Town.

Scribner, K., Meffe, G., and Groom, M. (2006). Conservation Genetics: The Use and Importance of Genetic Information. In 'Principles of Conservation Biology'. (Eds

M. Groom, G. Meffe, and C. Carroll.) pp. 377–415. (Sinauer: Sunderland.)

Sebastián-González, E., Pérez-García, J. M., Carrete, M., Donázar, J. A., and Sánchez-Zapata, J. A. (2018). Using network analysis to identify indicator species and reduce collision fatalities at wind farms. *Biological Conservation* **224**, 209–212. doi:10.1016/j.biocon.2018.06.003

Shimazaki, H., Tamura, M., Darman, Y., Andronov, V., Parilov, M. P., Nagendran, M., and Higuchi, H. (2004). Network analysis of potential migration routes for Oriental White Storks (*Ciconia boyciana*). *Ecological Research* **19**, 683–698.

Simmons, R. E., and Jenkins, A. R. (2007). Is climate change influencing the decline of Cape and Bearded Vulures in southern Africa? *Vulture News* **56**, 41–51.

Smallwood, K. S. (2007). Estimating wind turbine-caused bird mortality. *The Journal of Wildlife Management* **71**, 2781–2791. doi:DOI: 10.2193/2007-006

Smallwood, K. S., Bell, D. A., and Standish, S. (2020). Dogs Detect Larger Wind Energy Effects on Bats and Birds. *Journal of Wildlife Management* **84**, 852–864. doi:10.1002/jwmg.21863

Spiegel, O., Harel, R., Centeno-Cuadros, A., and Hatzofe, O. (2015). Moving beyond Curve Fitting: Using Complementary Data to Assess Alternative Explanations for Long Movements of Three Vulture Species. *The American Naturalist* **185**.

Szewczuk, S. (2014). Review of the wind energy activities in South Africa. Available at: http://researchspace.csir.co.za/dspace/handle/10204/7522

Tauler, H., Real, J., Hernández-Matías, A., Aymerich, P., Baucells, J., Martorell, C., and Santandreu, J. (2015). Identifying key demographic parameters for the viability of a growing population of the endangered Egyptian Vulture *Neophron percnopterus*. *Bird Conservation International* **25**, 426–439.

Tellería, J. L. (2009). Overlap between wind power plants and Griffon Vultures *Gyps* *fulvus* in Spain. *Bird Study* **56**, 268–271. doi:10.1080/00063650902792056

Thaxter, C., Buchanan, G., Carr, J., Butchart, S. H., Newbold, T., Green, R., Tobias, J., Foden, W., O'Brien, S., and Pearce-Higgins, J. (2017). Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. *Proceedings of the Royal Society B: Biological Sciences* **284**.

Tomé, R., Canário, F., Leitão, A. H., Pires, N., and Repas, M. (2017). Radar Assisted Shutdown on Demand Ensures Zero Soaring Bird Mortality at a Wind Farm Located in a Migratory Flyway. In 'Wind Energy and Wildlife Interactions'. pp. 119–133. (Springer, Cham.) doi:10.1007/978-3-319-51272-3_7

Tsiakiris, R., Halley, J. M., Stara, K., Monokrousos, N., Karyou, C., Kassinis, N., Papadopoulos, M., and Xirouchakis, S. M. (2021). Models of poisoning effects on vulture populations show that small but frequent episodes have a larger effect than large but rare ones. *Web Ecology* **21**, 79–93. doi:10.5194/we-21-79-2021

UNEP-WCMC, and IUCN (2021). Protected Planet: The World Database on Protected Areas (WDPA). Available at: www.protectedplanet.net

Velevski, M., Grubač, B., and Tomovic, L. (2014). Population Viability Analysis of the Egyptian Vulture *Neophron percnopterus* in Macedonia and Implications for Its Conservation. *Acta Zoologica Bulgarica* **66**, 43–58. Available at: http://acta-zoologica-bulgarica.eu/downloads/acta-zoologica-bulgarica/2014/66-1-43-58.pdf

Venter, J. A., Martens, F. R., and Wolter, K. (2019). Conservation buffer sizes derived from movement data of adult Cape vultures (*Gyps coprotheres*) in South Africa. *African Zoology* **54**, 115–118. doi:10.1080/15627020.2019.1600428

Venter, J. A., Pfeiffer, M. B., and Downs, C. T. (2015). The flight and ranging behaviour of Cape Vultures (*Gyps coprotheres*): implications for wind turbine placement in the Eastern Cape Province , South Africa. Unpublished report.

