Conservation in a Changing World: Assessing the Conservation Status of an Agriculturally Adapted Species, the Blue Crane

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Plagiarism declaration

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05 February 2024

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Abstract

With rapid human development and global change, conservation scientists need to stay abreast of changes to threatened species' demographics. The Blue Crane *Anthropoides paradiseus* has adapted to land-use change in some parts of its range. By the 1980s, numbers of cranes in their natural core range in the eastern grasslands and Karoo of South Africa had declined dramatically due to agricultural development and poisoning, leading to the species being listed as Vulnerable. These impacts were partly offset by the species colonising a novel ecosystem, the Western Cape wheatlands. Currently approximately half of all Blue Cranes are found in these wheatlands. However, there are concerns that the Western Cape population may be decreasing, given the many threats in intensive agricultural landscapes. This thesis assesses the conservation status of the Blue Crane, with particular focus on the Western Cape wheatlands.

In Chapter 1 I frame the topic, review the literature, and describe the study areas. In Chapter 2, I use aerial survey data to estimate the Blue Crane population at 51000 (range 34000–68000) cranes, which is double the last conservative estimate in 2002. To assess population trends for Blue Crane over the last 30 years, I analyse two citizen science datasets: Southern African Bird Atlas Projects (SABAP) and Coordinated Avifaunal Road-counts (CAR). These datasets indicate that Blue Crane numbers have increased over the long term but CAR data show that the population trend changed from positive to negative in 2010. Since 2011, summer crane counts have declined by 19% (95% CI –31% to –5.2%), driven primarily by numbers in the Overberg (southern Cape wheatlands) declining by 22% from 2011–2019 (–37% to –1.9%).

In Chapter 3 I focus on one of the key threats to Blue Cranes, collision with powerlines. For two years I conducted quarterly surveys for dead birds along powerlines in the Karoo, and annual surveys in two areas in the Western Cape wheatlands (Overberg and Swartland), where agricultural activity prevented quarterly surveys. The Blue Crane was the most frequently recorded species in all three regions, with collision rates of 0.18 (95% CI 0.13–0.24) cranes/km/year in the Karoo, 0.08 (0.02–0.17) in the Swartland and 0.05 (0.02–0.08) in the Overberg. Estimates of scavenger, observer and crippling bias indicate that we may underestimate collision rate by factors of 6, 7 and 8 times respectively. I developed the first predictive model based on rigorous survey data to identify key collision risk factors for Blue Cranes. Using a binomial Generalized Linear Mixed Model, I found proximity to seasonal water to be the strongest predictor of Blue Crane collision on powerlines; collision probability reduced to nearly zero for powerlines > 2.5 km from a seasonal water body. This finding could guide placement of new powerlines, and to guide marking of existing powerlines close to water bodies.

In Chapter 4, I explore Blue Crane movements and survival from GPS-GSM and Iridium satellite trackers fitted between 2016 and 2021, on 31 adults, 3 juveniles and 25 Blue Crane fledglings. Using autocorrelated kernel density home range analysis, I demonstrate that Western Cape Blue Crane home ranges were on average 1655 km^2 (SD 2757). Mean daily distance travelled did not differ between regions, Swartland: 9.5 km (SD 11.7), Overberg: 7.5 km (SD 9.8), but non-breeding cranes moved significantly farther per day, 9.5 km (SD 13.3) than breeding cranes, 5.8 km (SD 5.4). As a result, non-breeding cranes intersect powerlines twice as often as breeding cranes. This may contribute to the lower immature survival rate than adult Blue Cranes. Using a Known Fate Mark Recapture Model, I estimate survival for non-breeding birds to be 0.85 (95% CI 0.61–0.95, n = 13), and 0.95 (0.71–0.99, n = 12) for breeding birds.

In Chapter 5, I summarise my findings and use these insights to assess the Blue Crane on the IUCN Red List and the Green Status of Species. In the Red List assessment, I draw from a population viability analysis and the CAR data in Chapter 2 and project that the Blue Crane population (currently 21860 mature individuals) will decline by 53% (95% CI –19% to –72%) over three generations, narrowly meeting the criteria for Endangered. However, with the lower end of uncertainty indicating that a Near Threatened listing is appropriate, I recommend that Blue Crane be listed as Vulnerable. I conclude that the Western Cape wheatlands may pose an ecological trap for the species, and that declines are likely being driven by poor breeding productivity and recruitment (Appendix 1). Drawing from the literature, and interviews with farmers (Appendix 2), I contextualise Blue Crane conservation in this landscape and make recommendations for the conservation of this flagship species. This study highlights some of the risks in land-sharing conservation approaches, and the challenges of conservation in man-made ecosystems. In this context, it is important for conservation science to be interdisciplinary and crosscutting in its approach.

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Lastly PhDs do not happen in a vacuum, these last five years have been challenging on a personal and societal level. I could not have done it without the love, advice, and encouragement from my treasured support network.

Ethics and Permits

Chapter 3: The scavenger bias trial was approved by the UCT (2020/V6/PR/A1) and Endangered Wildlife Trust (EWT) ethics committees (EWTEC2019 003) and was performed under a research permit from Cape Nature (CN 44-31-11529) and a Section 20 permit from the Department of Environment, Forestry and Fisheries (SDAH-Epi020011014340). Research permits were requested well in advance from Eastern Cape and Northern Cape provincial authorities but were not received within 4 years, despite repeated requests for feedback.

Chapter 4: Pre-fledgling leg-based trackers were fitted prior to me registering for a PhD and it was therefore approved by the Endangered Wildlife Trust ethics committee: EWTEC2018_005. These trackers were fitted under the following provincial permits: CN44-31-6805 (Cape Nature), CRO 74/19CR & CRO 75/19CR & TOPS 09872 (Eastern Cape), FAUNA 0698/2019 (Northern Cape). Foot noose captures of flighted cranes were done under permit CN44-31-11529 (Cape Nature) and ethics clearance 2020/V7/PR/A1 (University of Cape Town) and EWTEC2020_008 (Endangered Wildlife Trust). In addition, I used data from trackers fitted in 2016/7 under CapeNature permit (permit No.: 0056-AAA041-00114, 0056-AAA041-00182) and EWT ethics review (reference:1/2/1/6/5/S).

Appendix 2: Farmers interviews were conducted under UCT Faculty of Science ethics clearance number FSREC 57 – 2019.

Ethics Approval letters can be found at Appendix 3.

Dedication

I dedicate this work to the farmers, who are the custodians of South Africa's Blue Cranes

Photograph: Ciming Mei

Chapter 1: Introduction

Conservation and agriculture

Traditionally, conservation has tended to focus on protected areas, so called fortress conservation (Soulé 1985; Williams et al. 2020a). However, as destruction of natural habitats has accelerated, it has become clear that more diverse and nuanced approaches are needed (Tscharntke et al. 2012; Ripple et al. 2017; IPBES 2019). Modern conservation has a greater focus on integrating and balancing the needs of nature and people, conserving species in transformed landscapes outside of protected areas (Kowarik 2011; Kareiva & Marvier 2012; Tscharntke et al. 2012). Agriculture is responsible for most of the land transformation, with an estimated 12% of Earth's land used for cropping, and 22% used for livestock grazing (Ramankutty & Rhemtulla 2012). Overharvesting and agriculture are the two most prevalent threats to Threatened and Near Threatened species on the International Union of the Conservation of Nature (IUCN) Red List (Perrings & Halkos 2015; Maxwell et al. 2016), driving or contributing to the threat status of 60% of threatened birds and amphibians, and 18% of mammals (Norris 2008). As such, considerable attention has been directed towards conservation in agricultural landscapes (Wolff et al. 2001; Norris 2008; Scherr & McNeely 2008; Phalan et al. 2011; Tilman et al. 2011; Balmford et al. 2012; Wright et al. 2012; Erisman et al. 2016; Hemminger et al. 2022).

Some of the thinking around conservation and agriculture includes debates around land-sharing vs land sparing (Phalan et al. 2011; Perrings & Halkos 2015). Land sharing involves the simultaneous pursuit of both goals on the same piece of land, whereas land sparing spatially segregates high-yield intensive farming practices from conservation of natural habitats on others (Phalan et al. 2011; Balmford et al. 2012). Land sharing approaches tend to work better in low-yield extensive agricultural systems, for example, grasslands used for grazing livestock provide habitat for at least 30 threated bird species (Norris 2008; Wright et al. 2012). Intensive agricultural landscapes tend to support less biodiversity than extensive agricultural, or undisturbed landscapes (Mangnall & Crowe 2003; Lindell et al. 2004; Norris 2008; Tscharntke et al. 2008; Karp et al. 2012; Tsiafouli et al. 2015). However, when combined with conservation of natural habitats, this matrix approach is thought to be more effective than land-sharing approaches (Phalan et al. 2011). For example, in Colombia there was a higher functional diversity of birds in areas with land-sparing than land-sharing approaches (Cannon et al. 2019). The relative merit of each approach depends on the focal species, the type of natural habitat and the nature of the agricultural system (Phalan et al. 2011).

Agricultural areas as ecological traps

Regardless of the approach, most animals utilise both agricultural and natural land to some extent (Fieberg et al. 2021; Assandri et al. 2022). As a result, source-sink dynamics can occur between agricultural land and untransformed land. In source-sink dynamics, reproduction exceeds mortality in some patches (sources) and in others mortality exceeds reproduction (sinks); sinks are sustained by immigration from source populations (Pulliam 1988; Dias 1996). Early theories postulated that immigration occurred passively e.g., wind or water currents, or because of social dynamics e.g., subordinate animals are pushed out of optimal habitat patches (Pulliam 1988; Delibes et al. 2001). This assumes that animals can distinguish a sink habitat from a source habitat. However, 'attractive sinks' may exist, particularly in transformed habitats where animals have not evolved the ability to detect novel threats to survival or breeding (Delibes et al. 2001; Robertson et al. 2013). These attractive sinks have also been referred to as ecological traps, which is the term I use in this thesis (Gates & Gysel 1978; Battin 2004). Agriculture and forestry commonly create ecological traps for species (Robertson et al. 2013). For example, in Ohio, USA, dolichopodid flies are more abundant in agricultural patches than set-aside patches, but within agricultural patches diversity and abundance is lower in patches with more intensive agricultural practices (Kautz & Gardiner 2019). Further intensification could create an ecological trap for species which are found in higher numbers in agricultural patches (Kautz & Gardiner 2019). Similarly, Red-backed Shrikes *Lanius collurio* in north-west Europe preferentially select new open patches in felled plantations, and yet breeding success, prey availability and provisioning rates are lower in these patches (Hollander et al. 2011; Hollander et al. 2013). Western Yellow Wagtails *Motacilla flava* breeding in farmland in the UK show maladaptive habitat selection for both territories and nest sites (Gilroy et al. 2011). Such ecological traps pose a significant challenge to conservation efforts, particularly because they can be difficult to detect (Battin 2004; Kautz & Gardiner 2019). Key indicators are high abundance and low reproductive output; there needs to be evidence that an animal preferentially selects for the trap, and that the population is not viable (Battin 2004). This requires intensive, long-term monitoring, including techniques such as mark-recapture studies (Battin 2004).

Flagship species in conservation

The concept of using surrogate species for prioritising conservation action i.e., flagship species, is foundational in conservation science (Simberloff 1998; Jepson & Barua 2015). Flagship species are "high profile, charismatic, or ambassadorial species that act as symbols and rallying points for conservation projects, issues, campaigns and the wider conservation movement" (Jepson and Burua 2015, p. 95). The concept of flagship species operates in the social rather than the ecological realm (Anderson & Devlin

1996; Jepson & Barua 2015). For example, unlike umbrella species, flagship species do not necessarily result in the protection of a host of other species (Seddon & Leech 2008). In my study I focus on the Blue Crane *Anthropoides paradiseus*, the national bird of South Africa. The Blue Crane is beautiful and charismatic and can be considered a flagship species for conservation. However, whether Blue Cranes, and cranes in general (Gruiformes), are umbrella species is debateable, given their frequent association with agriculture, which is often detrimental to biodiversity. Conservation interventions, such as powerline mitigation, efforts to reduce poisoning and awareness raising, can benefit other species that use or pass through agricultural landscapes. In this way, cranes can act as umbrella species to some extent. Nonetheless, cranes can act as ambassadors for conservation (flagships) within agricultural systems, provided the perceived benefits of cranes to farmers outweigh the costs (e.g. crop damage or cranes causing disturbance at feedlots). The cranes' beauty and charisma can serve as powerful motivators, encouraging farmers to adopt more sustainable practices. Blue Cranes serve as good flagships, as unlike some other crane species, they seldom cause significant crop damage, so most farmers have a positive attitude towards them (van Velden et al. 2016).

Cranes and agriculture

The cranes are a highly threatened order of birds, with 10 of the 15 species listed as threatened on the IUCN Red List (IUCN 2022). All crane species are associated with, and impacted by, agriculture to some extent (Austin et al. 2018). Agricultural areas benefit cranes by providing predictable and abundant sources of food, in the form of crops and livestock feed, and water from dams and troughs (Austin et al. 2018). The association between agriculture and cranes is ancient, but with rapid human development and agricultural changes, cranes are increasingly threatened, rather than benefited by agriculture (Austin et al. 2018). Of the 19 threats to cranes identified by Mirande and Harris (2019), nine are linked to agriculture (Austin et al. 2018). These include: altering water courses (e.g. dams), conversion of wetlands (breeding habitat for many cranes), disturbance of wetlands, changes in agricultural practice, grassland conversion for agriculture, fire, disease crossover from farm animals, poisoning, exposure to agrochemicals and lead, causing sublethal or lethal poisoning (Mirande & Harris 2019). Several crane species can damage crops, and in some cases, this leads to farmers injuring or killing cranes (van Niekerk 2010; van Velden et al. 2016b; Austin et al. 2018; Hemminger et al. 2022). Despite the threats posed, the effects of agricultural changes on cranes have been varied (Austin et al. 2018). Hemminger et al. (2022) reviewed these impacts, identifying the factors that lead to crane species being 'winners' or 'losers' in the face of agricultural change. Wetland specialists, such as Wattled Cranes *Bugeranus carunculatus*, Siberian Cranes *Grus leucogeranus* and the migratory population of Red-crowned Cranes *G. japonensis* have fared worst with

the expansion and/or intensification of agriculture (BirdLife International 2021b; Hemminger et al. 2022). Crane species that have done well with agricultural expansion are the more generalist species such as the Sandhill Crane *G. canadensis*, Common Crane *G. grus* and Demoiselle Crane *Anthropoides virgo*, which have adapted to make use of agricultural fields for foraging e.g., waste grains (Hemminger et al. 2022). Other generalist crane species, like the Blue Crane, have had mixed responses to agriculture, declining in parts of their range but increasing in others (McCann 2001; Hofmeyr 2012).

Introducing the Blue Crane

The Blue Crane is a near-endemic to South Africa (Figure 1), with a very small (< 50 cranes), isolated and declining population in northern Namibia (Namibia Crane Working Group 2020). The stronghold for this species was once the eastern grasslands of South Africa (Figure 2), but as this habitat became degraded through afforestation, mining and intensive agriculture, the population is estimated to have halved since the 1970s, leading to it being listed as Vulnerable on the IUCN Red List in 1994 (Meine and Archibald 1996, BirdLife International 2021a). More recently, the grassland Blue Crane population appears to have stabilised and is increasing in parts of KwaZulu-Natal (Galloway-Griesel et al. 2022), but as of 1999 only holds an estimated 14% of the population, appreciably less than the former 35% found in grasslands in the 1980s (McCann 2001).

While the grassland population was dwindling, the Blue Crane population was increasing in the Western Cape. Historically Blue Cranes did not occur in great numbers in the Western Cape, with shrubby renosterveld and fynbos being generally unsuitable habitat for cranes (Allan 1995). However, as humans began to clear the fynbos for crop and pasture fields, artificial 'grassland' habitats became available for cranes (Figure 2). In the Western Cape, the core areas for Blue Crane are the wheatlands of the Overberg and the Swartland (Figure 3). The Overberg is the southern coastal region of the Western Cape, east of the Kogelberg/Bot River fold mountain ranges and south of the Langeberg. The eastern Overberg district boundary is near Swellendam, but the wheatlands extend as far east as Mossel Bay. The Swartland extends from the Cape Town urban edge, delineated by the Boland mountains in the east, and north to Namaqualand. In this study I refer to the Overberg and Swartland as the broader areas under wheat agriculture, rather than the municipal boundaries. The cultivated lowlands are characterised by low undulating hills of fertile soils of shale origin, bordered by the Cape Fold mountains, with sandy infertile lithosols (Cowling et al. 2009). The natural lowland vegetation is renosterveld, but more than 90% of this has been cleared for agriculture (Moncrieff 2021). Today the landscape is dominated by a mosaic of grain (wheat *Triticum aestivum*, barley *Hordeum vulgare* and oats *Avena sativa*), oil seed crops (canola *Brassica*

napus), and pastures for livestock (often planted with nitrogen fixing plants such as lucerne (alfalfa) *Medicago sativa*, medics *Medicago spp.* or lupins *Lupinus spp.*).

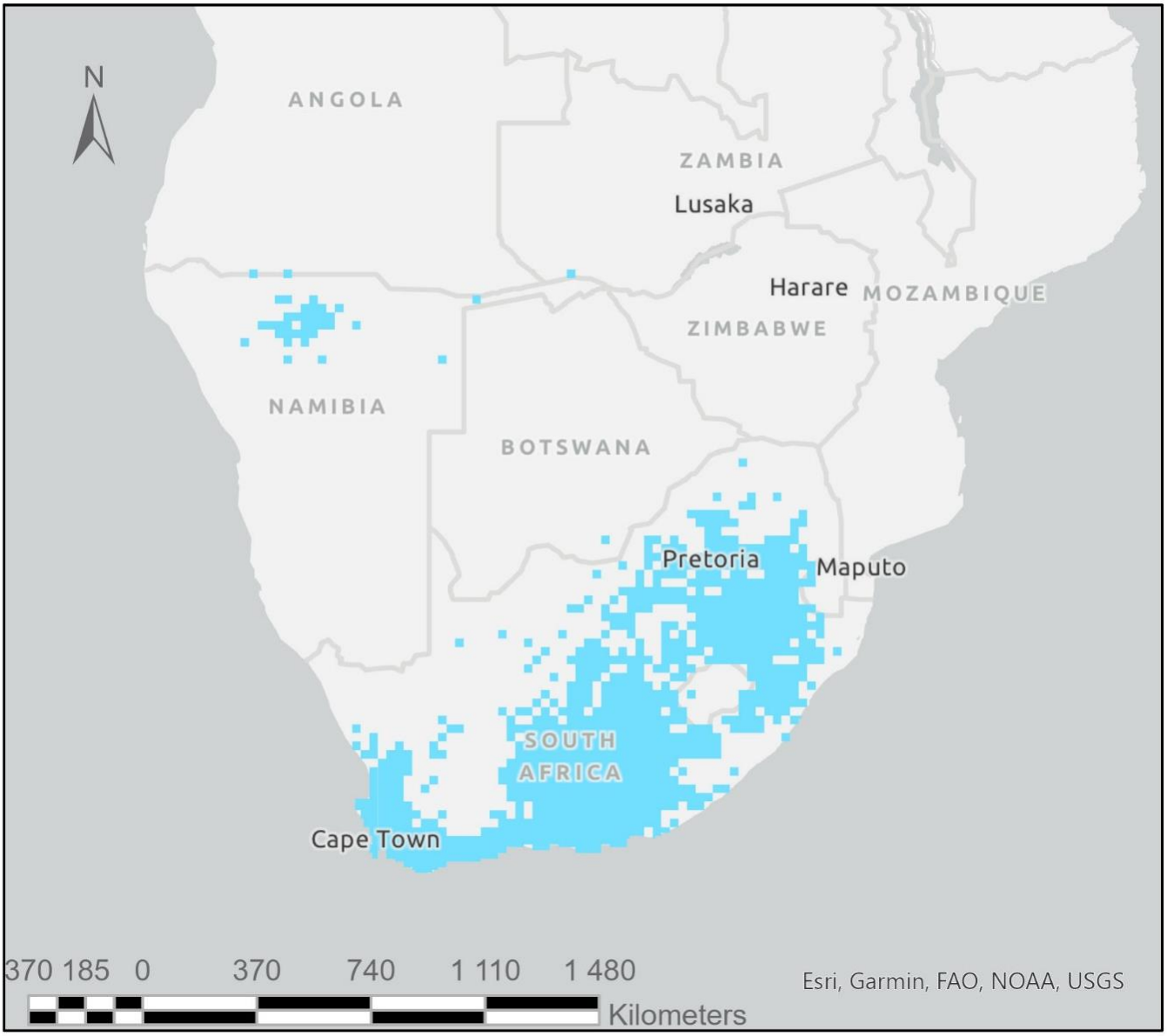


Figure 1: Blue Crane global range, based on South African Bird Atlas 1 & 2 data (since 1987) (Harrison et al. 1997; Southern African Bird Atlas Project 2 2022).

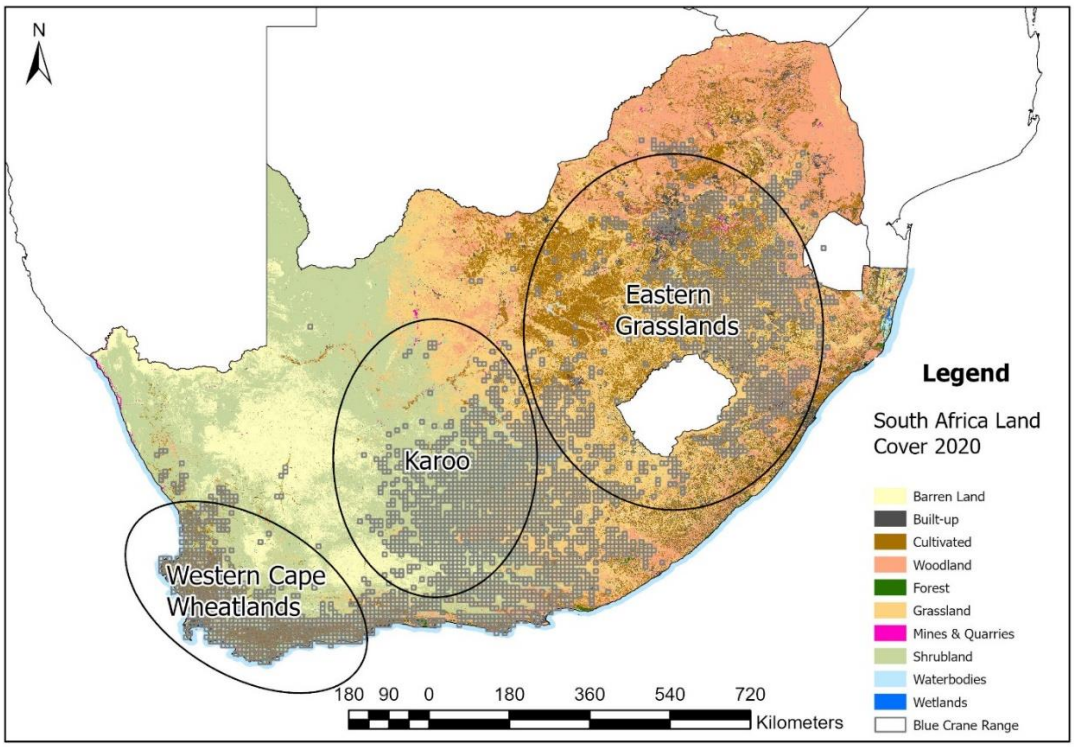


Figure 2: The South African Blue Crane range (Southern African Bird Atlas Project 2 2022) in relation to vegetation and other land-use types (Department of Environment Forestry and Fisheries 2020b), showing the three populations within the metapopulation.

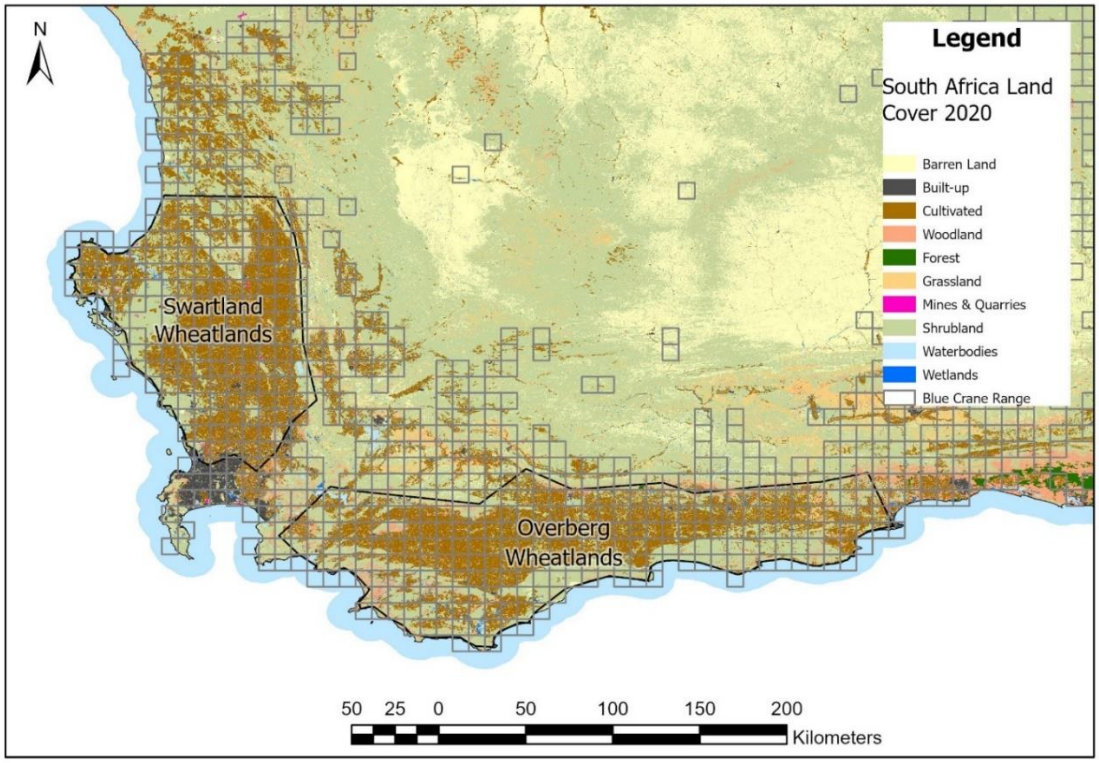


Figure 3: The delineations of the broader Swartland and Overberg, along with Blue Crane range (Southern African Bird Atlas Project 2 2022) and vegetation (Department of Environment Forestry and Fisheries 2020b).

The first record of a Blue Crane in the Western Cape was in 1884 near Mossel Bay (Grill 1958), and by the start of the 20th century they were recorded from farther west in the Overberg (Sclater 1906; Allan 1993). From there, Blue Cranes expanded their range into the Swartland, with a museum specimen collected near the Berg River in 1906 (Sclater 1906; Allan 1993). A century later, 47% of South Africa's Blue Cranes were found in the Western Cape wheatlands (McCann 2001; McCann et al. 2007). The Blue Crane population in the Western Cape wheatlands grew rapidly, increasing by 500% increase in the Overberg and 300% in the Swartland, between 1993 and 2010 (Hofmeyr 2012). The Swartland population increased up until 2007, and then declined by 2% per annum for the next 3 years, whereas the Overberg was still increasing as of 2010 (Hofmeyr 2012).

Currently the largest population of Blue Cranes living in natural habitat is found in the eastern Nama Karoo (hereafter Karoo) (Figure 4) (McCann 2001). The Karoo is an arid grassy shrubland in the centre of South Africa; the vegetation shifts from shrubby grassland in the north-east to grassy shrubland in the west (Mucina & Rutherford 2006). Rainfall is low and erratic, and mainly falls in summer (Mucina & Rutherford 2006). The dominant agricultural practice is extensive livestock farming, including sheep, goats, and cattle (Archer 2000). Farmers pump ground water to provide drinking water to livestock, to irrigate pasture and grow lucerne for fodder (Archer 2000). In areas where people have access to water for irrigation, there has been some agricultural conversion, such as along perennial rivers like the Orange River.

The Karoo Blue Crane population declined to some extent at the same time as the grassland cranes declined, particularly in the Eastern Cape, but for the most part has been fairly stable (Vernon et al. 1989; Hofmeyr 2012). The reasons for the decline were thought to be because of a switch to higher stocking rates leading to breeding disturbance, and persecution due to cranes trampling irrigated lucerne, leading to farmers shooting or poisoning cranes (Vernon et al. 1989; Verdoorn 2015). The expanding powerline network may have also contributed to declines of Blue Cranes in the Karoo in the 1980s, and powerline collision remains one of the main threats to Blue Cranes in this region (Shaw et al. 2021).

Figure 4: The largest population of Blue Cranes in natural habitat is found in the Karoo of South Africa, an arid shrubby grassland.

What is the concern?

In the Western Cape, Blue Cranes rely almost entirely on agricultural fields (Allan 1995; Hofmeyr 2012). The increasing population, at least until 2010 (Hofmeyr 2012), indicates that this artificial habitat is reasonably suitable for them. Nonetheless, they face many threats in this highly transformed, intensively farmed landscape. Blue Crane nesting coincides with when crops are harvested between October and December (Allan 2005). Pairs that choose to nest in newly harvested wheatfields, as opposed to pasture fields, are vulnerable to being disturbed or having their eggs crushed when farmers bring combine harvesters in to collect wheat windrows or balers to bale straw (Bidwell 2004; van Velden et al. 2016b). Blue Crane chicks, and sometimes adults, get entangled in barbed-wire fences, which can cause injury, and subsequently death (van Velden et al. 2016b). Blue Crane chicks occasionally climb into livestock water troughs to drink, are unable to get out and then drown.

Blue Cranes also frequently collide with powerlines, and this is likely to be the primary cause of mortality for fully-grown Blue Cranes in the Western Cape (Shaw et al. 2010a; Shaw et al. 2010b). A 2008 survey in the Overberg estimated that 12% of the local Blue Crane population died on powerlines each year (Shaw et al. 2010b). This estimate might be inflated because it was calculated using a minimum population count from a citizen science census (farmer counts); which is likely an underestimate (McCann 2001; McCann et al. 2007), and therefore overestimates the mortality rate. Nonetheless, the study indicates a concerningly high powerline collision rate for Blue Cranes, 0.31 (95% CI 0.13–0.59) cranes/km (Shaw et al. 2010b). South African power utility Eskom has been working in partnership with the Endangered Wildlife Trust since 1996 to address wildlife incidents on powerlines. A long-term experimental study in the Karoo shows that for Blue Crane, markers on transmission lines can reduce collisions by around 90% (Shaw et al. 2021). It is therefore useful to identify potential collision hotspots, so that markers can be deployed pro-actively to

reduce crane collision mortality. A desktop model was developed for predicting Blue Crane powerline collisions (Kotoane 2003), but it did not accurately predict collision hotspots detected in the field (Shaw et al. 2010b). More research is needed to understand the key drivers of Blue Crane powerline collisions, so that they can be more effectively predicted.

During winter, Blue Crane flocks aggregate in pasture lands, when crop fields become too tall for them to use (Figure 5). Farmers routinely supplement their sheep's diet with grains and concentrates, particularly in dry years when grazing is scarce (Figure 5). In these pasture lands with supplemental feeding stations (Figure 5), farmers are occasionally annoyed by Blue Cranes, as they disturb sheep at troughs and eat the feed (van Velden et al. 2016b). Fortunately, targeted poisoning of Blue Cranes happens seldom compared to the past (Allan & Ryan 1996; Verdoorn 2015); farmers are generally either positive towards or tolerant of Blue Cranes, although in the Swartland, tolerance is lower as they damage Sweet Lupin *Lupinus angustifolius* crops (van Velden et al. 2016b). This risk is minimal as Sweet Lupins are not widely planted; the Bitter Lupin variant is more commonly planted, which cranes do not damage. However, opportunistic species such as rodents and geese (Spur-winged *Plectropterus gambensis* and Egyptian Geese *Alopochen aegyptiaca*) have become numerous and can cause significant crop damage during the planting and growing season (Mangnall & Crowe 2001, 2002; Mangnall & Crowe 2003). Poison baits set out for these species may be eaten by Blue Cranes, which are thereby poisoned indirectly (Overberg Crane Group 2022, 2023).

Figure 5: In summer, Blue Cranes feed and breed in stubble fields (left) and planted pastures (centre). Pastures are available year-round, but when crops mature (in winter), they become too tall for Blue Cranes to use (right: a rare occurrence of a pair moving through mature crop). In winter they typically occur in planted pastures, where vegetation is shorter, and they can feed at sheep troughs (centre).

Given these threats, the concern is that the Western Cape wheatlands, last estimated to be home to half of the Blue Crane population (McCann et al. 2007), could become an ecological trap for the species, which would jeopardise the viability of the population as a whole (Pettifor et al. 2009). In addition to current ongoing threats, there are also potential future threats from climate change (and resultant changes in agricultural practices) as well as further infrastructure development e.g. powerlines and renewable energy. The Overberg has been designated by the South African government as a Renewable Energy Development Zone (REDZ), which makes it a priority area for renewable energy development (Department of Environmental Affairs 2018). Monitoring of wind farms indicates that Blue Crane collision mortalities with wind turbines are relatively uncommon (Perold et al. 2020), but the associated powerline infrastructure is an issue for this collision-prone species (Shaw et al. 2010a).

The Western Cape is predicted to get hotter and drier with climate change (Engelbrecht et al. 2009; Engelbrecht et al. 2011; du Plessis & Schloms 2017). This could pose challenges to Blue Cranes, which breed in the summer dry season; in their natural range (grasslands and Karoo), they also breed in summer but there summer is the wet season (South African Weather Service 2023). Hotter and drier summers could put additional pressure on these ground-nesting birds during incubation, making it harder for them to thermoregulate themselves and their eggs (DuRant et al. 2019; Bouwer 2023). Climate change may also trigger socio-ecological changes that alter the agricultural landscape upon which Blue Cranes depend (Turner et al. 2010). The concern is that climate change may lead farmers to alter crops or adopt farming practices which are less suitable for Blue Cranes. Little is known about farmers' views of local climate change and climate change adaptation.

Because the Blue Crane population was still increasing in 2010 (Hofmeyr 2012), it was down-listed from Vulnerable to Near Threatened in the regional Red List in 2015 (Taylor et al. 2015). However, concerns have been raised about the viability of the population (Pettifor et al. 2009) given that the population stronghold in the Western Cape is in an intensively farmed landscape, with a multitude of threats. Other than existing and possible future threats, there have also been some warning signs that indicate that further investigation is needed for this population. A 2020 review of Western Cape bi-annual road-counts indicated that the increasing trend ceased in 2010 (Young & Harrison 2020). This review did not statistically interrogate the trends (Young & Harrison 2020), and there is scope to analyse these data further, and to look at other population trend data.

These knowledge gaps are hampering effective conservation planning for the Blue Crane. With this PhD I aim to assess the conservation status, threat status and viability of Blue Cranes, with particular focus on the Western Cape wheatlands. Specifically, I aim to:

1. Assess the state of the South African population, by developing current population estimates and analysing population trend data (Chapter 2).

2. Quantify powerline collision rates in the two Blue Crane strongholds, the Western Cape and Karoo, and develop a collision risk model for these regions (Chapter 3).

3. Describe Blue Crane movements and survival in their Karoo and Western Cape strongholds, using satellite tracking technology, focusing particularly on how movements put them at risk of powerline collision (Chapter 4).

4. Drawing from the data gathered in the thesis, assess the conservation status of the Blue Crane, using the Red List and Green Status. This includes performing a Population Viability Analysis (PVA), drawing from an assessment of Blue Crane breeding productivity across their range (Appendix 1). I then synthesize key messages and recommendations, with insights from farmer interviews about climate change, climate change adaptation and attitudes towards Blue Cranes and their conservation (Appendix 2) (Chapter 5).

I have structured Chapters 2–4 as stand-alone entities to facilitate their publication in the primary literature. Appendices 1 and 2 are based on preliminary data and monitoring data, and did not fit neatly within the data chapters, but are nonetheless important for answering the research questions. These appendices are written in the format of short note articles.

Chapter 2: Blue Crane population estimates and trends

Flight team for the Western Cape summer aerial survey in 2019.

Abstract

Understanding the population demographics, distribution and habitat use of a species is key to its conservation. Using aerial survey, road count and ad-hoc sighting data, I detail the population estimates, flock demographics, distribution, and habitat use of Blue Crane *Anthropoides paradiseus*. I analyse citizen science data from the Coordinated Avifaunal Roadcounts (CAR) and Southern African Bird Atlas Projects (SABAP) to assess population trends across the Blue Crane range. I conducted winter and summer aerial surveys in the Western Cape wheatlands (Overberg and Swartland), using transects/distance sampling and one in winter 2021 in the Karoo. A quadrat design was used in the Karoo because Blue Crane distribution is patchier than the Western Cape. Using distance modelling, I estimate there to be 25458 (95% CI 21883–29618) Blue Cranes in the Overberg and 6072 (5211–7076) in the Swartland. In the Karoo, the total count was 9331, and a crude stratified extrapolation gave an estimate of 16464. Given the grassland population of some 4000 cranes, I estimate a population of 51000 (range 34000–68000) Blue Cranes in South Africa,

which is double the last estimate from 2002. Across all CAR precincts, summer counts of Blue Cranes increased by 24% (95% CI 3.4–51%) between 2000 and 2019 and SABAP reporting rates increased by 6.3% between SABAP1 (1989–1994) and SABAP2 (2007–2022). However, in 2010, the CAR population trend changed from positive to negative; since 2011, summer counts have declined by 19% (95% CI –31 to –5.2%), driven primarily by Overberg numbers declining by 22% from 2011–2019 (–37 to –1.9%). Continued CAR counts will be important to ascertain whether the population has stabilised at a lower density or is continuing to decrease. In winter, Blue Cranes select for pastures (especially lucerne and lupin fields) in the Karoo and Western Cape wheatlands. Flock sizes were significantly larger in the Karoo than the Western Cape, with flocks up to 1200 counted on irrigated lucerne fields. In both areas there is occasional conflict between farmers and cranes, as cranes can trample lucerne, damage sweet lupins and be perceived as a nuisance at feedlots. Selecting for pastures is a potential ecological trap for the species, particularly if social factors lead to lowered tolerance among farmers. Coupling these risks with observed declines in the last 10 years, raises concerns about the status of the Blue Crane population.

Introduction

Gathering information about species' demography and habitat use is a vital part of conservation (Volis & Deng 2019; Williams et al. 2020a). This is particularly important in the Anthropocene as ecosystems are impacted by rapid human development (Corlett 2015; Evans 2021). Now more than ever, conservation scientists need to understand changes to species' demographics, distributions, and habitat use (Evans 2021). This is especially important for long lived species, where an extinction debt may exist, where there is a lag between a negative impact and the observed effect on the population (Kuussaari et al. 2009; Watts et al. 2020). Monitoring species becomes increasingly complex when species occur outside of protected areas, for example in agricultural land. This is because land users need to be considered as part of the monitoring process, and socio-economic drivers can lead to land-use change, causing knock on impacts on species. Agricultural land can provide animals with abundant and reliable food sources (Ditmer et al. 2016; Hemminger et al. 2022). However, species reliance on transformed landscapes can be precarious if conditions are not optimal for survival or breeding but the species are still attracted to the area or have no alternative habitat i.e., the area becomes an ecological trap (Delibes et al. 2001; Kautz & Gardiner 2019). This can occur due to human-wildlife conflicts, pollutants, increased mortality, or agricultural intensification (Donald et al. 2001; Boatman et al. 2004; Ogada et al. 2012; Gibbons et al. 2015; Duriez et al. 2019).

For most species, agriculture has had a negative impact, particularly crop farming, which is the second most important driver of biodiversity decline (Donald et al. 2001; Phalan et al. 2011; Balmford et al. 2012; Maxwell et al. 2016). However, globally, the impact of agriculture on crane populations has been mixed (Austin et al. 2018; Hemminger et al. 2022). This is especially true for Blue Cranes *Anthropoides paradiseus*, which found the intensively farmed Western Cape wheatlands to be favourable, with numbers in this region increasing four-fold since 1993 (Allan 1993; Hofmeyr 2012; Young & Harrison 2020). Blue Cranes did not occur in great numbers in the Western Cape, prior to fynbos being converted for wheat production (Allan 1993). Based on the last nationwide census in the early 2000s, 47% of all Blue Cranes occur in the Western Cape wheatlands (McCann et al. 2007). The remainder of the South African population is found in the Karoo (42%), and in the eastern grasslands (10%) (McCann et al. 2007). Outside of South Africa a very small, isolated population occurs in northern Namibia (counts consistently <50 cranes since 2008 (Namibia Crane Working Group 2020). The grasslands population is a small remnant of what it used to be, this population diminished in numbers in the 1970s and 80s (Allan 1993; McCann 2001; Hofmeyr 2012; Young & Harrison 2020). These declines, and declines in the Karoo, lead to Blue Cranes being listed as Vulnerable on the global IUCN Red List (Johnson 1989; Vernon et al. 1989; Meine & Archibald 1996; Hofmeyr 2012; BirdLife International 2021a) (for further details see Chapter 1).

There is now evidence that the remnant population in the grasslands has been increasing; aerial survey counts of Blue Crane in KwaZulu-Natal increased by 366% between 2003 and 2018 (Galloway-Griesel et al. 2022). However, an analysis of citizen science road count data up until 2010 did not find an increasing trend in this area (Hofmeyr 2012). In the Western Cape wheatlands, counts were increasing up until 2007–2010 (Hofmeyr 2012), but seemingly have not continued (Young & Harrison 2020). With these contradicting and changing trends in the Blue Crane population, there is uncertainty about the state of the population. In this chapter, I address this, by doing a comprehensive assessment of the current state of Blue Cranes in South Africa.

The last population estimate for the Blue Crane is over 20 years old, it was derived from the National Crane Census, a citizen science initiative where landowners counted cranes on their farms on a set day each year until the early 2000s (McCann 2001; McCann et al. 2007). This minimum count estimated that South Africa had 20100–25520 Blue Cranes (McCann 2001; McCann et al. 2007). In this chapter I provide a current population estimate for the Blue Crane, based on my aerial surveys in the Karoo and Western Cape wheatlands as well as aerial surveys in KwaZulu-Natal (Jordan et al. 2021). In addition, I present seasonal information on flock size and structure, as well as habitat use, in the Karoo and Western Cape wheatlands.

Aerial surveys are ideal for surveying large areas effectively, they are however costly, especially as a long-term monitoring tool. This is where citizen science can serve as a valuable tool to bolster monitoring efforts and spread costs over more people (Hofmeyr et al. 2014; Dunn & Weston 2016; Barnard et al. 2017; Chandler et al. 2017; Dennis et al. 2017; Robinson et al. 2018; Dirzo et al. 2022; Lee & Hammer 2022). Citizen science datasets can lack precision and accuracy, creating uncertainty in estimates (Dennis et al. 2017; Hertzog et al. 2021), although for the most part this noise is offset by the power of large datasets, or can be mitigated by using multiple data sources (Robinson et al. 2018). I use two South African citizen science datasets to assess Blue Crane population trends over the last 30 years for all three populations in the South Africa, an update of the analysis done 10 years ago by Hofmeyr (2012). These datasets are the Coordinated Avifaunal Roadcounts (CAR) (FitzPatrick Institute of African Ornithology 2020), and the Southern African Bird Atlas Projects (SABAP) (Brooks et al. 2022).

The CAR project began in 1993 in the Overberg and expanded nationally, covering most of the Blue Crane range. The project involves citizen scientists counting large birds along roads twice a year (January and July). Hofmeyr (2012) found that the CAR counts are a reliable method for surveying Blue Crane, especially in areas where they are abundant and during summer when they are not flocking. The SABAP project started in 1987, it involves recording all species of birds within a grid structure (Brooks et al. 2022; Lee et al. 2022). For an individual species, a reporting rate can be derived from these species lists by calculating how often the species is recorded in that grid. It is well established that reporting rates are correlated with abundance e.g. SABAP (Allan 1994), BirdTrack and Breeding Bird Survey in the UK (Boersch-Supan et al. 2019) and butterfly counts in the UK (Dennis et al. 2017). Comparing reporting rates over time can therefore give insight into population trends for a species. An inherent risk of citizen science datasets is the increased sampling error, because a wide range of people, with varying levels of skill and precision, contribute data. This is why it is useful to draw from multiple citizen science datasets to check for consistency in observed trends and patterns.

In this chapter I draw from multiple data sources to do a comprehensive assessment of the state of the Blue Crane population. This includes a current population estimate and assessment of distribution, information on flock size and habitat selection during winter, and an analysis of population trends. This population wide assessment is the first step towards assessing the conservation status of the species.

Methods

Population estimates and distribution

I used aerial survey data to derive population estimates for the Blue Crane. When estimating the population size for a species, there are two approaches: total population count or sample population count (Norton-Griffiths 1975). For a widespread and mobile species like the Blue Crane, it is not feasible to do a total count, so an aerial survey was designed to do a sample population count, initially in the Western Cape wheatlands (Swartland and Overberg) and then in the Karoo. Based on the available data i.e., bird atlas distribution data (Southern African Bird Atlas Project 2 2022) and previous studies (Allan 1995; Hofmeyr 2012), Blue Cranes in the Western Cape are largely constrained to agricultural lands, where they are fairly evenly distributed. Therefore, simple transects were set up across each region (Overberg & Swartland), as opposed to quadrats or a stratified sampling design (Norton-Griffiths 1975). Transects (Overberg: 662 km, Swartland 329 km) were flown in summer (Overberg: 19 November 2019, Swartland: 20 November 2019) and winter (Swartland: 28 July 2018, Overberg: 11 September 2018), to compare seasonal differences in distribution. Blue Cranes breed in the summer, typically from late September, with chicks fledging three months after hatching, between December and May (Allan 2005), and are likely more evenly distributed in the landscape, than in winter when they congregate in flocks (Allan 1995; Allan 2005).

In the Western Cape wheatlands, I used Distance sampling (Thomas et al. 2010; Strobel & Butler 2014). Distance sampling accounts for imperfect detection by using the distances from a line transect to estimate the probability that an animal will be detected (Thomas et al. 2010). The further the animal is from the line, the lower its probability of detection (Thomas et al. 2010). In Distance analysis, a detection function is used to estimate the density in a specified area, which can then be extrapolated across the known range to give a population estimate. In the Western Cape wheatlands, Blue Cranes are almost exclusively found in agricultural habitats (crop fields, stubble fields, planted pastures, fallow lands), and do not typically use natural renosterveld or wooded areas (Allan 1995; Hofmeyr 2012). Within these agricultural landscape, Blue Cranes avoid cereal/canola crops when they get tall (from July/August up until harvest in November). Knowing these habitat preferences in Blue Crane, I used agricultural land as the area which I extrapolate the distance model density estimate to, to estimate Blue Crane abundance in the landscape. During the summer I specified all agricultural land as the available area, as cranes will use both crop stubble fields and pasture/fallow. The agricultural lands have been mapped to a fine scale (Western Cape Department of Agriculture 2016), allowing for an accurate area measurement.

In the Karoo, Blue Cranes are distributed over a much larger area than the Western Cape and tend to be more patchily distributed (Southern African Bird Atlas Project 2 2022). Simple line transects would likely be inefficient in this area, so I used a different approach. I used a similar survey design to the long-standing South African KwaZulu-Natal aerial survey, where a loose grid structure is flown over core crane areas (Galloway-Griesel et al. 2022). With this methodology, I chose quadrats (of approximately 100–200 km^2 in area) in areas where cranes occur; occurrence was informed by atlas data, field observations and expert opinion (Bradley Gibbons, EWT, pers. comm.). I accounted for variation in crane density by including areas known to have high densities of cranes, and areas with lower densities. I chose quadrats so that there was even coverage over the core Blue Crane range in the Karoo. These quadrats are intensively surveyed; the pilot flew transects across the quadrat, 1 km apart. Blue Cranes are highly visible in the landscape, and I assumed a near 100% detection probability within 500m on either side of the transect. I did not estimate distance from the plane to each sighting because accurately estimating distance in flight is challenging. When Blue Cranes were flushed by the plane, they typically fly and settle a short distance away, when this happened, their movements were observed to prevent double-counting. As this was the first survey, we did some exploratory flights between quadrats to assess whether Blue Cranes occur in these areas e.g. the south-west flight near Murraysburg (Figure 4). Over 8 days (2–10 September 2021, with one rest day), 19 quadrats were surveyed (total area = 5286 km^2, mean area per quadrat = 278 km^2 (SD 153); Figure 4). During active surveying (flights taking place < 600 m above the ground), a total length of 3941 km was surveyed. On flights between quadrats, active searching took place, and cranes and other large bird species were recorded. I assume detection probability to be the same on transects within quadrats and on transects between quadrats.