Vernon, C. J. (1999). The Cape Vulture at Colleywobbles: 1977–1997. *Ostrich* **70**, 200–202. Available at: http://www.tandfonline.com/doi/abs/10.1080/00306525.1999.9634236

Vignali, S., Lörcher, F., Hegglin, D., Arlettaz, R., and Braunisch, V. (2021). Modelling the habitat selection of the bearded vulture to predict areas of potential conflict with wind energy development in the Swiss Alps. *Global Ecology and Conservation* **25**, e01405. doi:10.1016/j.gecco.2020.e01405

Watson, R. T., Kolar, P. S., Ferrer, M., Nygård, T., Johnston, N., Hunt, W. G., Smit-Robinson, H. A., Farmer, C. J., Huso, M., and Katzner, T. E. (2018). Raptor Interactions with Wind Energy: Case Studies from Around the World. *Journal of Raptor Research* **52**, 1–18. doi:10.3356/JRR-16-100.1

Welbergen, J. A., Meade, J., Field, H. E., Edson, D., Mcmichael, L., Shoo, L. P., Praszczalek, J., Smith, C., and Martin, J. M. (2020). Extreme mobility of the world's largest flying mammals creates key challenges for management and conservation. *BMC Biology* **18**. doi:10.1186/s12915-020-00829-w

Whitfield and M. Madders, D. P. (2006). Flight height in the hen harrier *Circus cyaneus* and its incorporation in wind turbine collision risk modelling. Banchory, UK. Available at: www.natural-research.org [accessed 3 June 2019]

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., and Yutani, H. (2019). Welcome to the Tidyverse. *Journal of Open Sourc e Software* **4**, 1686.

doi:10.21105/joss.01686

Willmot, J., Costello, E. ., Gordon, C., Forcey, G., Casto, S., Beaulac, G., and Pilla, E. (2012). Bird and bat collision risks & wind energy facilities.

Wilson, J., and Primack, R. (2019). 'Conservation Biology in Sub-Saharan Africa'. (Open Book Publishers: IK.) Available at: https://doi.org/10.11647/OBP.0177

Wolter, K., Piper, S., Neethling, M., Vernon, C., Botha, A., Boshoff, A., Borello, W., Borello, R., Mundy, P., and Neser, W. (2011). Cape Vulture (*Gyps coprotheres*): Breeding colony conservation & monitoring protocol update. Available at: http://www.vulpro.com/wp-content/uploads/2016/08/Cape-Griffon-Vulture-colony-monitoring-Protocol-KW.pdf]

World Bank (2020). World Development Indicators. Available at: https://data.worldbank.org/indicator/SL.UEM.TOTL.NE.ZS?locations=ZA

Xu, Y., Si, Y., Takekawa, J., Liu, Q., Prins, H. H. T., Yin, S., Prosser, D. J., Gong, P., and De Boer, W. F. (2019). A network approach to prioritize conservation efforts for migratory birds. *Conservation Biology* **34**, 416–426. doi:10.1111/cobi.13383