In the Western Cape, flights were done using a Piper Dakota (low wing), and in the Karoo a Cesna 182 (high wing). On all flights, there were two dedicated observers, on opposites side of the plane, the pilot and a data recorder/photographer. The flight track was continuously recorded (including altitude) with a Garmin GPS, and for each crane sighting, the GPS location, habitat, flock size, and, for the Western Cape surveys, estimated straight line distance from the plane to the crane sighting was recorded. In previous studies flown at $\pm$150 m above ground, in the same model of aircraft as used in the Western Cape surveys, the authors calibrated distance on the ground relative to markers on the plane wing (Shaw et al. 2015a). They established that at this flight height, the length of the plane wing relates to a distance of approximately 500 m on the ground (Shaw et al. 2015a). Therefore, when a crane was sighted, distance was estimated to the nearest 100 m based on where the sighting was in relation to the plane wing e.g., a crane sighted near the wing tip was classed as being 500 m away. Western Cape flights were at an average height of 136 m

(SD 64) above ground level, calculated by subtracting the GPS altitude recorded in flight from the ground altitude from a digital elevation model Esri WorldElevation/TopoBathy layer (Airbus et al. 2022). On the Karoo survey, flights were at a mean height of 131 m (SD 113). When large flocks were encountered, the data recorder took photographs of the flock, so that it could be counted accurately at a later stage. In the Karoo, habitat information was missing for 16% of sightings. Cloud cover was minimal on most surveys, allowing good visibility of the ground from the plane. However, the Swartland summer survey was overcast, which may have hindered the ability to detect cranes. Consequently, the mean detection distance was lower in the Swartland: 103 m (SD 63) than the Overberg: 134 m (SD 87).

Flock size and habitat use

To explore Blue Crane flock size, I gathered data on Blue Crane sightings of more than four individuals (so as to exclude pairs and family groups), collected between 2018 and 2022 in the Western Cape wheatlands and Karoo. I drew from several data sources: the aerial surveys (Karoo: n = 111 flocks, Western Cape: n = 54), road counts (2018 & 2019, Karoo: n = 3, Western Cape wheatlands: n = 190), and ad-hoc sightings collected opportunistically by Endangered Wildlife Trust field workers between 2018 and 2022 (Karoo: n = 42, Western Cape wheatlands: n = 311). During ad-hoc sightings I would record basic details of habitat use, including whether a feed trough was present. The summer/breeding season was taken as 1 October – 30 April (Karoo, n = 23, Western Cape n = 312); some cranes breed earlier than this, and some will stay on territory into May, but most breed within this window (Allan 2005). All sightings between May and September were classified as winter/flocking season (Karoo n = 137, Western Cape n = 418). GPS coordinates were not available for the road count flock sightings, so only ad-hoc and aerial survey sightings were used to analyse habitat use by flocks (n = 518). I recognised the following habitats in the Western Cape: dams, fynbos, and annual dryland agriculture crops; and in the Karoo: low shrubland, dams, and pivot-irrigated annual crops.

Population trends

I used data from two citizen science projects (Coordinated Avifaunal Roadcounts and Southern African Bird Atlas Project) to assess population trends in Blue Crane over the last 34 years, updating an analysis done by Hofmeyr (2012), which assessed the datasets up until 2010.

Coordinated Avifaunal Roadcounts

The project started in the Overberg in 1993 and expanded nationally from there. Routes along roads were set out, and repeatedly driven by citizen scientists in January and July each year. Counts follow a standard

methodology and can be treated as repeat surveys (Young et al. 2003; Hofmeyr 2012). Routes are grouped into precincts, which are areas deemed to be ecologically distinct. There are routes covering most of the Blue Crane range in South Africa (Figure 1). I repeated Hofmeyr's (2012) analysis of these data, adding counts from 2010 to 2019, analysing data from 1993 to 2019, although I excluded some precincts in years with too few data (see statistical analysis).

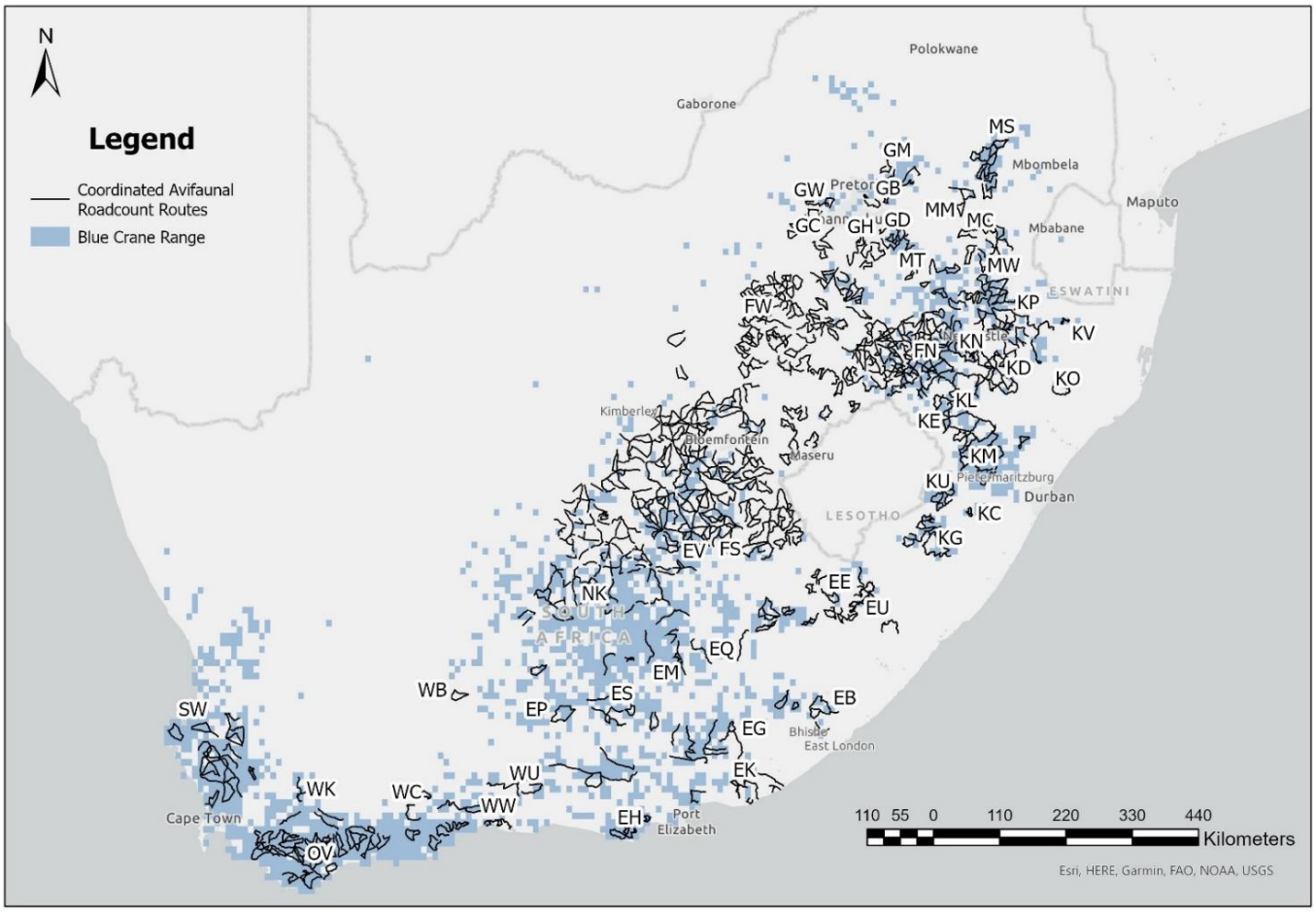


Figure 1: Coordinated Avifaunal Road-count (CAR) routes (black lines; letters indicate the precinct), overlaid with the Blue Crane occurrence map from SABAP2 (blue shaded pentads).

Participation in CAR in the Karoo precincts has dwindled over the last 5–10 years, and the data is limited. To supplement the Karoo CAR data I included Blue Crane counts from a long-term powerline survey near De Aar (Shaw et al. 2021 & Chapter 3). A 109 km section of the Droerivier Hydra and Hydra-Poseidon transmission lines were surveyed quarterly between 2008–2016 and 2019–2021. I include the numbers of live Blue Cranes counted for the summer and winter surveys, to match the timing of the CAR protocol.

Southern African Bird Atlas Projects

I used data from the Southern African Bird Atlas Projects, SABAP1 and SABAP2. The former ran from 1987–1991, and the latter, started in 2007, is ongoing. Both projects involve recording all birds heard and seen within a defined geographic space-grid, which are then submitted as an atlas card. For SABAP1 the geographic unit was the quarter degree grid cell (QDGC, 15 x 15 minutes) and in SABAP2 it is the 'pentad' (5 x 5 minutes). There are 9 pentads in a quarter degree grid cell. The methodology was slightly different in SABAP1, compared to SABAP2, in SABAP1 there was no imperative to cover the full QDGC and cards could be a duration of up to a month, with no minimum time, whereas in SABAP2, the advice was to cover as many habitats within the pentad as possible and observers had to record birds for at least 2 hours and at most 5 days, before submitting a card (Harrison et al. 1997; Brooks et al. 2022; Lee et al. 2022). For a full explanation of SABAP history and methodology see Harrison et al. (1997), Hofmeyr (2012) and Lee et al. (2022). Reporting rates are known to be related to abundance (Underhill et al. 1992; Robertson et al. 1995; Griffioen & Clarke 2002; Hofmeyr 2012; Amar et al. 2015; Lee et al. 2018), and by comparing reporting rates between and within the two different projects we can make inferences about changes in Blue Crane abundance in South Africa.

Statistical analyses

Western Cape Distance Analysis

I used the Distance package (Miller et al. 2019) in R 3.5.3 (R Core Team 2022) to estimate Blue Crane density and abundance in the Overberg and Swartland, based on the aerial survey data. I used ArcGIS (ESRI 2019) to delineate the study areas, Overberg and Swartland, with polygons (Figure 2). Using the Western Cape CapeFarmMapper 2016 crop census data (Western Cape Department of Agriculture 2016), I calculated the area within this polygon that was under crop agriculture, fallow and pasture (Overberg: total agricultural area 6802 km^2; pasture/fallow 4036 km^2; cereal/canola crop 2766 km^2; Swartland total agricultural 5692 km^2; pasture/fallow 3352 km^2; cereal/canola crop 2340 km^2). I used these area measurements to delineate the area the distance model density extrapolates to, to estimate population size.

Since distance was not estimated to precise accuracy, I performed a binned analysis (100 m intervals), which treats distance as ordered categories, rather than a continuous variable. I modelled the data with different key detection functions, considering distance as the only function of detection, as well as region and flock size as covariates, given that larger flocks are more likely to be detected. I used a χ^2 goodness-of-

fit test to assess model fit and Akaike Information Criterion (AIC) to select the most parsimonious model (Table S1). Models within 2 AIC points of the best fit model were considered plausible models for the data (Table S1) (Burnham 2002).

In winter, most crop fields are not available to cranes, because they were too tall, especially in late winter/spring. I calculated the proportion of Blue Cranes sighted in crop fields using the aerial survey (10% of cranes; see Results) and ad-hoc sightings data (4%), to understand the frequency of use. To account for some use of crop fields, I ran three different distance models for the winter surveys; one where I assumed the only available habitat is pasture/fallow (assuming crops are not used by cranes in winter), one where I set it as the area pasture/fallow + 5% of the crop area, and one where I set area as pasture/fallow + 10% crop (assuming some crops in July & September are still short enough to be used by cranes, and accounting for uncertainty in this %). I drew population estimates from the +5% model and use the other two to demonstrate upper and lower bounds.

I used the crop census data (Western Cape Department of Agriculture 2016) to compare habitat availability with habitat use, i.e., to look at habitat selection. If no habitat selection was occurring, I would expect the number of cranes using each habitat type to be in accordance with the area of each habitat available i.e., even distribution across habitats. I ran a χ2 goodness of fit test in Microsoft Excel to test this.

Karoo aerial survey

To understand variation in Blue Crane density in the Karoo, I assessed density per quadrat. In ArcGIS Pro 3.0.3 I drew polygons around each quadrat and used the Summarize Within tool to calculate the density of Blue Cranes counted within each quadrat. To make inferences on habitat selection, I created a 1 km buffer around the survey track (500 m either side) and summarised the percentage of each habitat category in the area based on the 2020 South African National Land Cover dataset (Department of Environment Forestry and Fisheries 2020b), simplifying these categories to 'natural' or 'agricultural'. I then performed a χ^2 goodness of fit test to test habitat selection, comparing the actual Blue Crane numbers per habitat type to the expected distribution (evenly distributed, according to availability). To quantify agricultural change in the Karoo, I compared the area under irrigated pivot fields per province between 1990 and 2020 (Northern Cape/Eastern Cape), by looking at the area that was classified as pivot-irrigated fields in 1990, with the area that had changed from shrubland to pivot-irrigated fields in 2020, using the national land cover change dataset (Department of Environment Forestry and Fisheries 2020a).

To extrapolate the minimum crane count to a population estimate I stratified the crane densities by habitat. Blue Crane density was particularly high on planted agricultural land (pivot-irrigated fields; see Results), so I stratify by agricultural land vs natural land. To extrapolate to the whole of the Karoo, I drew a polygon encompassing the survey area and wider Karoo biome, including only the area where Blue Cranes occur; an area of 46870 km^2. I calculated the area classed as natural vs agricultural using the 2020 South African National Land Cover dataset (Department of Environment Forestry and Fisheries 2020b). I then calculated the density of Blue Cranes in the surveyed area in natural vs agricultural, and applied these densities to the un-surveyed area, to get a total population estimate for the Karoo.

Flock analysis and habitat use

I used a generalised linear model to assess whether flock size was dependent on region (Overberg, Swartland, Karoo), season (flocking/breeding), or presence of a feed trough (no Karoo flocks were sighted at feed troughs). I used a quasi-Poisson model, as the Poisson model was over-dispersed. I included the CAR data in this model, to maximise sample size, this data does not have coordinates for each crane count, therefore I was not able to include habitat in the flock size model, as the methods described below require coordinates.

To look at the relationship between habitat and flock size, I considered two datasets: surface water, using the yearly classification layer from the Global Surface Water dataset (Pekel et al. 2016, 2019a, b, c, 2020a, b) and land use using the 2020 South African National Land-cover dataset (Department of Environment Forestry and Fisheries 2020b). Using the Near function in ArcGIS Pro, I calculated the distance between each flock and the nearest waterbody (seasonal and permanent), using the surface water data for the nearest year to when the data were collected. I created a circular buffer with a radius of 1 km around each flock to estimate the area (number of raster pixels) of each landcover type within each buffer, using the Summarise Categorical Raster function in ArcGIS Pro. Relationships between flock size and habitat covariates were non-linear, so I used Spearman Rank Correlations to look at the relationship between flock size and distance to water, and flock size and quantity of the various habitat types within the 1 km buffer. All geoprocessing was done using ArcGIS Pro 2.9.2. Data analysis was done in R 4.2.0 (R Core Team 2022). This analysis excluded the CAR data, because each crane count does not have coordinates.

Coordinated Avifaunal Roadcounts

Long term citizen science datasets inevitably have missing data (ter Braak et al. 1994); which can lead to misleading results. This is particularly the case with the Coordinated Avifaunal Roadcount dataset as

participation was lower at the beginning of the project and has dropped significantly in the last 7 years. One method to account for this is to impute missing values (ter Braak et al. 1994; Underhill & Prys-Jones 1994). I used the Underhill Index (Underhill & Prys-Jones 1994) to impute the data, which uses a χ^2 calculation to fill in an expected value for missing values, based on the observed values for that route and year (Hofmeyr 2012), using R (R Core Team 2022). I imputed the data per precinct for summer and winter, including all precincts with cranes, except for Beaufort West, as crane numbers counted are very low (only five in total). I pooled adult, juvenile and chick counts to get a total crane count. I ran the imputing process for 100 iterations. I set limits to ensure that I was not over-imputing and creating meaningless data: for a route to be included in the imputing process, 60% of the years had to have been surveyed. For example, the Swartland precinct, which has been active for 23 years, a route needed to have at least 13 years of data to be considered for the imputing analysis. I also set an upper limit for number of cranes imputed per year, at 60% of the total count each year e.g., in the Swartland, for 2018 and 2019 many routes had missing data and the percentage of cranes imputed was over 70%, so these years were excluded. Likewise, the north-west Free State precinct was excluded because of too few data. For the summer counts, an average of 12% of the crane numbers were imputed (range 0.6–21%), for the winter counts this was 11% (range 3–25%). The counts from the imputed dataset were then divided by the average route length for each route, to give cranes counted per km, per year and per route.

I then used the poptrend R package (Knape & Siriwardena 2016) to analyse the population trends in the CAR data, fitting Generalised Additive Models to the data (Knape & Siriwardena 2016). The best models, as assessed by % deviance explained, were with random temporal effects and a random smoother for route, using a Poisson distribution. I ran models per precinct, per season, as well as a model for the combined dataset between 2000 and 2019, to look at the national trend. I chose to look at the data from 2000 as by this date all precincts had initiated counts. The counts for some of the precincts were right censored, as participation became very limited or non-existent from the mid 2010s. The random smoother in the model accounts for this variability in the data. I also analyse the De Aar transmission line live counts using GAMs.

Southern African Bird Atlas Project

I use an approach developed by Hofmeyr (2012), repeating her analysis to compare the latest reporting rates for Blue Crane between SABAP1 and SABAP2, up until 25/04/2022. Comparisons are made by quarter degree grid cell (the scale of SABAP1), so for SABAP2 9 pentads were combined. To visualise the degree of change in reporting rate, I use the calculation developed by Hofmeyr et al. (2014), which is a Z score, weighted by the number of atlas cards submitted i.e. sample size. I only included cards that had 4 or more

cards for both projects, those that had fewer are marked on the map (Figure 8 & 9) (12 cards in South Africa, and 16 in Namibia). The Z scores have a normal distribution, so to display the results I categorise the Z scores by standard deviation, negative Z scores indicate a decline in reporting rate from SABAP1 to SABAP2, and positive Z scores an increase in reporting rate. To calculate the overall reporting rate change across the range, considering QDGCSs with 4 or more cards, I took the average reporting rate for all QDGCs in SABAP2, minus that for SABAP1 and divided by the average reporting rate for SABAP1 (Lee et al. 2017). SABAP2 has now been running for 16 years, so I do a comparison of reporting rates within this project. I compare 2007–2016 to 2017–2023, as this was the most even split of the data (173874 records vs 200067). I use the same methods as the SABAP1 vs SABAP2 comparison. Only 1233 of 3317 pentads had 4 or more cards for each time period.

Results

Population estimates and distribution

On the summer Overberg aerial survey, I counted 244 cranes in 83 sightings (range 1–44 cranes per sighting) at an average rate of 0.3 cranes/km flown; 61% of sightings were in pairs and 24% single. By comparison, in winter I counted 1231 cranes in 122 sightings (range 1–106 per sighting; Figure 2), at an encounter rate 6 times higher (1.9 cranes/km); only 42% of crane sightings were in pairs and 4% single. Far fewer cranes were counted in the Swartland compared to the Overberg; only 45 cranes in summer (3 pairs, and two flocks; range 1–34; Figure 2) at an average rate of 0.1 cranes/km, and 200 in winter (4 pairs and six flocks; range 2–94) at a rate of 0.6 cranes/km (Figure 2). Combining both regions, during the summer, 33% of Blue Cranes counted were in pairs. In winter the greatest concentration of larger flocks was in the eastern Overberg, east of Swellendam (Figure 2).

There were too few data to model the summer counts, so population estimates are based on the winter counts. Using distance modelling, I estimated there to be 25458 (95% CI 21883–29618) Blue Cranes in the Overberg and 6072 (5211–7076) individuals in the Swartland, based on the pasture + 5% crop area model (Table 1). Considering the other models, this estimate could range between 18574 and 38042 for the Overberg and 4124 and 9963 for the Swartland (Table 1). The models estimated Blue Crane density to be 3.4–3.5 times higher in the Overberg than the Swartland (Table 1).

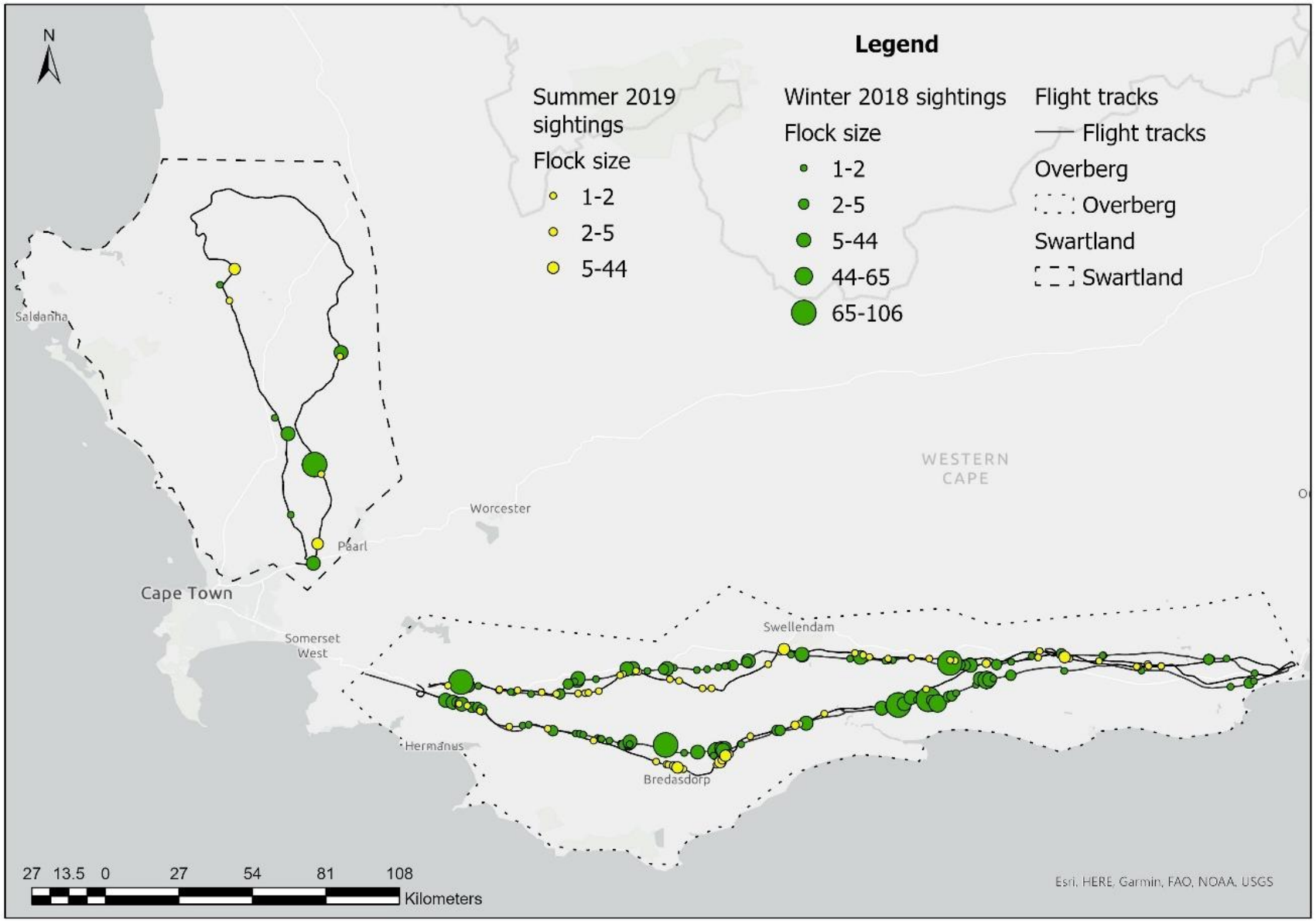


Figure 2: Flight paths of aerial censuses in the Western Cape, with study area outlined and Blue Crane sightings for summer (yellow) and winter (green), size of icon indicates flock size.

Table 1: The results of the top two Distance models developed to estimate Blue Crane population in the Overberg and Swartland, from two winter aerial censuses. Crane density is estimated, as well as the estimated population for each area based off three scenarios of habitat availability: considering pasture fields only, and pasture and some crop fields (5 and 10%).

Area	**Estimated population (95% CI)**			**Crane density·km^2 (95% CI)**
Model	Pasture area only	Pastures + 5% crop	Pastures + 10% crop	
Overberg				
Hazard rate detection function (no covariates)	24615 (20918–28312)	25458 (21883–29618)	26303 (22354–30252)	6.10 (3.75–8.45)
Hazard rate detection function (covariate: flock size)	26937 (18574–35300)	27859 (20402–38042)	28784 (19846–37722)	6.67 (3.52–9.82)
Swartland				
Hazard rate detection function (no covariates)	5868 (4976–6760)	6072 (5211–7076)	6278 (5325–7231)	1.75 (0.12–3.38)
Hazard rate detection function (covariate: flock size)	6609 (4124–9094)	6840 (4695–9963)	7071 (4413–9729)	1.97 (0.03–3.91)

In the Karoo, I counted 9331 Blue Cranes in 151 sightings. The median count per sighting was 19 cranes (range 1–1207) and 40% of sightings were pairs or singles. I counted five exceptionally large flocks of over 500 cranes; three (>700) were on pivot-irrigated lucerne fields (Figure 3), and the other two (605, 521) were in natural shrubland near Middelburg (Figure 4). The other large birds commonly recorded were Ludwig's *Neotis ludwigii* and Denham's Bustard *Neotis denhami* and Blue Korhaan *Eupodotis caerulescens* (for full species list see Table S2).

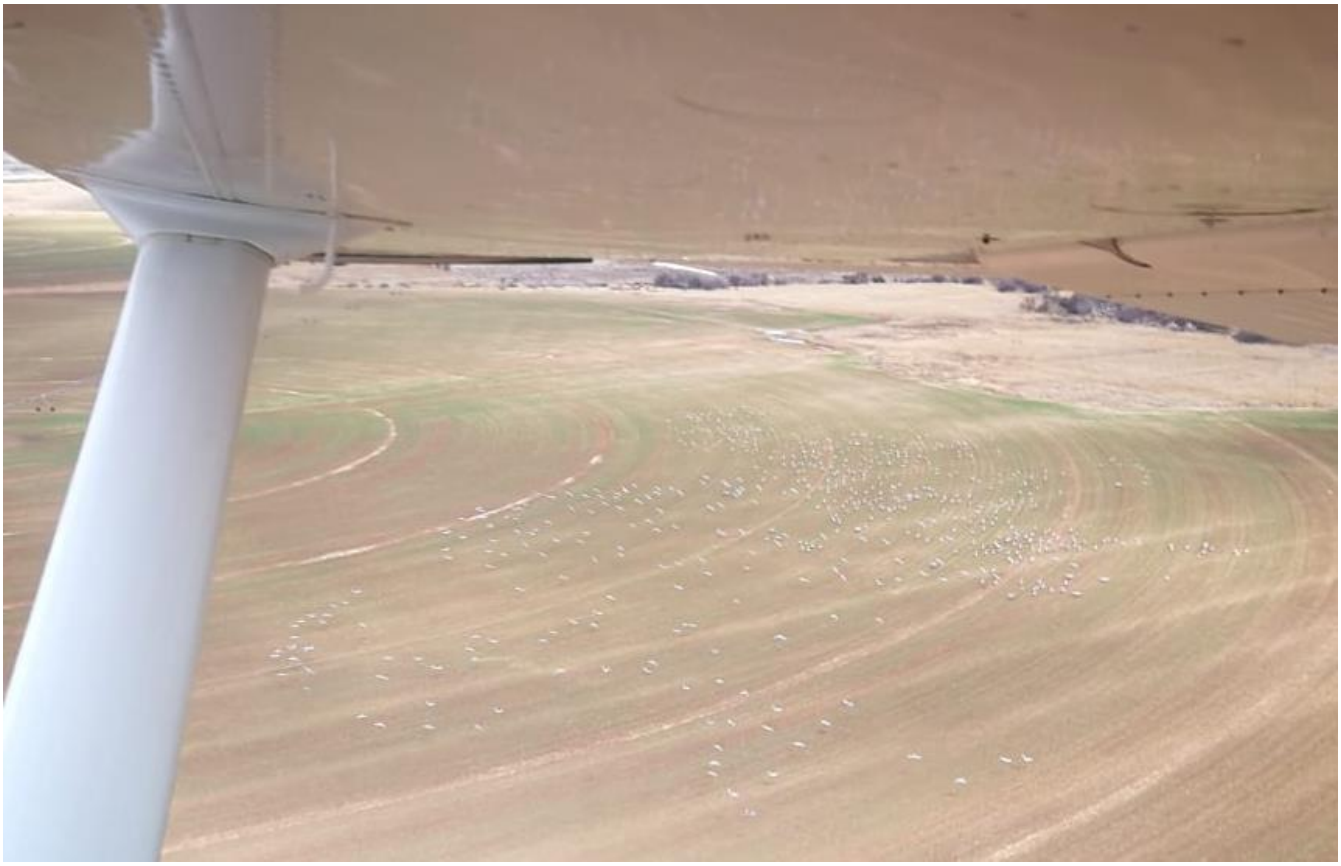


Figure 3: A Blue Crane flock of 1207 on a pivot-irrigated lucerne field in the Karoo, near Orania, Northern Cape (Photograph: Christie Craig).

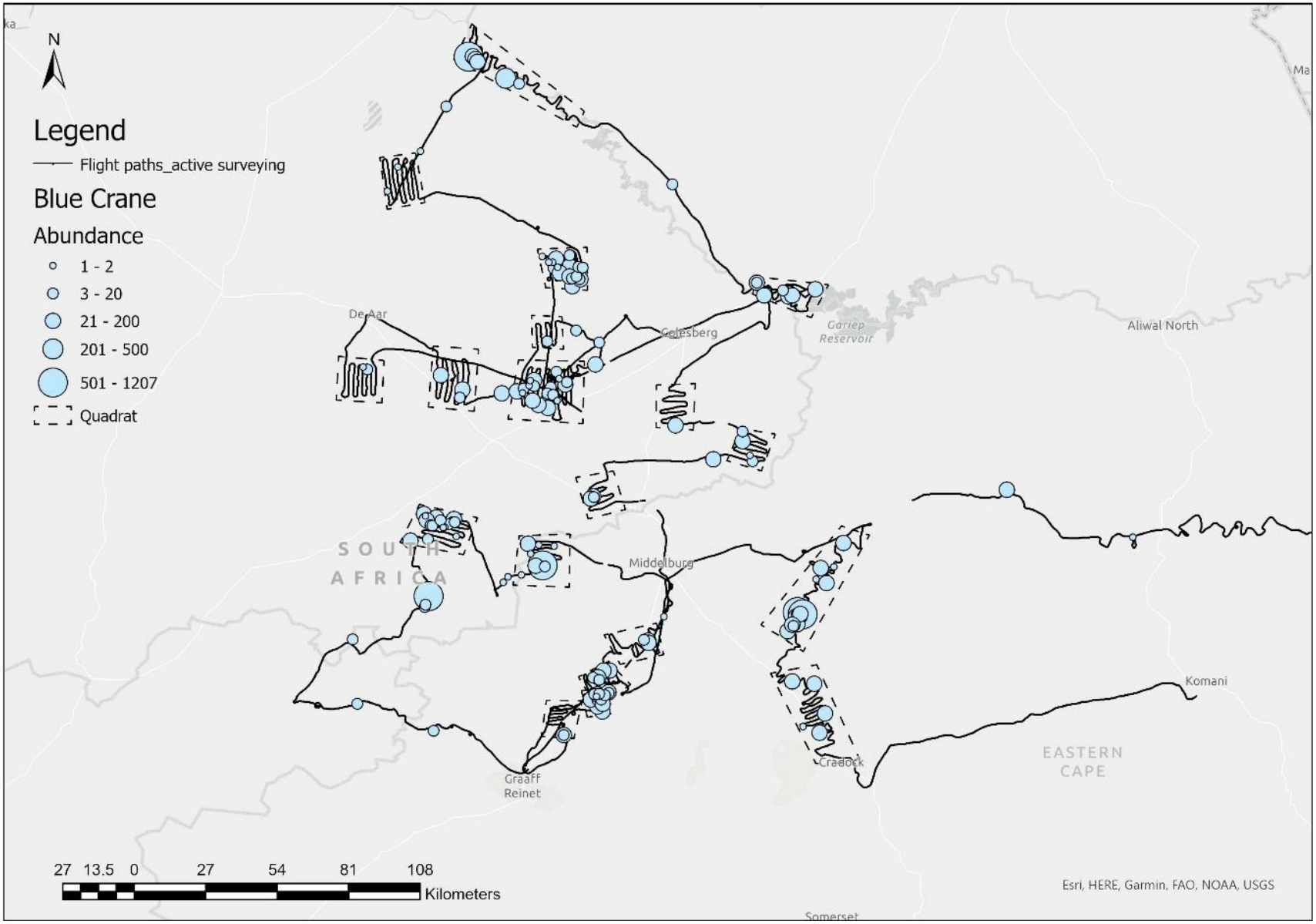


Figure 4: Map showing quadrats and flight paths of Karoo aerial survey conducted in September 2021, Blue Crane sightings are displayed in blue, the size of the icon indicates the size of the flock.

Most (62%) of the survey effort (distance flown) was within quadrats, and 91% of cranes counted were within the quadrats (Figure 4). Within quadrats, Blue Cranes were counted at an average density of 1.6 cranes/km^2 (range per quadrat: 0.02–8.6 cranes/km^2). Outside of quadrats the density was higher (2.6 cranes/km^2), driven primarily by one flock of 605 cranes west of Middelburg. Removing this flock gave a density of 0.8 cranes/km^2 outside of quadrats. The quadrat with the highest density was in the Nieu Bethesda Basin between Graaf Reinet and Middelburg (Figure 4) (8.6 cranes/km^2), followed by the quadrat at Grassridge Dam (east of Middelburg/north of Cradock) (3.8 cranes/km^2) and the northern most quadrat, along the Orange River near Orania (3.6 cranes/km^2). All three quadrats had a high density of cranes on pivot-irrigated lucerne fields (e.g. Figure 3). Since 1990, there has been a 63% increase in the area under pivot irrigation in the Northern and Eastern Cape (1990: 483 km^2, 2020: 785 km^2), namely along the Orange River and near Grassridge Dam (along the Teebus and Groot-Brak Rivers).

Blue Crane density on agricultural lands was 7.3 cranes/km^2 and 0.05 cranes/km^2 on natural land. Extrapolating this to the areas in the Karoo which were not surveyed (39498 km^2 natural and 589 km^2 agricultural), this gives a crude population estimate of 6133 cranes in the un-surveyed area. Adding this to the minimum population count of 9331 from the survey, gives a population estimate of 16464 for the Karoo as a whole.

Taking a conservative population estimate from the Western Cape distance models, I round the Overberg population to 25000 cranes and Swartland to 6000. Drawing from the Karoo aerial survey, I round the Karoo population estimate to 16000 individuals. The latest Blue Crane population estimate for KwaZulu-Natal was 1963 individuals (Jordan et al. 2021), based on aerial surveys. The last population estimate for the other provinces of the eastern grasslands is from the early 2000s (McCann et al. 2007). Assuming that Blue Crane numbers have on average stayed stable across the grasslands, which seems like a reasonable assumption from the CAR data, I can add the counts from the other provinces from McCann et al. (2007) to the latest KwaZulu-Natal aerial survey estimate to get a total grasslands population of 4000 individuals. To estimate uncertainty in the grasslands and Karoo estimates, I use the minimum count as the lower end and the extrapolated count as the upper end (Table 2). This comes to a national population estimate of 51000 (range 34000–68000) (Table 2). This is close to the global population estimate, as there are fewer than 50 cranes in Namibia (Namibia Crane Working Group 2020).

Table 2: Summary of the rounded population estimates, with rounded range of uncertainty, per subpopulation for South Africa (in italics, the breakdown of subregions).

Subpopulation	Population estimate	Range	% of national estimate
Western Cape wheatlands	31000	23000–48000	61%
Overberg	*25000*	*19000–38000*	
Swartland	*6000*	*4000–10000*	
Karoo	16000	9000–16000	31%
Grasslands	4000	2000–4000	8%
KZN	*2000*		
Mpumalanga, Free State, North West, Gauteng, Limpopo	*2000*		
Total	51000	34000–68000	

Habitat selection

In the Western Cape wheatlands, 60% of the habitat is pasture/fallow and 40% is crops. Cranes are not evenly distributed between the available habitats, in summer they select for stubble fields ($\chi^2 = 144.18$, df = 1, $p < 0.01$), 75% of cranes were counted in this habitat. Whereas in winter they select for pasture/fallow lands ($\chi^2 = 387.44$, df = 1, $p < 0.01$), 20% of sightings (groups) were in a pasture with a sheep feedlot (Figure 5 & Table 3).

In the Karoo, 89% of the land-cover (excluding buildings and infrastructure) was natural shrubland or grassland, and 8% was agricultural, namely lucerne pastures, the remaining 3% was waterbodies. As in the Western Cape wheatlands, in winter Karoo Blue Cranes were not evenly distributed, and selected for pastures ($\chi^2 = 52336.11$, df = 1, $p < 0.01$), 78% of cranes counted during the survey were on pastures (Table 3).

Figure 5: A Blue Crane flock of 44 at a sheep feedlot during the Overberg winter aerial survey (Photograph: Roelf Daling).

Flock size and habitat use

In the Western Cape wheatlands and Karoo, mean flock size in winter, 40 (SD 84, n = 556) was double that of summer flocks, 18 (SD 20, n = 333), this was statistically significant (Estimate = 0.54, SE = 0.13, $p < 0.01$). Mean Karoo flock sizes, 65 (SD 148, n = 159) were significantly larger than in the Overberg, 23 (SD 25, n = 625) (Estimate = –0.96, SE = 0.12, $p < 0.01$) and Swartland, 34 (SD 32, n = 105) (Estimate = –0.61, SE = 0.18, $p < 0.01$). However, averages were skewed by large flocks in the Karoo; median flock sizes were similar between the Karoo and Swartland, and lower in the Overberg (Overberg = 12, Swartland = 24, Karoo = 23). Mean flock sizes at feedlots (40) were significantly larger than those not at feedlots (23, Estimate = 0.40, SE = 0.17, $p = 0.02$).

In the Western Cape I did not find any correlations between crane flock size and available land cover within a 1 km radius. In the Karoo, crane flock size was positively correlated with availability of irrigated pivot lucerne fields within a 1 km radius of the flock ($\rho = 0.4$, $p < 0.01$). Flocks were significantly smaller in areas with more natural Karoo shrubland ($\rho = 0.3$, $p < 0.01$).

Table 3: The % of groups and % individuals in each habitat type during Karoo and Western Cape aerial surveys.

Habitat	Karoo Winter		Western Cape Summer		Western Cape Winter	
	% individuals	% groups	% individuals	% groups	% individuals	% groups
Bare ground			1	1		
Dam	4	7	12	1		
Crop					10	10
Crop stubble			75	75		
Fallow/pasture	78	34	12	22	64	70
Natural grassland/shrubland	13	43				
In flight	4	5	0.3	1		
At feed/water trough*	2	11			26	20

*in the Western Cape wheatlands these troughs were in pasture fields

Population trends

Over the last 20–30 years, Blue Crane numbers have been increasing. Across all CAR precincts (summer counts), Blue Crane numbers increased by 24% (95% CI 3.4–51%) between 2000 and 2019 (Table S3). Across the Blue Crane range in South Africa reporting rates per QDGC increased on average by 6.3% between SABAP1 and SABAP2, if Namibia is included, this reduces to 3.7%, due to the strongly declining trend of this population. In 2010 the population trend changed from positive to negative, according to CAR data (Figure 6). Since 2011, across all precincts, the summer counts have declined by 19% (95% CI –31 to –5.2%) (Table S3), mainly due to decreases in the Overberg, where Blue Crane density is highest (Figure 11). In the Overberg, Blue Crane numbers increased significantly between 1994 and 2010 (261%, 95% CI 169–400%), but declined by 22% from 2011–2019 (–37 to –1.9%; Table S3).

Participation was poor in the Swartland CAR project between 2018 and 2019, so I was only able to analyse the data up until 2017. The Swartland followed a similar trend to the Overberg, summer counts increased by 222% (95% CI 102–401%) between 1997 and 2010 (Table S3), but unlike the Overberg remained stable after 2011 (Figure 7). CAR trends in the Little Karoo are similar to trends in the Overberg and Swartland (Table S3, Figure 7), this area is a fringe population of the Western Cape wheatlands. SABAP reporting rates increased throughout the Western Cape between the two projects, Overberg declines are not yet evident in this data set (Figures 8 & 9).

There was little data available for the Eastern Cape and Eastern Karoo (Northern Cape) precincts, so I could only analyse the summer counts until 2017 and 2016 respectively. In the Eastern Cape Karoo precinct, Blue Crane summer counts have been declining (Table S3), particularly since 2015 (Figure 7), however this decline was not significant (the confidence interval includes zero). In the Northern Cape (Eastern Karoo precinct) there were significant declines since 2011 (–49%, 95 CI –71 to –17%), but this was based on only 6 years of data (Table S3, Figure 7). Counts of live cranes during the De Aar transmission line surveys echo the declining trend in the Northern Cape (–68%, 95% CI –89 to –5.6%). There is no evidence of declines in the Karoo, based on SABAP reporting rates which indicate little change between the projects (Figure 9). However, there are far fewer SABAP1 and 2 cards submitted for the Karoo, compared to the rest of the country (Figure 10).

Blue Cranes are counted at low density in the grasslands, compared to the Karoo and Western Cape (Figure 7). As a result, the grassland CAR trend models have very broad confidence intervals (Table S3), so although all grasslands precincts (except for the North-eastern Free State) indicate a positive population

trend, there is little confidence in these estimates (Table S3, Figure 7). The only grasslands precinct model that has a significant trend, is winter counts in the north-eastern Free State, where counts have declined overall by 94% (95% CI –99 to –22%) (Table S3), although the data are very variable (Figure 7). The SABAP reporting rate change map does however support a declining trend in the north-eastern Free State between the two atlas periods (Figure 9). This map also indicates strong declines in reporting rate in Gauteng and more moderate declines in southern KwaZulu-Natal (Figure 9).

There is evidence of range contraction in Blue Crane, between SABAP1 and SABAP2 (Figure 8). Overall, 22% of QDGCs that recorded Blue Crane in SABAP1, didn't record Blue Crane in SABAP2. This is compared to 18% of QDGCs that recorded Blue Crane in SABAP2 but not SABAP1 i.e. new range. This indicates a net loss in Blue Crane range of 4% between the projects. Loss of range is occurring predominantly in the grasslands, particularly in the Free State and North West Provinces, and in Namibia (Figure 8). Whereas Blue Crane range has expanded along the west coast and along the western fringes of the Karoo range (Figure 8).

Comparing within SABAP2, the change in reporting rate (5%) between 2007–2016 and 2016–2023 was overall positive across South Africa (Table 4). Increases in reporting rates were highest in the grasslands and Karoo (Table 4), although the data available for the Karoo was sparse (Figure 12). There is an indication that reporting rates are declining in the western Overberg and southern Swartland (Figure 12).

Table 4: Average reporting rates (% cards reporting Blue Cranes) within SABAP2 (2007–2016 and 2017–2023), and the average change between the two time periods, per region and as whole.