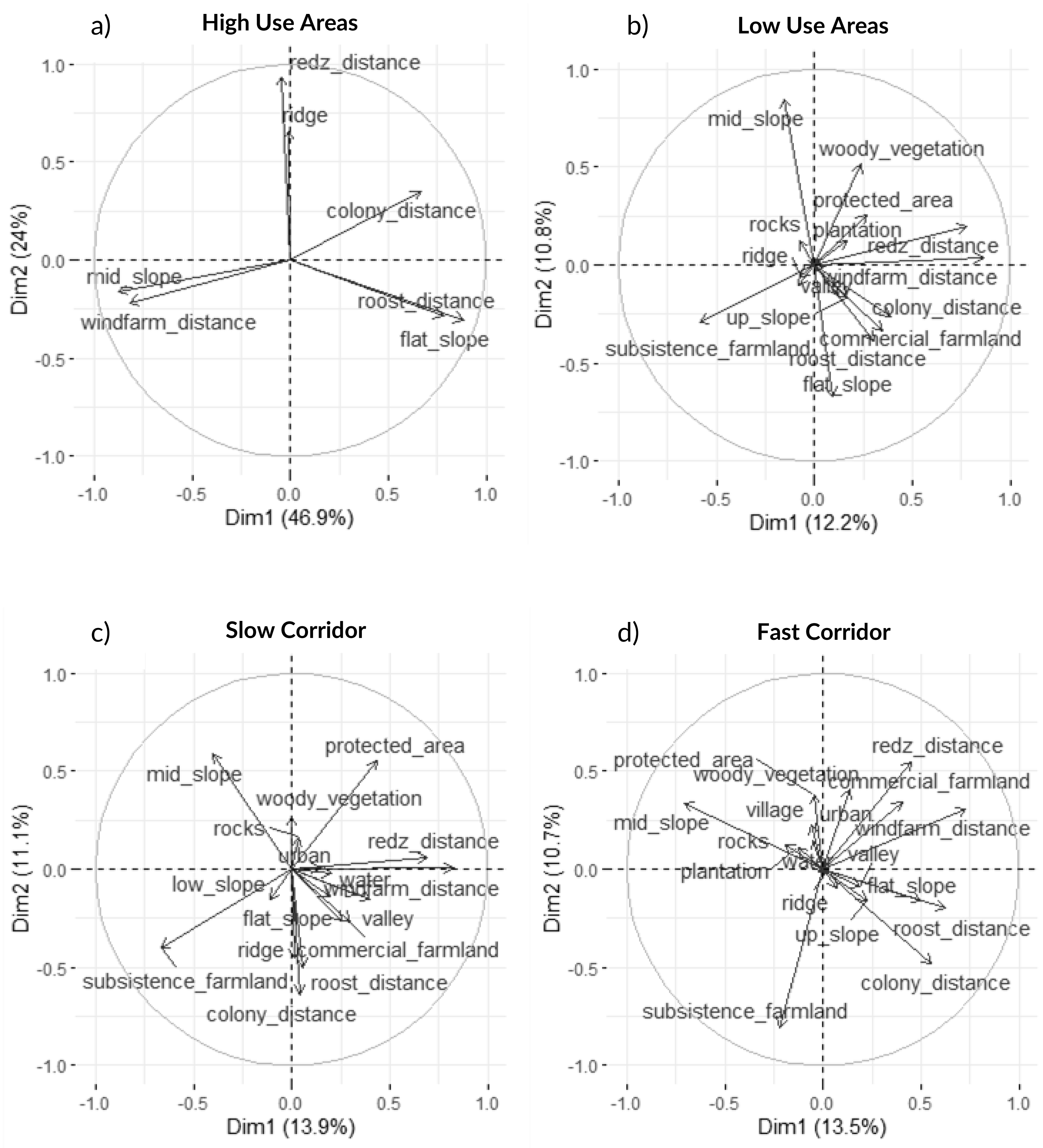
Yamaç, E., and Bilgin, C. C. (2012). Post-Fledging Movements of Cinereous Vultures *Aegypius monachus* in Turkey Revealed by GPS Telemetry. *Ardea* **100**, 149–156. doi:10.5253/078.100.0206

Zwart, M. C., McKenzie, A. J., Minderman, J., and Whittingham, M. J. (2015). Conflicts between birds and on-shore wind farms. In 'Problematic Wildlife: A Cross-Disciplinary Approach'. pp. 489–504. (Springer, Cham.) doi:10.1007/978-3-319-22246-2_23