Region	Average Reporting Rate 2007–2016 (%)	Average Reporting Rate 2017–2023 (%)	Average Change in Reporting Rate (%)
Grasslands	11	17	6
Karoo	24	32	9
Western Cape	40	42	2
Total	26	31	5

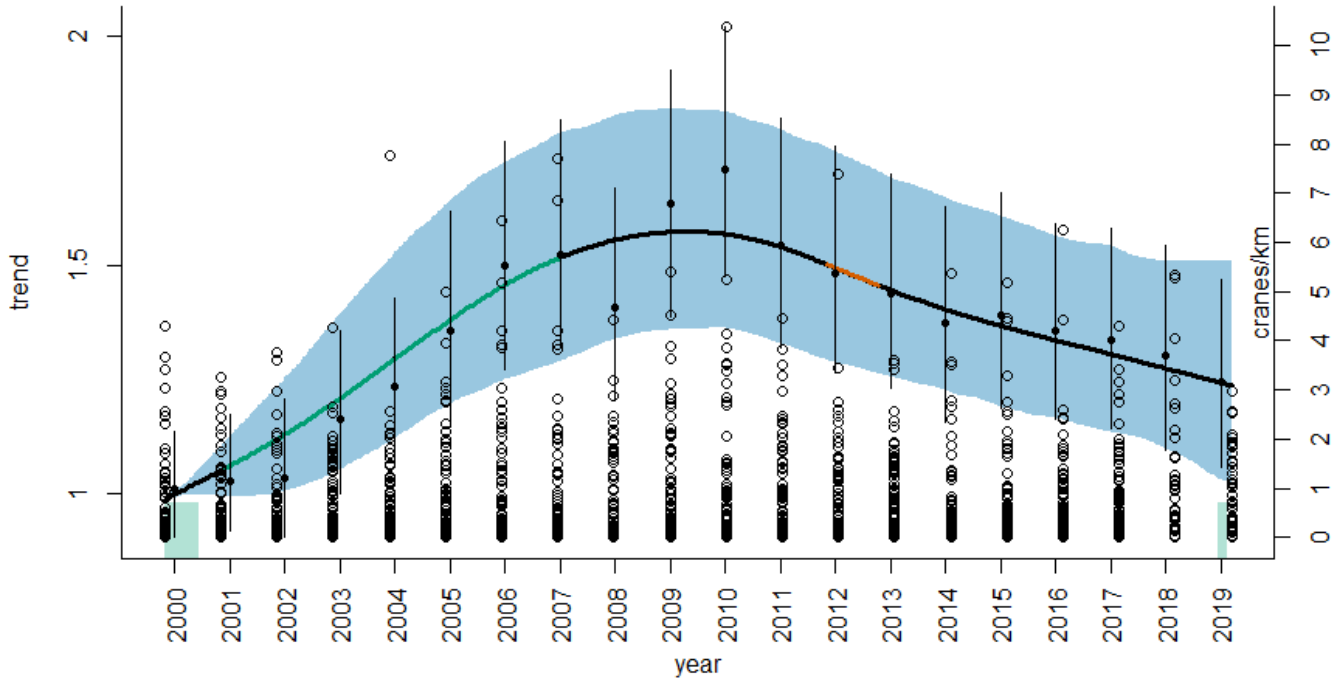
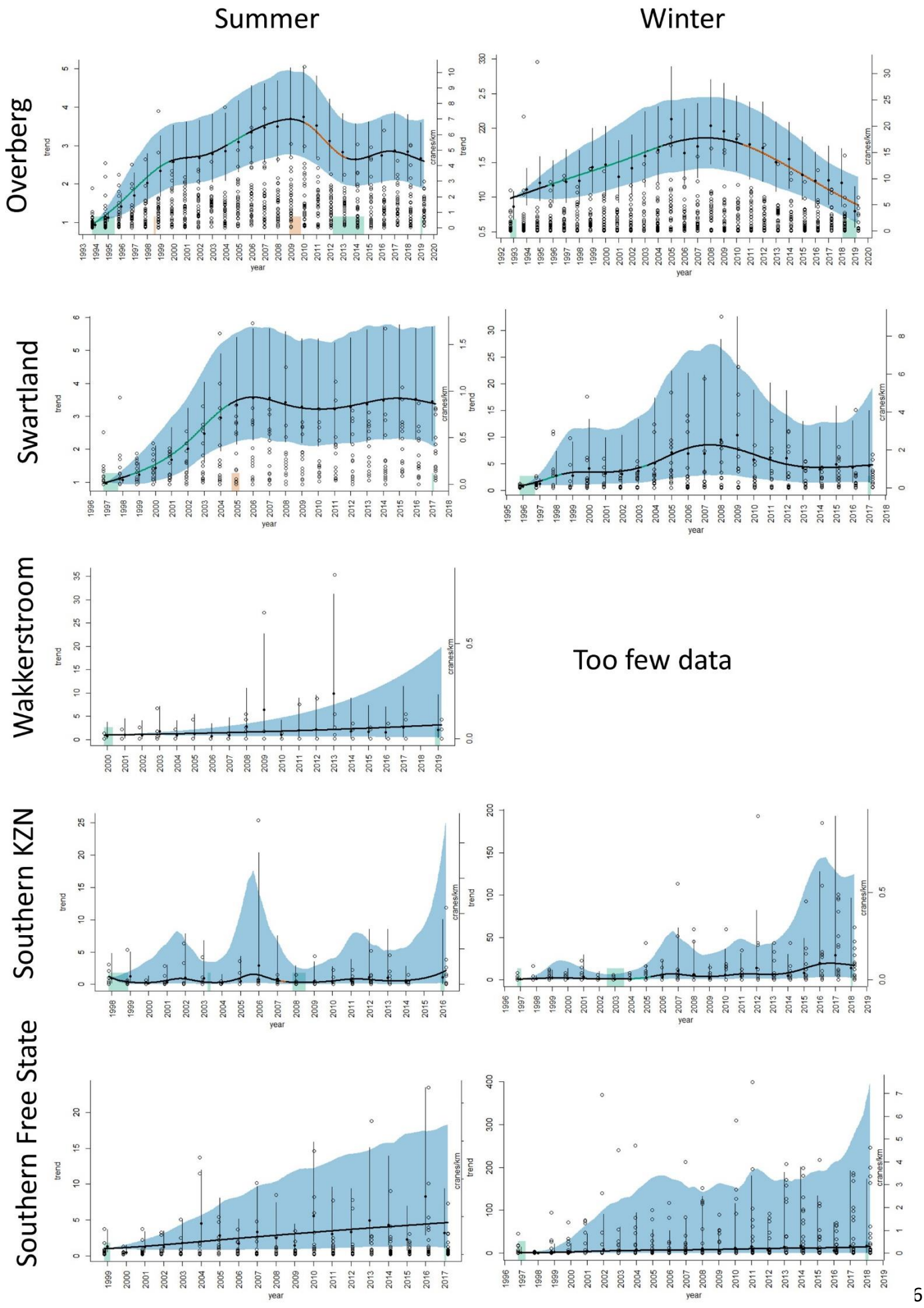
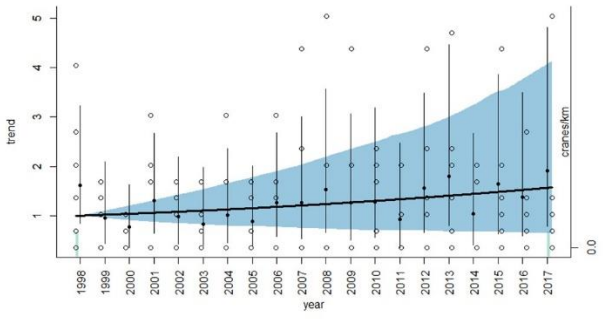
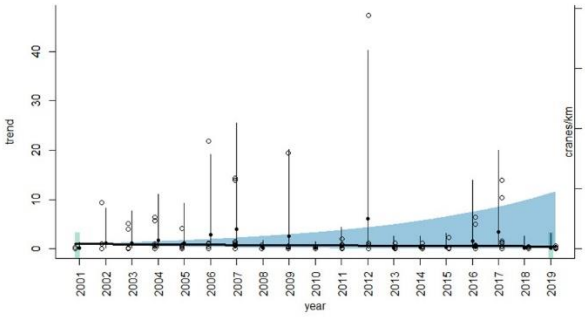
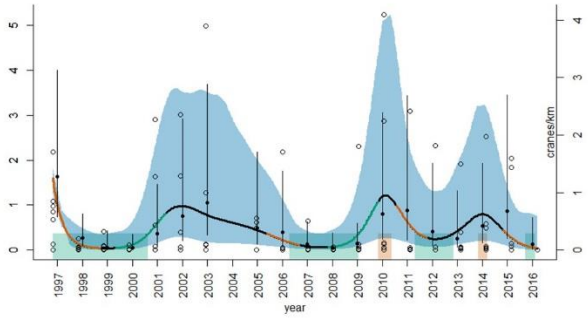
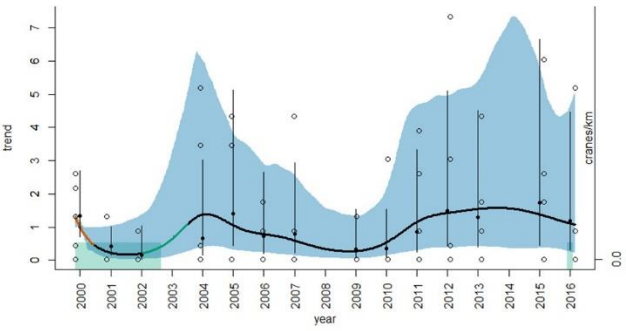
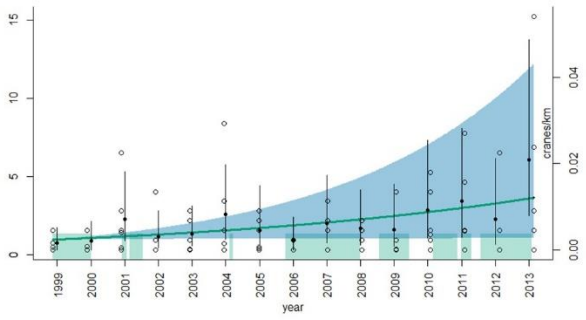
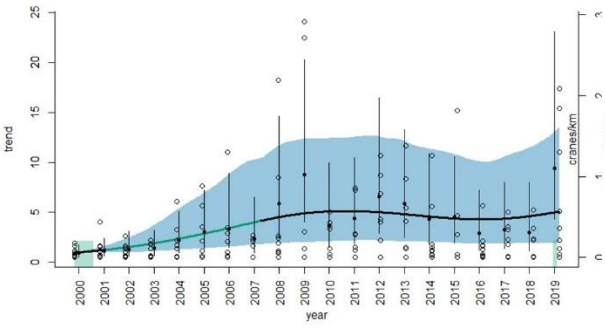
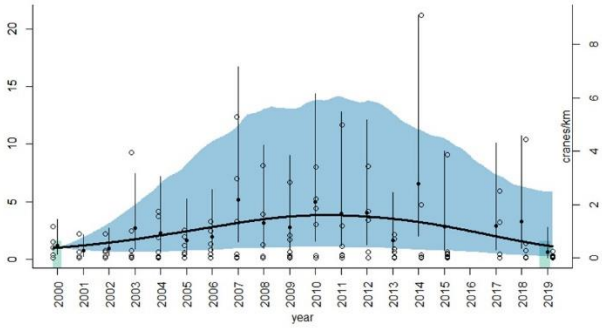


Figure 6: The GAM models fitted in poptrend for summer counts for all CAR precincts combined, between 2000 and 2019. The long-term trend is indicated by the solid black line with the 95% confidence intervals in blue, and the estimates of trend per years as the point, with the vertical lines indicating 95% confidence intervals of the year estimate. Where the line changes colour indicates a significant increase (green)/decline (red) based on the first derivative of the GAM used to derive the trend line from the data. The coloured blocks on the x axis indicate where the trend changes significantly, based on the second derivative. The raw imputed Blue Crane numbers/km are plotted as open circles.


Summer
Winter
Overberg
Swartland
Wakkerstroom
Too few data
Southern KZN
Southern Free State
trend
cranes/km
year

	Summer	Winter
North-western KZN		Too few data
North-eastern Free State		
Mpumalanga		Too few data
North-eastern Eastern Cape		Too few data
Little Karoo		

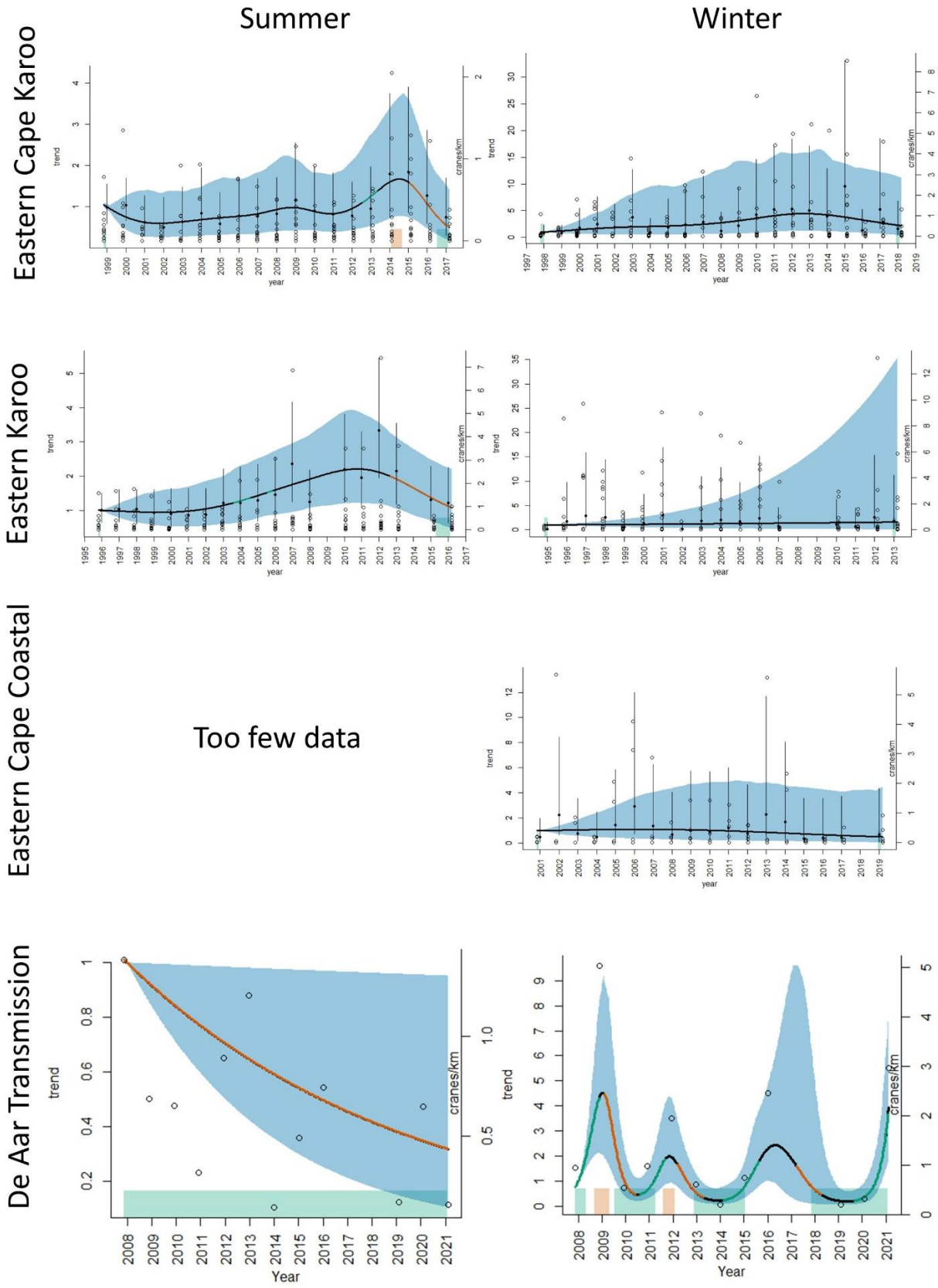


Figure 7: The GAM models fitted in poptrend for each CAR precinct and the De Aar Transmission live counts for summer and winter. Conventions as per Figure 6.

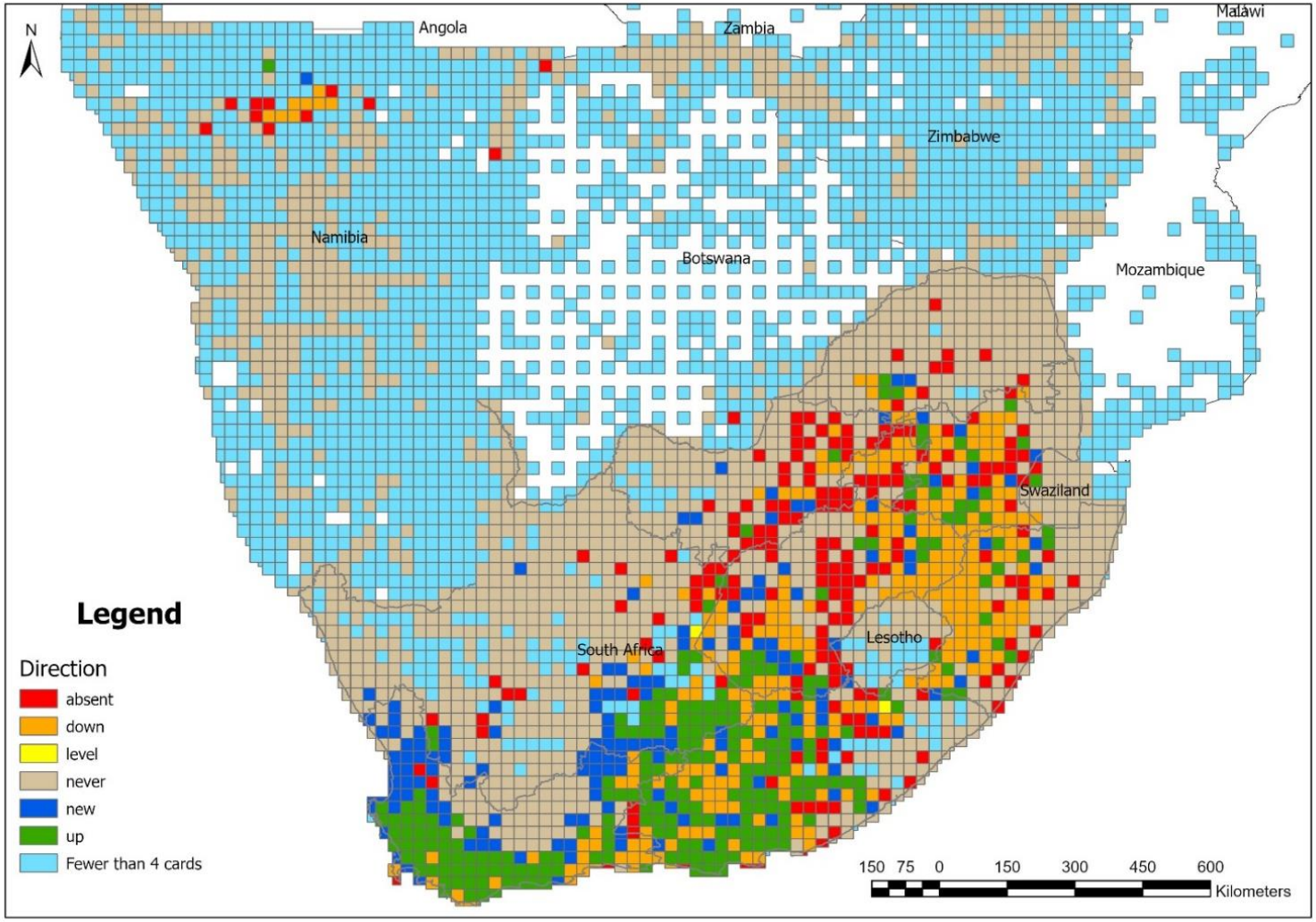


Figure 8: Comparison of Blue Crane reporting rates in SABAP1 vs SABAP2, indicating Quarter Degree Grid Cells (QDGCs) where cranes have never been recorded (never), where they were recorded in SABAP1 but weren't in SABAP2 (absent) and vice versa (new), and where they were recorded in both projects, the direction of reporting rates from SABAP1 to SABAP2 (down, level or up). QDGCs with fewer than 4 cards in either project are indicated in blue.

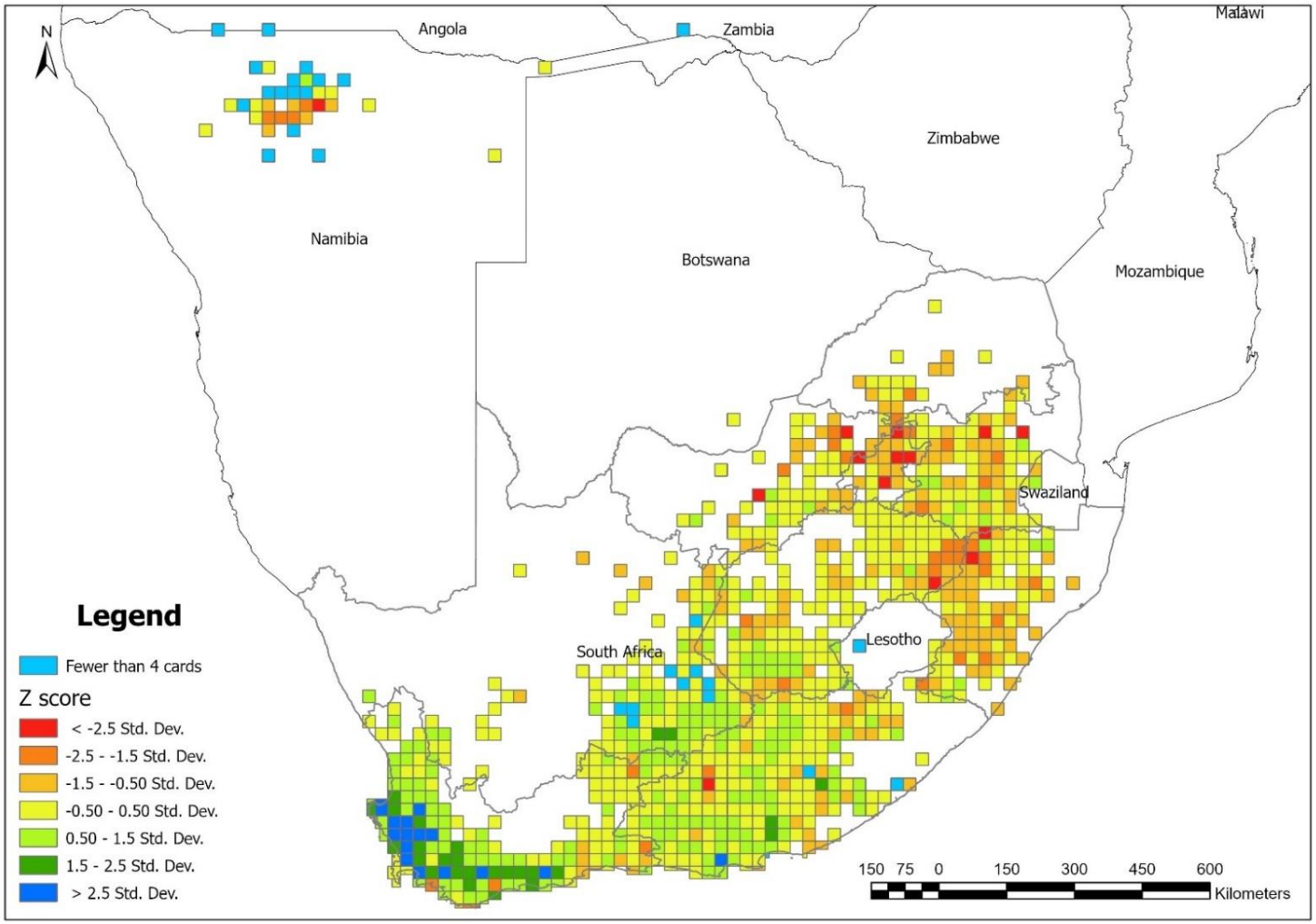
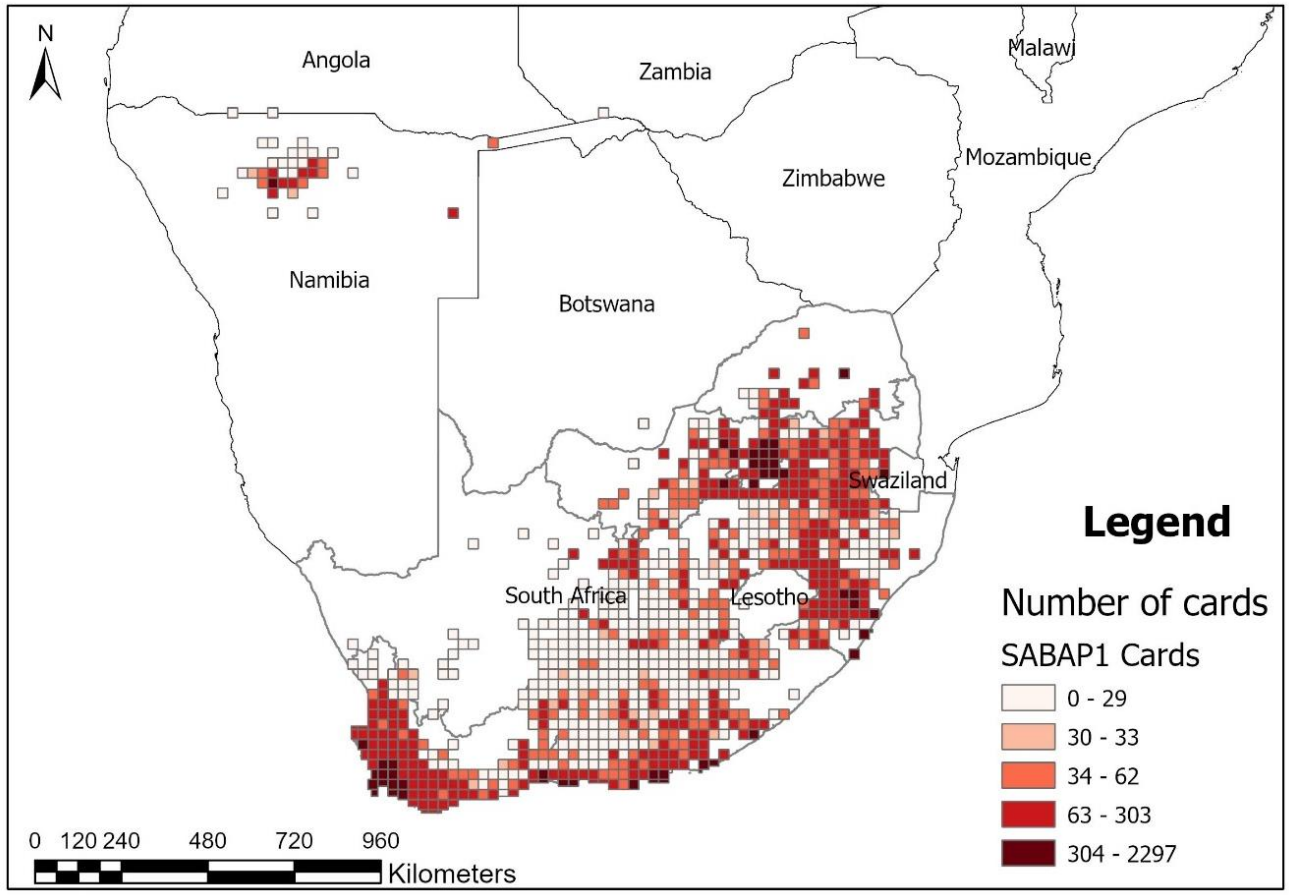


Figure 9: The change in reporting rate for Blue Crane by Quarter Degree Grid Cell between SABAP1 and SABAP2, the strength of the change in reporting rate is indicated by the Z score, factoring in reporting rate and number of SABAP cards submitted. Z scores are displayed by their standard deviation from the mean, red and orange indicate declining reporting rates, yellow a stable or weak change in reporting rate and green or blue increasing reporting rates.



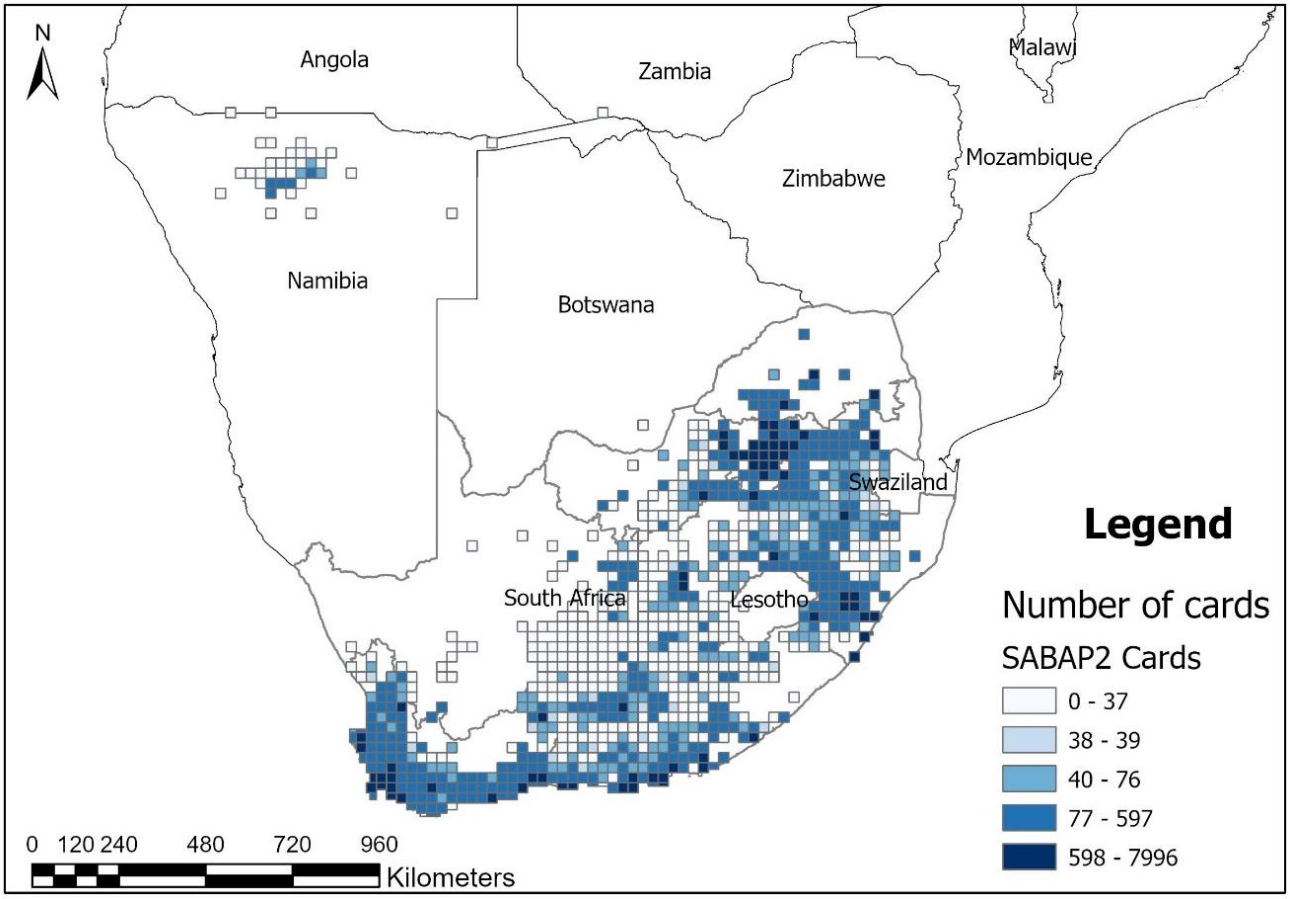


Figure 10: Number of cards submitted for SABAP1 (top) and SABAP2 (bottom), categorised by the geometric interval of the data to highlight areas of under-sampling.

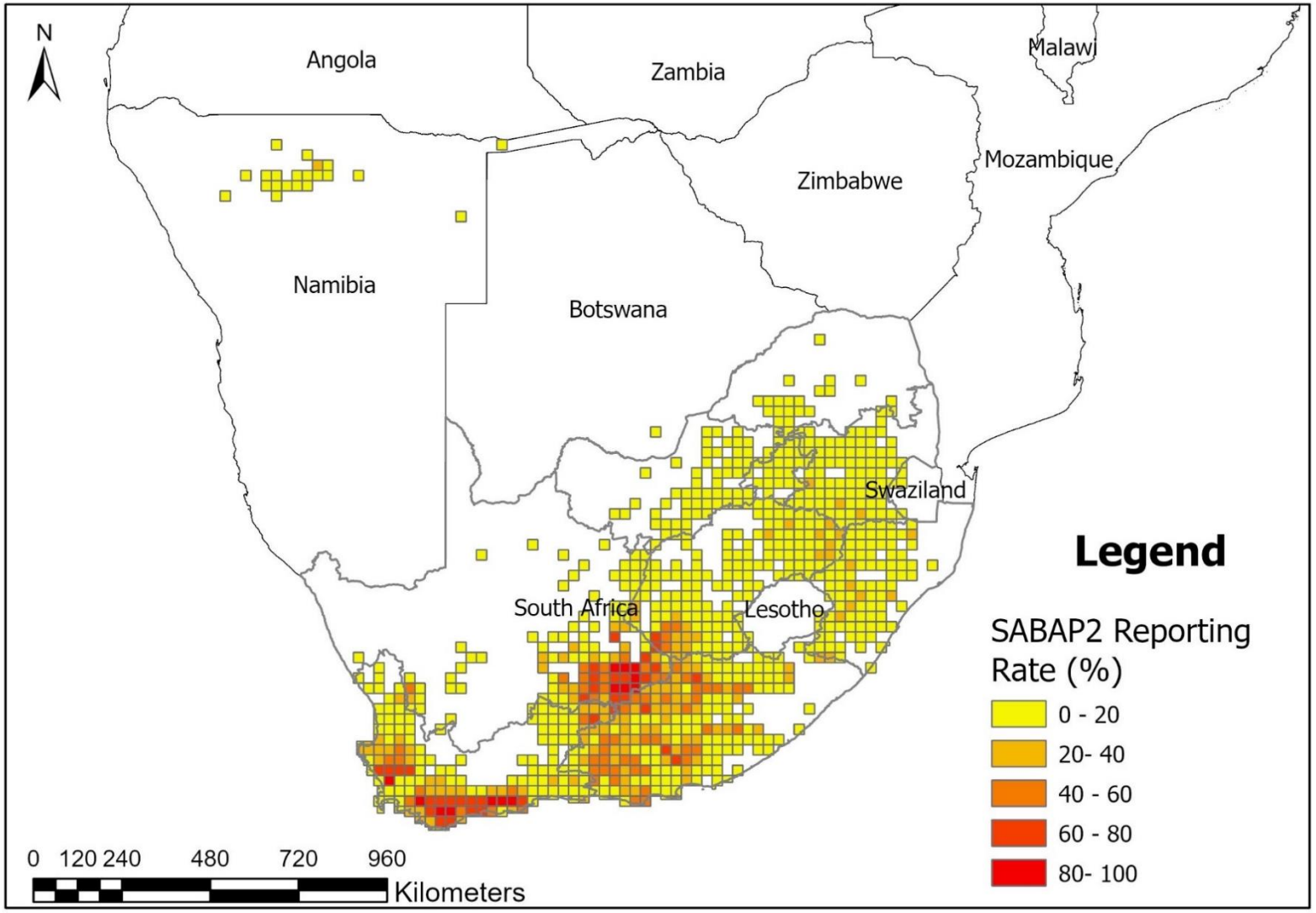


Figure 11: Blue Crane reporting rates (%) for SABAP2 by QDGC.

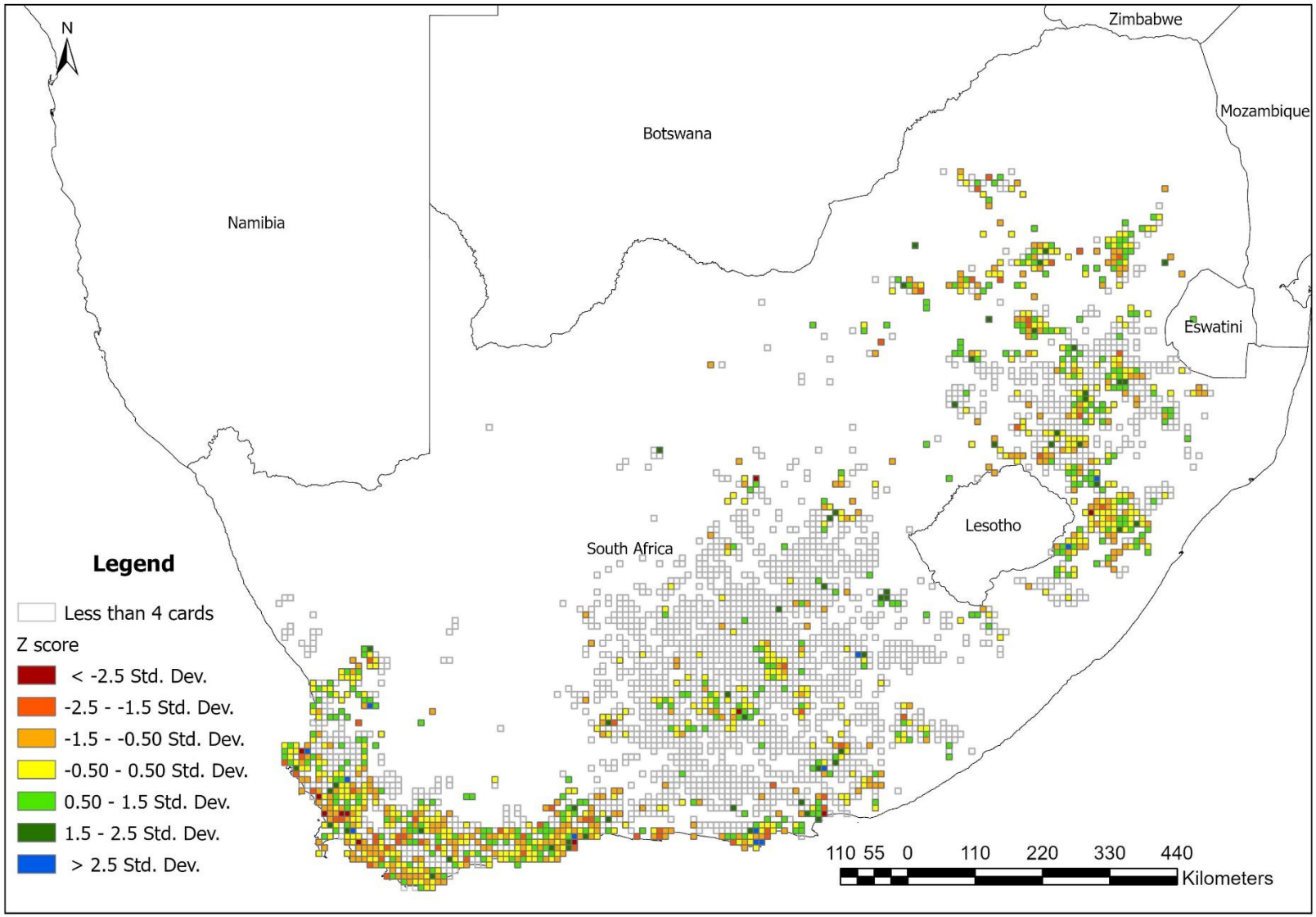


Figure 12: The change in reporting rate for Blue Crane by pentad within SABAP2 (2007–2016 vs 2017–2023), conventions as per Figure 9.

Discussion

Over the last 20–30 years, the South African Blue Crane population has been increasing, according to my analysis of the citizen science project data and Hofmeyr (2012). However, extending Hofmeyr's analysis to include the last 10 years indicates that in 2010 the population trend changed from positive to negative, primarily due to declines in the Overberg, but also in the Karoo, although data quality is poorer in the Karoo. This is concerning as these areas support the largest population of Blue Cranes. The reasons for these declines are uncertain but are likely related to depressed breeding success in the Western Cape wheatlands (Appendix 1), and the cumulative impact of powerline collisions in the Western Cape and Karoo, particularly on immature cranes (Chapters 3 & 4). I discuss this further in Chapter 5.

The Blue Crane national population estimate I present here (51000) is double the 2002 estimate (25502), and 2.5 times higher than the 1999 estimate (20103) (McCann 2001; McCann et al. 2007). The methods used to derive these estimates differs; mine being from aerial surveys, and the 1999/2002 estimates from national coordinated counts conducted by farmers (McCann 2001; McCann et al. 2007), which is a minimum count, rather than a total count. Indeed, the CAR data indicates a much more moderate increase (24%) between 2000 and 2019. Data that are more comparable, based on similar methodology are Allan (1993)'s distance estimates (road count data), conducted between 1988 and 1993. My population estimates for the Overberg are approximately five times larger than Allan's (1993) estimate, which is congruent with the population trends seen in the summer CAR data. The population estimate I present for the Karoo is 2.8 times higher than Allan's (1993); this is not supported by CAR trends but is partially supported by Karoo SABAP reporting rates showing weak increases from the 1980s until 2022.

In the Swartland, my model of the CAR data shows an increase (240%) in numbers over 20 years. If I compare my population estimate (~6000) with Allan's (1993) (145 individuals) from 26 years prior, the scale of change is much greater. The latter comparison is a longer time, but it is likely that 145 individuals was an underestimate. Given the scarcity of Blue Cranes in the Swartland at the time of Allan (1993)'s study, it is expected that there is a fair amount of uncertainty in his estimates, as evidenced by my models of the grassland CAR data. Where species are at low densities, Hofmeyr (2012) demonstrated that CAR is not reliable or effective for monitoring population trends. In these areas an approach like an aerial survey would be more effective.

SABAP1 vs 2 is not detecting the observed declines in the Karoo or Overberg, where cranes are at relatively higher densities. Atlas reporting rates tend to have a logarithmic, rather than linear, relationship with abundance (Allan 1994; Lee et al. 2018), which means that reporting rates should be more sensitive to

changes in density at low than high densities. In the Overberg, pentads often have a 100% reporting rate because Blue Cranes are large and conspicuous in open landscapes. Once reporting rates reach 100%, further increases in density will not be captured by reporting rates (Lee et al. 2018). In Namibia where cranes are rare and declining (Namibia Crane Working Group 2020), a declining trend in reporting rates is detected. However, in the grasslands, where cranes are also at a low density, SABAP2 reporting rates are still substantially lower than SABAP1 across much of KZN, despite aerial surveys indicating that counts are increasing (Galloway-Griesel et al. 2022). It is possible that numbers have not yet increased sufficiently to be detectable by SABAP reporting rates, as Loftie-Eaton (2014) demonstrates, comparisons between the atlas projects are more likely to be conservative than to exaggerate changes.

Comparisons within SABAP2 are detecting some of the observed trends, for example, reporting rates declined in the western Overberg, and pentads in the grasslands have an overall increasing trend, although data was sparse. Likewise, the Karoo had an overall increasing trend, but very few cards had sufficient data to compare. It would be valuable to encourage regular atlassing in these areas, through initiatives like Birdlife South Africa's BioBash events. This data is necessary, as it is evident that SABAP1 vs 2 comparisons are not detecting changes in population trend, while comparisons within SABAP2 may be. In addition, comparisons within SABAP2 are more robust as they follow the same protocol.

In many CAR precincts, the uncertainty around winter count trends was very high. Hofmeyr (2012) similarly found winter counts to be more variable than summer. Survey accuracy tends to be lower when animals aggregate, due to larger variance around the mean density (Norton-Griffiths 1975). During summer, when cranes are more evenly distributed, and breeding pairs are constrained to territories (Allan 2005), compared to winter flocks that do not always return to the same sites each year (pers. obs.). In the Western Cape wheatlands, the variability in the location of flocks is partly due to crop rotation, e.g., a field planted with lucerne over winter one year, may be planted with a cereal crop the next year, and will therefore be unattractive to Blue Crane flocks during the winter. Farmers also move their sheep feedlots, which influences where Blue Crane flocks aggregate. This is why winter CAR data has limited utility in analysing population trends. The variability of winter flocks would also impact the reliability of the winter aerial survey population estimates because the variance of the mean density will be greater. With aerial surveys, this greater variance is a trade off with survey effort, because during winter more of the population can be detected with less effort, compared to summer when cranes are highly dispersed.

Winter flock sizes reported in my study in the Karoo were larger than those in the Overberg, even though crane density was 3–4 times higher in the Overberg than the Karoo. This is probably because there are

fewer pasture areas in the Karoo, and Blue Cranes prefer to aggregate in pastures in winter. This contrasts with Allan (1993), who found that Overberg flock sizes were on average larger than in the Karoo. One reason for Karoo flock sizes now being larger may be related to habitat selection and habitat availability. Selection for pastures appears to be a relatively recent development in the Karoo. Hofmeyr (2012) found that Blue Cranes select for agricultural habitats, but Allan (1995) did not. It is possible that as irrigated pasture lands have become more common in the Karoo (a 63% increase since 1990; see Results), Blue Cranes have adapted to, and begun to select for them.

When assessing population demography, trends and habitat use, long-term and consistent population monitoring will give the most accurate results (Bonebrake et al. 2010). This is why I advocate for continuing the CAR routes in the Western Cape and reviving the CAR routes in the Karoo. CAR is a suitable monitoring technique in these areas, where Blue Crane densities are high enough to produce trend models with acceptable error margins. CAR will be particularly important in the Overberg, to ascertain whether the population is in dynamic equilibrium as suggested by Young & Harrison (2020), oscillating around a new lowered density, but not declining, or if the population is indeed declining and will continue to do so.

Extrapolating Blue Crane density to un-surveyed areas to produce a population estimate introduces a level of uncertainty, as it is possible that Blue Crane densities differ outside of the survey area. When interpreting the population estimates, the range of uncertainty should be considered. With Blue Cranes extending their range from the Swartland northwards into the Succulent Karoo (Simmons 2011) and westwards from the eastern Nama Karoo into the drier parts of the Great Karoo, population censuses will need to include these areas in future, my project did not, and this will mean that my national population estimate is an under-estimate. To improve the accuracy of the grasslands population estimate, surveys would need to be done outside of KwaZulu-Natal, so that the minimum counts presented here can be extrapolated to the general area. For future aerial surveys in the Western Cape, I would recommend a different survey approach, given the difficulties in estimating distance in flight. Distance models assume that distances measured between the observer and animal are accurate, this assumption is tenuous in this case (Thomas et al. 2010). A quadrat approach, as taken in the Karoo and grasslands, would be preferable and would allow more comparison between the regions and over time. With the quadrat approach, careful attention needs to be given to survey design. With the Karoo surveys I took a non-random sampling approach, aiming to target known Blue Crane range evenly and thoroughly. This may have introduced some bias to the surveys, especially as agricultural areas were targeted. Although, the stratified extrapolation method would have accounted for some of this bias. With expensive methods such as aerial surveys, there are trade-offs that need to be made with balancing good sampling design with efficiency.

For future surveys I recommend that the sampling design is critically evaluated to minimise the influence of sampling bias.

The Blue Crane expansion into the Western Cape wheatlands has been the species saving grace, and their ability to adapt to agricultural areas has facilitated the recovery of the national population numbers, much like the Sandhill Crane *Grus canadensis* in the United States (Mirande & Harris 2019; Hemminger et al. 2022). This may however not be sustainable, threats that are currently at a low level, could intensify if socio-economic conditions change. Such threats include indirect poisoning (farmers targeting species that cause crop damage e.g. geese, but cranes are impacted) and direct persecution (due to crop damage or disturbance of sheep at feed lots) (van Velden et al. 2016b). In general, farmers in the Western Cape wheatlands are tolerant of Blue Cranes; although in the Swartland damage to sweet lupin is an issue (van Velden et al. 2016b) and I have received complaints of large Blue Crane flocks causing disturbance at sheep feedlots in the Overberg. There have also been reports of Blue Cranes damaging irrigated pastures in the Karoo (Bradley Gibbons, EWT, pers. comm). I recommend further investigation of this issue, especially in the Orania and Grassridge Dam areas, where very large flocks were sighted. Such large numbers create the potential for crane-farmer conflict, and one mass poisoning event e.g. Verdoorn (2015), could have a large impact on the population. Disease is also a risk when cranes aggregate in such large numbers, particularly at feedlots (Austin et al. 2018), where pathogens can pass between species. For example, Ostrich *Struthio camelus* feedlots are common in the eastern Overberg and avian influenza could be transmitted between Ostriches and Blue Cranes (Abolnik et al. 2016; Peyrot et al. 2022). For these reasons (farmer/crane conflict and disease), Blue Crane selection for pasture lands could be an ecological trap for the species. Conservation within agricultural landscapes is challenging, particularly intensively farmed areas, which tend to be highly dynamic. Conservationists need to keep abreast of changes, through thorough and consistent monitoring of species, and through understanding the social, economic, and political contexts that influence these landscapes and the people that create them.

Supplementary materials

Supplemental Table 1: The top two Distance models for the winter aerial survey of Blue Cranes, indicating the model name, key detection function used, what covariates were used in the model, χ^2 goodness of fit p value, log likelihood, k and the AIC for the models.

Model	χ^2 goodness of fit test p value	Log likelihood	k	AIC
Hazard rate detection function (no covariates)	0.26	-129	2	262.8
Hazard rate detection function (covariate: flock size)	0.14	-129	3	264.1

Supplemental Table 2: A list of other bird species recorded on the Karoo aerial survey.

Species	Number counted
Ludwig's Bustard *Neotis ludwigii*	78
Blue Korhaan *Eupodotis caerulescens*	14
Denham's Bustard *Neotis denhami*	12
African Fish Eagle *Haliaeetus vocifer*	8
Verreaux's Eagle *Aquila verreauxii*	5
Jackal Buzzard *Buteo rufofuscus*	4
Rock Kestrel *Falco rupicolus*	2
Secretarybird *Sagittarius serpentarius*	2
Black-chested Snake Eagle *Circaetus pectoralis*	1
Kori Bustard *Ardeotis kori*	1
Martial Eagle *Polemaetus bellicosus*	1
Northern Black Korhaan *Afrotis afraoides*	1
Pale Chanting Goshawk *Melierax canorus*	1

Supplemental Table 3: Trend in Coordinated Avifaunal Road-count data and Karoo De Aar Transmission Live Counts by region and season, as determined by GAMs fitted in poptrend, for three time periods. Also indicated is the percentage deviance explained by the model. *a significant trend, determined by the 95% confidence intervals excluding 0. In italics are estimates which should be interpreted with caution, given the large confidence intervals. The CAR precincts included are indicated in brackets.

Region	Overall trend. Years: Trend (95% CI)	Trend from starting year-2010 (95% CI)	Trend from 2011-ending year (95% CI)	Deviance explained (%)
Western Cape				
Overberg (CAR: OV)				
Summer	1994–2019: 163% (90–271%)*	1994–2010: 261% (169–400%)*	2011–2019: –22%(–37 to –1.9%)*	61.6
Winter	1993–2019: –8.8% (–38 to 32%)	1993–2010: 79% (34–143%)*	2011–2019: –47% (–61 to 31%)	66.6
Swartland (CAR:SW)				
Summer	1997–2017: 240% (111–452%)*	1997–2010: 222% (102–401%)*	2011–2017: 4.9% (–23 to 41%)	55
Winter	*1996–2017: 280% (56–1665%)*	*1996–2010: 582% (134–1887%)*	2011–2017: –17% (–62 to 81%)	42.7
Little Karoo (CAR: WC, WK,WU)				
Summer	*2000–2019: 399% (93–1194%)*	*2000–2010: 409% (112–1140%)*	*2011–2019: –2.5% (–55 to 100%)*	72
Winter	*2000–2019: 17% (–77 to 481%)*	*2000–2010: 282% (9.2–1262%)*	2011–2019: –69% (–92 to 20%)	85
Grasslands				
Wakkerstroom (CAR: MW)				
Summer	*2000–2019: 216% (–49 to 1787%)*	*2000–2010: 83% (–30 to 365%)*	*2011–2019: 62% (–25 to 247%)*	59.7
Winter		Too little data		
Southern KZN (CAR: KG, KM, KU)				
Summer	*1998–2016: 89% (–85 to 1973%)*	*1998–2010: –46% (–94 to 286%)*	*2011–2016: 128% (–69 to 1754%)*	68.1
Winter	*1997–2018: 1665% (171–11961%)*	*1997–2010: 423% (–6.7 to 3504%)*	*2011–2018: 153% (–36 to 916%)*	63.2
Southern Free State (CAR: FS)				
Summer	*1999–2017: 362% (16–1715%)*	*1999–2010: 229% (–2.6 to 1117%)*	2011–2017: 32% (–55 to 237%)	86.1
Winter	*1997–2018: 1414% (–64 to 34434%)*	*1997–2010: 877% (–48 to 14947%)*	*2011–2018: 44% (–92 to 1998%)*	79.7
North Western KZN (CAR: KD, KL,KN,KV, KE,KO)				
Summer	1998–2017: 56% (–36 to 299%)	1998–2010: 30% (–30 to 148%)	2011–2017: 17% (–19 to 67%)	51.2
Winter		Too little data		

North-eastern Free State (CAR: FN)				
Summer	*2001–2019: –49% (–99 to 1024%)*	2001–2010: –29% (–88 to 232%)	2011–2019: –26% (–85 to 195%)	75.2
Winter	1997–2016: –94% (–99 to –22%)*	*1997–2010: 19% (–73 to 408%)*	2011–2016: –91% (–99 to –16%)*	61.6
Mpumalanga (CAR: MC, MM,MS,MT)				
Summer	*2000–2016: 12% (–74 to 362%)*	2000–2010: –46% (–85 to 111%)	2011–2016: –3.3% (–78 to 221%)	76.4
Winter		Too little data		
North-eastern Eastern Cape (CAR: EB, EE)				
Summer	*1999–2013: 261% (9.2–1088%)*	1999–2010: 174% (13–508%)	2011–2013: 20% (0.87–42%)	56.8
Winter		Too little data		
Karoo and Karoo fringes				
Eastern Karoo (CAR: NK)				
Summer	1996–2016: 13% (–49 to 124%)	1996–2010: 118% (20 to 286%)*	2011–2016: –49% (–71 to –17%)*	80.3
Winter	*1995–2013: 59% (–93 to 3257%)*	*1995–2010: 48% (–89 to 1911%)*	2011–2013: 5.3% (–27 to 49%)	62.6
Eastern Cape Karoo (CAR: EG, EP, ES)				
Summer	1999–2017: –43% (–78 to 50%)	1999–2010: –11% (–57 to 81%)	2011–2017: –32% (–71 to 40%)	58.9
Winter	*1998–2018: 128% (–54 to 1024%)*	*1998–2010: 258% (–19 to 1280%)*	2011–2018: –44% (–85 to 108%)	71.9
Eastern Cape Coastal (CAR: EH, EK)				
Summer		Too little data		
Winter	*2001–2019: –48% (–78 to 365%)*	*2001–2010: 3% (–78 to 365%)*	2011–2019: –47% (–88 to 195%)	63.4
De Aar Transmission Live Counts			**Trend from 2008–2016 & 2019–2021**	
Summer			2008–2021: –68% (–89 to –5.6%)*	30
Winter			2008–2021: 181% (39–486%)	97.8
National (all CAR precincts)				
Summer	2000–2019: 24% (3.4–51%)*	2000–2010: 57% (37–83%)	2011–2019: –19% (–31 to –5.2%)	85.5

Chapter 3: Modelling powerline collision risk for Blue Cranes in the Western Cape and Karoo

A Blue Crane collision victim in the Karoo (Photograph: Matt Pretorius).

Abstract

Overhead powerlines pose a significant risk to birds. Blue Cranes *Anthropoides paradiseus* (IUCN Red List: Vulnerable) are particularly prone to colliding with powerlines. Between 2019 and 2022, I conducted powerline surveys in three Blue Crane strongholds, the Swartland, Overberg and Karoo. In the Overberg I repeated a previous powerline survey conducted in 2008. The Overberg and Swartland are intensively farmed and could only be surveyed once per year, in summer after crops have been harvested, whereas Karoo lines were surveyed quarterly. Between March 2019 and January 2022, I surveyed 1994 km of powerlines, recording 556 carcasses of 40 bird and two mammal species across all regions. Ten of the bird species are globally threatened. The Blue Crane was the most frequently recorded species in all three regions, with collision rates of 0.18 (95% CI 0.13–0.24) cranes/km/year in the Karoo, 0.08 (0.02–0.17) in the Swartland and 0.05 (0.02–0.08) in the Overberg. With scavenger, observer and crippling bias, these collision rates may be up to 6 times higher in the Karoo, and 7 and 8 times higher in the Swartland and Overberg respectively. Overberg collision rates were almost half those recorded in 2008, possibly due in part to lower Blue Crane abundance (Chapter 2). A greater proportion of the lines were marked in my study compared to 2008 but I did not find a correlation between proportion line marked and mortality rate per line (r = –0.19, 95% CI = –0.49 to 0.14, p = 0.26). Using a binomial Generalized Linear Mixed Model, I found that proximity to seasonal water was the strongest predictor of Blue Crane collisions; mortality probability reduced to nearly zero for powerlines > 2.5 km from a seasonal water body. This finding could guide placement of new powerlines, and proactive retro-marking of existing powerlines close to water bodies. A previous study on transmission lines in the Karoo found that line marking reduced Blue Crane collision rate by over 90%. Further research is needed to thoroughly test line marker effectiveness on distribution lines, especially near roost sites where many collisions occur at dawn and dusk, when markers may be less effective in low light conditions.

Introduction

Overhead powerline collisions and electrocutions are a well-documented source of mortality and injury for many bird species (Smallie 2009; Jenkins et al. 2010; Dwyer et al. 2014; Bernardino et al. 2018; D'Amico et al. 2018). Collisions cause injury or death by impact, when birds fly into powerline wires (Shaw 2013; SAEP/EWT 2022). Electrocution typically occurs when birds perch or nest on powerline structures and get electrocuted by touching two or more conductors (Shaw 2013; SAEP/EWT 2022). Electrocution may occur secondarily during a collision if large birds touch two wires. The risk of a powerline incident (collision and/or electrocution) is related to habitat suitability (e.g. high resource areas like waterbodies and rubbish

dumps), species characteristics (e.g. flocking behaviour, poor binocular vision, large body size and high wing loading, making manoeuvring difficult) and characteristics of the powerline (e.g. transmission lines tend to have a higher collision rate than distribution) (Bevanger 1998; Jenkins et al. 2010; Martin & Shaw 2010; Shaw et al. 2010a; Avian Power Line Interaction Committee 2012; Silva et al. 2014; Bernardino et al. 2018; Marcelino et al. 2021; SAEP/EWT 2022). Wildlife powerline incidents not only impact populations, but can also cause damage to powerline infrastructure, resulting in broken lines and conductors, fires, and loss of income from disruptions to supply and repair costs. In South Africa the total cost of wildlife incidents on powerlines has been estimated at over R50 million (~$2.6 million) per year (Schorn 2019).

Blue Cranes *Anthropoides paradiseus* are one of the most commonly recorded mortalities on powerlines in South Africa (19% of incidents, 1996–2021), second only to Cape Vultures *Gyps coprotheres* (20%) (Smallie 2009; Endangered Wildlife Trust/Eskom Strategic Partnership 2021). This is based on anecdotal records in the Central Incident Register (CIR), a database set up in 1996 when power utility Eskom and conservation NGO the Endangered Wildlife Trust (EWT) formed a partnership to address wildlife incidents on energy infrastructure in South Africa (Endangered Wildlife Trust/Eskom Strategic Partnership 2021). The CIR is biased towards large, charismatic species, but the same results are found in systematic studies (Shaw et al. 2010a; Shaw et al. 2021). Blue Cranes do not perch and are therefore primarily susceptible to powerline collision rather than electrocution. A once-off survey in the Overberg in 2008 found that Blue Cranes collided with powerlines at an average rate of 0.31 cranes/km/year (95% CI 0.13–0.59), considering only remains deemed to be < 1 year old, and corrected for sampling biases i.e. scavenging (Shaw et al. 2010b). Extrapolated across the region, this was estimated to be 1444 (95% CI 604–2703) Blue Crane mortalities per annum (Shaw et al. 2010b). This is a significant impact, and likely the greatest source of mortality for post-fledging cranes in this region. The silver lining is that Blue Cranes are responsive to line marking; a Before-After-Control-Impact study on transmission lines in the Karoo demonstrated a 92% (95% CI 77–97%) reduction in Blue Crane collisions (Shaw et al. 2021).

Given the vast powerline network in South Africa (>370 000km of lines), it is not feasible to retroactively mark all lines. Line marking on existing transmission lines is traditionally done by helicopter, which is costly, although recently line marking has been achieved using a drone, which will be more cost effective (SAEP/EWT 2022). Aside from the initial cost, there are ongoing maintenance costs. Markers, particularly those that move (e.g. flappers), break and need to be replaced every few years. Therefore, it is useful to be able to predict where collisions are going to occur so that markers can be deployed strategically. In 2003, a desktop GIS model was developed to predict Blue Crane powerline collisions in the Overberg, based on expert observations, including factors such as distance to roost site, water bodies, surrounding hills (that

obscure the line), habitat and prevailing wind (Kotoane 2003). The desktop model was tested against anecdotal Blue Crane collision data; 30% of collisions occurred on high risk lines, and 66% on moderate risk lines (Kotoane 2003). Shaw et al. (2010b) sampled a selection of powerlines in the Overberg and demonstrated that Blue Crane collisions tend to be at hotspots in the Overberg, but they did not find support for any of the predictive factors from Kotoane (2003), other than cultivated land, where Blue Crane collisions occurred at a higher rate than natural vegetation.

In this study I develop a predictive model for Blue Crane collisions. In the last decade or so since the previous studies (Kotoane 2003; Shaw et al. 2010b) there have been substantial improvements in the amount and resolution of spatial data available. I report current powerline collision data and model collision risk by powerline characteristics and habitat factors. I also expand the spatial scale of collision coverage to include the Overberg, Swartland and eastern Karoo. Together, these areas support 92% of Blue Cranes (Chapter 2).

Several factors can bias the results of powerline collision surveys: scavenger bias (scavengers remove the carcass, and it is not detected), crippling bias (the bird collides with the powerline and is injured but moves away from the search area), observer bias (searchers do not detect all carcasses) and habitat bias (visibility of carcasses differs according to the habitat) (Bevanger 1995; Schutgens et al. 2014; Baasch et al. 2022). Crippling bias is very difficult to assess, but it is possible to estimate the other biases through experimental trials, and to use these estimates to develop correction factors (Bevanger 1995; Shaw et al. 2010b). In South Africa, studies have estimated observer and scavenger bias in the Succulent Karoo (Schutgens et al. 2014; Shaw et al. 2015b). From these, and international studies, it is evident that scavenger bias varies substantially among sites and with season (Prosser et al. 2008; Shaw et al. 2015b; Barros et al. 2022). For example, at one site in the Succulent Karoo, only 16% of geese carcasses were removed after 3 months in summer (Schutgens et al. 2014), compared to 60% in winter (Shaw et al. 2015b).

In this chapter, I report which species are impacted by powerline collision and electrocution in the Western Cape wheatlands and Karoo. I conduct experimental trials to quantify scavenger and observer bias in the Karoo and Western Cape wheatlands. I use these to develop a bias correction factor for collision rates. I develop regional collision rates for Blue Cranes, adjusted for biases, to understand the severity of the issue and to compare with past studies (Shaw et al. 2010b; Shaw et al. 2021). I also develop a spatial model to predict where Blue Crane collisions are most likely to occur, to assist the Eskom/EWT partnership to identify lines for pro-active mitigation, assist the mitigation decision-making process when collisions occur (reactive mitigation), and inform powerline placement for future developments.

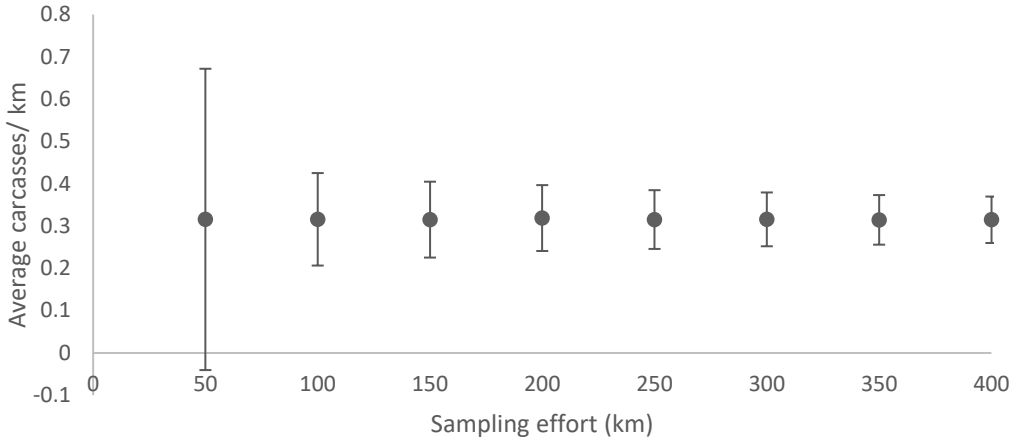
Methods

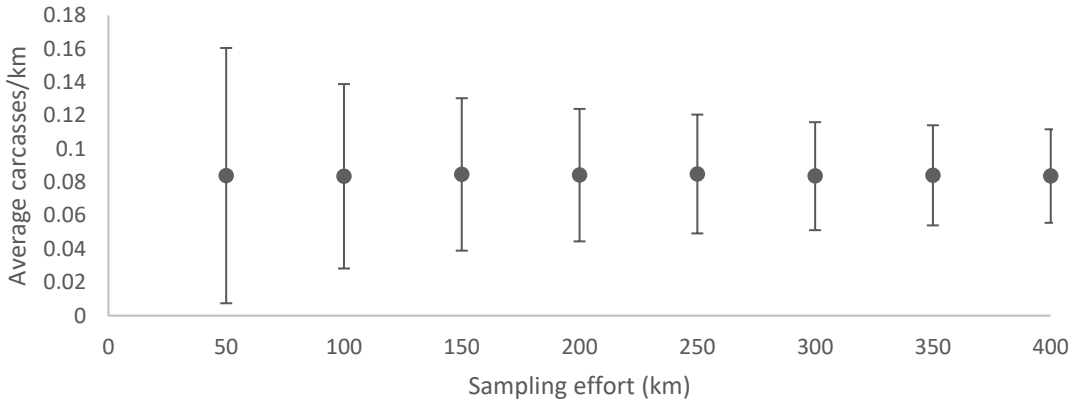
Surveys

Powerline surveys were conducted in the three core areas for Blue Cranes: Overberg, Swartland and Karoo. I initially chose eight ~10 km sample lines evenly spread over the core Blue Crane range in the Swartland (crop and pasturelands) and Karoo. I used data from the Eskom CIR to choose lines across a range of Blue Crane collision rates to get a mixture of high-risk and low-risk lines. I chose lines on the map, and then adjusted in the field, if necessary, based on landowner permission and accessibility. In the Swartland, I included both transmission and distribution lines in the sample. In the Karoo I included only distribution lines, because I had access to data from the ongoing Eskom/EWT survey on 95 km of transmission lines near De Aar, Northern Cape (Shaw et al. 2021). Since there has already been a study looking at Blue Crane collisions in the Overberg (Shaw et al. 2010a) (survey length: distribution: 155 km, transmission: 44 km), I planned to survey a small subset of this study's lines to assess the current collision rate.

In March 2019 I completed the first pilot survey in the Karoo (79 km), Overberg (35 km) and Swartland (87 km). I used the results from these surveys to infer the optimal sample size using a power analysis. I simulated three datasets of 4000 data points (Poisson distribution) with collision rates of 0.31 cranes/km (Shaw et al. 2010b), 0.089 cranes/km (average collision rate in pilot study) and 0.045 cranes/km (hypothetical low collision rate). I then resampled each of these datasets in R, starting with a sampling effort of 50 km, and increasing up to 400 km, at intervals of 50 km. From each of these resampled datasets I extracted a mean and 95% confidence interval (Figure 1).

From these graphs I established that the variance in the mean reduces substantially when sample sizes go from 50km to 150km, thereafter the variance reduces less with increasing sample size. In 2019, additional funding was secured which allowed me to scale up the powerline surveys, increasing the length of the pilot sample lines from 10 to 20 km. In some cases, I chose a new line if there were access issues during the pilot survey. I increased the line length in the Karoo (158 km distribution) and Swartland (transmission 33 km, distribution 121 km), and repeated 84% of Shaw et al. (2010a)'s Overberg survey (distribution 148.5 km, transmission 19.5 km) (Figures 2 and 3). The Nuwejaars Special Management Area team surveyed a further 56 km of distribution line within the Overberg Agulhas Plain once off in December 2019 (Figure 2).





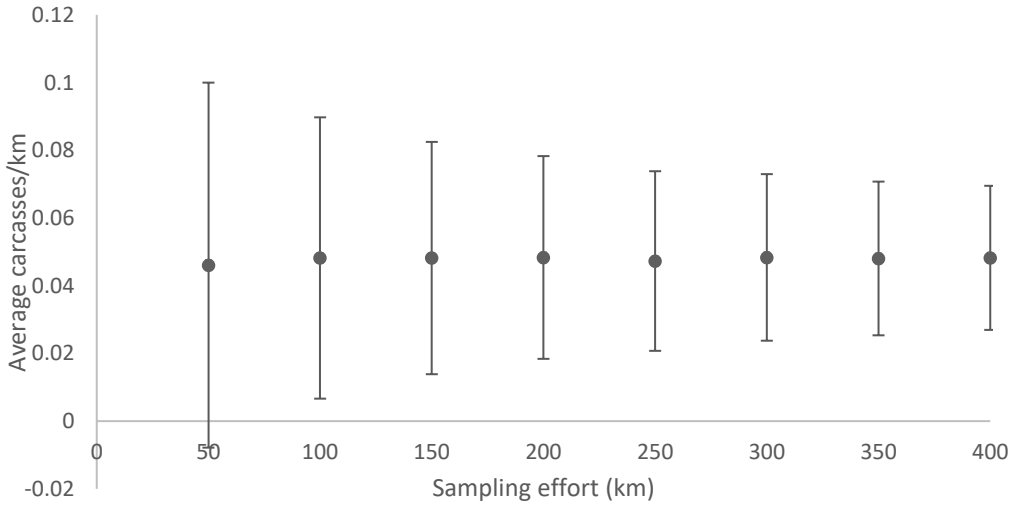


Figure 1: Mean and associated 95% CI at each sampling effort (km), for three different mean collision rates.

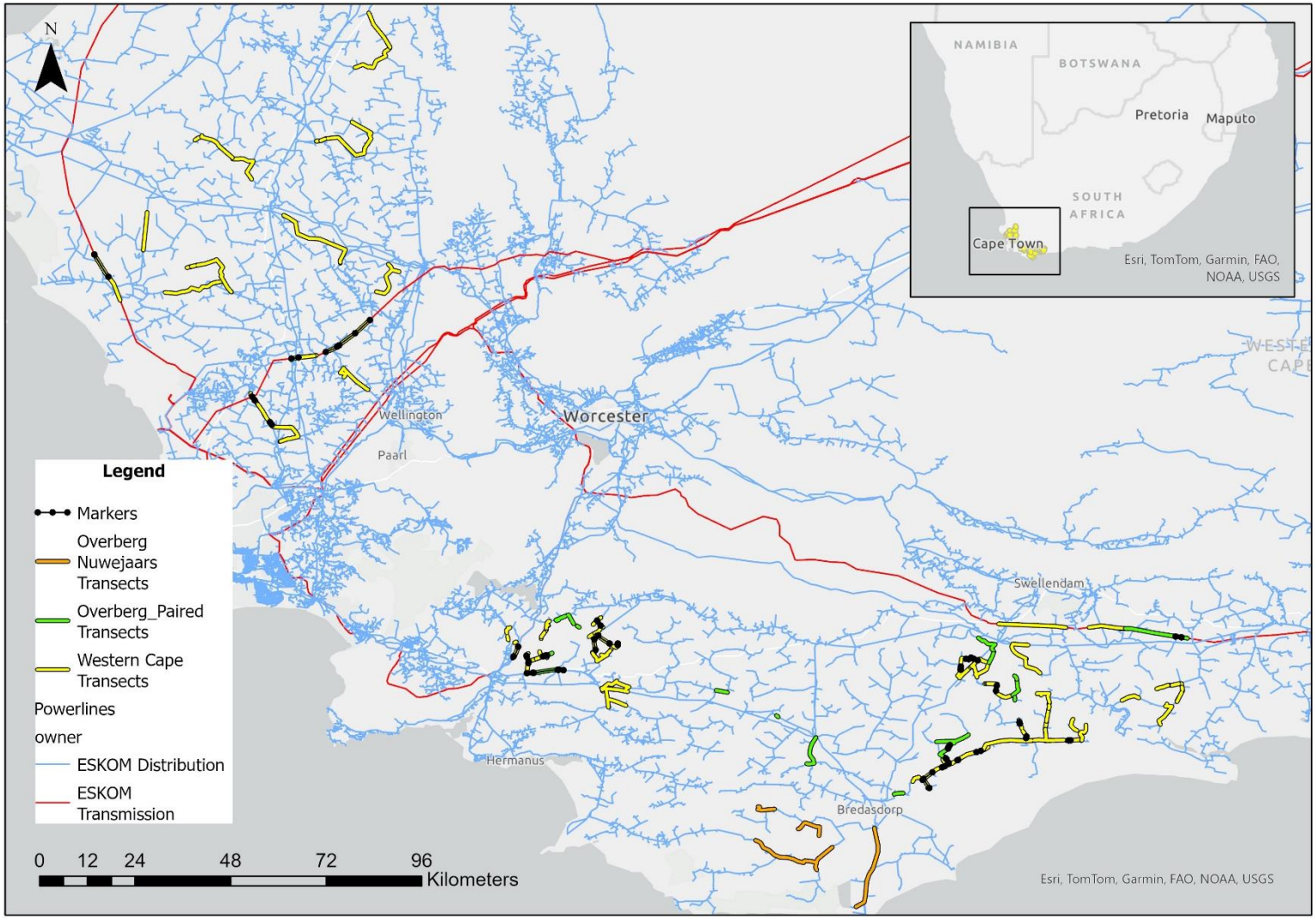


Figure 2: Powerlines surveyed in the Overberg and Swartland between 2019 and 2022 overlaid on the national grid (transmission lines in red, distribution lines in blue). Yellow = study lines, black = marked lines, orange = new lines surveyed in Nuwejaars, new lines (paired) not surveyed by Shaw et al. (2010a) in green.

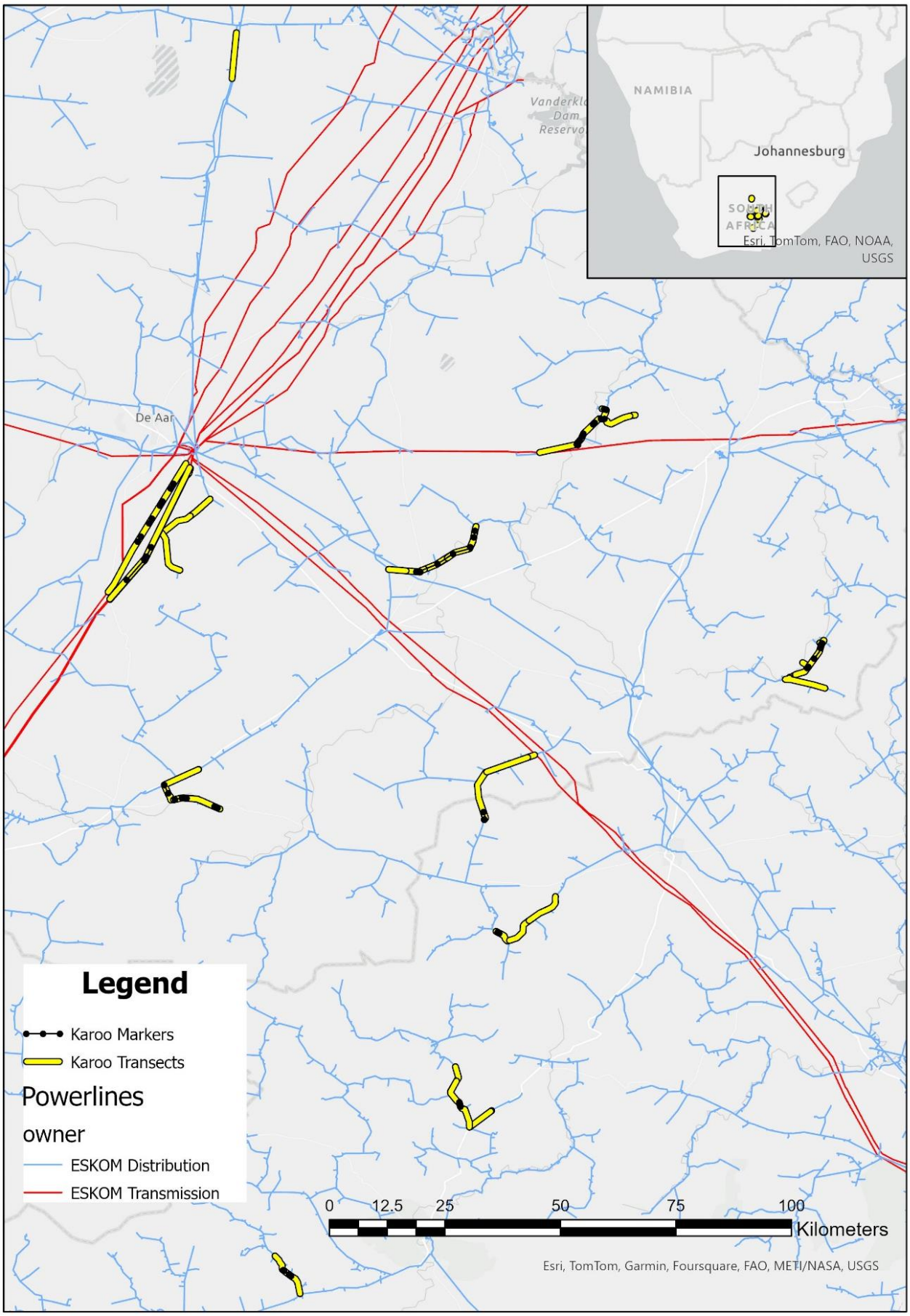


Figure 3: Karoo powerlines surveyed between March 2019 and February 2021; conventions as per Figure 2.

In the Overberg and Swartland, crop farming activities made it difficult to survey lines between April and late November, when farmers are reluctant to allow surveys through growing crops. As a result, surveys took place once a year in summer. In the Swartland, I did two surveys, one in December 2019 and one in January 2021. In the Overberg I did the first survey in November 2020. On this survey I picked up surprisingly few incidents; six times less than Shaw et al. (2010a), possibly because many of the original study lines have been marked since as a result of the study, leading to a lower collision rate. Therefore, between November 2021 and January 2022, I surveyed 105 km of lines randomly selected from Shaw et al. (2010a)'s and paired them with 72 km of nearby lines to assess whether there was a difference in line marking, and whether this correlated with lower collision rates.

In the Karoo, surveys took place every 3 months from July 2019 to February 2021, the interval was affected by COVID-19 travel restrictions; as a result, in 2020, surveys took place in January, June, August and November. All eight lines were completed in every survey, except for January 2020 when heavy rain prevented access to one line near Hanover. The De Aar transmission surveys took place at the same time as the distribution line surveys.

Lines were mostly walked (100% of Swartland line length, 71% Overberg, 63% Karoo) or driven at a maximum speed of 20 km/h, following a straight path underneath the powerline. In the Karoo, the transmission lines had servitudes underneath them, so all these surveys were driven. Observers searched for carcasses underneath and either side of the line, and when one was found, pole numbers, species and location were recorded, as well as an approximate distance from the line to the carcass, measured by number of paces. Where possible I recorded the age of the bird (juvenile/adult), but in most cases this was not possible due to carcass degradation. Observers recorded the start and end of the survey (pole numbers and location), as well as the start and end of any line mitigation (type and condition). There were different types of mitigation on lines in the surveys: dynamic devices (flappers), dynamic devices with LED lights (designed for making lines visible at low light/at night i.e., at roosts), stationery devices (spirals) or aviation balls (deployed for aircrafts but likely make the line more visible to birds too) (Figure 4).

Carcass remains were removed to prevent double counting on the next survey. A sample of feathers and bones was retained for later identification if the species was not known, and these were later verified. Initially the lines were walked by one observer, but after two security incidents in the Swartland in December 2019 and February 2020, we walked in teams of at least two in the Karoo, and in the Western Cape we did surveys accompanied by a security guard.

Figure 4: Collision mitigation on powerlines in the Overberg: stationary devices (spirals) (left, photo: Heather D'alton) dynamic device/flapper with an LED (centre, photo: Matt Pretorius) and dynamic devices (flappers) (right, photo: Christie Craig).

Bias estimation

I did not expect habitat bias to be a significant factor, particularly in the Overberg and Swartland where surveys took place mostly in open agricultural fields and visibility is good. In the Karoo, the short shrubland or shrubby grassland was fairly uniform within surveys, but grass cover increased dramatically between 2019 and 2020, following good rains in summer 2020. I did not account for this habitat bias using a correction factor, but rather included seasonal effects in my models.

To account for observer bias in the Karoo I draw from Schutgens et al. (2014), they did not find a significant difference in observer bias between experienced (75% detected, 95% CI 68–83%) and inexperienced observers (67%, 58–75%). I used their estimate for experienced observers (0.75 carcasses detected), since most observers on my surveys had conducted powerline collision surveys before. There have been no studies estimating observer bias in the Western Cape wheatlands. Observer bias is related to observer skill and habitat structure (e.g. vegetation height, Schutgens et al. 2014). I therefore conducted a trial to estimate observer bias in the Western Cape wheatlands. In January 2022, I obtained four Spur-winged *Plectropterus gambensis* and eight Egyptian Geese *Alopochen aegyptiaca* carcasses from a professional hunter, who culls 'problem' geese on request by farmers who experience crop damage. I placed them in

wheat stubble under a 2 km-stretch of powerline on Uitvlugt farm in the Overberg (–34.200, 20.275). Spur-winged Geese (2.5–7kg) and Egyptian Geese (1.5–3.5kg) are a similar weight to Blue Cranes (4–5.5kg) (Hockey et al. 2005) so should be a fair substitute. I also placed 18 older remains (bones and feathers from previous powerline surveys) of various species under the same line to look at how detectability changes with carcass age. The carcass density (15 birds/km) is similar to that found naturally at powerline collision hotspots. An independent observer then walked the line on the same day and recorded all remains. This observer was experienced in powerline surveys. Afterwards I plotted the carcass locations on a map to check which were detected and which were not. I did not expect observer bias to differ between the Overberg and Swartland, as the habitat is the same.

To estimate scavenger bias I conducted experimental trials in the Karoo and Swartland study areas. For the Overberg, I obtained a scavenger bias estimate from (Shaw et al. 2010b), and from follow-up checks of observer bias carcasses (see above). For each scavenger experiment, 10 Spur-winged or Egyptian Geese were placed out 1 km apart underneath powerlines following the methodology of previous studies in the Succulent Karoo (Schutgens et al. 2014; Shaw et al. 2015b). The proportions of Spur-winged vs Egyptian Geese in each trial varied based on what was hunted; 21 Spur-winged Geese and 49 Egyptian Geese were used. This uneven sample limited my ability to assess the effect of species on carcass persistence for each region/season.

The Swartland trials took place on powerlines traversing wheat and pasture fields on the Tweekuil/Paddavlei/Drostenes farms near Malmesbury (–33.348, 18.654). Wheat is planted in April/May and harvested in November/December. In the Karoo, trials were conducted in the north-west (Wortelfontein/Rosendal farms south-west of De Aar, –31.153, 24.130), where vegetation is shrubbier, and in the south-east where vegetation is grassier (New Holme farm east of Middelburg, –31.481, 25.455). These sites were chosen to avoid close proximity to the powerline survey lines (so as not to confound scavenging rates on the lines).

Previous studies of scavenger bias in the Karoo found distinct seasonal differences in scavenging activity (Schutgens et al. 2014; Shaw et al. 2015b), so I conducted trials in summer (commenced 18 January 2020) and winter (7 June 2020). In the wheatlands, collision surveys only took place during summer, so it was important to understand how many carcasses persisted and what the effective survey window was. I did three trials, one in summer to measure short term persistence (6 December 2019), and then 3 months (23 September 2020) and 6 months (25 July 2020) prior to summer.

I used two models of motion-triggered camera traps (Bushnell and Little Acorn) to capture the exact date of removal and the scavenger. Camera traps were placed 5–12 m from each carcass, attached to an existing pole (powerline or fence pole). Cameras were initially set to take 2 photos every 2 minutes when triggered by motion, i.e., for the summer trials. After these trials, the interval was reduced to 10 seconds to better capture mammalian predators. Despite adjusting the camera settings, the different cameras appeared to have different sensitivities, as some captured far more photographs than others. I checked camera trap batteries within the first week and then approximately 3 weeks later, although in the Karoo winter trial this was 6 weeks later due to COVID-19 travel restrictions. Most cameras were collected after 3 weeks, as the carcass was either removed or was dry and no longer attractive to mammal or bird scavengers (Schutgens et al. 2014). In some cases, the camera traps did not capture the exact moment of removal; removal was confirmed by the next photograph triggered showing no carcass or during the next physical check, if the camera failed to take any more photos. I identified all species captured on the cameras and made a list of the species that are known to scavenge on carrion in each region (Hockey et al. 2005; Klare et al. 2011; Apps 2012). Due to the unreliability of the cameras, I could not make inferences on frequency of species visiting the carcasses, so just present a list of occurrences for each region.

In the Karoo summer trials, I did physical carcass checks 4–5 days, 23–24 days and 141–142 days after deployment. In winter, COVID-19 travel restrictions delayed the carcass checks, which occurred 3–5 days, 79–80 days and 161–162 days after deployment. In the Swartland, physical carcass checks occurred as follows: summer, 2, 5, 15 and 96 days; winter, 4, 17, 60 and 88 days; and spring, 5, 29 and 112 days after deployment. The Overberg trial was designed to assess observer bias, but I checked these carcasses 5 and 43 days after deployment to assess carcass persistence. Carcass removal was defined as all remains removed, i.e., no bones or flesh. However, in some cases carcasses were removed but several feathers remained. For the purposes of the scavenger bias calculation, I only considered carcasses which had been removed without a trace i.e., fewer than 5 feathers remained.

When I did physical checks of carcasses, I categorised the degree of deterioration of each carcass as follows: 0 = no sign of carcass, 1 = feathers only, 2 = feathers and/or one or two bones, 3 = part of carcass present, 4 = most of carcass present, 5 = carcass heavily scavenged or dismembered, 6 = carcass mostly intact, some evidence of picking/scavenging, or insect feeding, 7 = carcass complete, no scavenging/ deterioration. I calculated an average of this index per region, per season for each check to track the deterioration over time.

Crippling bias is difficult to assess, it requires observing collisions and then tracking injured birds to find out their fate (Bevanger 1995). US studies show that 65–73% of birds fly away from the line after collision (Murphy et al. 2016; Baasch et al. 2022), but it is not known how many of these are mortally injured. Given that the purpose of the crippling bias correction factor is to correct for mortality rates, I take a conservative estimate of 0.8 for crippling bias from Bevanger (1995), where a pointing dog was used during powerline surveys to retrieve all carcasses that died away from the line.

The overall bias correction factor was calculated as the inverse of the product of each bias factor (i.e. bias factor as the % detected) ($1 / (Bi*Bi*Bi*Bi)$) (Bevanger 1995). The bias correction factor was rounded to the nearest whole number, given the uncertainty in the estimates. I only applied the correction factors to mortality rates of species that are of a similar size to the geese used in the trials: Blue Cranes and Ludwig's Bustards *Neotis ludwigii*.

Statistical analysis

Mortality rates

To calculate mortality rates for each region, by line type, I quantified the number of incidents (in total, and for each species of interest) per km of line surveyed. In ArcGIS Pro 3.0.0. I generated points at 1 km-intervals along each powerline, per survey. Using the 'Split line at Point' function, all lines were divided into 1 km sections. I deleted edge sections if they were less than 450 m long. I then used a spatial join to assign incidents to the relevant 1 km section. I used this dataset to generate average per kilometre mortality rates with confidence intervals, using hierarchical bootstrapping (1000 iterations), with code from Shaw et al. (2021). This resamples based on the spatial (line) and temporal (season and year) structure of the data. Bootstrapped rates were calculated for Blue Cranes, Ludwig's Bustards (Karoo only) and all mortalities combined (all species, electrocutions, and collisions). In the Karoo, where surveys were quarterly, I multiplied the bootstrapped rate by four to get the annual per kilometre rates. However, I only considered surveys from October 2019 in the bootstrapping since some mortalities recorded on the pilot and first full survey may have been from more than three months ago and multiplying this by four would over-estimate mortality rates. Western Cape survey intervals were annual, and since carcasses older than a year are unlikely to be detected (see Results of scavenger bias experiment), I used all surveys to calculate mortality rates.

To get a crude estimate of the relative contribution of distribution vs transmission lines to the total annual Blue Crane mortality, I multiplied the collision rates by the total length of powerlines in the study area. I

defined the study area by drawing a minimum convex polygon around all lines surveyed, with a 10 km buffer around the edge using the Minimum Bounding Geometry Tool and Buffer Tool in ArcGIS Pro 3.0.3. I then used the Summarise Within tool in ArcGIS Pro to quantify the length of distribution and transmission lines in each study area.

I obtained the raw data from JM Shaw, for the 2008 Overberg survey (Shaw et al. 2010a; Shaw et al. 2010b). I then quantified the collision rate (cranes/km) for each line surveyed in 2008 and in 2020–2022, by the line name, as well as the percentage of each line that was marked then versus now. I used a Pearson's Correlation to assess whether line marking explained the difference between Blue Crane collision rates in 2008 vs 2020–2022. I could not simply look at collision rates on marked vs unmarked lines, as line marking is not random, lines are marked because they have high collision rates.

Models

I ran Binomial Generalized Linear Mixed Effect models to assess what factors predict the presence of Blue Crane collisions, using the lme4 package in R (Bates et al. 2015; R Core Team 2022). I used a mixed-effects model because powerlines were surveyed multiple times i.e., repeated measures meant the data were not independent and spatially autocorrelated (Bolker et al. 2009; Bates et al. 2015). Accordingly, I included survey and line name as random effects in the model to account for this. The response variable was presence/absence of a Blue Crane powerline collision. To produce the absence points, I used ArcGIS Pro to generate points every 500 m along each powerline transect, for each survey. I deleted any points that were within 500 m from a recorded incident (any species) on that survey; using a buffer around each point and the erase function in ArcGIS. Using point data, as opposed to analysing the data as counts per km, allowed for greater precision in calculating covariates e.g., distance to water. There were insufficient data to develop models for the Overberg and Swartland separately, so the datasets were combined for modelling.

I then assigned covariates to each of these points. I considered several combinations of fixed effects, for each dataset, including region in the wheatland models (Swartland/Overberg), survey method (walking/driving) and habitat covariates (see below), as well as features of the powerline such as line type (transmission/distribution), and presence/absence of line markers. I evaluated the models for fit using the DHARMa package (Hartig 2022). The diagnostics indicated no major issues with over dispersion, zero inflation or fit for the candidate models. Models were selected based on AIC; the model with the lowest AIC and those within 2 AIC points are presented (Burnham 2002). I used the sjPlot package in R to produce marginal effects plots for each covariate (Lüdecke 2022). All data processing and mapping was done using ArcGIS Pro 3.0.0.

I included habitat type as a fixed effect in the Western Cape models because Blue Cranes are found almost exclusively in cultivated areas and tend to prefer areas with short vegetation. Surveys took place mainly in cultivated areas, but a few sections were not. Vegetation height affects detection of carcasses (Schutgens et al. 2014) and needs to be accounted for. I extracted habitat information for each point from the 2020 South African Land Cover dataset (Department of Environment Forestry and Fisheries 2020b). I categorised habitat as follows, based on vegetation height: fynbos/woodland/shrubs, cultivated/grassland and waterbody/bare.

Because Blue Cranes in the Karoo tend to congregate on cultivated fields during winter (Chapter 2), I expected that powerlines situated close to irrigated and cultivated land may have a higher probability of Blue Crane collision. I therefore included distance to irrigated fields as a fixed effect in the Karoo model, measuring the distance from each point to the nearest irrigated cultivated field, using the 2020 South African Land Cover dataset (Department of Environment Forestry and Fisheries 2020b).

Blue Cranes roost and drink at shallow dams and wetlands, and anecdotal data indicates that Blue Crane collisions are more likely on powerlines that are close to water. As a covariate for the point dataset, I calculated the distance to the nearest seasonal water body. I accessed the spatial data for water from the 2019–2021 Global Surface Water database and matched the dataset to the year the survey was conducted (Pekel et al. 2016, 2019a, b, c, 2020a, b, 2021a, b). This dataset records the presence of water, with seasonal waterbodies defined as areas inundated for less than 12 months of the year (Pekel et al. 2016, 2019a, b, c, 2020a, b, 2021a, b). This includes small ephemeral wetlands and dams, but also the edges of larger waterbodies, which are inundated only during the rainy season. I reasoned that this dataset would be the most useful for Blue Cranes, as it isolates shallower waterbodies most likely to be used for drinking, breeding and roosting. This variable caused some convergence issues in the models, so I transformed it by using the scale function in R (normalises by subtracting mean and dividing by standard deviation) or by log transforming it, to see which transformation produced a better fit (Bolker et al. 2009).

Results

Bias estimation

Based on the Overberg trial, observer bias was low for fresh carcasses (only 1 of 12 fresh carcasses was missed), but fairly high for older remains (12 of 18 old remains were missed). Combining these (1–(13/30)) gives an observer bias of 0.57 (proportion detected).

During the study I saw anecdotal evidence of crippling bias, I found two live Blue Cranes with broken legs next to/near powerlines and witnessed a Northern Black Korhaan hit a powerline and run off seemingly unable to fly. I used a published estimate of 0.8 for crippling bias (Bevanger 1995).

Carcasses were removed by scavengers at a substantially lower rate in the Swartland, compared to the Karoo, particularly in the spring and summer (Figure 5). In the summer Swartland trial, all 10 carcasses were still detectable in the landscape (as feathers and bones) after three months, and three were still detectable after six months. Scavenging activity increased in the Swartland in spring (8/10 detectable after 3 months) and was highest in winter, when crop fields were beginning to grow (Figure 6) (2/10 carcasses remained detectable after 3 months and one was detectable after 6 months).

Based on these findings, 63% of mortalities within the last 6 months are likely to be detected during summer powerline surveys, but it is unlikely that any carcasses older than 6 months are detected. Extrapolated over a year, this gives a scavenger bias of 0.63/2 = 0.32. Therefore, in the Swartland the bias correction factor calculation was 1⁄((0.8 crippling bias) x (0.32 scavenger bias) x (0.57 observer bias)) = 7.

In the Overberg, I did not conduct a scavenger bias trial, but I checked on the observer bias carcasses after 43 days. At this point 6 out of 12 carcasses (50%) were detectable, which is a higher scavenging rate than the Swartland, where all carcasses were present after 43 days in summer. A previous scavenger bias study in the Overberg got an estimate of 0.54 over a 5-month period, which I use in my study (Shaw et al. 2010b). This gives an Overberg bias correction factor of: 1⁄((0.8 crippling bias) x (0.54/2 = 0.27 scavenger bias over 1 year) x (0.57 observer bias)) = 8.

In the Karoo, carcasses tended to persist longer during winter, than summer (Figure 5). In summer, only 1 of 20 carcasses was detectable after 4.5 months, and it was represented by bones and feathers. In winter, 10/20 carcasses were detectable after 5 months, 6 of these were by feathers alone, and the rest by dismembered bones and feather. Of the 40 carcasses (summer and winter), 11 were detectable after 4.5–5 months, giving a scavenger bias estimate of 0.28 for the quarterly powerline surveys. Therefore the Karoo bias factor calculation was 1⁄((0.8 crippling bias) x (0.28 scavenger bias) x (0.75 observer bias)) = 6.

The number of species known to feed on carrion that were photographed at carcasses was similar in the Karoo (4 bird, 8 mammal species) and the Swartland (4 birds, 9 mammals) (Table S1). Of the 10 carcasses (7 Karoo, 3 Swartland) where the scavenger was photographed removing the carcass, the species were Cape Fox *Vulpes chama* (n = 5), Bat-eared Fox *Otocyon megalotis* (3) and domestic cat *Felis catus* (2).

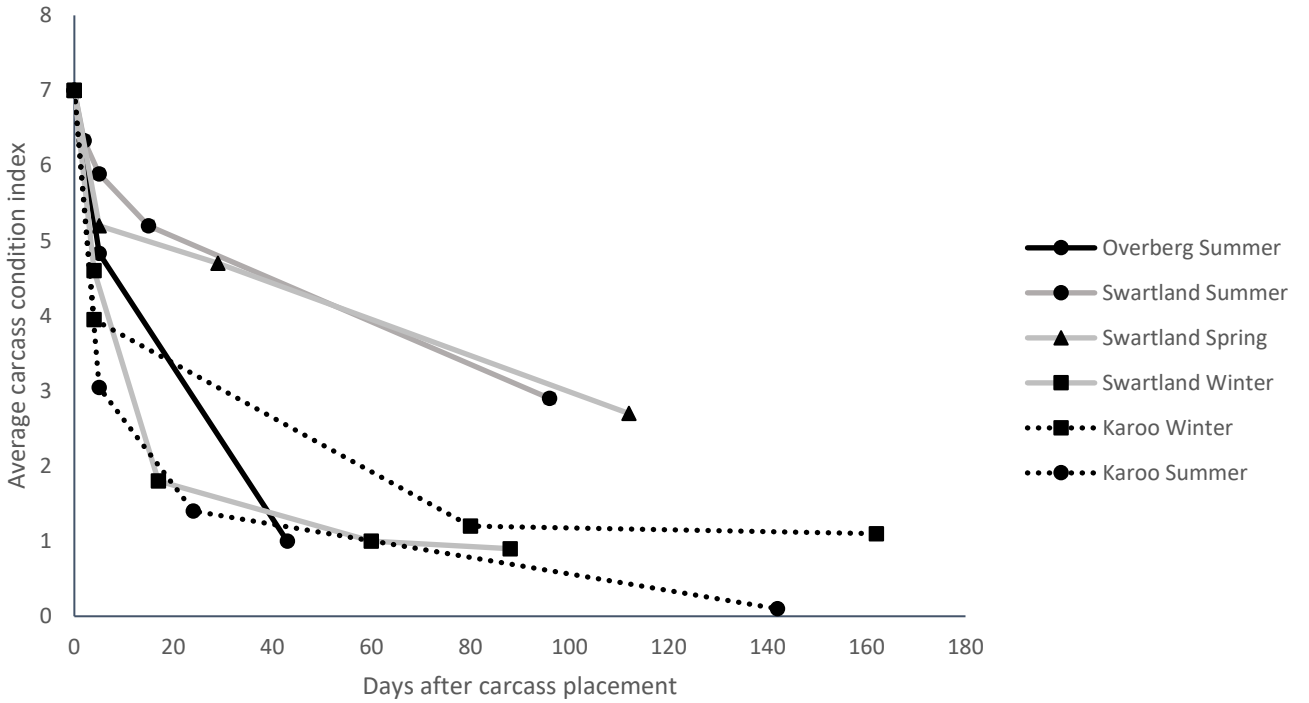


Figure 5: The average carcass condition index per region and season, by number of days after carcass placement, 7 = whole carcass, 0 = carcass removed without a trace.

Figure 6: Camera trap images of the same carcass site in the Swartland, demonstrating differences in vegetation in wheat fields in summer (stubble) (left), winter (growing crop) (centre) and spring (mature crop) (right).

Surveys

I recorded 556 carcasses of 40 bird species (6 Threatened, 4 Near Threatened) and 2 mammal species during powerline surveys across all regions between March 2019 and January 2022 (Table 1). Species richness was greater in the Karoo (25), and Swartland (25) than the Overberg (19) (Table 1). The Blue Crane was the most common fatality across all regions, followed by Ludwig's Bustard in the Karoo, Helmeted Guineafowl in the Overberg and flamingos in the Swartland (Table 1). Two transmission lines were surveyed in the Swartland, but the majority of species (all except four Sacred Ibis and one unidentified bird) were recorded on a 2 km section of the marked Ankerling-Aurora double transmission line, near

Darling. This section runs next to a pan frequented by waterbirds, and is a major collision hotspot for waterbirds, including Blue Cranes. Of all Blue Crane collisions in the Swartland, 69% were on this line in 2019 and 67% in 2021.

Table 1: Mortalities by species, in taxonomic order, and line type recorded on annual powerline surveys in the Overberg and Swartland, between March 2019 and January 2022, and quarterly powerline surveys in the Karoo between March 2019 and February 2021.