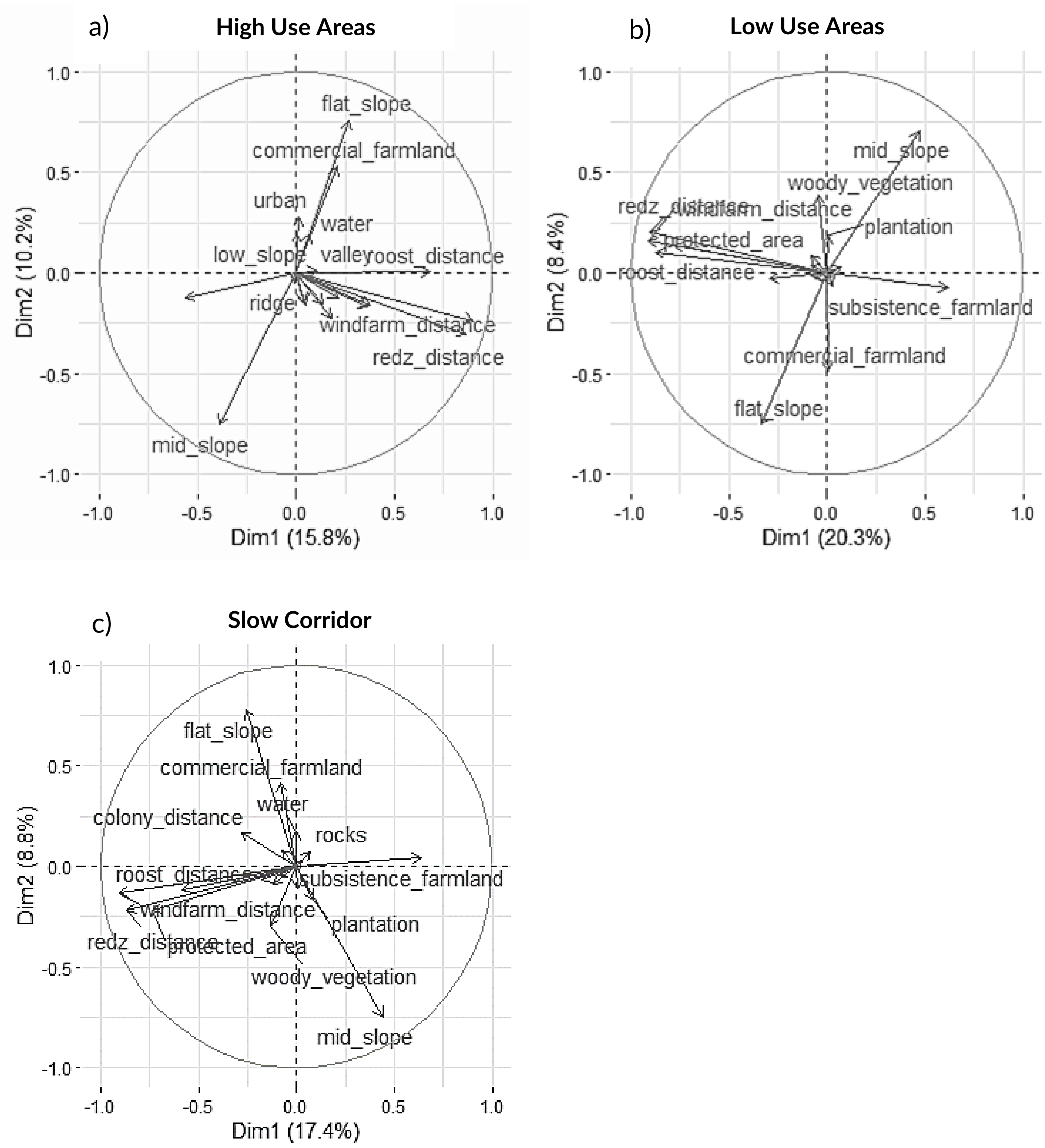
8 SUPPLEMENTARY MATERIAL

Supplementary Table 3.1: Details of 29 Cape Vultures tagged with GPS tracking units in the Eastern Cape and KwaZulu-Natal Provinces of South Africa. Tracking commenced for juvenile birds once they had fledged the nest.