	Swartland			Overberg			Karoo		
Common name (Global IUCN Red List Status)	D	T	Total	D	T	Total	D	T	Total
Helmeted Guineafowl *Numida meleagris*	18	3	21	19	1	20	7		7
Spur-winged Goose *Plectropterus gambensis*	8	2	10	12	1	13	2		2
Egyptian Goose *Alopochen aegyptiaca*	2	10	12	5		5	4	1	5
Red-billed Teal *Anas erythrorhyncha*	3	1	4						
Cape Teal *Anas capensis*				2		2	1		1
Yellow-billed Duck *Anas undulata*		1	1				1		1
Unidentified ducks	2		2						
Little Swift *Apus affinis*					1	1			
Western Barn Owl *Tyto alba*	2		2						
Speckled Pigeon *Columba guinea*				2		2			
Laughing Dove *Spilopelia senegalensis*	1		1						
Unidentified doves				1		1			
Ludwig's Bustard *Neotis ludwigii* (EN)							22	39	61
Kori Bustard *Ardeotis kori* (NT)							3	3	6
Denham's Bustard *Neotis denhami* (NT)				2	1	3			
Blue Korhaan *Eupodotis caerulescens* (NT)							2	4	6
Northern Black Korhaan *Afrotis afraoides*							5		5
Karoo Korhaan *Eupodotis vigorsii*							1		1
Blue Crane *Anthropoides paradiseus* (VU)	16	13	29	26	4	30	98	18	116
Common Moorhen *Gallinula chloropus*	1	1	2						
Red-knobbed Coot *Fulica cristata*	2		2	1	1	2			
Spotted Thick-knee *Burhinus capensis*	1		1						
Blacksmith Lapwing *Vanellus armatus*	1		1						
Cape Vulture *Gyps coprotheres* (VU)				1		1	2		2
White-backed Vulture *Gyps africanus* (CR)							1		1
Greater Kestrel *Falco rupicoloides*							1		1
Jackal Buzzard *Buteo rufofuscus*							1		1
Common Buzzard *Buteo buteo*	1		1						
Martial Eagle *Polemaetus bellicosus* (EN)							1		1
Secretarybird *Sagittarius serpentarius* (EN)							1		1
Black-headed Heron *Ardea melanocephala*		1	1	1		1			
Grey Heron *Ardea cinerea*							1		1
Unidentified herons	1		1						
Greater Flamingo *Phoenicopterus roseus*	1	17	18						
Lesser Flamingo *Phoeniconaias minor* (NT)		2	2						
Unidentified flamingos		6	6						
African Sacred Ibis *Threskiornis aethiopicus*	2	22	24						
Hadeda Ibis *Bostrychia hagedash*		2	2	1		1			
White Stork *Ciconia Ciconia*	1		1						
Pied Crow *Corvus albus*	13		13		1	1	15	2	17

Cape Crow *Corvus capensis*				5		5	2		2
White-necked Raven *Corvus albicollis*							1		1
Unidentified crows	2		2	1		1	1		1
Cape Canary *Serinus canicollis*				1		1			
Cape Sparrow *Passer melanurus*				1		1			
Unidentified birds	10	5	15	4	2	6	39	1	40
Vervet Monkey *Cercopithecus pygerthrus*							1		1
Chacma Baboon *Papio cynocephalus*							4		4
Total	**88**	**86**	**174**	**85**	**12**	**97**	**217**	**68**	**285**

Mortalities, of all species, were more evenly distributed among lines in the Karoo. The line with the most collisions (a distribution line east of Richmond, n = 42) had 15% of all collisions. In the Karoo there were on average 12 (SD = 6) Blue Crane collisions per line (lines were 20 km long) (Table 2). Powerlines close to roost sites (n =3) consistently had more Blue Crane collisions (average Blue Crane collision = 17 for the three lines close to roosts), despite being marked with flappers. In the Karoo, 12 km of transmission lines were marked and 29 km of the distribution lines (Figure 2), but of the marked distribution lines, all flappers had fallen off (leaving just the bracket) on 29% of these lines or had partially fallen off on 62% of lines. After the Karoo clearing surveys (March 2019 and July 2019), Blue Crane carcasses were recorded at a rate of between 6 and 20 per quarter (Table 2). The survey width varied by region; in the Karoo carcasses were recorded on average 6 m from the line (range = 0–118 m), whereas in the Western Cape wheatlands the average distance was 3 m (range = 0–63 m).

In the Karoo, Blue Crane collision rates were more than twice as high on distribution lines than transmission lines (Table 3). In contrast, Ludwig's Bustard collision rates were five times lower on distribution lines than transmission lines (Table 3). In the Karoo, the quarterly sampling schedule gives a comprehensive view of incident rates for the whole year, whereas the annual summer surveys in the Western Cape leave more room for error, as winter collision rates are not captured. This should be considered when interpreting the comparatively higher Karoo incident rates in Table 3. Over the whole study, similar numbers of Blue Crane mortalities were recorded in the Overberg, compared to the Swartland (Overberg, total survey length = 432 km, 30 Blue Cranes, Swartland, 380 km, 29 Blue Cranes). Broken down by line type, bootstrapped collision rates for Blue Cranes were similar in the Overberg and Swartland on distribution lines (Table 3). On transmission lines, Swartland incident rates tended to be higher than in the Overberg, although given the smaller sample sizes there was much uncertainty in these estimates (Table 3). In the Swartland, the Ankerling-Aurora line hotspot skewed the transmission collisions rates, if this line is removed from the data, the uncorrected bootstrapped collision rates for Blue Crane on

transmission and distribution combined is 0.05 (0.006–0.12) cranes/km/year, which is similar to the Overberg (Table 3).

I extrapolated transmission and distribution Blue Crane collision rates (Table 3) to all powerlines in the study area and found far more Blue Cranes die on the widely distributed distribution lines, relative to transmission lines. In the Karoo, 87% of mortalities are predicted to occur on distribution lines (95% CI 83–94%, D = 3394 km, T = 1332 km in study area), 93% in the Overberg (89–100%, D = 3279 km, T = 104 km) and 78% in the Swartland (72–100%, D = 3935 km, T = 222 km).

Blue Crane mortality rates were relatively consistent in the first two Swartland surveys in 2019 but were lower in 2020 (Table 2). Likewise, there were few Blue Crane mortalities in the Overberg in 2020 (Table 2). When considering all species, mortality rates in the Overberg in 2020 (21 mortalities in total) were much lower than the Swartland (63 mortalities). Notably, in the Overberg I recorded eight times fewer dead Blue Cranes in 2020 than Shaw et al. (2010a). In summer 2021, I surveyed new paired lines, along with a subset of Shaw et al. (2010a)'s lines to test whether the latter were marked at a higher rate than the paired lines. On this survey, 5 km of the transmission and 32 km of the distribution lines were marked (Figure 3). Most of the markers were on the lines sampled by Shaw et al. (2010a) (20% of lines sampled); of the paired lines, only 3 km (4%) were marked (Figure 3). Although this survey yielded more mortalities overall (57 mortalities of all species) than 2020, Blue Crane mortalities were similar to the previous survey in 2020 (Table 2). Looking at the Overberg 2008 and 2020–2022 data by line, there was no correlation between the Blue Crane collision rates on each line versus the percentage of the line that was marked at the time of the survey (r = –0.19, 95% CI = –0.49 to 0.14, p = 0.26). The extent of line marking was similar in the Overberg and Swartland, in the Swartland, 24 km of transmission lines were marked and 2 km of distribution lines (Figure 3).

Table 2: The distribution of all Blue Crane powerline mortalities (transmission and distribution), by region and survey. The length (km) of the survey is indicated.

Survey lines	Pilot Surveys									Total
	Summer 2018/ Autumn 2019	Winter 2019	Spring 2019	Summer 2019	Autumn 2020	Winter 2020	Spring 2020	Summer 2020	Summer 2021	
Karoo										
Survey km	79	255	255	232	255	255	255	255		1839
No. cranes	5	46	20	8	14	10	6	7		116
Overberg (Shaw lines)										
Survey km	35							168	105	308
No. cranes	11							8	8	27
Overberg (Paired lines)										
Survey km									72	72
No. cranes									2	2
Overberg (Nuwejaars)										
Survey km				56						56
No. cranes				1						1
Swartland										
Survey km	87			151				142		380
No. cranes	10			13				6		29

Table 3: The bootstrapped collision and electrocution rates, birds per km/year (95% CI), by region, species and powerline type. Unadjusted estimates are presented and adjusted estimates accounting for scavenging, observer and crippling bias.

Karoo	**Distribution**		**Transmission**		**All lines combined**	
Species	Unadjusted rate	Adjusted rate	Unadjusted rate	Adjusted rate	Unadjusted rate	Adjusted rate
All species	0.58 (0.47–0.72)		0.41 (0.29–0.54)		0.52 (0.43–0.61)	
Blue Crane	0.24 (0.17–0.32)	1.46 (1.04–1.95)	0.09 (0.03–0.17)	0.55 (0.18–1.04)	0.18 (0.13–0.24)	1.10 (0.79–1.46)
Ludwig's Bustard	0.05 (0.02–0.09)	0.30 (0.12–0.54)	0.25 (0.16–0.35)	1.53 (0.98–2.14)	0.12 (0.09–0.17)	0.73 (0.55–1.04)
Swartland						
All species	0.29 (0.18–0.44)		1.69 (0.17–4.40)		0.49 (0.25–0.98)	
Blue Crane	0.05 (0.01–0.12)	0.35 (0.07–0.84)	0.25 (0.00–0.82)	1.75 (0.00–5.74)	0.08 (0.02–0.17)	0.56 (0.14–1.19)
Overberg						
All species	0.21 (0.06–0.43)		0.24 (0.08–0.48)		0.21 (0.08–0.38)	
Blue Crane	0.04 (0.01–0.08)	0.32 (0.08–0.65)	0.09 (0.00–0.31)	0.73 (0.00–2.51)	0.05 (0.02–0.08)	0.41 (0.16–0.65)

In the Overberg and Swartland wheatlands, the modelling dataset contained 50 Blue Crane incidents and 1282 absence points (3.8%) and in Karoo dataset there were 98 Blue Crane incidents and 1834 absence points (5.1%). I chose four candidate models for the Western Cape, and five for the Karoo, based on AIC (Table 4). For the Western Cape, I included one model which had an AIC greater than 2 points of the top model (Table 4). This model is the top model (WC1) with a different transformation of the continuous variable (distance to seasonal water) (Table 4). A log transformation is the best fit for the data (WC1) (Table 4, Figure 7a), this is likely due to the influential points from the Ankerling Aurora data (a major hotspot close to seasonal water). I was not able to model the Western Cape data without these influential points (the model does not converge), but I would expect that a scale transformation of this variable (WC4) produces a model that is more generalisable to the area (Table 4, Figure 7b), given that in the Karoo, where collisions were more evenly distributed in the landscape, a scale transformation produced a more parsimonious model, compared to a log transformation.

All models in both the Karoo and Western Cape indicate that lines closer to seasonal waterbodies were significantly more likely to have a Blue Crane collision (Tables S2 and S3). The probability of a collision halved for powerlines > 2 km from a seasonal waterbody, based on models with a scale transformation of this variable, the collision rate drops more steeply with distance with a log transformation (Figures 7 and 8). It must be noted that sampling effort was higher on lines closer to water than those further away (Figure S5). In the Western Cape, Blue Crane collisions were significantly ($p < 0.05$) less likely to occur in fynbos, woodland or shrubland habitats than in cultivated land, grassland, waterbodies or bare land (Figure 9, Table S2). Blue Crane collisions are significantly ($p < 0.01$) more likely to occur on lines fitted with markers in the Western Cape, whereas in the Karoo collisions were more likely on marked lines, but not significantly so ($p = 0.07–9$) (Figure 10, Tables S2 and S3).

In the Western Cape, line type (transmission/distribution) was not a significant predictor of Blue Crane collision (Table S2, Figure S2), but in the Karoo the effect of this variable approached significance, with collision probability being higher on distribution lines (Figure 11, Table S3). Blue Crane collision probability did not differ between the Overberg and Swartland (Table S2, Figure S1). In the Karoo, Blue Crane collisions were more likely to occur closer to irrigated cultivated fields (Table S3, Figure S3) but this effect was not significant.

The Western Cape models including survey method (walking vs driving) had a higher AIC than the candidate models, and in these models this variable was not significant in predicting presence/absence of a

powerline collision. In the Karoo, model K5 included survey method but, as in the Western Cape, it did not have a significant effect on the probability of detecting a Blue Crane collision (Table S3, Figure S4). The effect of the survey method variable was likely confounded by line type, given that all transmission surveys were driven, and most distribution surveys were walked.

In the Western Cape, the random effects for powerline transect (spatial grouping) explained more variance in the models than survey (temporal grouping) (Transect: 38 levels, variance = 1.5; Survey: 6 levels, variance = 0.2). In contrast, in the Karoo, the variances of these random effects were equal (Transect: 13 levels, variance = 0.53–0.76; Survey (month/year): 8 levels, variance = 0.50–0.52).

Table 4: The top models for predicting Blue Crane powerline collisions in the Western Cape (Overberg and Swartland) and Karoo, from data collected between March 2019 and January 2022.

Models: Western Cape **Fixed effects**	**Log likelihood**	**df**	**AIC**
WC1: log (Distance to seasonal water) + Habitat + Markers	–167.7	1325	349.3
WC2: log (Distance to seasonal water) + Habitat + Markers + Region (Overberg/Swartland)	–167.6	1324	351.2
WC3: log (Distance to seasonal water) + Habitat + Markers + Line type (Transmission/Distribution)	–167.7	1324	351.3
WC4: scale (Distance to seasonal water) + Habitat + Markers	–173.3	1325	360.6
Models: Karoo			
K1: scale (Dist. seasonal water) + Markers + Line type (Transmission/Distribution)	–435.1	2972	882.1
K2: scale (Dist. seasonal water) + Markers + scale (Dist. irrigated fields)	–435.7	2972	883.4
K3: scale (Dist. seasonal water) + Markers + scale (Dist. irrigated fields) + Line type (Transmission/Distribution)	–434.7	2971	883.5
K4: scale (Dist. seasonal water) + Markers	–436.4	2973	882.8
K5: scale (Dist. seasonal water) + Markers + Line type (Transmission/Distribution) + Survey Method	–434.8	2971	883.7

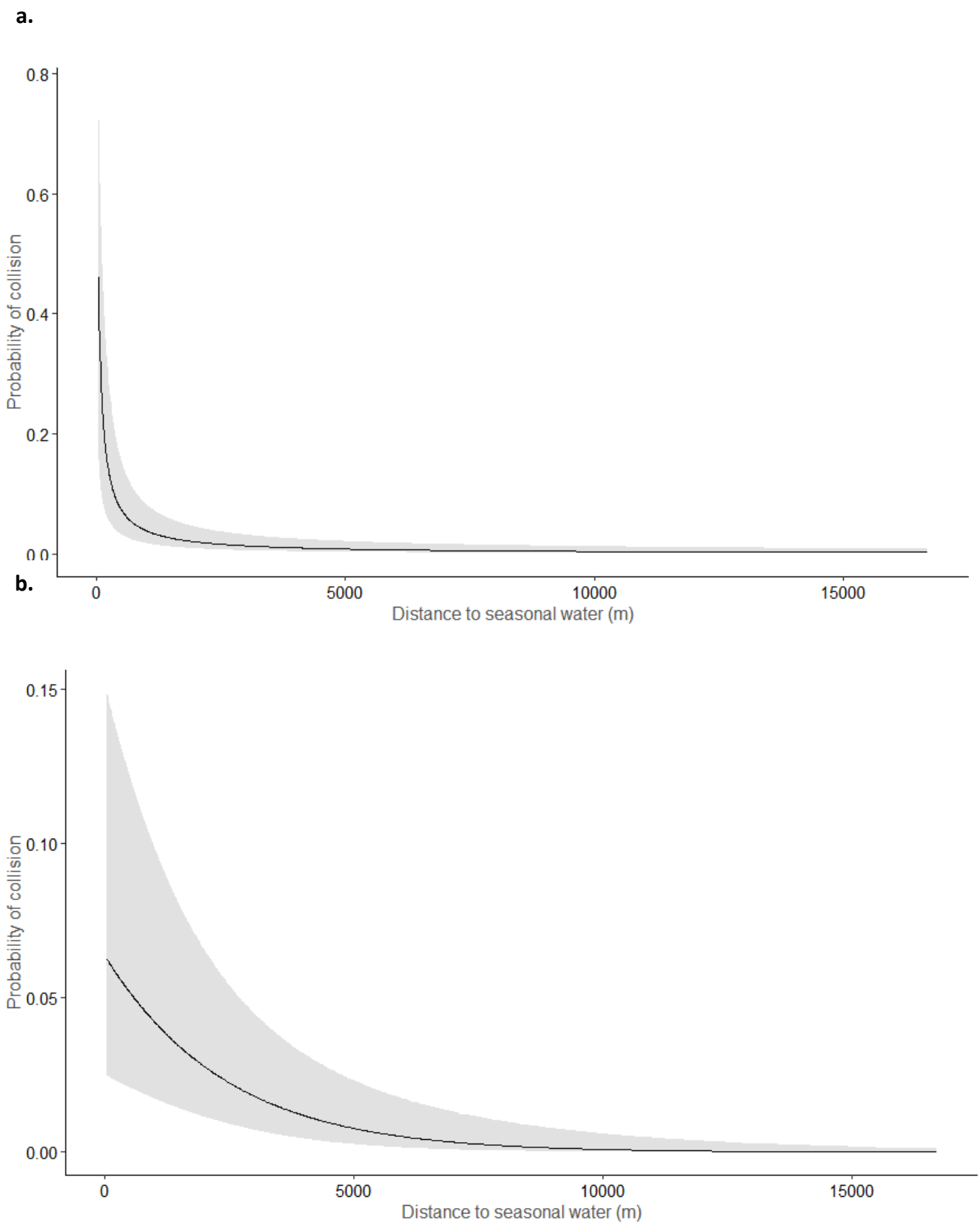


Figure 7: Marginal effects plots of effect of distance to seasonal water (m) on the probability of Blue Crane collision in the Western Cape, with a natural log transformation of the variable (a. Model WC1) and scale transformation (b. Model WC4), when other variables are held at base level. Confidence intervals (95%) are indicated by shading.

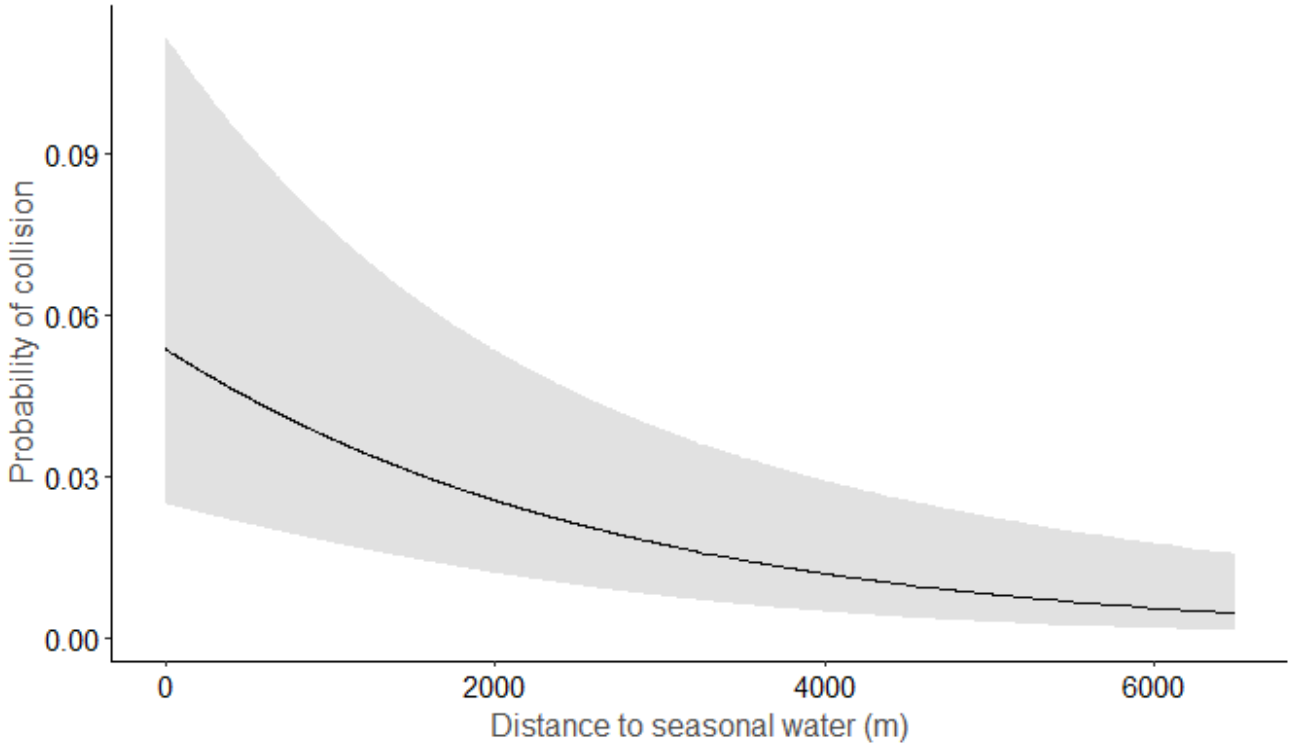


Figure 8: Marginal effect of distance to seasonal water (m) on probability of Blue Crane collision in the Karoo (Model K1), when other variables held at base level (categorical) or at average (continuous). Conventions as per Figure 7.

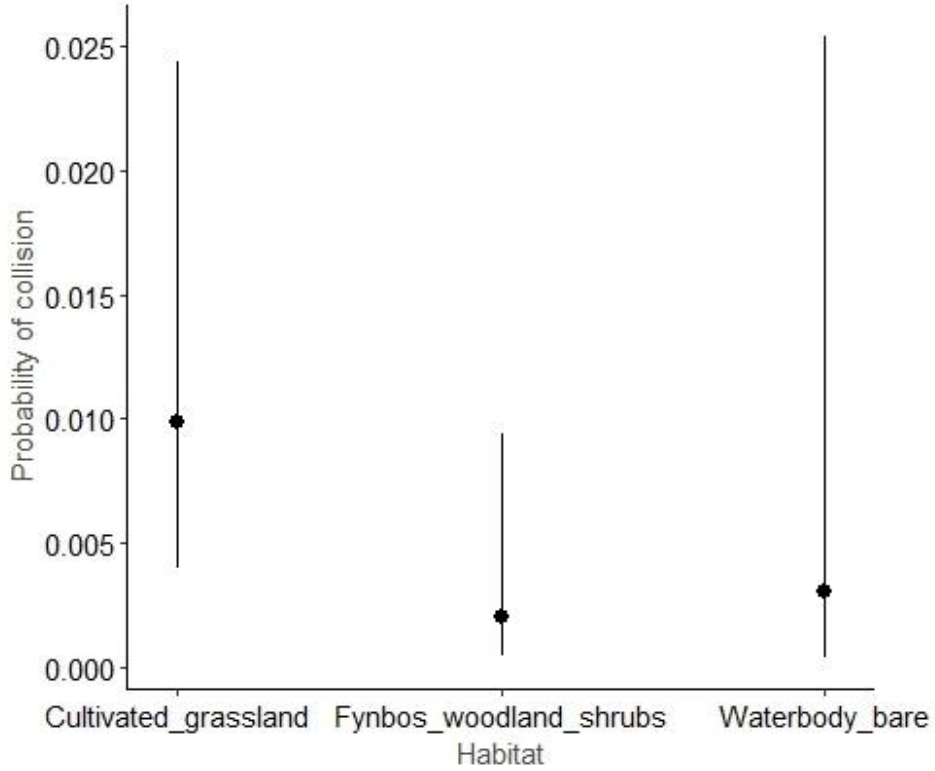


Figure 9: Marginal effects plot of effect of habitat on probability of Blue Crane collision in the Western Cape (Model WC1) when other variables held at base level (categorical) or at average (continuous). Vertical lines indicate 95% confidence intervals of estimates.

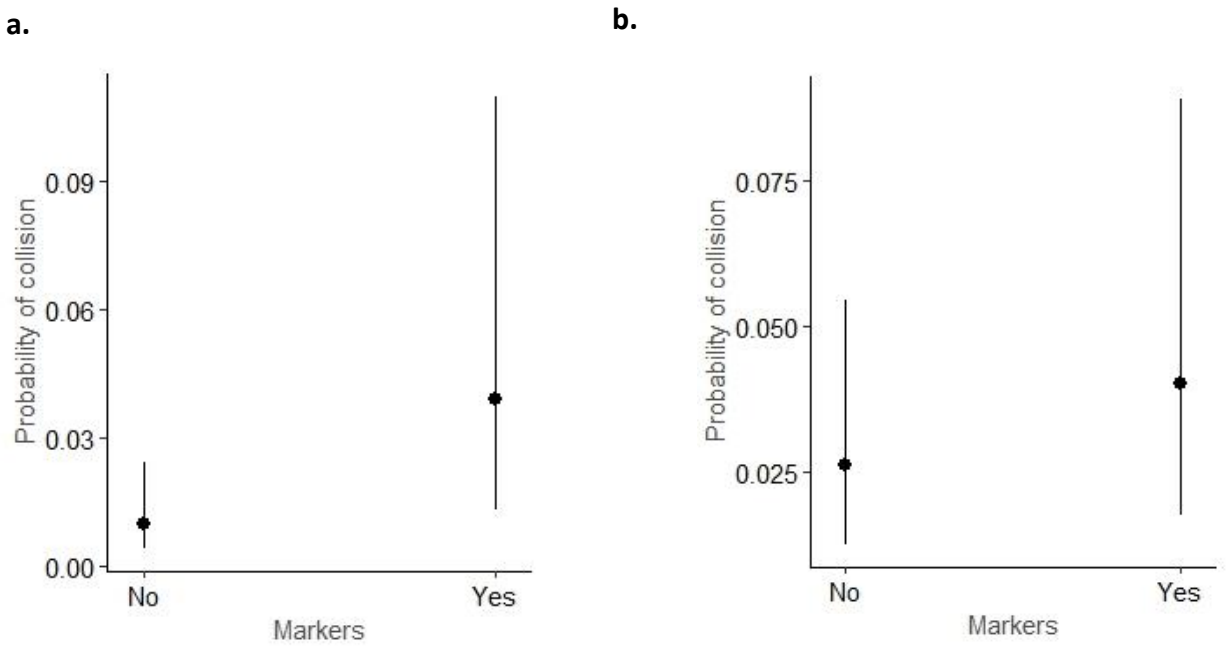


Figure 10: Marginal effects plot of effect of presence/absence of line markers on probability of Blue Crane collision in the Western Cape (a. Model WC1) and Karoo (b. Model K1). Conventions as per Figure 9.

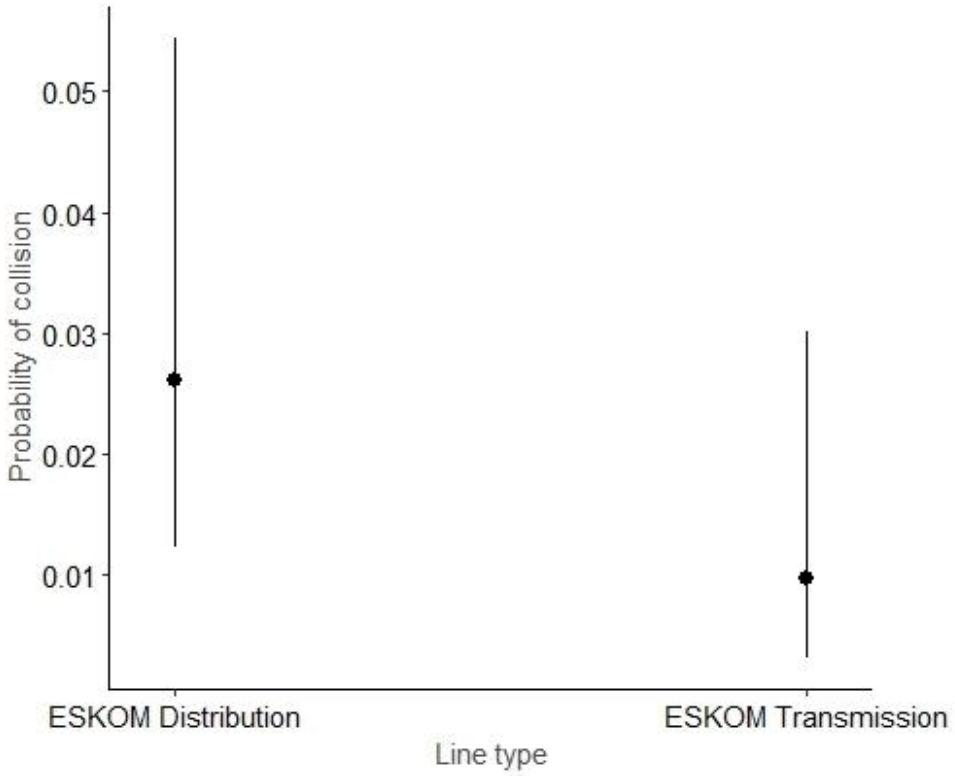


Figure 11: Marginal effect plot of line type on probability of Blue Crane collision in the Karoo (Model K1). Conventions as per Figure 9.

Discussion

A novel finding in this chapter is the first predictive model for Blue Crane powerline collisions in the Karoo and Western Cape from presence/absence survey data. The primary driving factor for Blue Crane collisions

in both areas is proximity to seasonal waterbodies. Blue Cranes are less wetland dependent than other crane species, but they often roost in shallow waterbodies (which will tend to be seasonal), drink at dams and some pairs nest on islands in farm dams, or on dam edges. Flights to and from roost sites are particularly risky because powerlines are less visible in low light and at night. Blue Cranes often fly low over the ground when approaching or departing waterbodies, increasing the risk of colliding with lines. A caveat is that sampling effort was higher on lines closer to water than those further away, therefore the power to detect powerline collisions further from water is lower. Powerlines near roost sites are known to be high risk for collisions for species like Sandhill Cranes *Antigone canadensis* and Dalmatian Pelicans *Pelecanus crispus* (McNeil et al. 1985; Morkill & Anderson 1991; Crivelli 1998; Baasch et al. 2022). Kotoane (2003) theorised that distance to water was likely to be important for predicting Blue Crane collisions in the Overberg and included it in their desktop model. When they checked the model against incidental collisions (i.e. presence only), they found that 98% (n = 157) of Blue Crane collisions were within 500 m of a waterbody in the Overberg (Kotoane 2003). However, Shaw et al. (2010b), who collected presence/absence data, did not find a relationship between Blue Crane collisions and distance to water. The only habitat variable that was significant in their model was cultivated land, which I also found support for in my Western Cape model. Since Blue Cranes tend to select for cultivated land in the Western Cape (Allan 1995; Hofmeyr 2012), this finding is not surprising.

There is evidence that Blue Crane collisions in the Overberg were more common in 2008 (Shaw et al. 2010b) than during my study, with uncorrected mortality rates half of what they were in 2008. Powerline collisions are chance events, and rates vary by survey. This variability was evident in my Overberg surveys, and in the 2009 monitoring of three hotspot lines identified in Shaw et al. (2010a)'s study (Jenkins et al. 2009a; Jenkins et al. 2009b). This is why long-term surveys are useful, to elucidate a trend despite this noise. If there has been a real decline in collision rates, I anticipate it could be due to two possible reasons. Firstly, Blue Crane abundance was at its highest in 2008/2009, and since then has declined by approximately 22% (see Chapter 2). Secondly, on the Shaw et al. (2010a) lines, the length of line with markers has trebled since 2008. Given that there is some evidence that markers are effective for Blue Cranes, at least on transmission lines (Shaw et al. 2021), this could potentially explain a reduced collision rate. I was unable to find support for this in my analysis, but this might be due to challenges with noisy data and infrequent surveys.

Using the Blue Crane population estimate at the time, Shaw et al. (2010b) estimated that 12% of the Overberg population was dying on powerlines annually. I did not attempt to do a revised population level estimate, as there are several uncertainties in estimating total annual mortality (extrapolating collision

rates to powerlines that were not surveyed), I do not think it is advisable to do this, or to apply this to a population estimate, which itself has many uncertainties (see Chapter 2). I believe that the previous estimate (12%) (Shaw et al. 2010b) was likely an overestimate, because the Blue Crane population estimate used in the calculation was a minimum count, rather a total count (McCann 2001; McCann et al. 2007).

At first glance the higher collision rate of Blue Cranes on marked lines seems counter-intuitive, but this need not imply that line markers are not effective. Most lines are selected for marking as a reaction to reported collisions, or a perceived high collision risk (e.g. adjacent to waterbodies). Therefore, lines with markers tend to be high risk sites for collisions and the finding that more collisions are occurring on marked lines is due to markers not being 100% effective. On Karoo transmission lines, markers reduce Blue Crane collision rates by at least 80% (Shaw et al. 2021), consistent with meta-analyses that estimated marker effectiveness to be 50–78% across species (Jenkins et al. 2010; Barrientos et al. 2011; Bernardino et al. 2019). There are species-specific differences in response to line marking; Blue Cranes respond more than bustards in South Africa (Shaw et al. 2021) and Sandhill Cranes *Grus canadensis* respond more than Canada Geese *Branta canadensis* in the USA (Brown & Drewien 1995). The confounding effect of line markers in my study could have been reduced by employing a random survey design, disregarding the Eskom CIR records in my survey design decisions. Lines known to be collision risk hotspots (from the Eskom CIR data) tended to have been marked. Surveying these lines was useful, to learn that collisions are still occurring on marked lines, but it did create a confounding variable in the dataset, and potentially some bias in the sampling design and ultimately the results. This bias should be minimal however, as I balanced lines with existing CIR records with lines that had none. In the design of future powerline surveys, it would be better to use a random sampling design.

In 2008, collision rates in the Overberg were twice as high on transmission lines than distribution lines (Shaw et al. 2010a). This is still the case in the Overberg and the Swartland, and a similar pattern has been observed for Ludwig's Bustard in the Karoo (Shaw et al. 2018). However, collision rates of Blue Cranes in the Karoo were higher on distribution than transmission lines. This difference may be attributed to line marking; transmission line surveys in the Karoo were part of a line-marking study (Shaw et al. 2021), currently in the post-marking monitoring stage. The Blue Crane collision rates I recorded on these lines were 4.3 times lower than the surveys in the pre-marking period (Shaw et al. 2021). Although the proportion of Karoo lines marked was similar between transmission (12%) and distribution line surveys (18%), we do not have robust estimates of line marker effectiveness on distribution lines, and there is evidence in my study that collisions are still occurring on these marked lines.

There have been no Before-After-Control-Impact (BACI) studies looking at distribution line marker effectiveness for Blue Crane, and marker effectiveness could be lower on these lines than on transmission lines. There is anecdotal evidence that flappers and stationary devices are not effective at roost sites when birds are flying at dusk e.g. Blue Cranes, or after dark e.g. flamingos (Rendón-Martos et al. 2000; McCulloch et al. 2003). There was evidence of this in this study, from the Ankerling-Aurora hotspot, which is marked with spirals, as well as several of the distribution lines near roosts in the Karoo, which are marked with flappers. Since 2015 the EWT/Eskom strategic partnership has been deploying Owl devices, a flapper with an LED light which flashes after dark (Matt Pretorius, EWT, pers. comm.), but there have not been any BACI trials to demonstrate their effectiveness. Distribution lines are far more common in the landscape, and Blue Crane collisions on distribution lines outnumber those on transmission lines, despite collision rates being higher on transmission lines. I therefore recommend that a BACI study be set up to quantify the effectiveness of distribution line marking, particularly for Owl devices which are expensive (~R450 per device), compared to flappers (~R100 per device). My study could serve as the pre-marking survey for a BACI study. Studies of distribution line marker effectiveness are not only lacking in South Africa, but globally as well (Bernardino et al. 2019).

My study confirms that scavenger bias varies substantially by site and by season (Prosser et al. 2008; Shaw et al. 2015b; Barros et al. 2022). It is difficult to compare studies because they are of different durations, with different carcass sizes and densities. The closest comparison I can make is with a summer trial done in the Succulent Karoo (South Africa) with Spur-winged, and Egyptian Geese, on which I based my study protocol (Schutgens et al. 2014). I recorded much higher carcass removal rates (95%) in summer, compared to Schutgens et al. (2014) (16%), but my study was 50 days longer than theirs. I found that Karoo carcasses persisted longer in winter, compared to summer, which is contrary to the Succulent Karoo trials (Schutgens et al. 2014; Shaw et al. 2015b) and a US study (Riding & Loss 2018). A study in tropical Mexico found carcass persistence to be higher in the dry season, compared to the wet (Villegas-Patraca et al. 2012), which is what I found in the Karoo. The eastern Nama-Karoo is a summer rainfall area where rain comes in the form of thunderstorms, and feathers and bones are likely to deteriorate/dissipate faster in summer, than winter, with the rain, wind and higher solar radiation leading to increased insect and microbial activity and physical deterioration. The Swartland on the other hand is a winter rainfall area (South African Weather Service 2023), and it is likely that different factors drive carcass persistence in this landscape. In the Swartland, carcass removal was highest in winter, when crops were just starting to grow, fairly low in spring, when crops were at their tallest, and lowest in summer when crops had been harvested and fields were bare/stubble. I suspect that during winter, when there is some vegetation cover,

mammalian scavengers are more likely to move through croplands. The species responsible for carcass removals were all mammals, similar to a study in Spain (Ponce et al. 2010), whereas birds tended to scavenge carcasses *in situ*. In summer, when crops have been harvested, carcasses are more visible to avian scavengers such as raptors. This pattern has also been observed in a European carcass persistence study (Oliva-Vidal et al. 2022), avian scavengers were more common in open habitats.

I anticipated that since the Overberg and Swartland have a similar mix of habitats (intensive cereal cropping/dryland pasture), that I could use the Swartland scavenger bias estimates in the Overberg. However, 50% of carcasses set out for the Overberg observer bias trial were removed by scavengers after 43 days, compared to 0% in the Swartland summer trial, suggesting that scavenging occurs at a higher rate in the Overberg. My assumption that scavenging rates would be equivalent in these two areas was incorrect, and ideally scavenger bias trials should have been done in the Overberg as well as the Swartland. It is counter-intuitive that my observer bias estimates (0.4) are higher than in the Little Karoo (0.25), as the Overberg stubble fields are open, and I would expect visibility to be better than in the Little Karoo. It is however easy to miss bones and feathers (older remains) in wheat stubble as the stubble is light in colour, similar to the colour of bones. Lastly it is uncertain whether geese carcasses are a good proxy for Blue Crane, as Egyptian Geese and female Spur-winged Geese can weigh approximately half that of a Blue Crane, and carcass weight is a significant predictor of persistence (Henry et al. 2021). Finding an adequate number of readily available bird carcasses of a more appropriate weight, is ethically challenging. Accurately estimating survey biases is challenging and time consuming, but important; the correction factors in my study significantly alter collision rates. These corrected collision rates should be interpreted with caution however, given that the bias trial sample sizes were relatively small. They are useful for understanding uncertainty but should not be interpreted as absolute collision rates.

In conclusion, my study confirms that the Blue Crane is the species most often killed by powerline collisions in the Karoo and Western Cape wheatlands. Statistical models indicate that proximity to seasonal water is the primary factor predicting Blue Crane powerline collision risk. This finding should guide future placement of powerlines, for example no powerlines should be built within two kilometres of Blue Crane roosts (shallow seasonal waterbodies). Existing lines close to seasonal waterbodies should be prioritised for pro-active line marking. Flappers are likely sufficient if there is no evidence of roosting, but LED devices are needed if the site is a known roost. More research is needed to quantify the effectiveness of line marking on distribution lines, particularly for LED devices.

Supplementary materials

Supplementary Table 1: Scavenging species recorded on the camera traps during the scavenger bias trials in the Swartland and the Karoo, listed by taxonomic order.

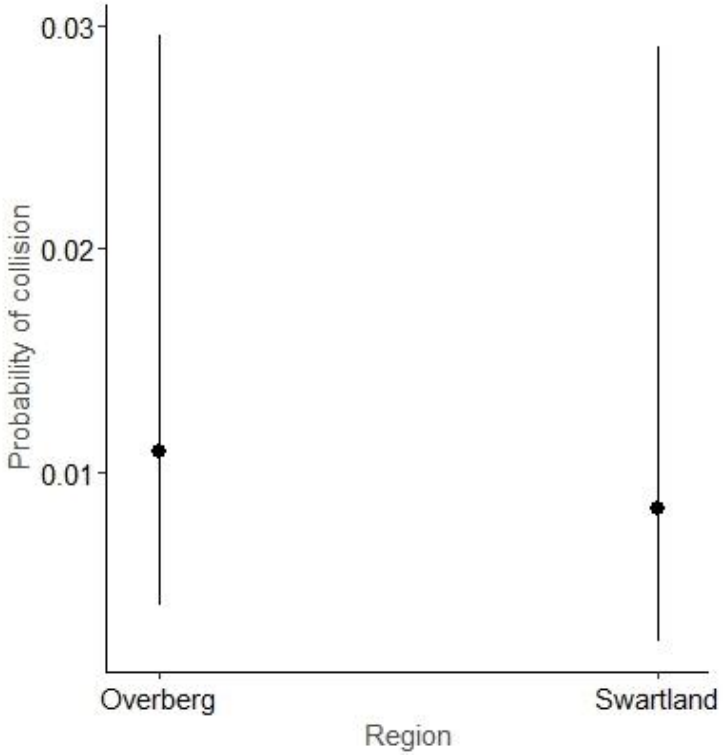
Species	Swartland	Karoo
Mammals		
Domestic Dog *Canis familiaris*	X	
Black-backed Jackal *Canis mesomelas*		X
Cape Grey Mongoose *Galerella pulverulenta*	X	
Slender Mongoose *Galerella sanguinea*		X
Honey Badger *Mellivora capensis*	X	
Porcupine *Hystrix africaeaustralis*	X	X
Domestic Cat *Felis catus*	X	X
Large Grey Mongoose *Herpestes ichneumon*	X	
Cape Fox *Vulpes chama*	X	X
Meerkat *Suricata suricatta*		X
Yellow Mongoose *Cynictis penicillate*	X	X
Bat-eared Fox *Otocyon megalotis*	X	X
Birds		
Jackal Buzzard *Buteo rufofuscus*	X	
Pale Chanting Goshawk *Melierax canorus*		X
Yellow-billed Kite *Milvus aegyptius*	X	
Lanner Falcon *Falco biarmicus*		X
Spotted Eagle Owl *Bubo africanus*	X	
Pied Crow *Corvus albus*	X	X
White-necked Raven *Corvus albicollis*		X

Supplementary Table 2: Model coefficients (Estimate, Standard Error, and p value) for four GLMM candidate models, predicting log odds of a Blue Crane collision occurring on a powerline in the Western Cape wheatlands, in relation to powerline and environmental covariates.

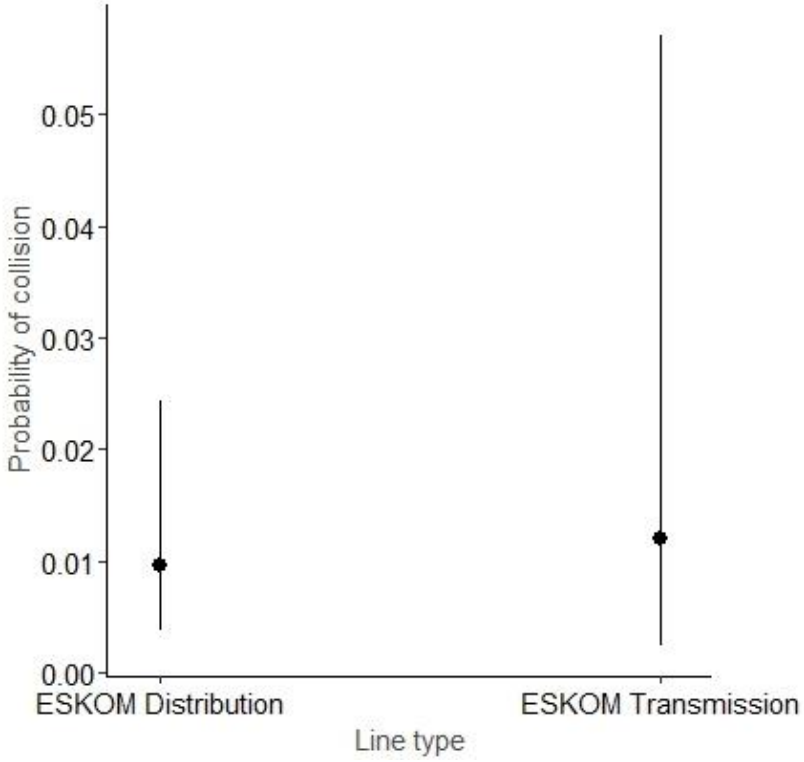
Model	WC1			WC4			WC3			WC2		
Coefficients	Estimate	SE	p	Estimate	SE	p	Estimate	SE	p	Estimate	SE	p
Intercept	3.54	1.29	0.01	–4.50	0.53	0.00	3.75	1.39	0.01	3.49	1.30	0.01
Distance to seasonal water (metres)	–0.98	0.17	0.00	–1.59	0.38	0.00	–0.99	0.18	0.00	–0.97	0.17	0.00
Habitat (base = Cultivated_Grassland)	–1.59	0.64	0.01	–1.51	0.64	0.01	–1.60	0.65	0.01	–1.58	0.65	0.01
Fynbos_Woodland_Shrubs												
Habitat: Waterbody_Bare	–1.20	0.97	0.22	–0.82	0.86	0.34	–1.21	0.97	0.21	–1.20	0.97	0.22
Markers: Yes (base = No)	1.40	0.47	0.00	1.57	0.48	0.00	1.39	0.47	0.00	1.37	0.48	0.00
Region: Swartland (base = Overberg)							–0.27	0.68	0.69			
Line type: Transmission (base = Distribution)										0.22	0.76	0.77

Supplementary Table 3: Model coefficients (Estimate, Standard Error, and p value) for five GLMM candidate models, predicting log odds of a Blue Crane collision occurring on a powerline in the Karoo, in relation to powerline, survey and environmental covariates.

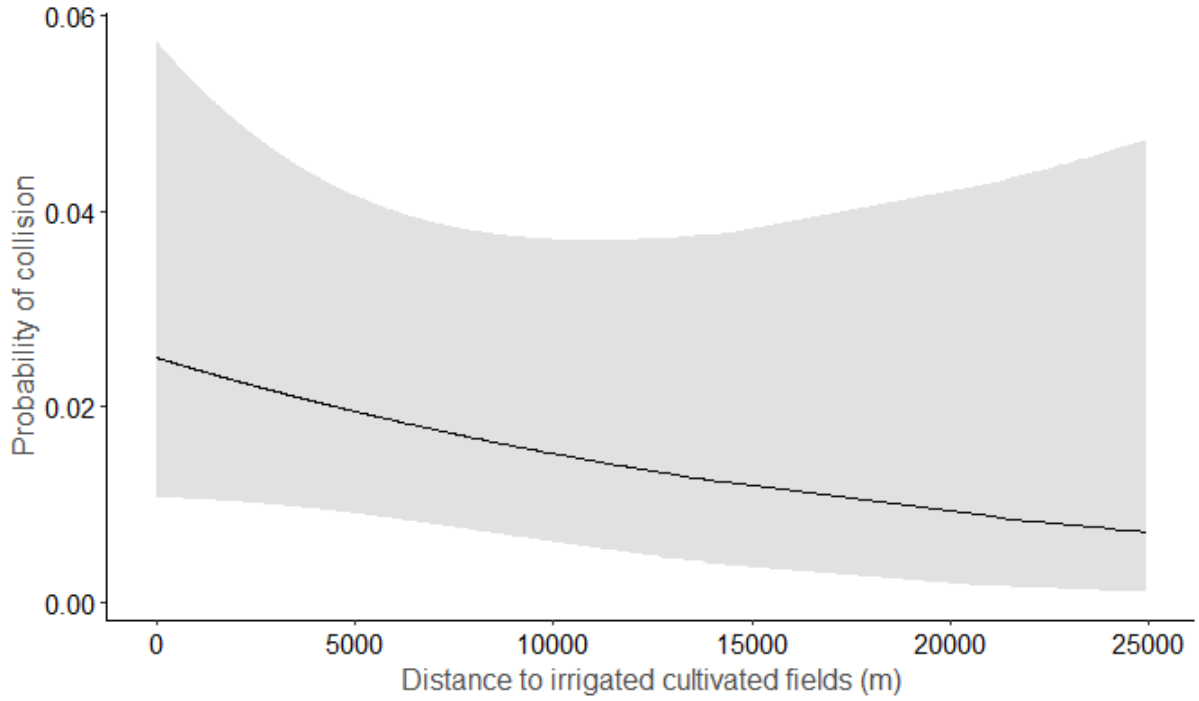
Model	K1			K2			K3			K4			K5		
Coefficients	Estimate	SE	p	Estimate	SE	p	Estimate	SE	p	Estimate	SE	p	Estimate	SE	p
Intercept	–3.62	0.39	0.00	–3.92	0.40	0.00	–3.66	0.40	0.00	–3.90	0.39	0.00	–4.28	1.10	0.00
Distance to seasonal water (metres)	–0.48	0.12	0.00	–0.48	0.12	0.00	–0.47	0.12	0.00	–0.50	0.12	0.00	–0.49	0.12	0.00
Distance to irrigated fields (metres)				–0.18	0.16	0.25	–0.13	0.16	0.41						
Markers: Yes (base = No)	0.44	0.25	0.07	0.42	0.25	0.09	0.42	0.25	0.09	0.45	0.25	0.07	0.44	0.25	0.08
Line type: Transmission (base = Distribution)	–1.00	0.58	0.09				–0.91	0.61	0.14				–0.34	1.18	0.77
Survey Method: Walking (base = Driving)													0.67	1.03	0.52



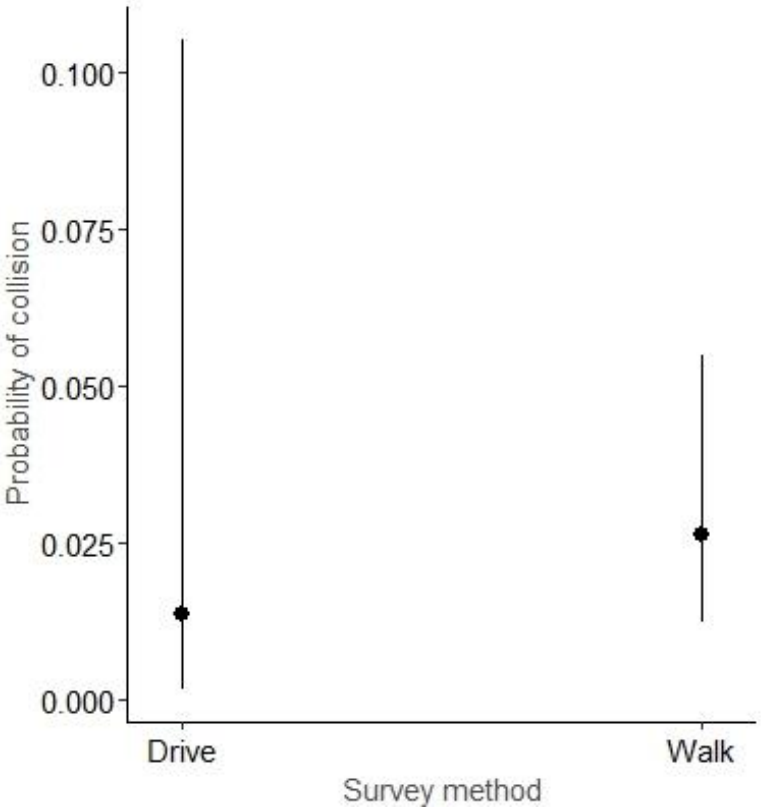
Supplementary Figure 1: Marginal effects plot showing the effect of region on probability of Blue Crane collision in the Western Cape, when other variables are held at their base level (categorical) or mean (continuous) (Model WC2). Confidence intervals (95%) are indicated by vertical lines.



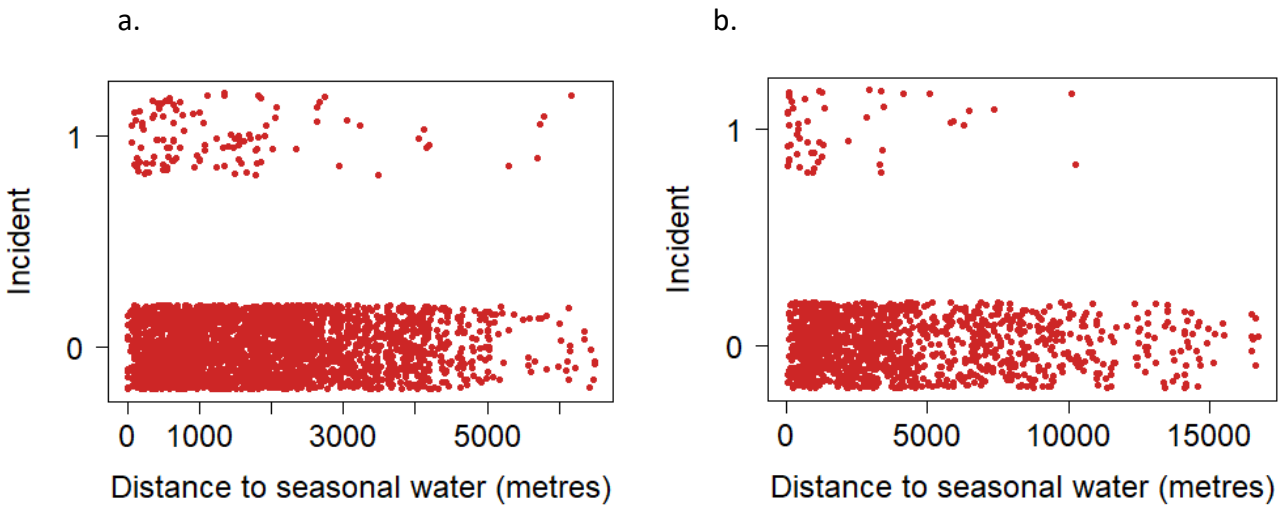
Supplementary Figure 2: Marginal effects plot showing the effect of line type on probability of Blue Crane collision in the Western Cape, when all other variables held at average (continuous) or at base level (categorical) (Model WC3). Confidence intervals (95%) are indicated by vertical lines.



Supplementary Figure 3: Marginal effect of distance to irrigated cultivated fields on probability of Blue Crane collision in the Karoo, when other variables held at base level (categorical), or at their mean (continuous) (Model K2). Confidence intervals (95%) are indicated by shading.



Supplementary Figure 4: Marginal effect plot of survey method on probability of Blue Crane collision in the Karoo, when other variables are held at their mean (Model K5). Confidence intervals (95%) are indicated by vertical lines.



Supplementary Figure 5: Distance of Blue Crane collisions (1) from seasonal water, compared to absence points (0) along powerline surveys for the Karoo (a) and Western Cape (b).

Chapter 4: Movement and survival of Blue Cranes as informed by satellite tracking

Blue Crane fitted with a tracker in the Swartland.

Abstract

Tracking data provides insights into bird movements and survival. One of the primary threats to Blue Cranes *Anthropoides paradiseus* is collision with powerlines, which is intrinsically linked to crane movement patterns. It is thus important to understand how and when Blue Cranes move. Between 2016 and 2021, 31 Blue Crane adults, 25 fledglings and 3 juveniles were fitted with GPS-GSM and Iridium satellite trackers in the Overberg, Swartland and Karoo. Of the fully-grown birds (juveniles and adults), fitted in the Western Cape only, 29 had sufficient data for analysis i.e., more than 5 months data (Swartland = 8, Overberg = 21). Mean daily distance travelled did not differ between regions: Swartland: 9.5 km (SD 11.7), Overberg: 7.5 km (SD 9.8); but non-breeding cranes moved significantly farther per day, 9.5 km (SD 13.3) than breeding cranes, 5.8 km (SD 5.4). Using autocorrelated kernel density home range analysis, I demonstrate that Swartland cranes have home ranges 2.7 times larger than Overberg cranes.

Home ranges of non-breeding cranes averaged 13 times larger than breeding cranes. Four different movement types were displayed: 28% resident birds (semi-variance < 20 km^2), 28% regional residents (semi-variance 20–100 km^2), 34% intra-regional migrants that remained within the general region they were captured (semi-variance 100–1500 km^2) and 10% inter-regional migrants (semi-variance > 4000 km^2). All three inter-regional migrants were captured in the Overberg; two moved to the Eastern Cape and one to the Swartland. Non-breeding cranes intersect powerlines at a significantly higher rate, 1.3 intersections per day (SE 1.4), than breeding cranes 0.64 intersections per day (SE 1.3). Using a Known Fate Mark Recapture Model, I estimate annual survival for non-breeding birds to be 0.85 (95% CI 0.61–0.95, n = 13), and 0.95 (95% CI 0.71–0.99, n = 12) for breeding birds. Tracker failure rates were very high for fledglings; only 11 sent a limited number of fixes over a short duration (less than a year), so I just describe the movements for these individuals, rather than doing detailed analyses. From these limited data, in the year post fledgling, most fledglings stay within 30 km of their natal site in the Karoo and 15 km in the Western Cape, but one Overberg chick moved 80 km east two months after fledging.

Introduction

Birds are one of the most mobile animal groups, which makes their movements in response to habitat quality and threats highly informative. As a result, a good understanding of bird movements is integral to many conservation questions (Bogliani & Mellone 2014), particularly in changing environments (McCann & Benn 2009; Assandri et al. 2022). These conservation questions include exposure to threats such as wind turbines (Péron et al. 2017) and powerlines (Silva et al. 2014; Hays et al. 2021; Marcelino et al. 2021) and climate change impacts (Visser et al. 2009). Movement and survival are often linked because movement can contribute to mortality risk. This is especially the case for the Blue Crane *Anthropoides paradiseus*, which is prone to flying into powerlines (Shaw et al. 2010b; Shaw et al. 2021). Studies of movement and survival are often linked as they rely on observing an individual on multiple occasions, which is usually achieved through some form of mark and recapture/resighting. Traditionally for birds this would be through ringing or tagging, but increasingly over the last few decades, GPS-satellite and GPS-GSM trackers have been used to follow the fate of individual birds (Kays et al. 2015).

Over the last 20 years, both ringing and satellite tracking have been used to gain insight into Blue Crane movements and survival (Altwegg & Anderson 2009; van Velden et al. 2016a; Davis 2018). Prior to this, very little was known. In 1986, Blue Crane movements were described as “Locally migratory but details poorly known” (Urban et al. 1986, p. 139). Mmonoa (2009) reported Blue Crane breeding home range and habitat use in the Mpumalanga grasslands, and Allan (1993) inferred inter-regional movements based on

the Southern African Bird Atlas Project data, but few concrete conclusions could be made. Survival rates were estimated from resightings of colour-ringed individuals in the Karoo (Altwegg & Anderson 2009) and the Western Cape (van Velden et al. 2016a), but the latter study produced a very low adult survival rate, 0.72, compared to 0.96 in the Karoo (Altwegg & Anderson 2009) due to ring loss.

Resightings of Blue Cranes with field-readable ring combinations indicated that birds were largely resident to locally nomadic in the Western Cape (van Velden et al. 2016a). Inter-regional movements were rare; only 3.8% of cranes were seen in both the Overberg and Swartland (van Velden et al. 2016a) and there was only one record of a crane leaving the Western Cape, from the Overberg to the Eastern Cape (van Velden et al. 2016a). Blue Cranes display natal site fidelity, with 60% of adults returning to within 10 km of their natal site (van Velden et al. 2016a). Ringing data is however coarse by nature and it is difficult to separate the processes driving re-encounter probability from actual movements (Bearhop et al. 2010; Thorup et al. 2014). Satellite trackers bridge this gap effectively, although sample sizes are limited by the costs of this technology. In 2017, a preliminary study analysed the movements of 13 fully-grown Overberg Blue Cranes equipped with GPS-GSM satellite trackers (Davis 2018). Home ranges (95% kernel density and minimum convex polygon) were estimated at between 2.0 km^2 (SD 4.0) and 606 km^2 (SD 679) with no significant difference between home range of breeding and non-breeding cranes (Davis 2018).

Identifying home range is the first step in understanding how animals use space and the mechanisms that drive their movement patterns such as behaviour, resources, habitat quality, season, age, etc. (Borger et al. 2008; Cumming et al. 2012). The concept of home range was defined as the “area traversed by the individual in its normal activities of food gathering, mating, and caring for young. Occasional sallies outside of the area, perhaps exploratory in nature, should not be considered as in part of the home range” (Burt 1943, p. 351). In the last 30 years there has been rapid development of the technology used to track animal movements and statistical methods used to analyse these data. The most commonly used statistical methods, minimum convex polygon and kernel density estimation, were developed before the advent of high-resolution satellite tracking data (Hayne 1949; Worton 1989). These methods assume statistical independence in the data (Noonan et al. 2019), which means they do not take into account the inherent spatial and temporal autocorrelation in high resolution tracker data, often under-estimating home ranges (Swihart & Slade 1985; Hansteen 1997; Noonan et al. 2019). Autocorrelation can be addressed by selecting fewer fixes, but this leads to significant data loss (Swihart & Slade 1985). Recently statistical methods have been developed which include the autocorrelation as a function in the model (Fleming et al. 2015; Calabrese et al. 2016; Fleming et al. 2016).

In this chapter, I use tracker data to describe the movement patterns of Blue Cranes in the Overberg and Swartland (i.e., daily distance travelled and daily activity budgets). I then develop home range estimates, addressing autocorrelation issues in the tracker data by using a continuous-time stochastic process (Calabrese et al. 2016; Fleming et al. 2016). There are other statistical methods that can be used for high resolution fix data (e.g. Brownian bridge models), but these methods are limited in their ability to handle irregular fix intervals (Horne et al. 2007). I build on the data analysis by Davis (2018), augmenting her data with further data from the same individuals, and novel data from 16 more trackers fitted on both Overberg and Swartland Blue Cranes. These trackers had differing fix intervals, which motivated my choice to use continuous-time stochastic process methods to develop home range estimates. I also fit 25 trackers on Overberg, Swartland and Karoo fledglings. With these datasets, I provide the first estimates of home ranges in the Swartland, which provides some insight into habitat quality in these regions, assuming home range size varies with habitat quality (Reid et al. 2007; McCann & Benn 2009; Ditmer et al. 2016). Using movement tracks, I assess Blue Crane movements in relation to powerlines to estimate how frequently individuals are at risk of collision. When a tracker stops moving, it provides the opportunity to investigate possible mortalities. I assess adult survival this way, using the satellite trackers fitted on fully-grown cranes, these estimates are essential for the Population Viability Analysis performed in Chapter 5. Through this research I gain further insight into Blue Crane movements and survival in their strongholds, the Western Cape and Karoo.

Methods

Fully-grown birds

For this study I had access to tracker data analysed by Davis (2018) (crane 1–10 and BCRA01–03). The data I used from this study was from two models of GPS-GSM trackers (Ecotone Telemetry Inc., Sopot, Poland; BioLog Wildlife Tracking, KZN, South Africa) fitted to 11 adults and 1 juvenile Blue Crane in the Overberg in 2016/2017. Capture methods and tracker fitting followed the same process as below. The cranes were monitored between September and October 2017 to ascertain breeding status. Eleven of these trackers continued transmitting after Davis (2018) analysed the data (for a further 16–1542 days), so I include all the data available for these trackers (Table 1).

The GPS-GSM trackers used by Davis (2018) were unreliable if the crane was resident or stationary in an area with poor GSM signal, so I used Iridium satellite trackers in my study (Beegle Solar Flight Micro-

Tracker from Intricode Solutions, Cape Town) (Figure 1). The units weigh approximately 55 g, excluding the harness, well below the generally accepted guideline of < 3% of a bird's body weight (Barron et al. 2010), given that Blue Cranes weigh 4.5–5.1 kg (Allan 2005). Devices were attached to the crane's back with a Teflon harness fitted around each wing, crossing over the breast. To hold the crossover point secure on the breast, and to prevent chafing on the breast bone, I fed the Teflon straps through a circle of leather which sits on the breast bone, a technique recommended by Gareth Tate (Endangered Wildlife Trust) (Figure 2). Because the harnesses would not allow for substantial growth, these trackers could only be fitted on fully-grown birds. Blue Cranes tend to come into their adult plumage after 1 year (Allan 2005). Juveniles, distinguished by their lack of long tertial feathers, a less bulbous head shape and darker head feathers had to weigh a minimum of 4.5 kg to be fitted with a transmitter.

To catch fully-grown cranes, I set foot noose traps at sheep feedlots at three locations in the Overberg and two locations in the Swartland between June and September 2020 and 2021. During winter, Blue Cranes congregate at these sites to eat the sheep feed. I asked the farmer to remove the sheep for the day and I set up noose lines around the troughs. These traps are lines of slip-knot nooses that catch the feet of the birds and have been used to catch cranes and bustards (Hereford et al. 2001; Shaw et al. 2014). Observers sat in a vehicle at a distance from the traps and drove straight to the traps to release a crane as soon as one was caught. The captured crane is fitted with a hood to keep it calm, while the tracker is fitted, as well as a combination of five colour plastic rings and an individually numbered metal ring on the tibiotarsus. A drop of blood was taken by pricking the toe with a sterile needle, so that cranes could be sexed using an avian sexing kit (Molecular Diagnostic Services Pty Ltd., Westville, South Africa). Cranes were restrained for approximately 15 minutes, after which the crane is released back into the flock. In the Swartland I had one adverse effect on a crane; a juvenile caught in the traps was too young for a tracker to be fitted so we fitted rings only. After release the crane was temporarily unable to get up (see video), we moved a few hundred metres away to monitor it without stressing it further, after a few minutes it got up and returned to its parents. The crane was resighted the next day with its parents.

Figure 1: Fitting a Beegle Solar Flight Micro-tracker on a Blue Crane in the Overberg, using a Teflon harness. Trackers are designed tall enough to clear the feathers which would shade the solar panel. Clamps are used to hold the Teflon while adjusting the harness to fit (Photograph by Gareth Tate).

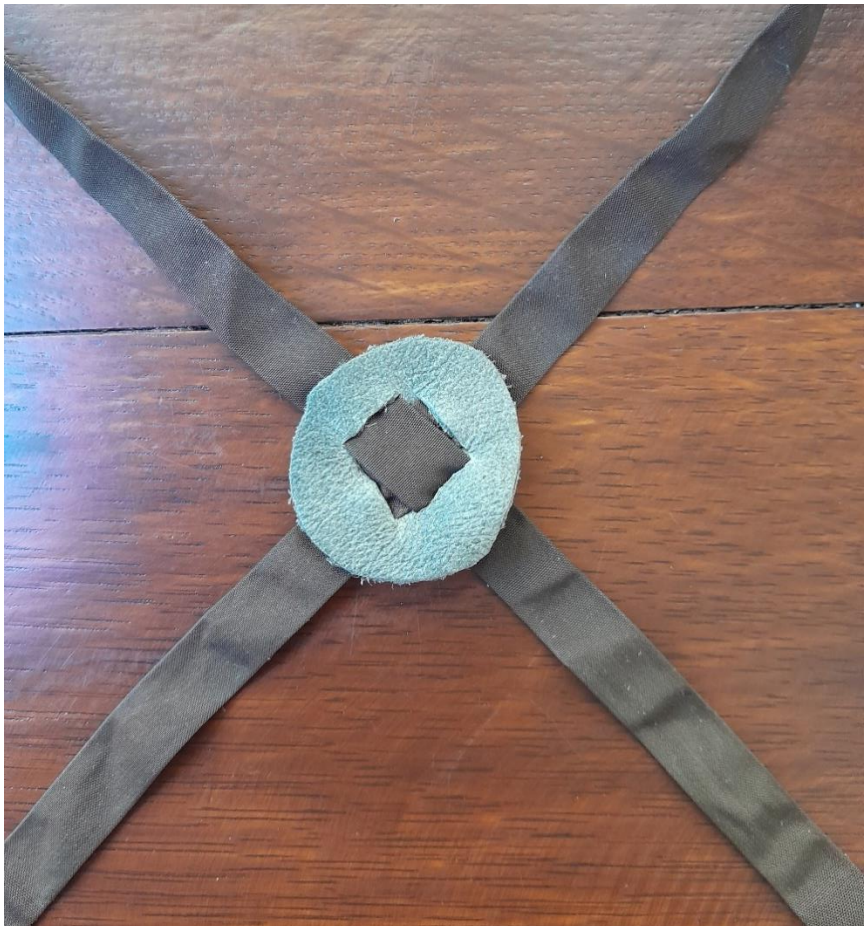


Figure 2: A Teflon harness fed through a piece of leather at the cross-over point, which sits on the breastbone.

The first batch of trackers (crane 1 – crane 10) were set to transmit every 2 hours between 06:00 and 12:00 and every three hours between 12:00 and 18:00, with the rationale being that Blue Cranes are less active in the afternoon. The second batch BCRA01 – BCRA03 transmitted every 6 hours for the first four months, after which BCRA01 had failed, but BCRA02 and BCRA03 were switched to a 2 hourly schedule. The Iridium trackers were set to take a fix every 30 minutes between 4:00 and 19:00. Trackers occasionally took fixes outside of set intervals or missed an interval. Since Blue Cranes roost overnight or tend a nest (during the breeding season) during which they make limited movements, I decided it was not necessary to record fixes throughout the night.

The trackers remained on until they stopped transmitting, because of tracker failure or mortality. By 15 December 2022, the eight trackers still transmitting were turned off as I had run out of budget for the satellite data costs. I extracted all the data from the Movebank portal and cleaned it, removing implausible locations by visual inspection and any that had a recorded accuracy >2000 m (Iridium trackers only).

From 2020–2022 I attempted to observe the cranes that had been fitted with trackers every two to three months. I downloaded their latest known locations and searched in these areas. Because all cranes were fitted with a unique colour ring combination, I could confirm the identity of tagged cranes. In addition to detecting any possible adverse effects of the trackers, these observations confirmed breeding status of the cranes. I defined breeding cranes as those that paired up and defended a territory (regardless of whether they nested) during the breeding season. Non-breeding cranes were cranes that remained in the floater flock during the breeding season. It is possible that some of these were indeed breeding cranes, that skipped a year, or failed early in the season and joined a floater flock. This is unlikely however as I monitored the majority (14 out of 17) of these cranes for at least two breeding seasons (Table 1).

Fledglings

Between 16 and 27 February 2019, 25 (11 Karoo, 7 Overberg, 7 Swartland) Blue Crane fledglings were fitted with ring-mounted solar powered GPS-GSM trackers (size = crane small) (Max Planck Institute). All trackers were tested for 2 weeks prior to fitting, and all were transmitting regularly. The tracker was fitted on one tibiotarsus, with a combination of three plastic colour rings on the other (Figure 3) and an individually numbered metal ring on the tarsometatarsus. I identified Blue Crane family groups where fledglings were 10–12 weeks old, well developed enough to be ringed and equipped with a tracker but were not yet able to fly strongly. A team of four people then drove as close to the family group as possible, before two people got out the vehicle to chase and capture the fledgling/s on foot, with as short a chase as possible. The fledglings were hooded to keep them calm while trackers and rings were fitted. A drop of blood was taken by pricking the toe with a sterile needle, so that cranes could be sexed using an avian sexing kit (Molecular Diagnostic Services Pty Ltd., Westville, South Africa). In the Karoo, the fledglings captured had an equal sex ratio (6 females, 6 males), whereas in the Western Cape, the sample was female biased (Swartland: 5 females, 2 males; Overberg: 5 females, 2 males).

During captures there was one possible case of capture myopathy. On a cool and overcast day in the Swartland, we chased the chick for a very short time, but after fitting the crane fledgling was unable to get up. We placed it near water to recover, and the next day it was still at the same site. I returned to the site a few days later and was unable to find it. The tracker never transmitted, so I was unable to trace it, I assume that the bird was predated or removed by humans. Another Swartland fledgling struggled to get up when released, but recovered after a few minutes and was subsequently resighted regularly (individual in Figure 3). After release, and through monitoring post-capture, I noted that this crane has a leg deformity, with one leg bent inwards (see video).

Figure 3: Top: Max Plank ring-mounted trackers, crane size small was used for Blue Cranes. Bottom: Swartland crane with rings (right leg) and Max Planck tracker (left leg), resighted in October 2022.

Statistical analyses

Daily distance travelled

To calculate daily distance travelled, I used 11909 sample days from 27 cranes (average 441 days per crane (SD 217), range 120–886). I excluded BCRA01, because it transmitted at 6 hourly intervals and the distance measurements would therefore not be comparable. I excluded all intervals greater than 24 hours (when the tracker went offline temporarily), and days where there were fewer than five fixes per day, to limit noise from irregular fixes. I used the Move package in R (Kranstauber et al. 2022) to calculate the distance between successive fixes, I then summed the distances per day for each crane and calculated the mean distances travelled per day per crane and extracted the maximum distance travelled per day per crane.

I modelled the daily distance travelled by Blue Cranes as a function of region (where the individual was captured: Overberg/Swartland), breeding status (whether it had been recorded to be breeding at any point, or not), crane season (breeding or non-breeding) and sex of the individual. I defined the breeding season as 1 September – 31 May as this covers the full range of dates that Blue Cranes breed in the Western Cape, from holding territory to fledging chicks. Since breeding status and breeding season of cranes are related, I included an interaction term in the model to account for this relationship. I excluded SW535, because by chance both this crane and her partner (SW514) were fitted with trackers, and because both partners stayed together throughout the year their movements are not statistically independent. I ran a linear mixed model using the lme4 package in R (Bates et al. 2015), with tracker ID as a random effect to account for non-independence of fixes within individuals. The model was over dispersed from visual diagnostics in DHARMa (Hartig 2022), so I log transformed the response variable. There were a variety of fix intervals between and within trackers, to account for this I included fixes per day as an offset term in the model. This was necessary as there was weak but significant positive correlation between daily distance travelled and number of fixes per day, according to a Spearman's rank correlation test ($\rho = 0.4$, $p < 0.01$).

Daily activity

To assess activity by time of day, I used data from the trackers with the highest temporal resolution (Iridium trackers), excluding any fix intervals that were > 1 hour. I used the suncalc package in R (Thieurmel & Elmarhraoui 2022) to extract the time of the start of nautical dawn and dusk for each date stamp according to the location of the crane. I then categorised time as follows: night = before dawn and after dusk, dawn < 1 hour after nautical dawn, morning = 1–4 hours after nautical dawn, midday > 4 hours after

nautical dawn & > 4 hours before nautical dusk, afternoon = 1–4 hours before nautical dusk, dusk < 1 hour before nautical dusk. Using the distance measurements calculated per successive fix (see above), I explored differences in distance travelled by time of day using a linear mixed model (tracker ID as random effect), with a log + 0.001 transformation of the response variable to improve model fit, as it was right skewed with several zeroes.

Movement types

I produced semi-variance function graphs (variograms) using the ctmm package in R 4.2.2 (Fleming & Calabrese 2022; R Core Team 2022). These variograms plot the average squared distance between locations (y axis) at all possible time lags (on the x axis). These plots can be used to visualise autocorrelation in the data and to understand movement patterns. I used these variograms to identify which Blue Cranes were range resident, defined by the semi-variance function reaching an asymptote. Those that do not, are not considered range resident, and therefore a home range cannot be calculated (Calabrese et al. 2016). Long-term site fidelity can be assessed visually on the variogram by identifying points along the time lag where average squared distance returns to 0 or a certain threshold (I decided on 5 km as a threshold for site fidelity). Using the variograms and interrogating movement maps I categorised the Blue Cranes into four movement types, resident (semi-variance within 20 km^2), regionally resident (semi-variance 20–100 km^2), intra-regional migrants (remained within the general region they were captured i.e. Overberg wheatlands or Swartland/West Coast; semi-variance 100–1500 km^2) and inter-regional migrants (moved out of capture region; semi-variance > 4000 km^2).

Home range

I used the ctmm package to infer home ranges from auto-correlated kernel density estimates (Calabrese et al. 2016; Fleming & Calabrese 2022). I used a 95% kernel density threshold, rather than a lower threshold, to gain a comprehensive measure of overall space use by Blue Cranes, rather than core range, which could be measured by a lower threshold (e.g. 50%). I produced home range estimates from all the data for each crane, and by season: summer breeding season (1 September – 31 May) and winter non-breeding season (1 June – 31 August). I only estimated a home range if the semi-variance function variogram had levelled off at time lags of approximately 6 months, indicating residency (Calabrese et al. 2016). I assumed 6 months was an appropriate time frame for Blue Cranes, as it encompasses at least two seasons, part of winter and part of the breeding season. Regardless of the variogram, I only estimated home range for cranes that stayed within the region they were fitted (Overberg/Swartland). The ctmm package can handle irregular sampling through weighting. I tried a weighted model for the trackers where the sampling

schedule varied during the project. These home range estimates only differed from the unweighted model by ± 1 km^2, so I used unweighted models rather. I produced polygons of the home ranges, and 95% confidence intervals. If the home range overlapped unsuitable habitat (e.g. the ocean or dense urban areas), I clipped the range to exclude these areas.

I ran a generalised linear model in R (R Core Team 2022) to explore home range estimates (total, summer and winter) as a function of several combinations of the following variables: sex, breeding status and region. I ran a Quasi-Poisson GLM, because the Poisson model was over-dispersed, as assessed by visual diagnostics. I excluded cranes where sex or breeding status was not known. As with the daily distance travelled model, I excluded SW535, because both her and her partner (SW514) were fitted with trackers by chance and since they remain together year-round the data is not independent. I ran a Pearson's correlation test in R to investigate the relationship between number of days tracked and home range size.

Powerline risk

I assessed powerline collision risk in one dimension (horizontal). Other studies have assessed risk in two dimensions, horizontal and vertical, using the flight height from the tracker (Silva et al. 2014; Hays et al. 2021), but this was not possible in my study as my older trackers did not record altitude, and on the newer trackers that did, I found the accuracy was too poor to be useful.

I only used the data from the Iridium trackers which were set to take fixes every 30 minutes (but some intervals were longer if the tracker missed a fix). To limit data loss, I included fix intervals up to 3 hours, but 78% of intervals were an hour or less. I used the Points to Tracks tool in ArcGIS Pro 3.0.3 to produce track segments between sequential fixes. I then used the Intersect tool in ArcGIS Pro to extract when and where each track segment intersected a powerline using the shapefile provided by Eskom, the South African electricity distribution company.

I summed the number of powerline intersections per day for each crane. I ran a Pearson's correlation to investigate the relationship between daily distance moved and number of powerline intersections. I then ran a negative binomial Generalised Linear Mixed Model using lme4 in R (Bates et al. 2015) to explore how the number of powerline intersections per day was related to the breeding status of the crane (whether or not the crane was a breeding adult or not), with tracker ID as a random effect.

Survival

I used Known-Fate Mark Recapture Models in RMark (Laake 2013) to calculate annual mortality for three datasets: fully-grown cranes (older than one year, n = 28), breeding cranes (n = 12) and non-breeding (n = 13) cranes. Most Blue Cranes begin breeding between three and five (Del Hoyo et al. 1996), so I assumed non-breeding cranes are younger than four. This allows for a crude comparison with other Blue Crane survival estimates, which are derived from age-structured models of ringed cranes (Altwegg & Anderson 2009; van Velden et al. 2016a). There were too few data to calculate juvenile survival (n = 2), so I only calculate survival for cranes older than one year. For cranes captured as juveniles that survived their first year (n = 1), I calculate survival from the age of one, assuming it reached this age in mid-February the year after they were captured (February is when most cranes fledge). Since the sample sizes are small, I combined Overberg and Swartland cranes to look at Western Cape survival, as did van Velden et al. (2016a) in their study. For input into RMark I produced monthly binary encounter histories for each crane between July 2016 and December 2022, where '10' = alive at start of month and survived month, '11' = alive at start of month and dead by the end of it, '00' = crane already dead or the tracker failed (referred to as right censored in MARK). I modelled survival as constant over time: S (~1). I chose the top model for each dataset based on the lowest Akaike Information Criterion (AIC) (Burnham 2002). I calculated annual survival by raising the monthly survival estimate to the power of 12.

Results

Fully-grown cranes

The 29 back-pack trackers fitted on fully-grown cranes transmitted for 174–1700 days. Twelve failed (after an average of 398 days; Table 1). The remainder were switched off at the end of the project (Table 1). Of the 24 Blue Cranes that were sexed, 14 were female and 10 male.

Daily distance travelled

Blue Cranes travelled significantly ($p < 0.01$) farther during dawn and dusk, than during the day (Figure 4). The daily distance travelled by fully-grown Blue Cranes was 5.6 km (SD 1.9, range 3.6–8.8 km) for trackers on a 2–3 hourly schedule (2016/2017 deployments) and 9.7 km (SD 3.8, range 4–18 km) for trackers on a 30-minute schedule (2020/2021 deployments) (Table 1). The different fix schedules preclude comparing distances travelled between tracker types, but comparisons can be made within each type. In the models I used an offset term to account for differing fix schedules. Mean daily distance travelled did not differ significantly with sex (female: 9.2 km (SD 13.1), male: 8.2 (SD 7.0); Estimate = 0.15, SE = 0.17, p = 0.41) or

region (Swartland: 9.5 km (SD 11.7), Overberg: 7.5 km (SD 9.8); Estimate = 0.19, SE = 0.18, p = 0.32). The maximum daily distance travelled was 309 km by an Overberg crane (OV514) that flew to the Eastern Cape, followed by an Overberg crane (OV512), that flew 295 km north-west to Vredendal, both in December 2020 (Table 1).

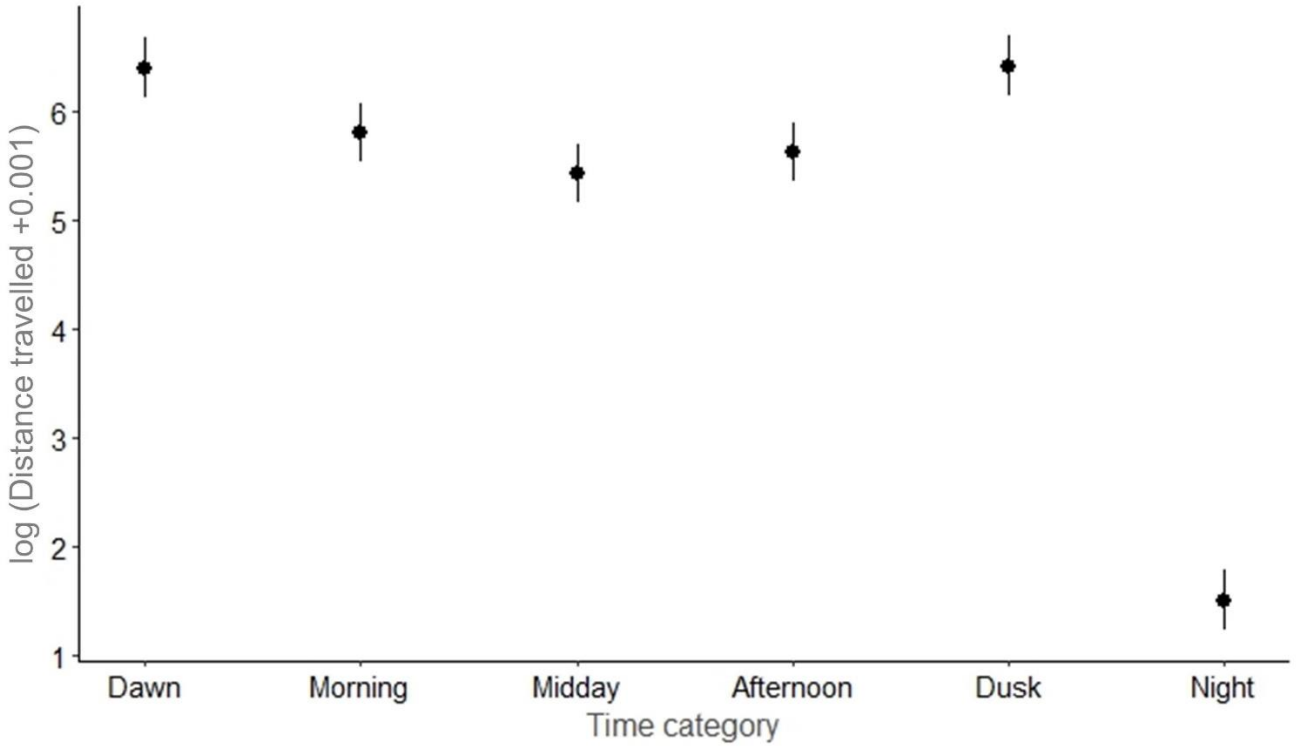


Figure 4: Model estimated average distance travelled (metres, log + 0.001 transformed) during each time of day (Error bars = 95% CI), from Iridium trackers on fully-grown Blue Cranes in the Overberg and Swartland.

Mean daily distance travelled differed significantly between breeding and non-breeding cranes (Estimate = 0.50, SE = 0.16, p = 0.005), with non-breeding cranes moving significantly farther, 9.5 km/day (SD 13.3) than breeding cranes, 5.8 km/day (SD 5.4). Distance travelled was significantly higher in winter, 8.9 km/day (SD 6.9) than in the summer breeding season, 7.8 km/day (SD 11.1; Estimate = 0.7, SE = 0.03, $p < 0.001$). There was a significant interaction between breeding status and season (Estimate = –0.56, SE = 0.04, $p < 0.01$); non-breeding crane movements only change slightly between seasons, but breeding cranes move much more in winter, compared to the breeding season (Figure 5).

Figure 5: Interaction plot showing how mean daily distance moved changes between season, for breeding and non-breeding Blue Cranes in the Western Cape.

Movement types

Most Blue Cranes were either regionally resident or intra-regional migrants (n = 18) (Figure 6 & S7). There were eight resident cranes, six of which were breeding cranes (Figure 6 & S7). Site fidelity (visiting a site within 5 km of a previously visited site) was common, with 17 resident and breeding cranes returning to breeding sites, although long-term site fidelity was also seen in non-breeding cranes (Figure 6 & S7). There were three inter-regional migrants in the Overberg; two moved to the Eastern Cape (OV514 and crane1) and one moved between the Overberg, Succulent Karoo and Swartland (Figure 6, 7 & S7) (OV512). OV512 moved from the Overberg to the Succulent Karoo in December 2020, moved south to the Swartland in November 2021, before returning to the Overberg in December 2021, and back to the Swartland in November 2022 (Figure 7). The tracker on OV512 developed a fault in December 2020, resulting in many fixes having low accuracy and being discarded, which is why the variogram is not smooth (Figure S7).

Table 1: Deployment details of 29 trackers fitted on fully-grown Blue Cranes in the Overberg and Swartland, between 2016 and 2021, and average and maximum daily distance travelled. Trackers fitted in 2016/7 have the same Tracker ID as in Davis (2018), except for the following which she renamed: BCRA03 = crane 11, BCRA02 = crane 12, BCRA03 = crane 13.

Start	End	Region fitted	Age fitted	Sex	Breeding status	Tracker ID	Sample days	Cut off reason	Average daily distance (km) (SD)	Maximum daily distance (km)
07/07/2016	31/03/2018	Overberg	Adult	Unknown	Non-breeding	crane 1	632	Failed	7.3 (7.7)	104.2
07/07/2016	24/03/2017	Overberg	Adult	Unknown	Breeding	crane 2	260	Failed	3.6 (2.4)	11
12/07/2016	11/01/2017	Overberg	Juvenile	Unknown	Non-breeding	crane 4	183	Died, unknown	4.8 (4.5)	26.3
12/07/2016	31/03/2018	Overberg	Adult	Unknown	Breeding	crane 6	627	Failed	4 (3.3)	15.2
13/07/2016	10/03/2018	Overberg	Adult	Unknown	Breeding	crane 5	605	Failed	3.9 (3.3)	22.4
02/08/2017	29/03/2022	Overberg	Adult	Female	Breeding	BCRA02	1700	Switched off	7 (6)	28.5
03/08/2017	01/04/2018	Overberg	Adult	Female	Non-breeding	BCRA03	241	Failed	4 (4.9)	25.8
04/08/2017	25/01/2018	Overberg	Adult	Male	Unknown	BCRA01	174	Fell off	Fixes too infrequent to calculate	
04/08/2017	20/03/2018	Overberg	Adult	Male	Non-breeding	crane 7	228	Failed	8.8 (10)	98.4
04/08/2017	29/04/2019	Overberg	Adult	Female	Non-breeding	crane 9	633	Tracker failed, later died on powerline (Nov 2020)	6.6 (7.4)	87.6
05/08/2017	08/02/2019	Overberg	Adult	Female	Breeding	crane 10	552	Failed	4.3 (5.2)	34.1
05/08/2017	20/06/2018	Overberg	Adult	Male	Non-breeding	crane 8	319	Failed	7.7 (6.3)	30.6
31/08/2020	13/11/2022	Overberg	Adult	Female	Non-breeding	OV410	804	Switched off	9.4 (5)	31
01/09/2020	14/11/2022	Overberg	Adult	Male	Non-breeding	OV502	804	Switched off	8 (4.7)	62.8
01/09/2020	03/03/2021	Overberg	Adult	Female	Non-breeding	OV514	183	Died, fence entanglement	18 (39.1)	309
02/09/2020	02/02/2022	Overberg	Adult	Female	Non-breeding	OV512	518	Faulty, low accuracy transmissions	13.1 (31.8)	295
04/09/2020	18/03/2021	Overberg	Adult	Male	Breeding	OV506	195	Failed	4.1 (3.1)	16.2
10/06/2021	13/12/2022	Overberg	Adult	Female	Unknown	OV524	551	Switched off	11.9 (7)	46.6
11/06/2021	14/12/2022	Overberg	Adult	Male	Breeding	OV520	551	Switched off	10.3 (8)	77.2
11/06/2021	14/12/2022	Overberg	Adult	Male	Unknown	OV501	551	Switched off	11.2 (7.8)	50.6
11/06/2021	13/12/2022	Overberg	Adult	Female	Non-breeding	OV545	550	Switched off	8.5 (12.3)	132.9
08/09/2020	15/11/2022	Swartland	Adult	Female	Non-breeding	SW503	798	Switched off	13.7 (12.7)	151
09/09/2020	21/11/2021	Swartland	Juvenile	Male	Non-breeding	SW517	438	Died, unknown	9.4 (10)	79.1
12/08/2021	14/12/2022	Swartland	Adult	Female	Breeding	SW522	489	Switched off	8.1 (5.5)	31.3
12/08/2021	13/12/2022	Swartland	Adult	Female	Non-breeding	SW533	488	Switched off	13 (21.4)	226.8
12/08/2021	14/12/2022	Swartland	Adult	Male	Breeding	SW537	489	Switched off	5.8 (3.9)	30.3

13/06/2021	08/03/2022	Swartland	Adult	Female	Breeding	SW542	268	Died, ill	4 (1.8)	12.3
13/08/2021	27/11/2022	Swartland	Adult	Female	Breeding	SW535*	471	Failed	6 (4)	42.1
13/08/2021	14/12/2022	Swartland	Adult	Male	Breeding	SW514*	488	Switched off	6.3 (3.7)	41.7

*these two cranes happened to be a breeding pair

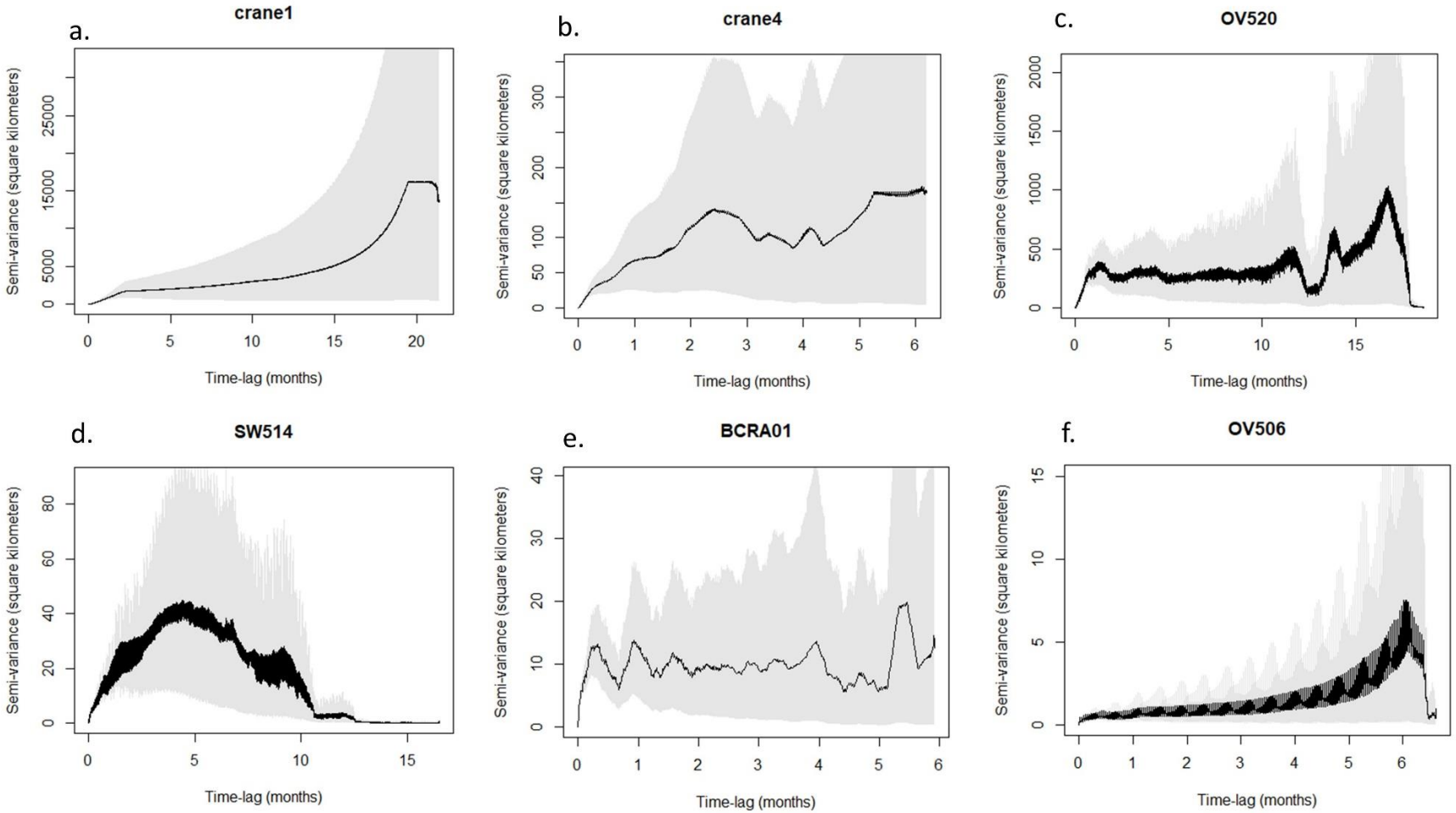


Figure 6: Semi-variance functions (variograms) fitted to Blue Crane tracker data, with the black line indicating the semi-variance and grey indicating 95% confidence interval. a. Non-resident inter-regional migrant in the Overberg, not showing site fidelity (crane1); b. & c. intra-regional migrants in the Overberg (crane 4- juvenile), OV520 is a breeding male showing site fidelity; d. regionally resident breeding male in the Swartland, showing site fidelity (SW514); e. resident male in the Overberg, breeding status unknown, no site fidelity; f. breeding male in the Overberg showing site fidelity but the variogram indicates it has not yet established a home range after 6 months (OV506). The variograms for the rest of the cranes can be found in Figure S7.

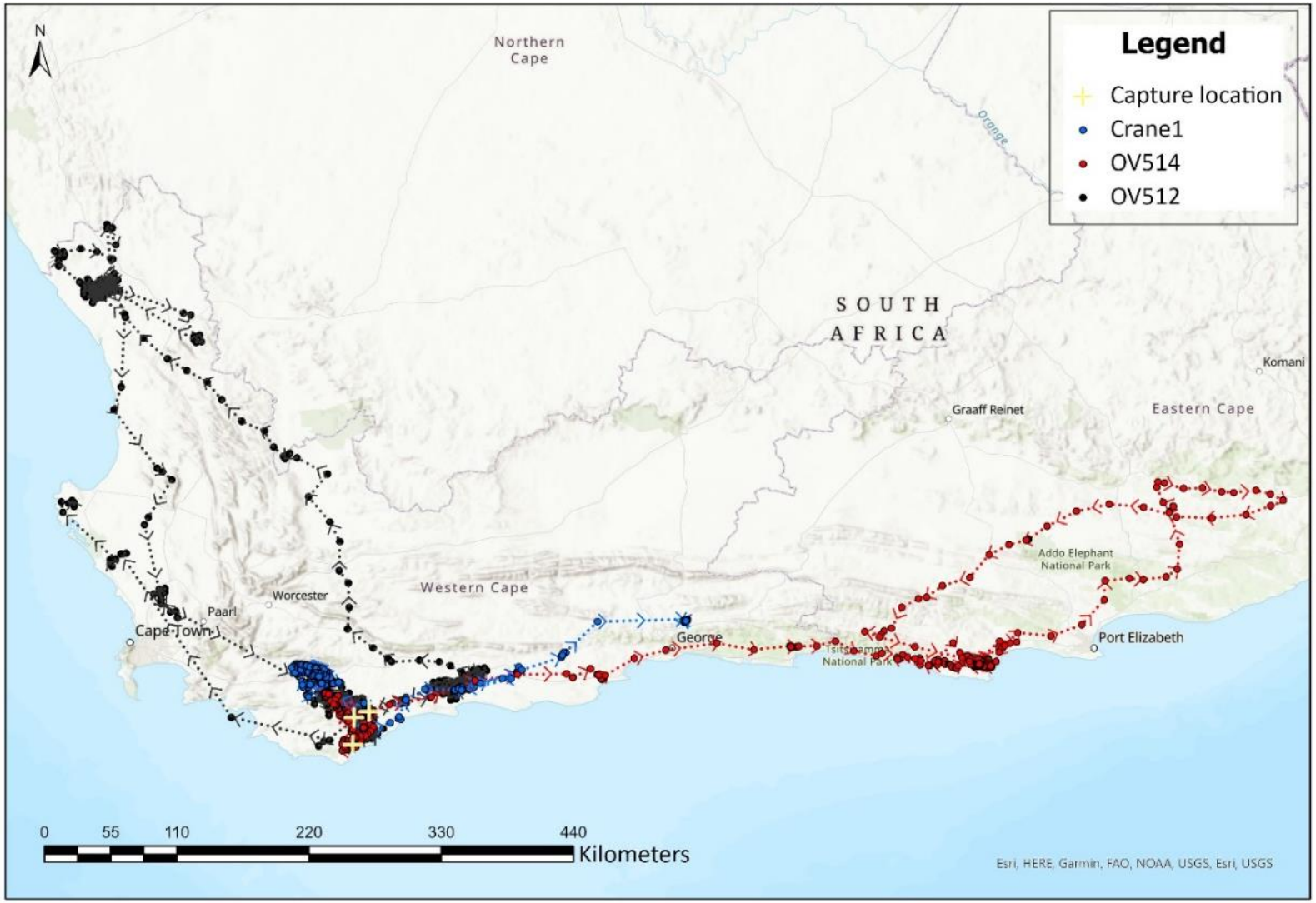


Figure 7: Movements of three inter-regional migrant Blue Cranes, fitted in the Overberg.