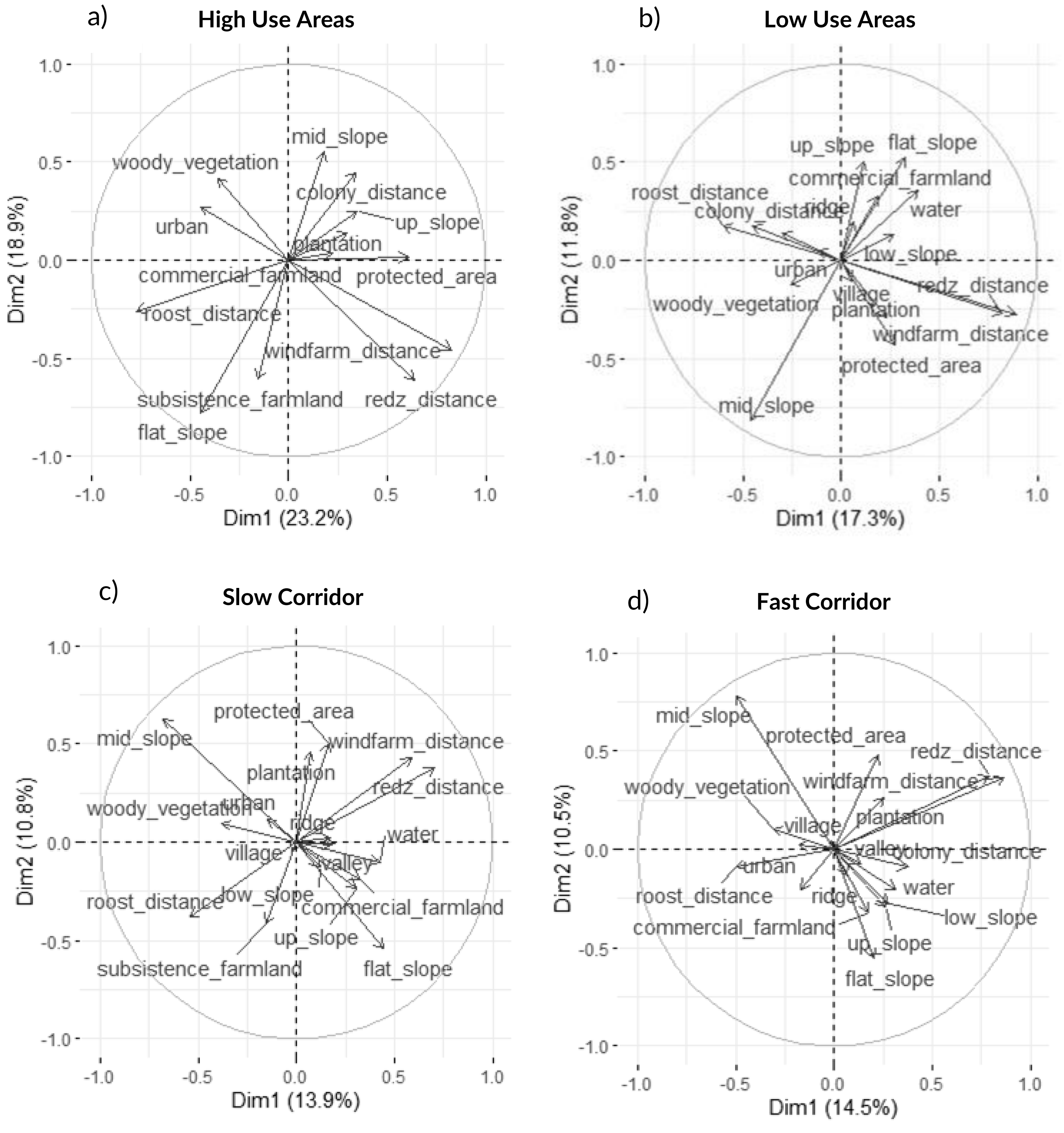
Bird ID	Bird age	Colony tagged	Tracking start date	Tracking end date	Days tracked
X016	Adult	Msikaba	26 November 2012	10 January 2014	411
X021	Adult	Msikaba	17 March 2013	09 April 2013	24
X022	Adult	Msikaba	17 March 2013	10 January 2014	300
X023	Adult	Msikaba	21 January 2013	31 August 2016	1319
X027	Adult	Msikaba	30 December 2012	18 December 2013	354
X033	Adult	Msikaba	26 November 2012	30 September 2013	309
X042	Adult	Msikaba	01 December 2012	28 October 2015	1062
X052	Juvenile	Colleywobbles	11 December 2015	09 November 2016	335
X053	Juvenile	Colleywobbles	31 December 2015	22 January 2017	389
X055	Juvenile	Colleywobbles	21 December 2015	22 January 2017	399
X056	Juvenile	Colleywobbles	16 December 2015	06 November 2016	327
X058	Juvenile	Colleywobbles	28 September 2015	18 April 2016	204
X071	Juvenile	Colleywobbles	16 December 2015	22 January 2017	404
N099	Immature	MzimKhulu	09 January 2016	08 October 2017	639
N101	Immature	MzimKhulu	15 January 2013	03 January 2015	719
N103	Immature	MzimKhulu	15 January 2013	16 July 2020	2740
N104	Immature	MzimKhulu	15 January 2013	21 May 2013	127
N106	Adult	MzimKhulu	10 January 2016	28 October 2017	658
N110	Immature	MzimKhulu	15 January 2013	15 May 2014	486
N134	Immature	MzimKhulu	14 January 2013	09 December 2013	330
N162	Immature	MzimKhulu	10 January 2016	06 May 2016	118
N164	Adult	MzimKhulu	10 January 2016	15 January 2018	737
N165	Immature	MzimKhulu	10 January 2016	24 November 2016	320
N166	Adult	MzimKhulu	10 January 2016	04 October 2019	1364
N171	Immature	MzimKhulu	11 January 2016	10 November 2018	1035
N172	Immature	MzimKhulu	11 January 2016	18 January 2021	1835
Marie	Immature	MzimKhulu	12 February 2015	24 March 2015	41
O31	Adult	Elliot	27 April 2015	21 August 2015	117
O32	Adult	Elliot	29 April 2015	10 June 2015	43