Home range

Blue Crane home ranges were on average 1655 km^2 (SD 2757), but varied widely, between 8 km^2 (95% CI 7.4–8.6 km^2) and 8956 km^2 (6758–11458 km^2) (Table 2). For non-breeding cranes, average winter home ranges tended to be smaller, 1781 km^2 (SD 2201) than average summer home ranges, 3723 km^2 (SD 3914), while the reverse was true for breeding cranes (summer 59 km^2 (SD 56), winter 887 km^2 (SD 1800); Figure 8, Table 2). For the Swartland breeding pair (both fitted with trackers) home ranges were identical (both in summer and winter (Figure 9), and the fixes overlap, indicating they stay together year-round.

I deemed OV506 to not be range resident overall (because its variogram failed to reach an asymptote within 6 months) (Figure 6). This crane did not move further than 5km from where it was fitted but was only tracked for 195 days; had it been tracked longer, the variogram may have levelled out (Figure 6). I deemed crane 4 to be range resident by the variogram reaching an asymptote (Figure 6), but the modelled summer and overall home range estimates were greatly over-estimated when mapped with the raw data points (Figure S12), I therefore removed these home range estimates from the dataset for the calculation of the averages, and modelling. It is possible that this juvenile crane's movements were too variable in the short time that it was tracked (6 months), to accurately estimate home range.

Of the 20 cranes that were range resident and sex was known, home range size was not explained by the sex of the crane (male: Estimate = –0.3, SE = 0.7, p = 0.7, deviance explained = 1%). The best models (by % deviance explained) for explaining home range variance were those that included breeding status and region. Considering total home range as a function of breeding status and region (n = 20, deviance explained by model = 55%), Swartland cranes had home ranges 2.7 times larger than Overberg cranes (Estimate = 0.99, SE = 0.52, p = 0.07) (Table 2). Non-breeding cranes had home ranges 13 times larger than breeding cranes (Estimate = 2.55, SE = 0.96, p = 0.02) (Table 2, e.g. Figure 10 vs Figure 11).

The effects of breeding status on home range are stronger when considering summer home range only (n = 20, deviance explained = 70%). Swartland home ranges were four times larger (Swartland: Estimate = 1.3, SE = 0.5, p = 0.01) and non-breeding cranes had home ranges 83 times larger (Non-breeding: Estimate = 4.4, SE = 1.9, p = 0.04). Models of winter home range as a function of region and breeding status did not have good predictive power (n = 19, 7% deviance explained). These models indicate that winter home range does not differ significantly by region (Swartland: Estimate = 0.2, SE = 0.8, p = 0.8), or by breeding status (Non-breeding: Estimate = 0.8, SE = 0.9, p = 0.4). The duration the tracker was active (in days) did

not have a significant effect on the home range estimate (r = –0.08, 95% CI = –0.47 to 0.35, p = 0.73). All home range maps are presented in the supplementary materials (Figures S8–24).

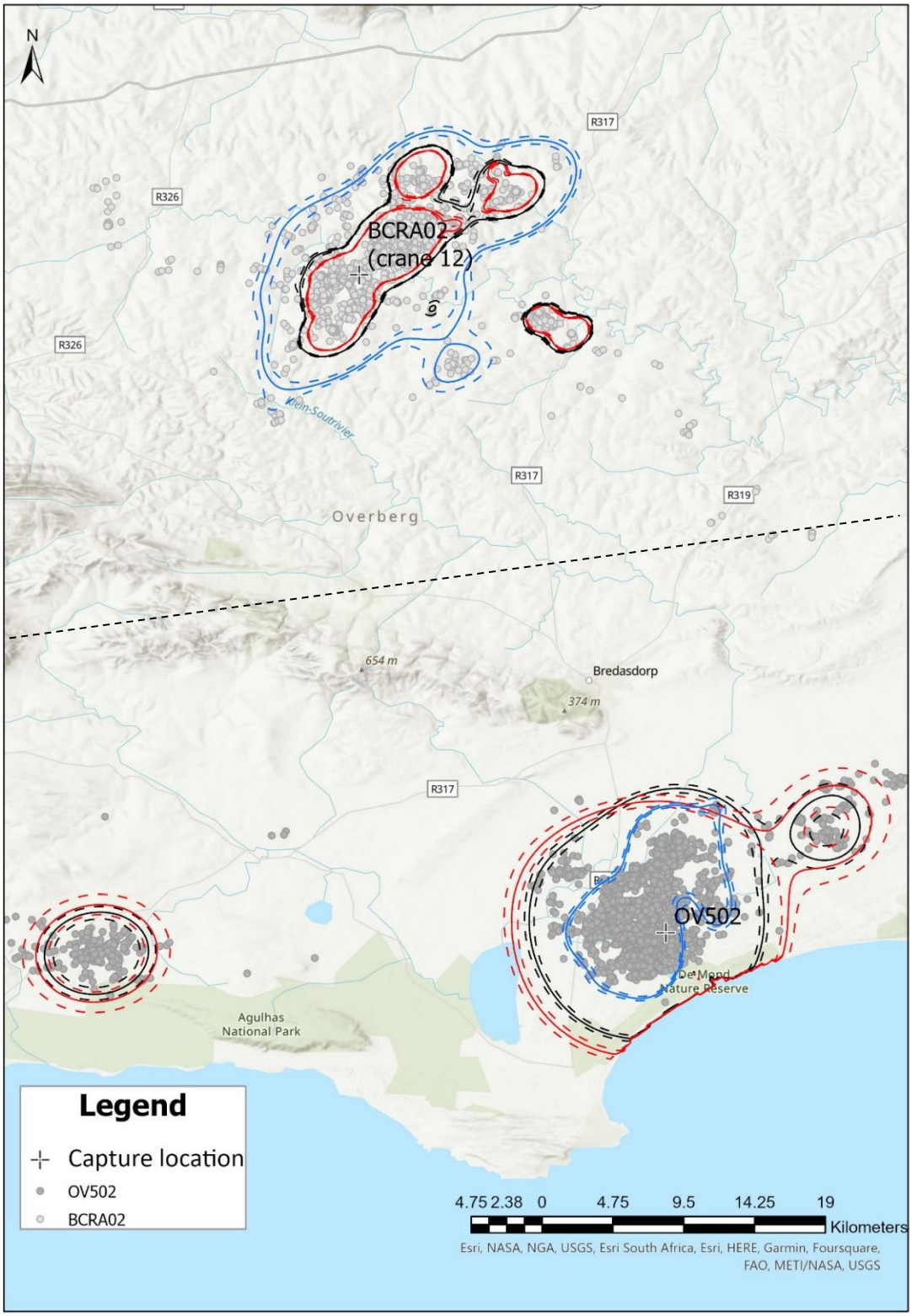
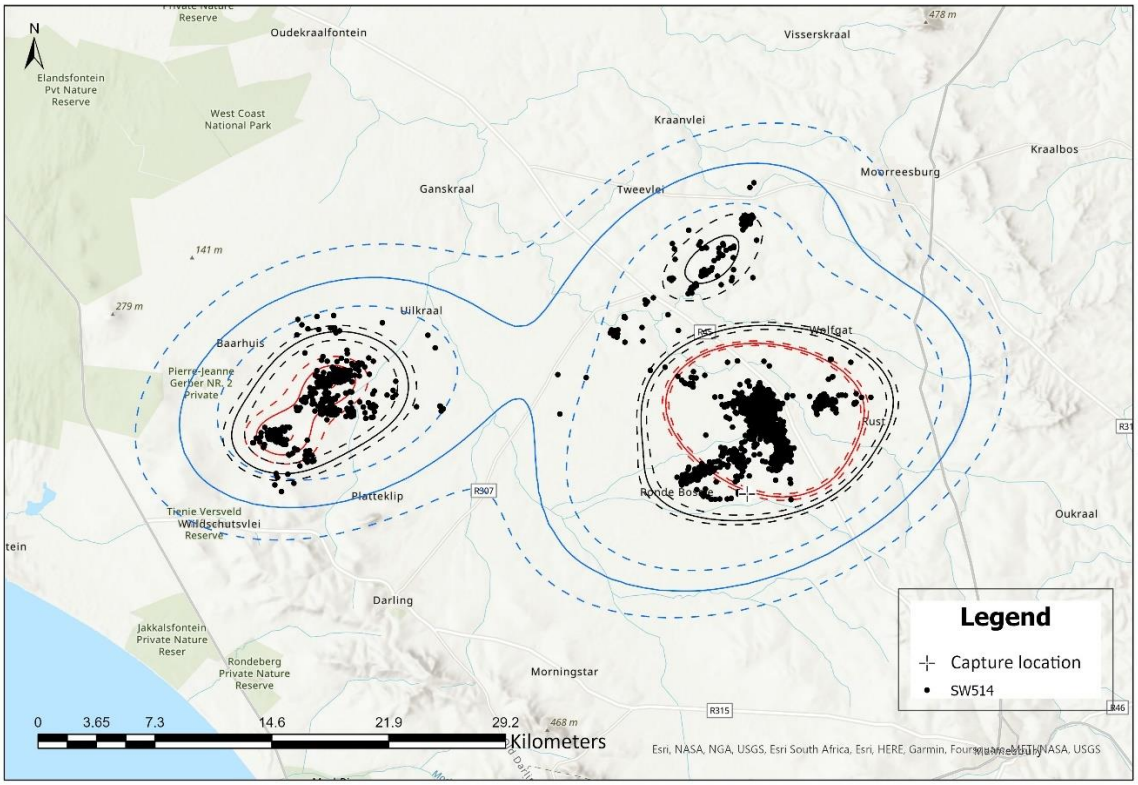


Figure 8: Overall (black), summer (red) and winter (blue) 95% home ranges for a resident adult breeding Blue Crane (BCRA02-top) and a regionally resident non-breeding Blue Crane (OV502-bottom) in the Overberg. 95% confidence intervals of the home range estimates are indicated by dashed lines.

Table 2: Autocorrelated kernel density estimates of 95% home range for each range resident Blue Crane, with 95% confidence intervals and number of fixes (n), when the crane was seasonally resident, the summer and winter home range were estimated. Trackers fitted in 2016/7 have the same Tracker ID as in Davis (2018), except for the following which she renamed: BCRA03 = crane 11, BCRA02 = crane 12, BCRA03 = crane 13.

Tracker ID	Breeding status	Overall home range (km^2)			Summer home range (km^2)			Winter home range (km^2)		
		n	AKDE	CI	n	AKDE	CI	n	AKDE	CI
Resident										
crane 2	Breeding	1563	8.0	7.4–8.6	732	4.7	4.1–5.3	336	15.7	13.3–18.3
crane 6	Breeding	3759	14.5	13.6–15.3	2905	14.5	13.5–15.6	854	8.5	7.7–9.4
crane 5	Breeding	3629	39.2	36.1–42.3	2777	8.7	8.1–9.3	852	121	98.6–145
SW522	Breeding	5015	55.7	51.8–59.8	3821	26.8	25–28.6	1194	154	129–183
OV410	Non-breeding	10397	60.9	57.8–64.2	8253	50.3	47.6–53.0	2134	75.3	67.5–83.6
BCRA02	Breeding	11918	81.7	76.3–87.2	9370	55.2	51.5–59.0	2496	180	155–206
BCRA01	Non-breeding	572	98.5	81.7–117	460	49.3	42.2–57.0	Not enough data		
Regionally resident										
crane10	Breeding	3306	93	82–104	2596	22.7	20.2–25.3	710	96	80.4–113
SW514	Breeding	5111	192	159–228	4090	88.9	73.0–106	1021	647	427–912
OV502	Non-breeding	10752	199	171–229	8564	244.5	199–295	2183	72	65–80
SW535	Breeding	4511	215	177–256	3511	99.9	81.3–120	1000	657	434–927
crane 8	Non-breeding	1918	237	195–282	1638	254.8	204–311	280	81	65.3–98.1
OV524	Unknown	5232	295	268–323	3620	182.4	166–199	1612	526	3155–10367
OV501	Unknown	4085	320	286–355	3051	227.8	202–255	1035	445	349–553
BCRA03	Unknown	1887	387	240–569	1785	403.4	236–615	Not enough data		
SW542	Breeding	1965	225	150–314	1280	89.4	65.9–116	685	387	126–792
SW537	Breeding	4288	297	240–361	3351	192	139–253	937	457	343–586
Intra-regional migrant										
crane 4	Non-breeding	1106			Model over-estimated			306	5.5	4.7–6.4
OV520	Breeding	7305	2081	1467–2800	4822	11.8	11.3–12.2	2483	6243	3155–10366
SW503	Non-breeding	11493	2487	2026–2994	9204	3153	2465–3924	2289	195	171–220
crane 7	Non-breeding	1371	2752	1734–4001	1206	2958	1736–4500	Not enough data		
crane 9	Non-breeding	3816	5024	2954–7633	3097	1785	1210–2470	719	5466	1778–11188
OV545	Non-breeding	4795	6729	4286–9713	3037	8594	5264–12727	1758	2065	678–4211
SW517	Non-breeding	7044	8870	4594–14531	5741	9727	4823–16322	1303	2394	756–4959
SW533	Non-breeding	4946	8956	6758–11458	3904	10056	7335–13200	1042	5675	2679–9777

a.



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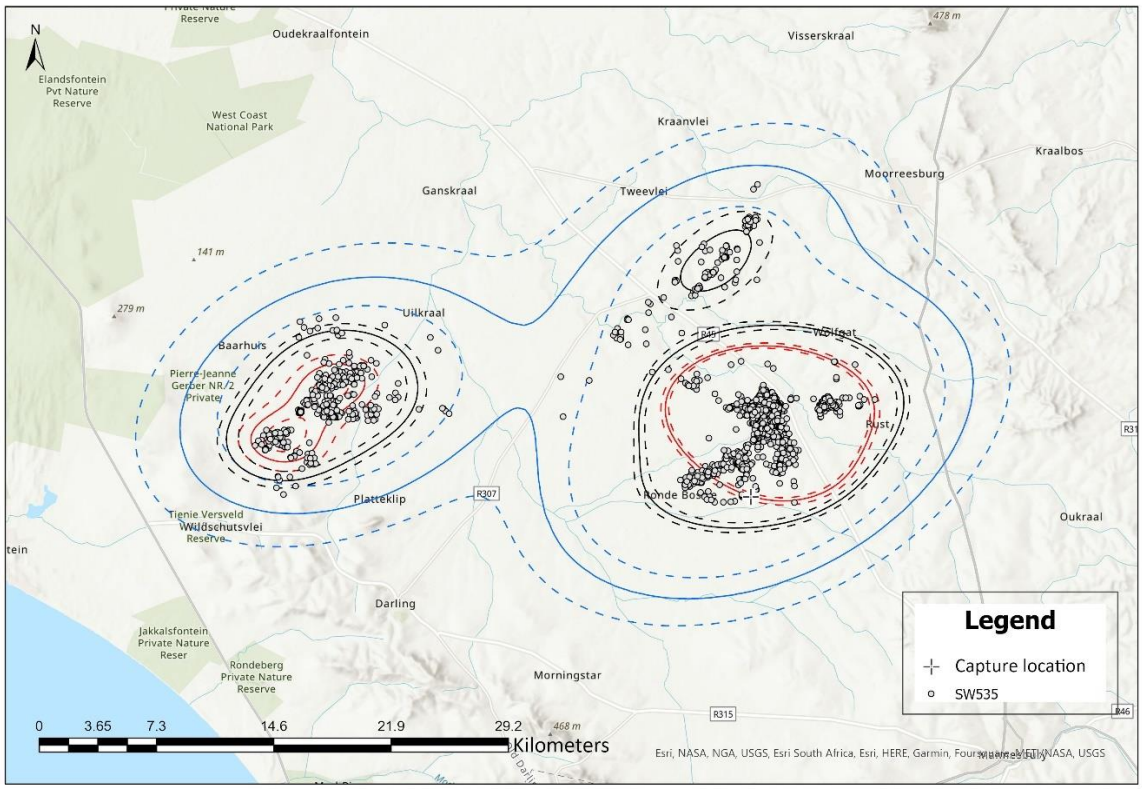


Figure 9: Overall (black), summer (red) and winter (blue) 95% home ranges for a resident breeding pair, both fitted with trackers in the Swartland, demonstrating identical home ranges for the male (a.) and female (b.) year-round. Conventions as Figure 8.

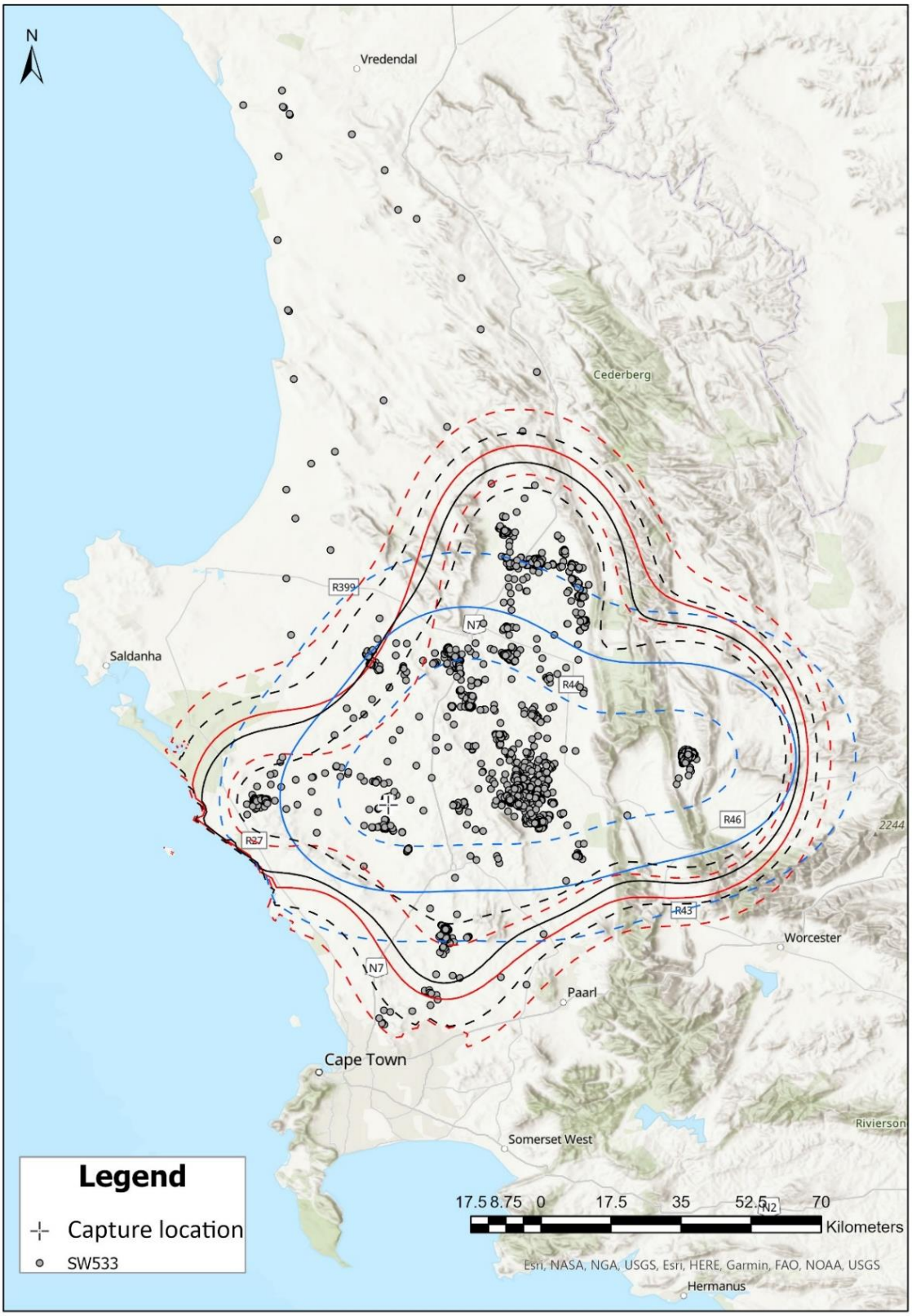


Figure 10: Overall (black), summer (red) and winter (blue) 95% home ranges for an adult non-breeding Blue Crane, making intra-regional movements in the Swartland. Conventions as Figure 8.

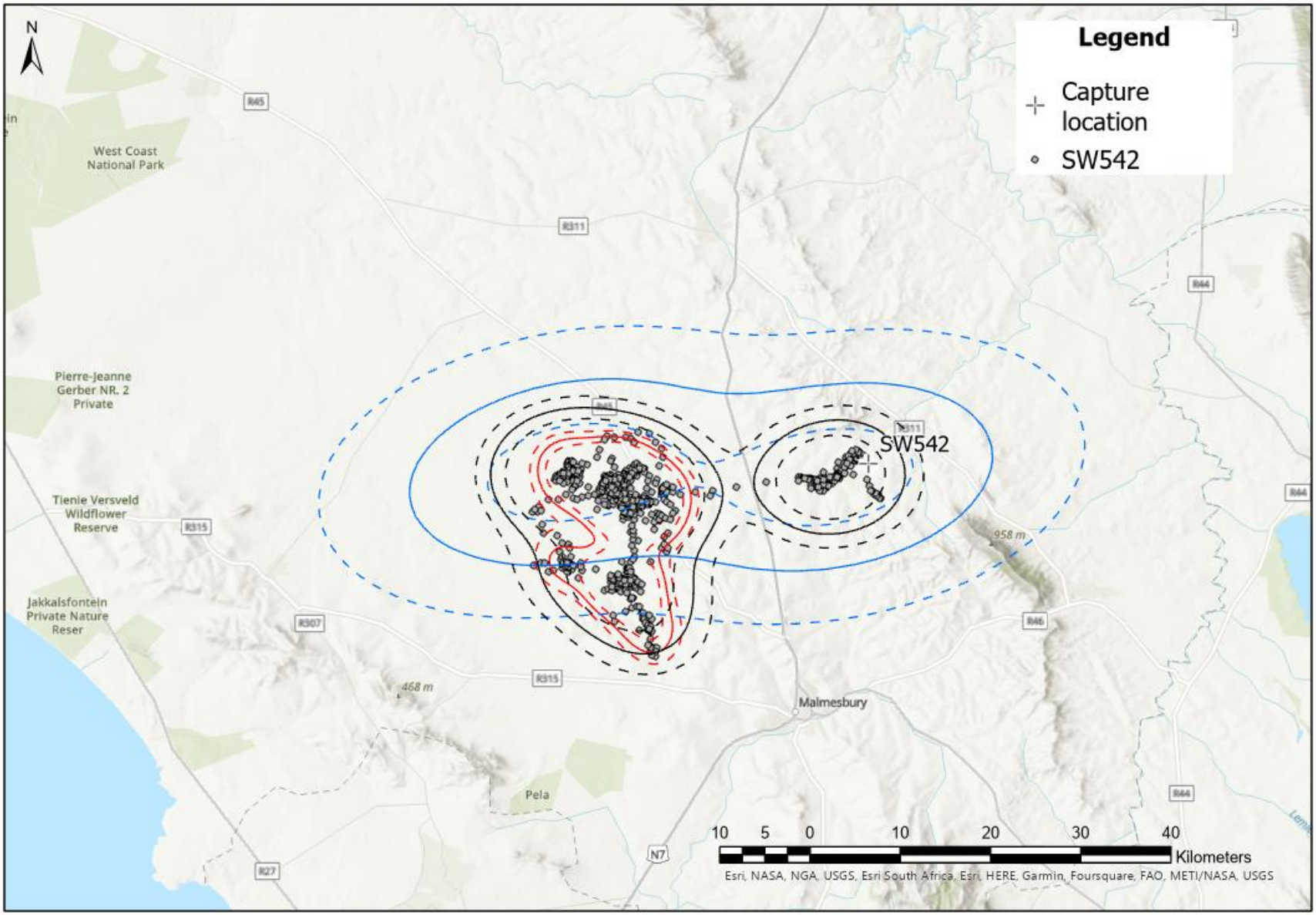


Figure 11: Overall (black), summer (red) and winter (blue) 95% home ranges for a resident breeding Blue Crane in the Swartland. Conventions as Figure 8.

Powerline risk

On average Blue Cranes crossed at least one powerline on 34% of the days they were tracked, with a range per crane of 11–54%. There was a positive correlation between the distance travelled per day and the number of powerline crossings (r = 0.83, 95% CI = 0.83–0.84, df = 7679, $p < 0.01$), indicating that Blue Cranes moving further are at greater risk of powerline collision. For example, when crane OV512 moved between the Overberg and Swartland, she crossed 58 powerlines (Figure 7). Non-breeding cranes intersected powerlines at a higher rate, 1.3 powerlines per day (SE 1.4) than breeding cranes, 0.64 (SE 1.3); this difference was statistically significant in the mixed effects model (Non-breeding: Estimate = 0.7, SE = 0.3, p = 0.04).

Survival

Over the duration of this project there were five confirmed mortalities (Table 1), one juvenile (cause unknown) and four fully-grown cranes (powerline collision, fence entanglement, crane appeared unwell for a month before being predated/scavenged and cause unknown; Figure 12). For Blue Cranes older than one year, annual survival rates were 0.91 (95% CI 0.78–0.97, n = 28). For non-breeding cranes (cranes that remained in floater flocks year-round) annual survival was 0.85 (95% CI 0.61–0.95, n = 13, 3 mortalities), and for breeding cranes annual survival was 0.95 (95% CI 0.71–0.99, n = 12, 1 mortality).

Figure 12: Swartland crane SW542 beginning to look ill, two months prior to his death in March 2022.

Fledglings

The 25 trackers fitted on fledglings had a high failure rate: only 11 transmitted at all (5 Karoo, 6 Western Cape), and these transmitted intermittently (with gaps of up to 2 months) and briefly (less than one year). The reasons for the trackers failing were uncertain, but the feedback that we received from the manufacturers was that they used unreliable, low-cost components.

Within their first year, the Karoo fledglings moved locally within 30 km of their natal site (Figures S2–4). Movement patterns of Overberg and Swartland Blue Cranes post-fledging were all within 15 km of their natal sites (Figures S5 and S6), except for one Overberg female that travelled approximately 80 km east of her natal site in early April (Figure 13). Of the 13 trackers that failed completely, I regularly observed one juvenile female from the Swartland between fitting (February 2019) and October 2022 (recognisable by leg rings, Figure S1). Over this period, she moved locally in a floater flock around the central Swartland (Figure S1), and by age 3 had not shown any sign of pairing up.

In the Western Cape, at least three fledglings died. Two siblings from the Swartland became weak and disorientated a month after fitting and died a week apart. A post-mortem on one indicated that she died of starvation. Neither of these trackers ever transmitted any movement data. Another tracker from a fledgling in the Overberg (Figure S5) was retrieved by a farmer at the end of 2019; cause of death was unknown.

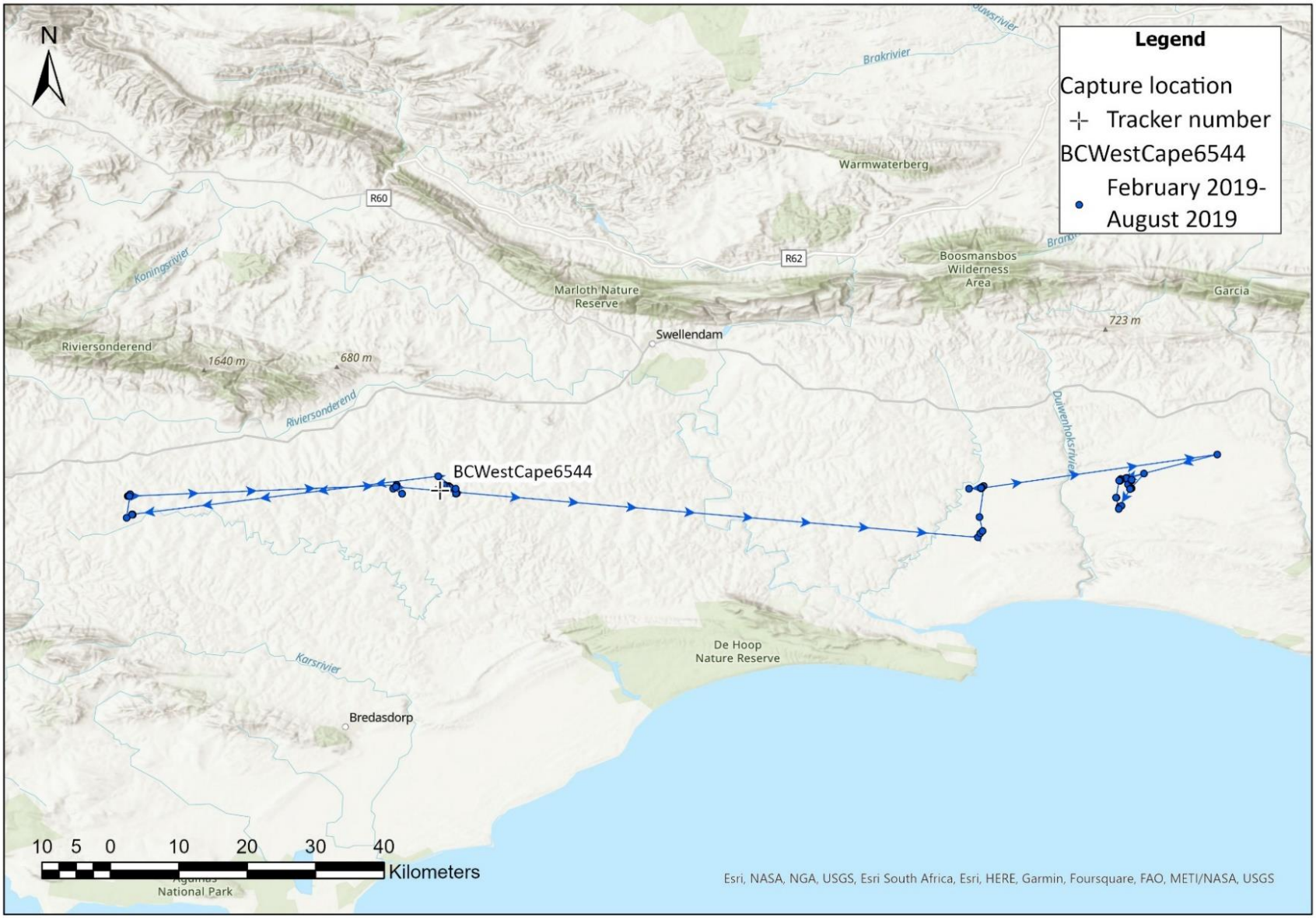


Figure 13: The movements of a fledgling Blue Crane in the Overberg, fitted with a GPS-GSM tracker in February 2019.

Discussion

This study adds to our current understanding of movements and home ranges of Blue Cranes in the Overberg and provides the first insights into tracked movements in the Swartland. In addition, I explored Blue Crane powerline collision risk, in relation to movement, and produced revised survival estimates for Blue Crane in the Western Cape.

My finding that most (62%) of Western Cape Blue Cranes are resident or regionally resident, moving within 100 km^2, were similar to what was observed from ringing records (van Velden et al. 2016a). However, the trackers picked up long range movements far more frequently than ringing records, where only 1% of ringed birds were resighted more than 100 km from their ringing site (van Velden et al. 2016a). Of 649 ringing records, there was only one record of a Western Cape ringed crane leaving the province (van Velden et al. 2016a), whereas two of 29 tracked Blue Cranes moved from the Western Cape into the Eastern Cape. This suggests that inter-provincial movements may be more frequent than ringing data indicate. Given the opportunistic and ad-hoc nature of ring resightings and recoveries, this finding is not surprising. Research studies tend to have a finite spatial range, which means that short-range movements are more likely to be detected within the study area (Cooper et al. 2008).

van Velden et al. (2016a) found that small numbers of Blue Cranes move between the Overberg and Swartland. One of the tracked Blue Cranes moved from the Overberg to the Vredendal region, well north of the Swartland, before moving south to the Swartland. The Cederberg, Langeberg and Boland mountain ranges pose something of a barrier to Blue Cranes moving between the Overberg and Swartland, but the tracked crane passed over the Langeberg near Robertson, flew over the Tankwa Karoo then turned west at Wuppertal, on the northern edge of the Cederberg, effectively avoiding the highest peaks of this mountain range. Fixes were not taken on the return flight, but the crane appeared to traverse between the Boland and Hottentots Hollands mountain ranges. This documents a potential flyway for Blue Cranes moving between the Overberg and Swartland.

I provide descriptions of how Blue Crane home ranges differ by season, age, and region. The larger home ranges in the Swartland, compared to the Overberg is consistent with the lower density of Blue Cranes in the Swartland (Chapter 2). The Swartland population has remained stable at these lower densities since the mid-2000s (Chapter 2), which suggests that the carrying capacity for cranes is lower in the Swartland. Home ranges are thought to develop through feedback between the environment and an animal's understanding of the environment; the home range is effectively a 'cognitive map' (Powell & Mitchell 2012). Home range sizes tend to be larger in resource-poor habitats than in resource-rich habitats, which

suggests that the habitat in the Swartland is poorer (McLoughlin & Ferguson 2000; McLoughlin et al. 2000). Blue Crane habitat in the Overberg and Swartland is broadly similar, intensive cereal cropping interspersed with pasture fields in equal proportions (Chapter 2). Blue Cranes may be more sedentary in the Overberg because sheep feedlots are more common (per. obs.), and access to this artificial food source means they move less to forage. This has been observed in other species, for example, Chacma Baboons *Papio ursinus* have shorter daily path lengths in human-modified than natural habitats (Hoffman & O'Riain 2012), and Black Bears *Ursus americanus* have smaller home ranges in urban areas (Beckmann & Berger 2003). Another key difference is that summers are drier in the Swartland, compared to the Overberg, especially the eastern Overberg (South African Weather Service 2023). Blue Cranes breed in spring/summer, so rainfall could be a limiting factor in the Swartland, with drier conditions driving larger home ranges.

My autocorrelated kernel density home range estimates from the trackers analysed by Davis (2018) are substantially larger i.e., on average 31 times larger than the kernel density estimates and 32 times larger than the minimum convex polygon estimates, comparing the same individuals. It must be noted however that 11 of the 12 trackers (included in Davis 2018) had accumulated more data by the time I analysed it, and since home ranges are not static, this would have influenced home range size. Nonetheless, this is consistent with the finding that traditional home range estimators like kernel density and minimum convex polygon, tend to underestimate home range with high resolution tracking data (Noonan et al. 2019). Like Davis (2018), I found that breeding cranes travelled significantly shorter distances per day, compared to non-breeding cranes. I found that overall home ranges were significantly smaller for breeding cranes than non-breeding cranes, whereas Davis (2018) did not find a significant difference.

In my study there was a significant 13-fold difference between non-breeding and breeding crane home ranges overall and this increased to an 83-fold difference during the breeding season. This was broadly similar to what has been observed in other crane species. For example, first year White-naped Cranes *Antigone vipio* in Mongolia had median summer home ranges 100 times larger than breeding cranes (Gao et al. 2023). Likewise sub-adult Sandhill Cranes *Grus canadensis pratensis* in Florida had home ranges 5.8 times larger than breeding adults (Nesbitt & Williams 1990). This is a common trend among birds (Warnock et al. 2013; Wang et al. 2020; Senar et al. 2021), juvenile and sub-adult birds undertake dispersal and exploratory movements before they reach sexual maturity and establish breeding territories.

Such exploratory movements may put juveniles at higher risk of mortality; indeed, juvenile and subadult Blue Crane survival estimates were lower than adults (Altwegg & Anderson 2009; van Velden et al. 2016a, this study). This can be partly attributed to more movement leading to greater chance of powerline

collision. In my study, non-breeding cranes intersect powerlines at twice the rate of breeding cranes. This is however an index of risk, rather than absolute risk, as I was only able to assess powerline collision risk in one dimension (horizontal), rather than in two dimensions, horizontal and vertical (Silva et al. 2014; Hays et al. 2021). Many movements intersecting powerlines will take place at heights that do not put cranes at risk of collision, and birds can avoid lines in flight (Baasch et al. 2022), therefore excluding the vertical dimension creates some uncertainty around actual powerline collision risk. Another source of error is interpolating straight line distances between fix intervals (mainly 30 minutes, but some up to 3 hours), which inevitably underestimates movement. To understand Blue Crane collision risk more fully, this index can be interpreted in conjunction with the powerline collision risk model I developed in Chapter 3, based on observed powerline collisions in relation to habitat.

Within age groups, my survival estimate for non-breeding cranes (0.85) is similar to the estimate for immature cranes from ringing data (0.87) (van Velden et al. 2016a). A caveat here is that most of the cranes in my study are of unknown age, and I assume that non-breeding cranes are younger than the age that cranes typically become sexually mature i.e. between 3 and 5 years old, and therefore non-breeding cranes are equivalent to the immature age group (age 2–3) in van Velden et al.(2016a). However, some cranes may take longer to become sexually mature, or simply never breed (e.g. Wattled Cranes *Bugeranus carunculatus*, Lara Jordan, EWT, pers. comm.). I found annual survival in breeding cranes (0.95) to be in line with adult Blue Crane survival estimates from the Karoo (0.96) (Altwegg & Anderson 2009) and modelled values (0.91) (Bird et al. 2020). This supports the conclusion that the very low adult survival estimates (0.72) derived by van Velden et al. (2016a) are inaccurate and are due to ring loss. It must be noted that my sample sizes were small, and therefore we must be cautious about extrapolating these survival rates to the population. Nonetheless, the survival estimates I present are plausible and are in line with adult survival estimates for Sandhill Crane *Grus canadensis tabida* (Fronczak et al. 2015) 0.950 (95% CI 0.885–0.979), a US crane population that is well adapted to agricultural landscapes (Hemminger et al. 2022). Even with relatively small sample sizes, satellite tracking technology can be a valuable tool to understand survival.

During captures in the Swartland we had three cranes unable to get up on release, one permanently and two temporarily. This is limited evidence, but I have heard of similar cases from previous ringing expeditions in the Swartland (Vicky Hudson & Kevin Shaw, CapeNature, pers. comm.). CapeNature staff have referred to this phenomenon as bent leg syndrome, due to the bent leg deformity that often occurs with cranes that struggle to get up after ringing. I witnessed this in only one of the cranes I captured. Bent leg syndrome is a condition found in sheep linked it to genetic markers and imbalances in phosphorus and calcium (van Niekerk et al. 1989; van Niekerk et al. 1990a; van Niekerk et al. 1990b). Micronutrient

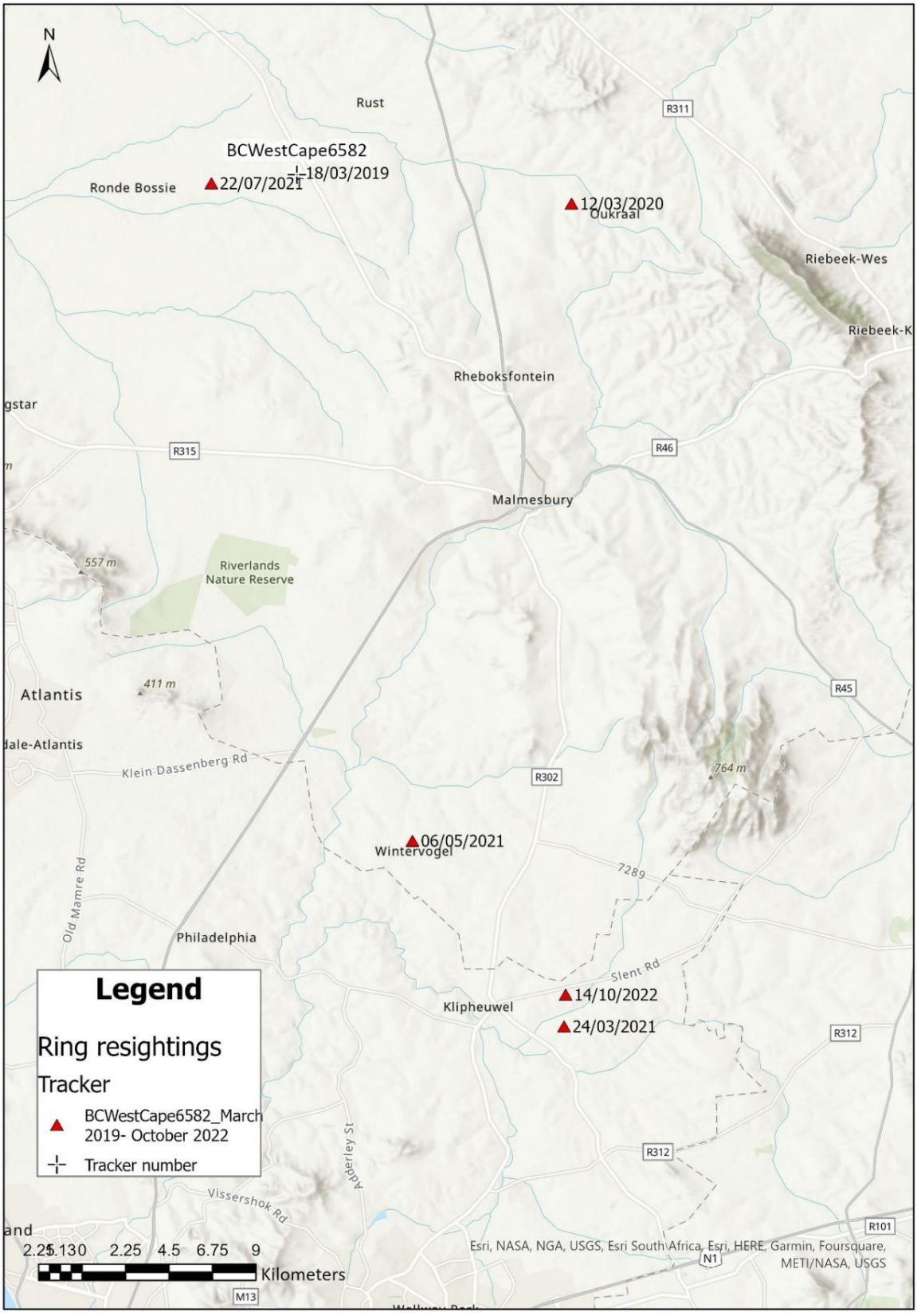
deficiencies in the Swartland ecosystem may cause developmental issues for Blue Cranes (Kevin Shaw & Donnie Malherbe, CapeNature, pers. comm.). Swartland soils tend to be calcium deficient (Liebenberg et al. 2020), but it is not known whether Blue Cranes suffer from calcium deficiency in this region. It is also possible that what we are observing in the Swartland cranes is capture or exertional myopathy, a phenomenon observed when capturing and handling long-legged bird species, like cranes, bustards and flamingos (Windingstad et al. 1983; Tully et al. 1996; Hanley et al. 2005; Shaw et al. 2014). The symptoms observed in the three Swartland Blue Cranes were consistent with capture myopathy (Windingstad et al. 1983; Tully et al. 1996; Hanley et al. 2005; Shaw et al. 2014), but I was unable to confirm this by post-mortem. It is unclear why we only observed these symptoms in juveniles in the Swartland; further research is needed to clarify what is causing this issue. Studies on Little Bustard *Tetrax tetrax* found longer handling times, canon nets and age (juveniles) to increase the likelihood of capture myopathy (Ponjoan et al. 2008). Using insights from experts and the literature there needs to be discussion around the ethics and procedures for catching and handling juvenile Blue Cranes in the Swartland to minimise harm.

In this chapter I provide new insights into Blue Crane movements and survival in the Overberg and Swartland. I provide a survival estimate for adult Blue Cranes in the Western Cape, which is a key input for population modelling (Chapter 5). Satellite tracking data is a rich data source and there is scope for further questions to be answered using the Blue Crane data. For example, investigating Blue Crane movements and home range in relation to habitat features. It would also be useful to fit trackers on Blue Cranes in the Karoo and grasslands, to understand how movement and survival differ in these populations, especially as wind energy developments expand in these areas.