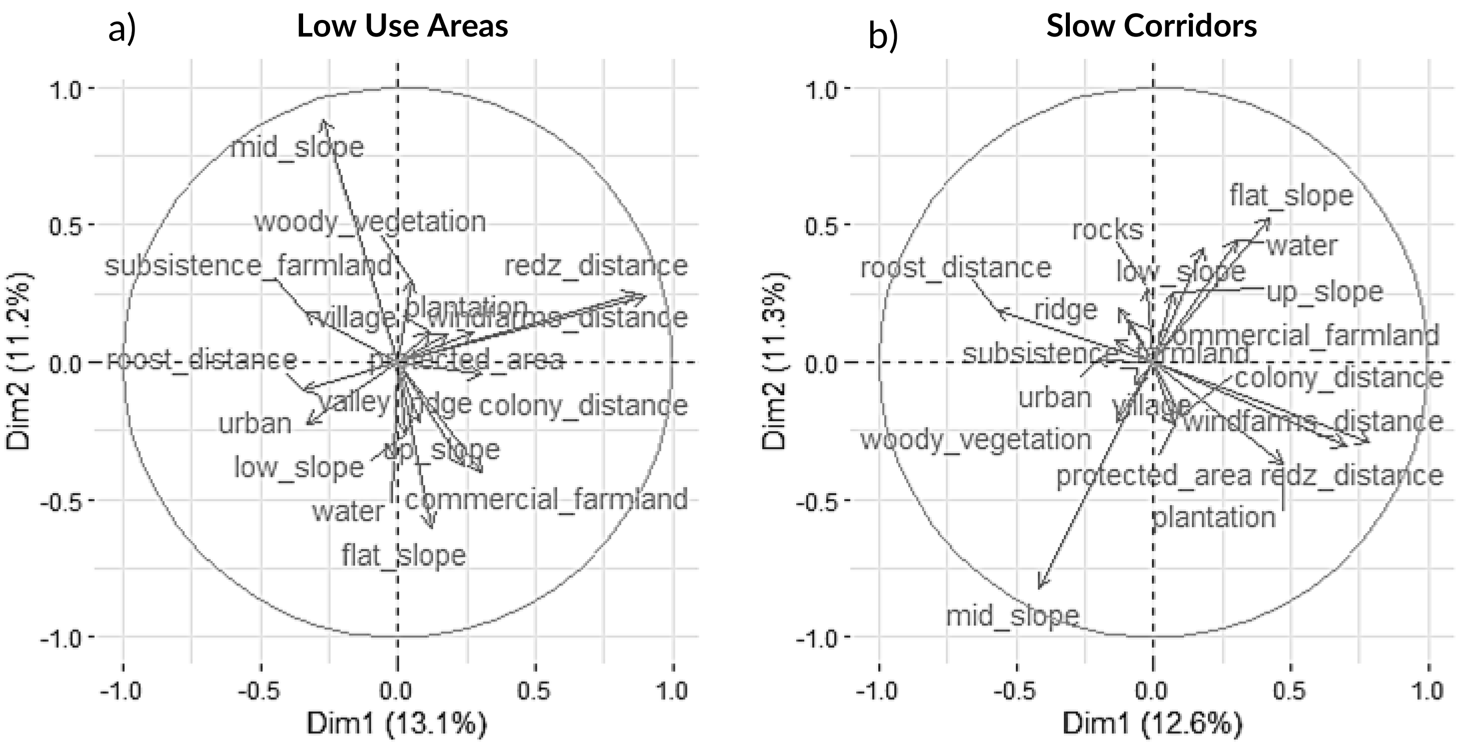
Supplementary Figure 3.1: Environmental variables prevalent within each cluster use for juvenile Cape Vultures from Colleywobbles Cape Vulture Colony within the associated principal component analysis (PCA).



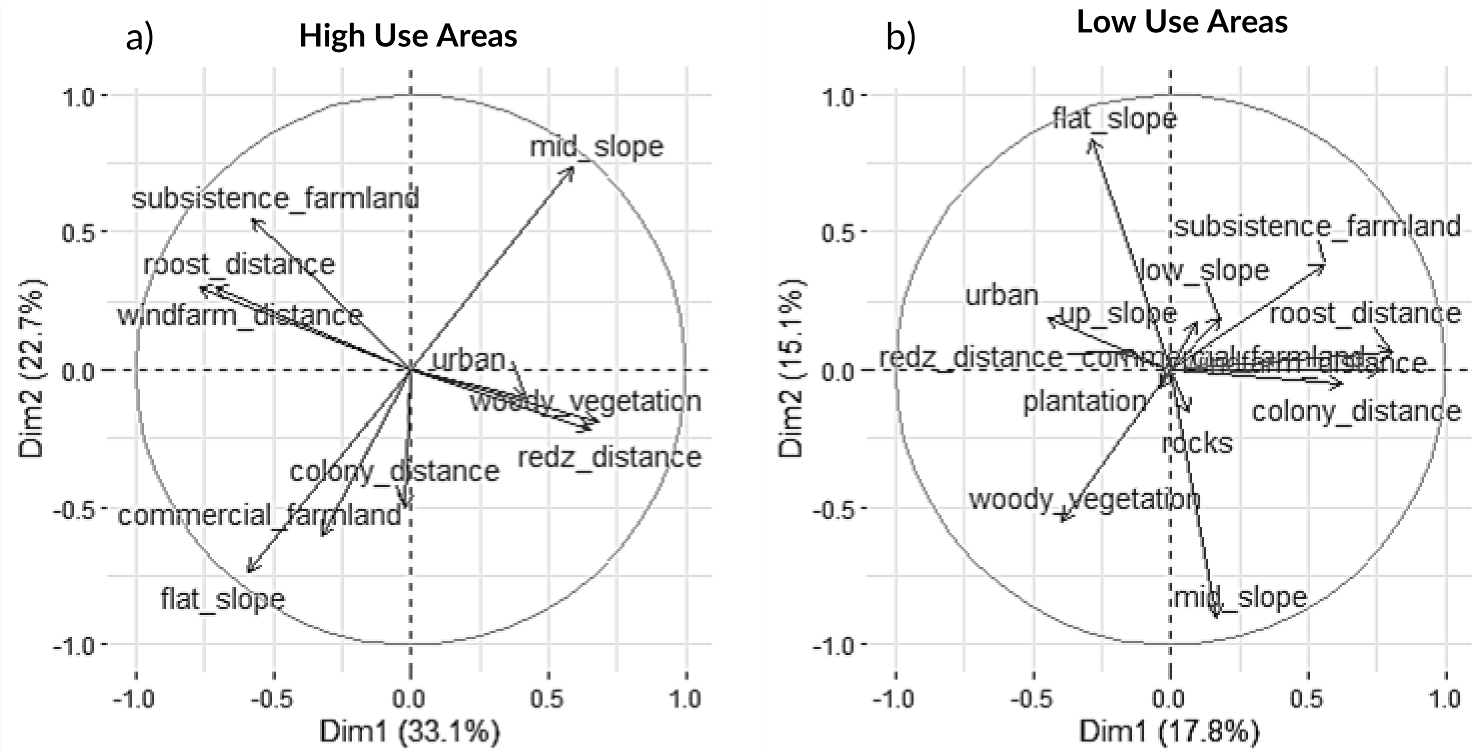
Supplementary Figure 3.2: Environmental variables prevalent within each cluster use for immature Cape Vultures from MzimKhulu Colony within the associated principal component analysis (PCA)



Supplementary Figure 3.3: Environmental variables prevalent within each cluster use for adult Cape Vultures from Msikaba Cape Vulture Colony within the associated principal component analysis (PCA)



Supplementary Figure 3.4: Environmental variables prevalent within each cluster use for adult Cape Vultures from MzimKhulu Colony within the associated principal component analysis (PCA)



Supplementary Figure 3.5: Environmental variables prevalent within each cluster use for adult Cape Vultures from Elliot supplementary feeding site within the associated principal component analysis (PCA)