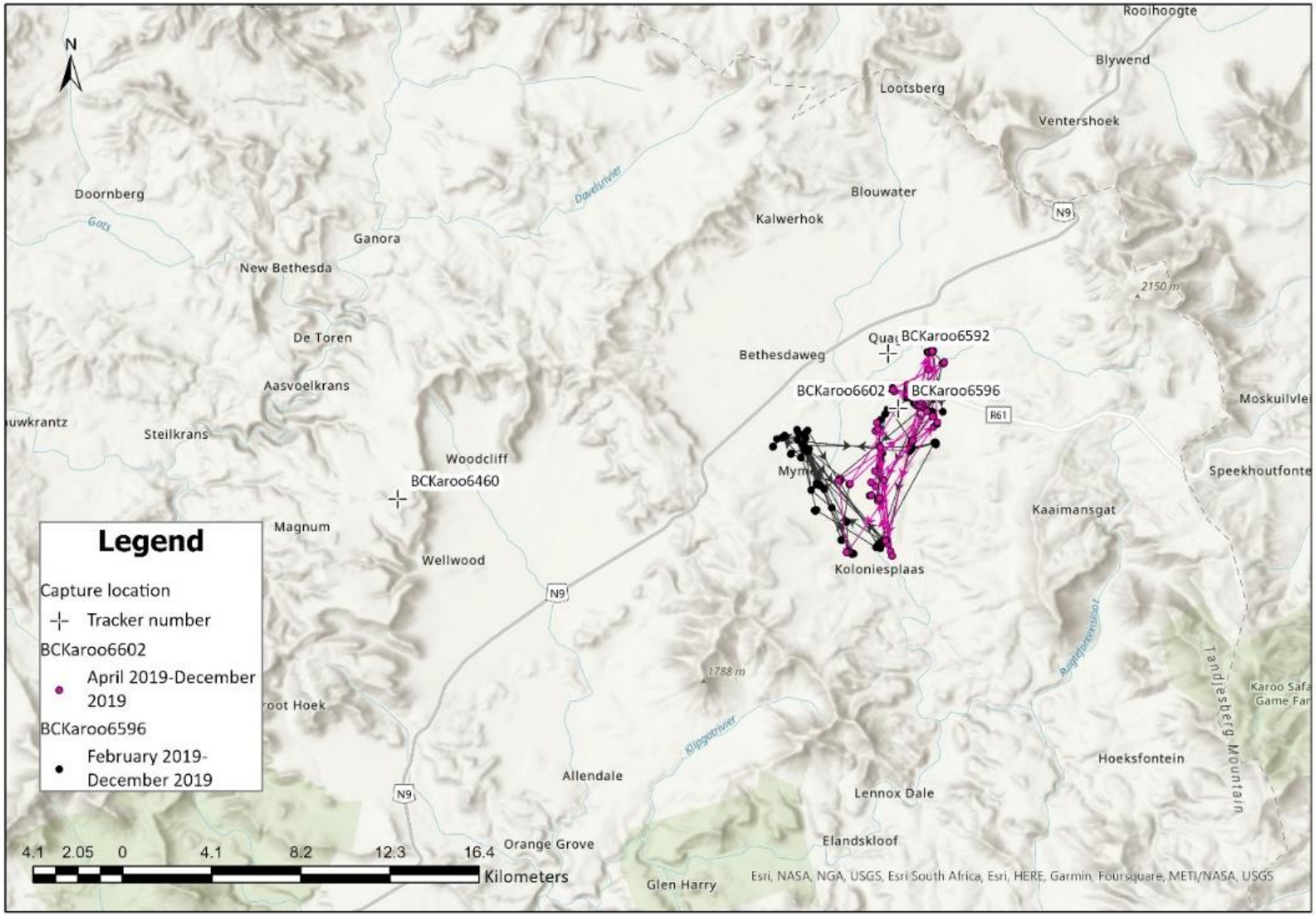
Supplementary Materials

Supplementary Table 1: Survival models

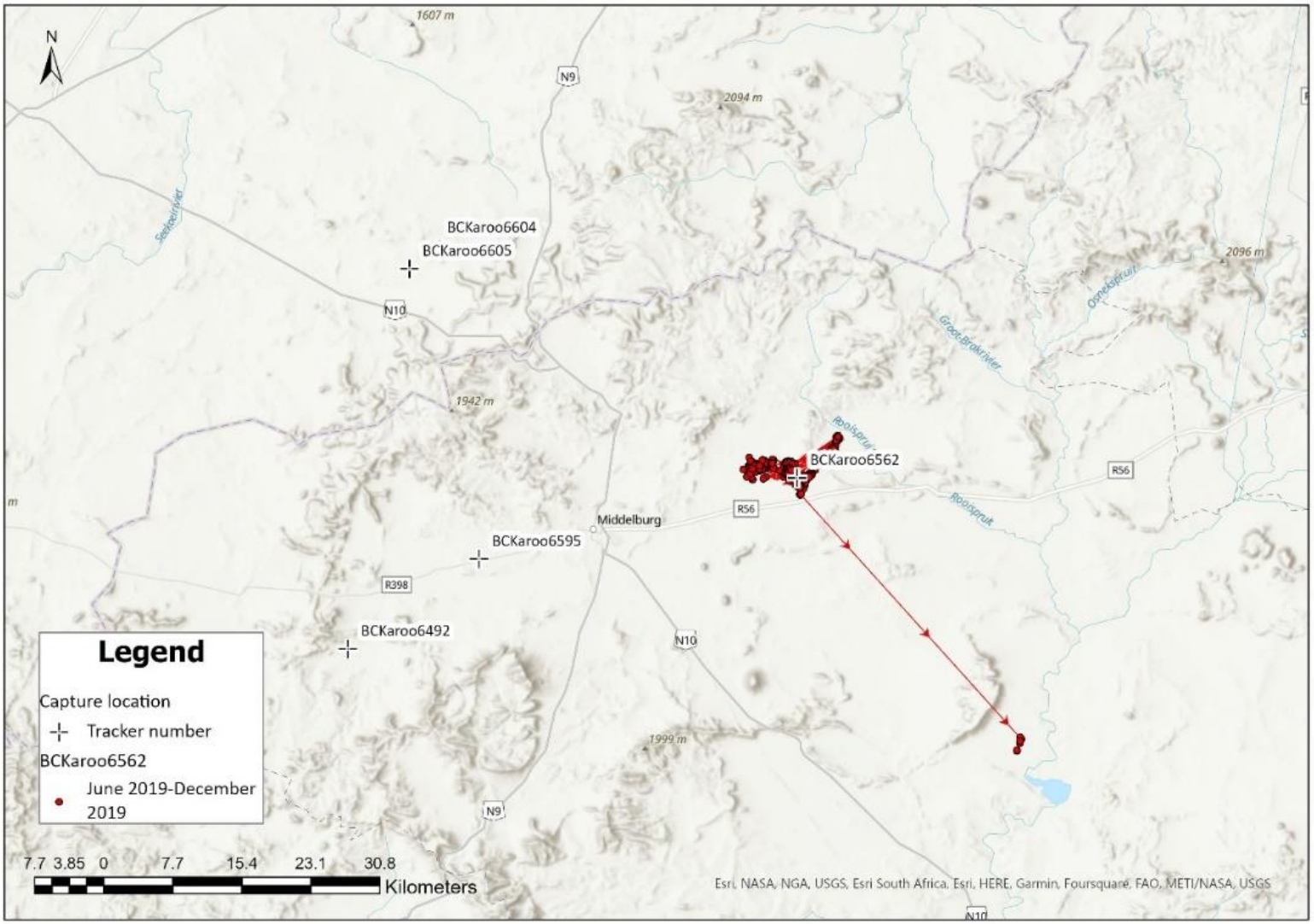
Model	Number of parameters	AIC	Deviance
Fully-grown cranes (n =28)			
S(~1)	1	48.86	19.46
Breeding cranes (n = 12)			
S(~1)	1	15.03	6.99
Non-breeding cranes (n = 13)			
S(~1)	1	33.86	15.28



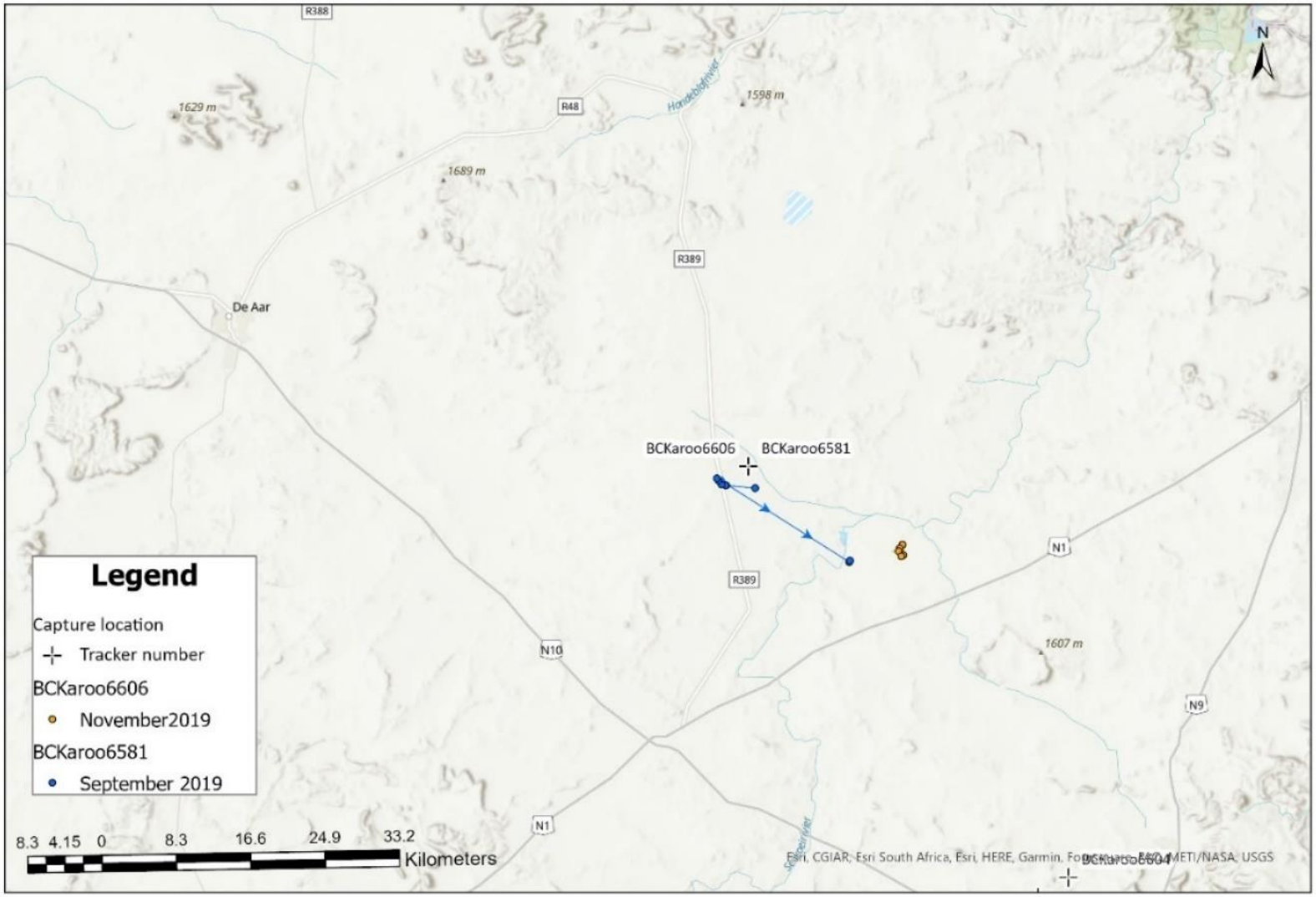
Supplementary Figure 1: Ring resightings between March 2019 and October 2022 of a fledgling crane fitted with a faulty tracker in the Swartland.



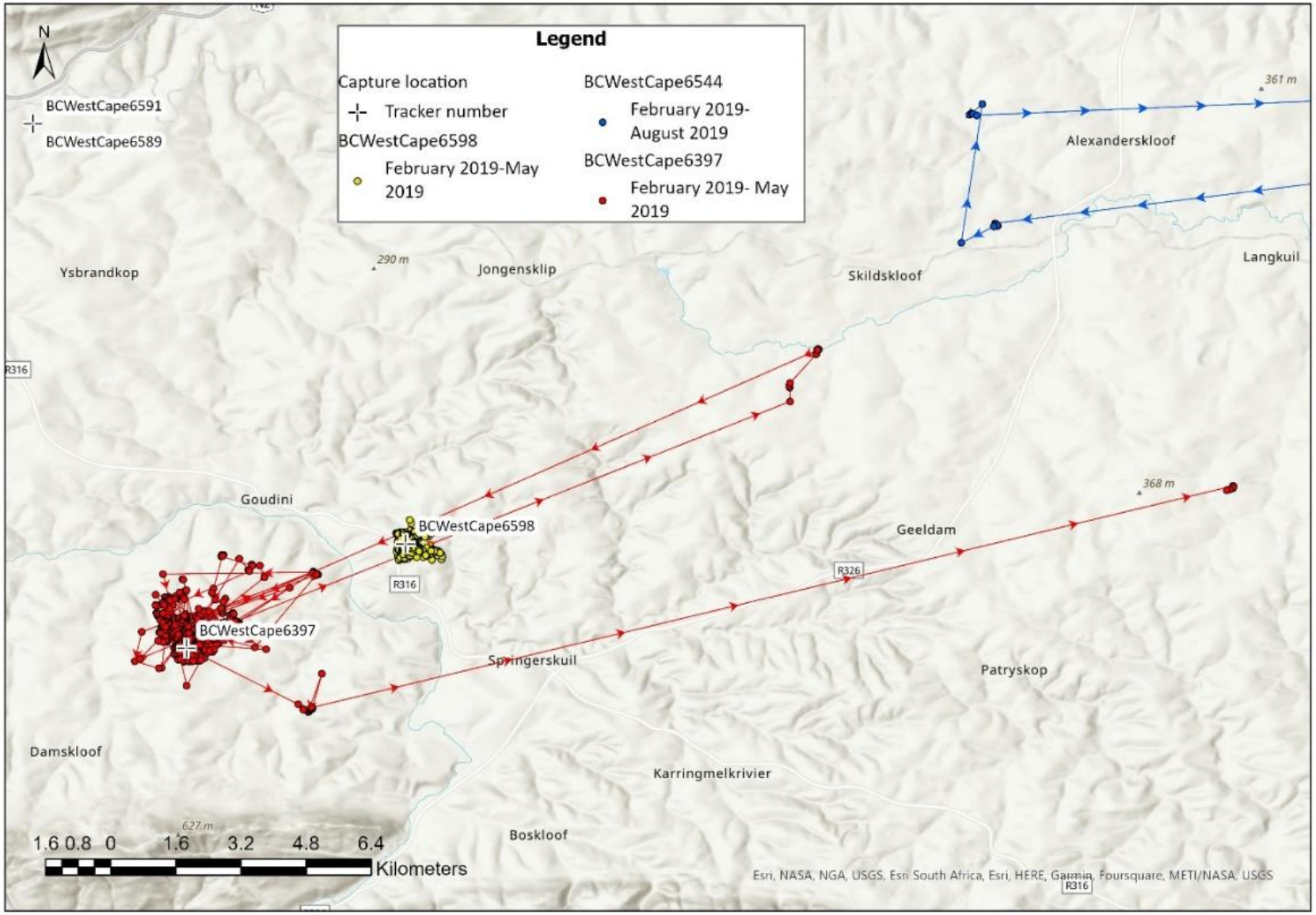
Supplementary Figure 2: Movements of two trackers fitted on fledgling Karoo fledglings that sent limited fixes between fitment (February 2019) and December 2019.



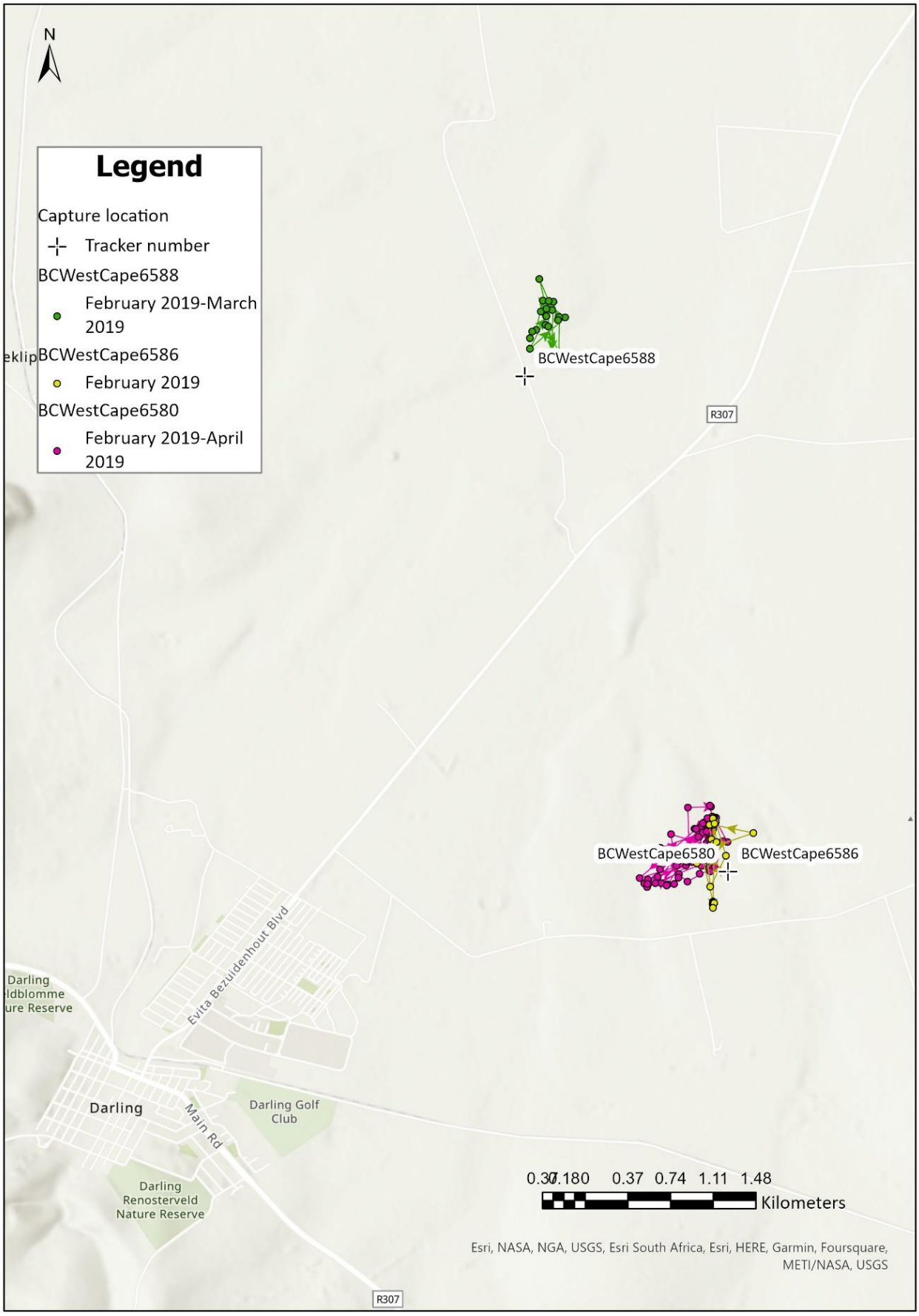
Supplementary Figure 3: Movements of a tracker fitted on a pre-fledgling Karoo chick that sent limited fixes between fitment (February 2019) and December 2019. Other trackers featured on the map did not send any fixes (failed).



Supplementary Figure 4: Movements of two trackers fitted on Karoo fledglings that sent very limited fixes between fitment (February 2019) and November 2019.



Supplementary Figure 5: Movements of two trackers fitted on Overberg fledglings that sent limited fixes between fitment (February 2019) and May 2019.

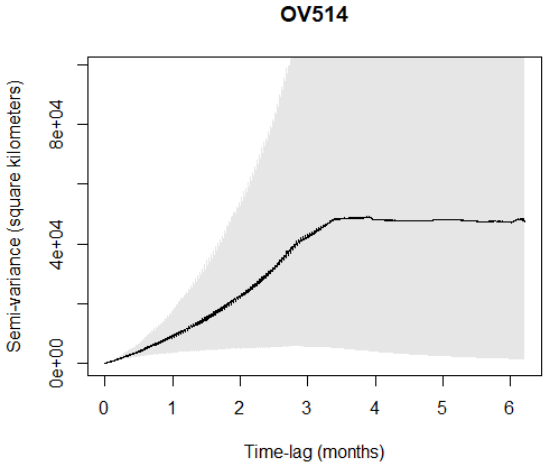


Supplementary Figure 6: Movements of three trackers fitted on Swartland fledglings that sent limited fixes between fitment (February 2019) and April 2019.

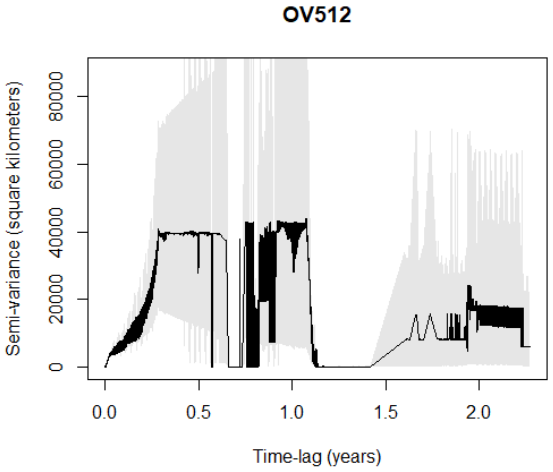
Supplementary Figure 7: Semi-variance functions (variograms) fitted to Blue Crane tracker data, organised by type of movement pattern- Inter-regional migrants, intra-regional migrants, regionally resident and resident. Above each variogram is the breeding status and whether the crane displays site fidelity.

Non-resident: Inter-regional Migrant

Non-breeding

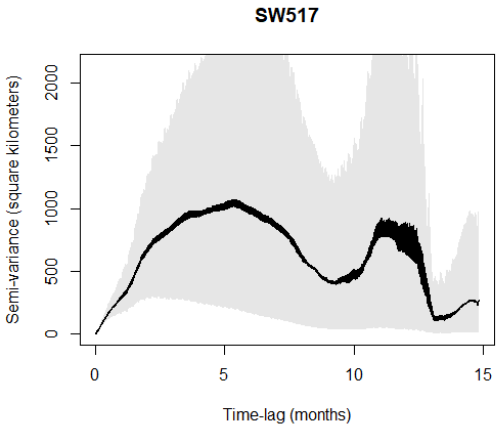


Non-breeding. Site fidelity

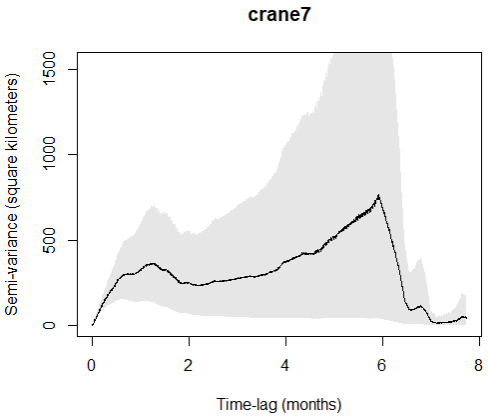


Intra-regional Migrant

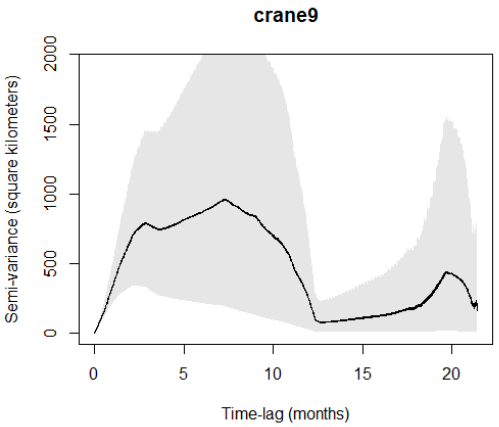
Non-breeding juvenile



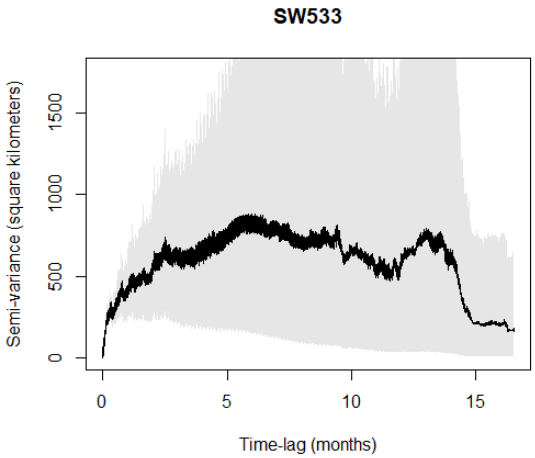
Non-breeding. Site Fidelity



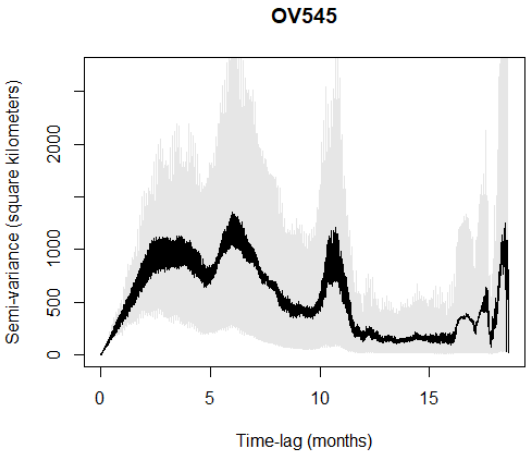
Non-breeding



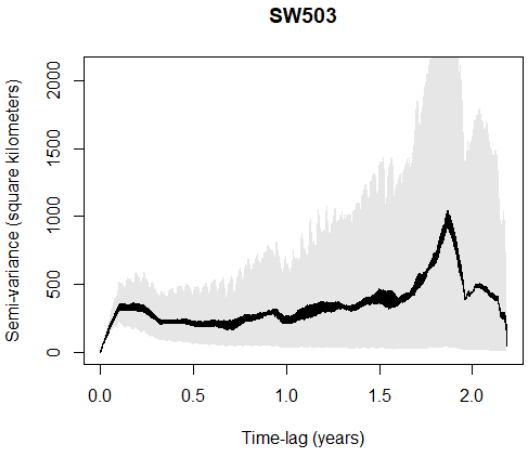
Non-breeding



Non-breeding. Site Fidelity

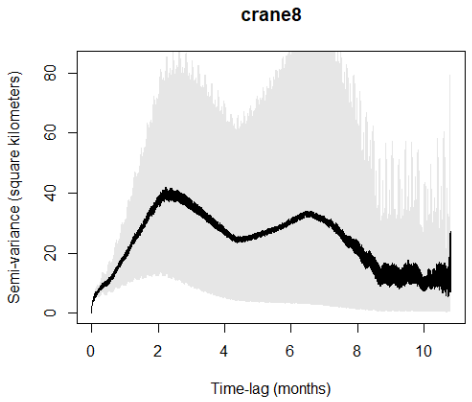


Non-breeding. Site Fidelity

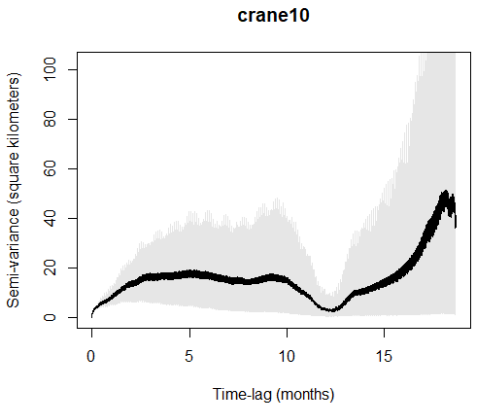


Regionally Resident

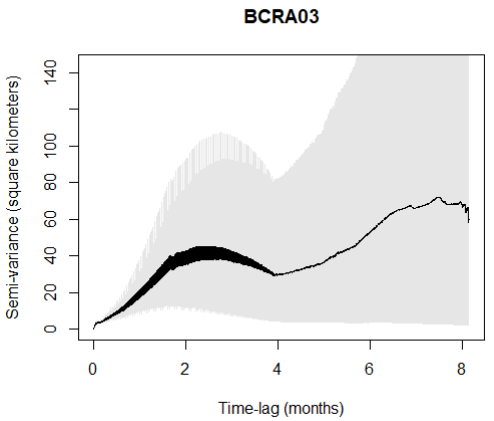
Non-breeding



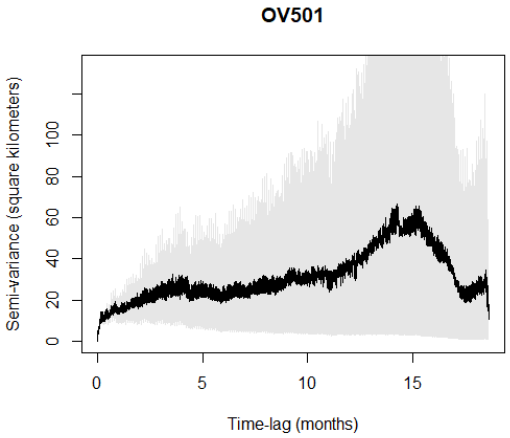
Breeding. Site Fidelity



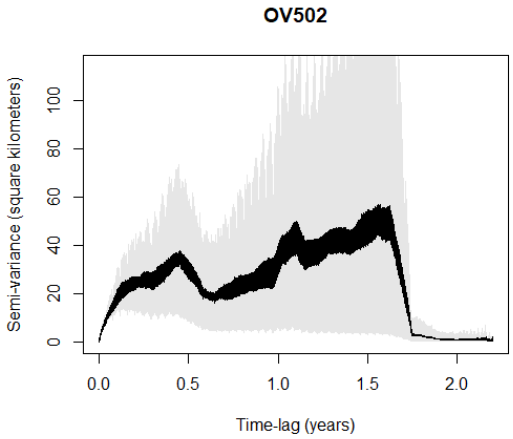
Unknown breeding status



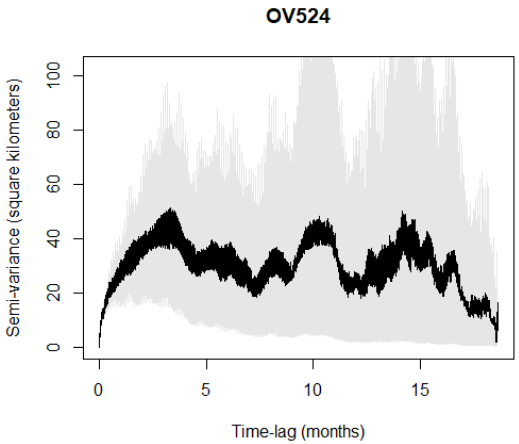
Unknown breeding status



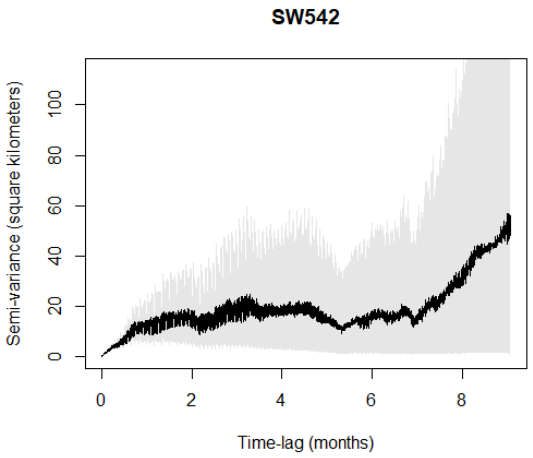
Non-breeding. Site fidelity



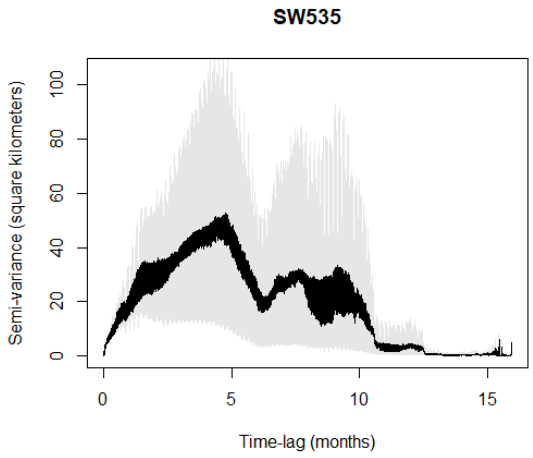
Unknown breeding status. Site fidelity



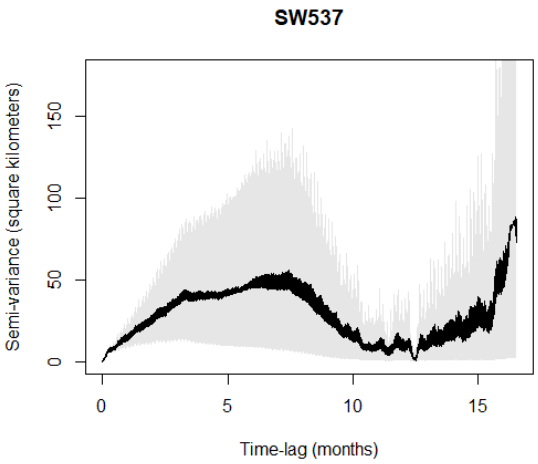
Breeding



Breeding. Site fidelity

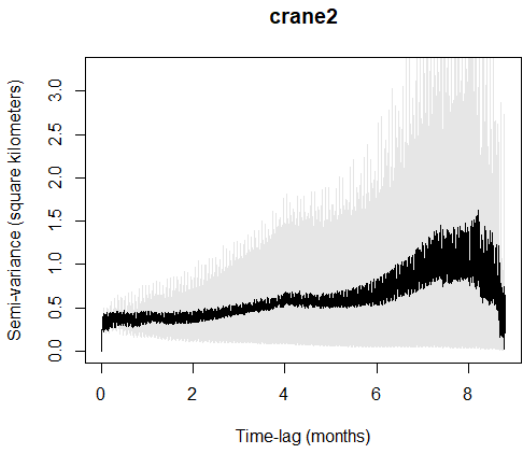


Breeding. Site fidelity

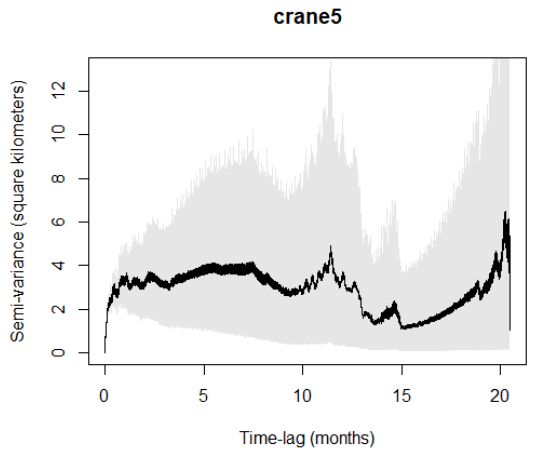


Resident

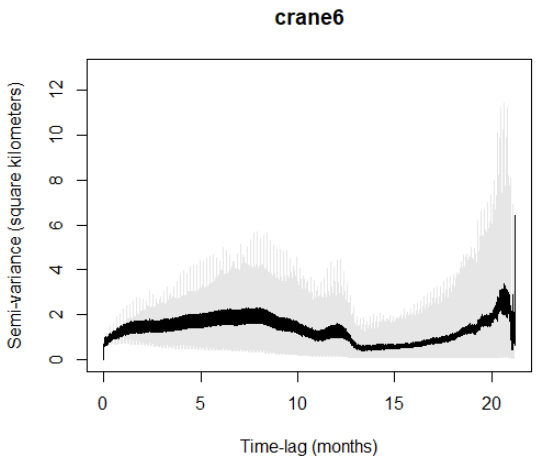
Breeding. Site fidelity



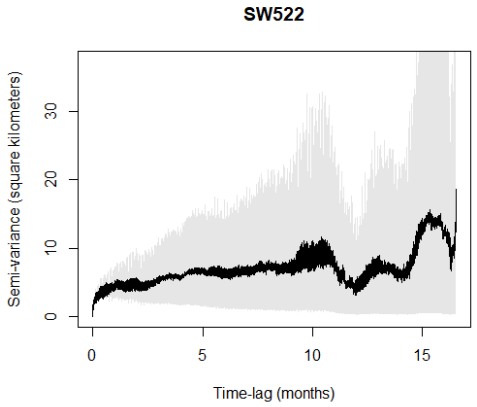
Breeding. Site fidelity



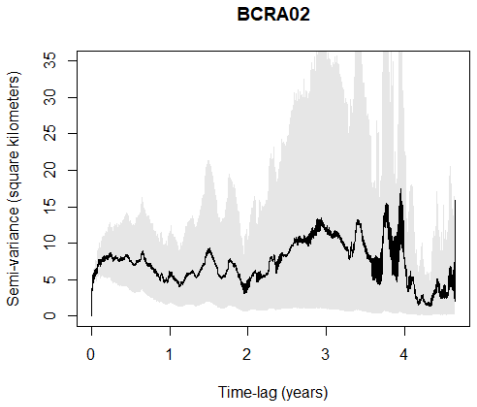
Breeding.Site fidelity



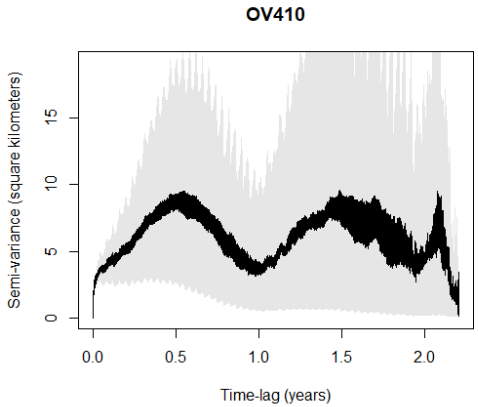
Breeding. Site fidelity

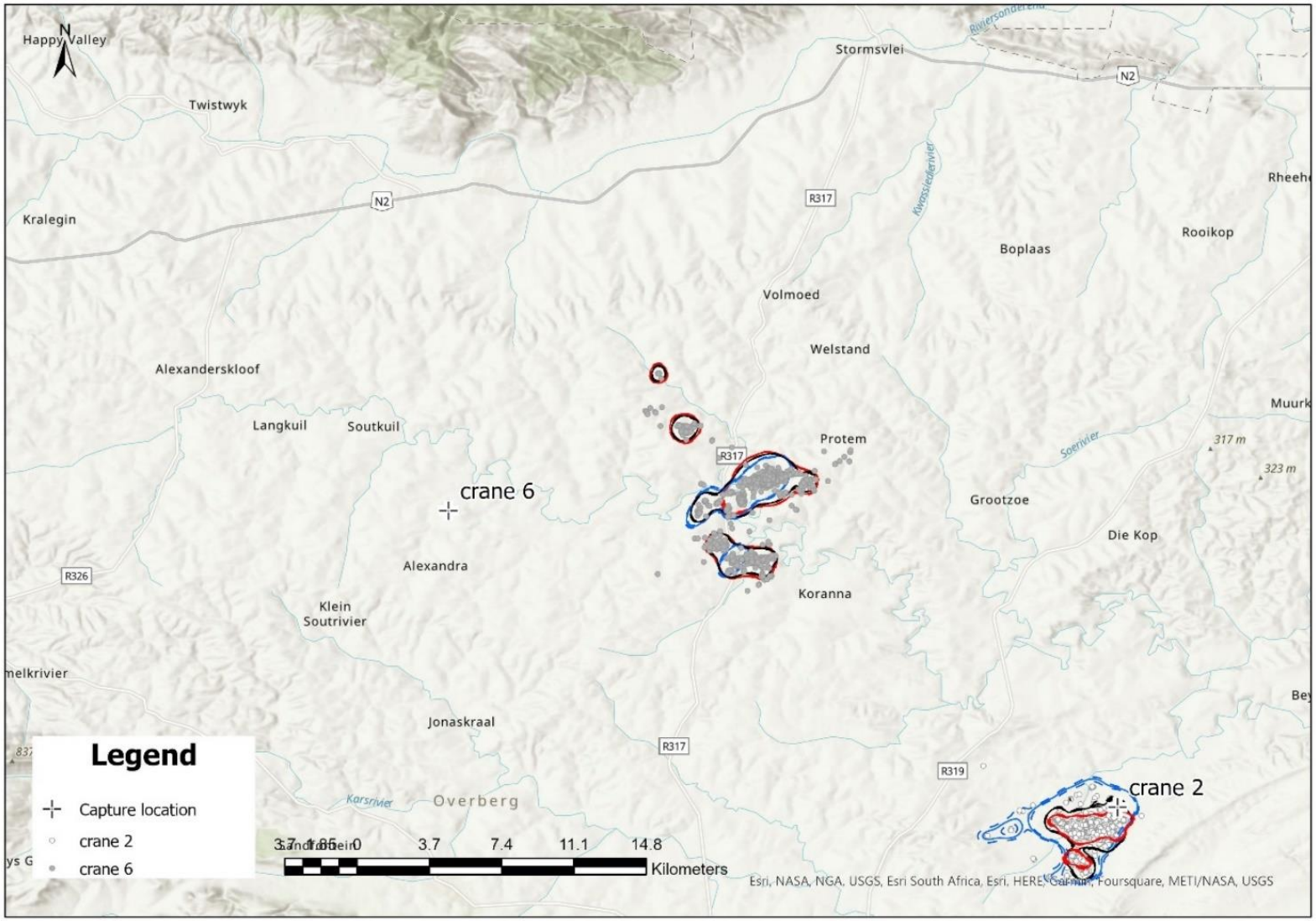


Site fidelity

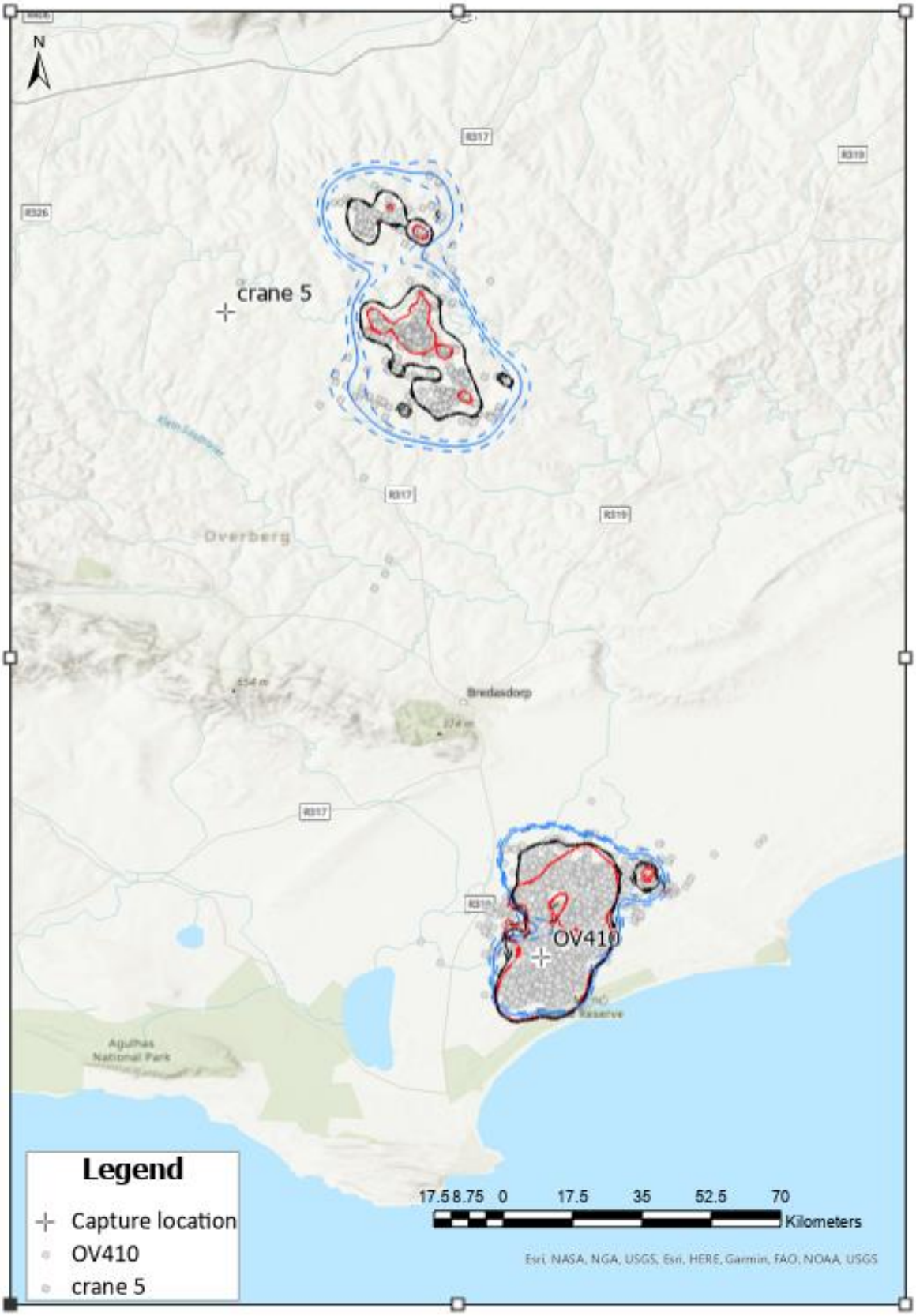


Non-breeding. Site fidelity

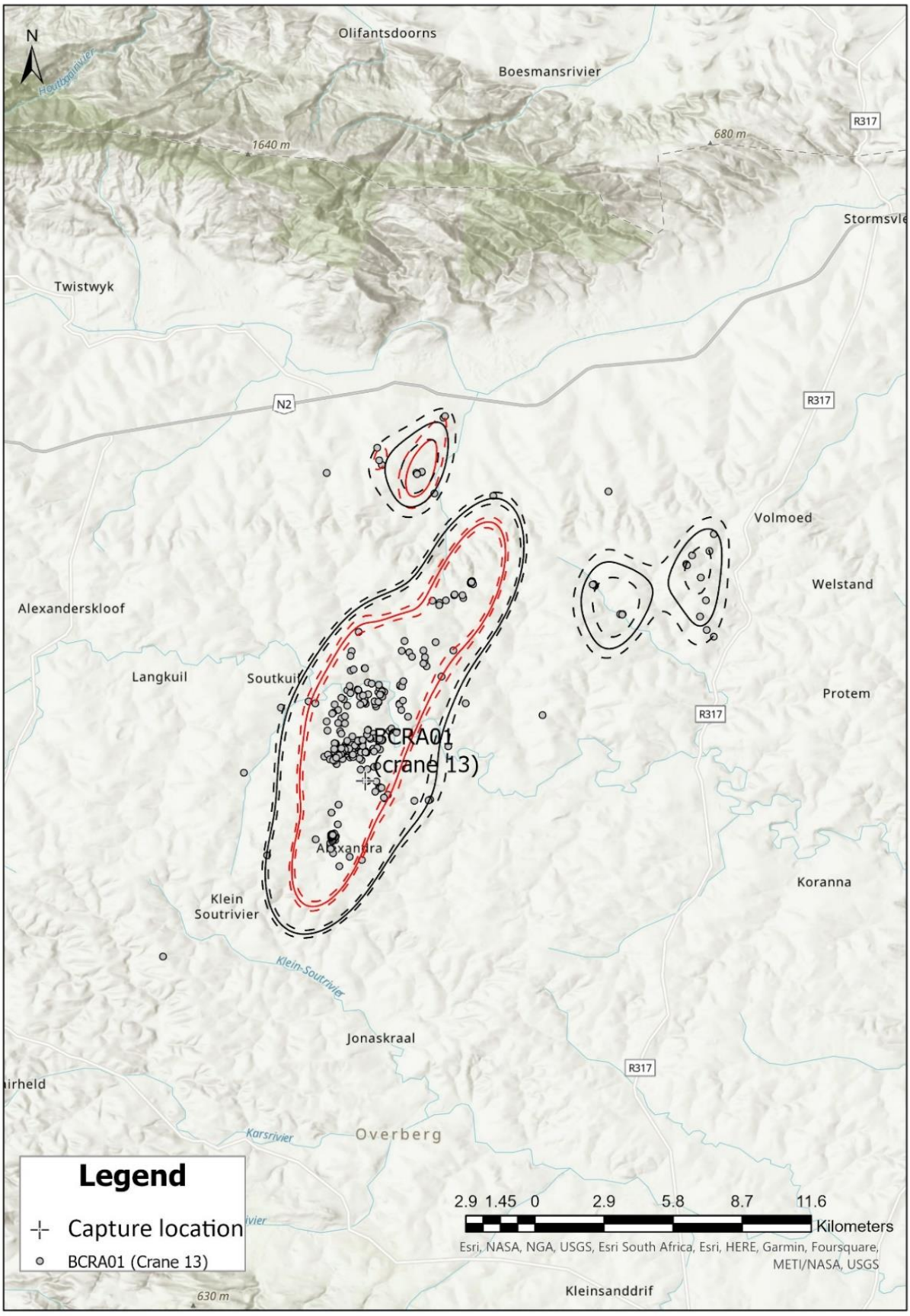




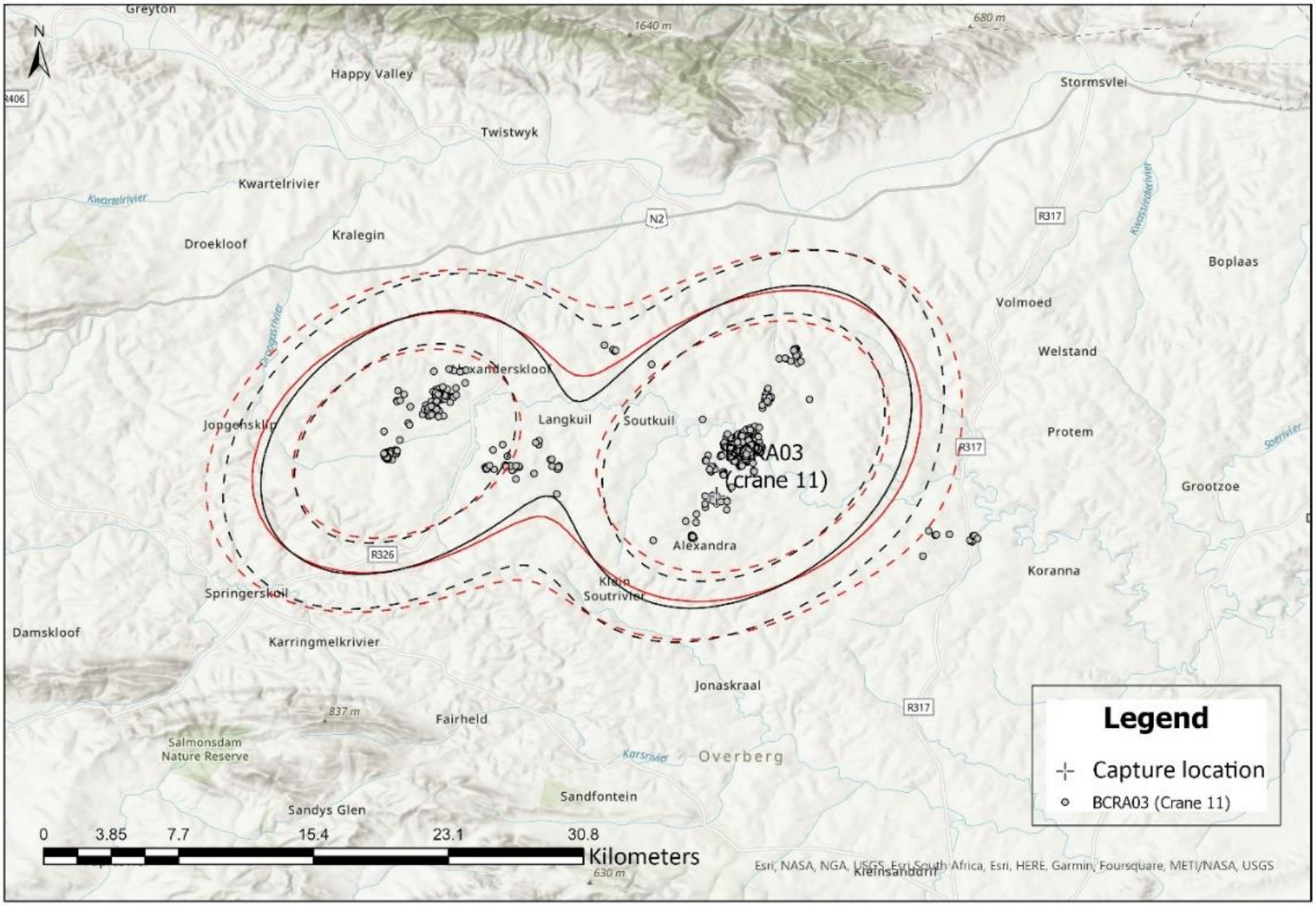
Supplementary Figure 8: Overall (black), summer (red) and winter (blue) 95% home ranges for two resident adult breeding Blue Cranes in the Overberg. 95% confidence intervals of the home range estimates are indicated by dashed lines.



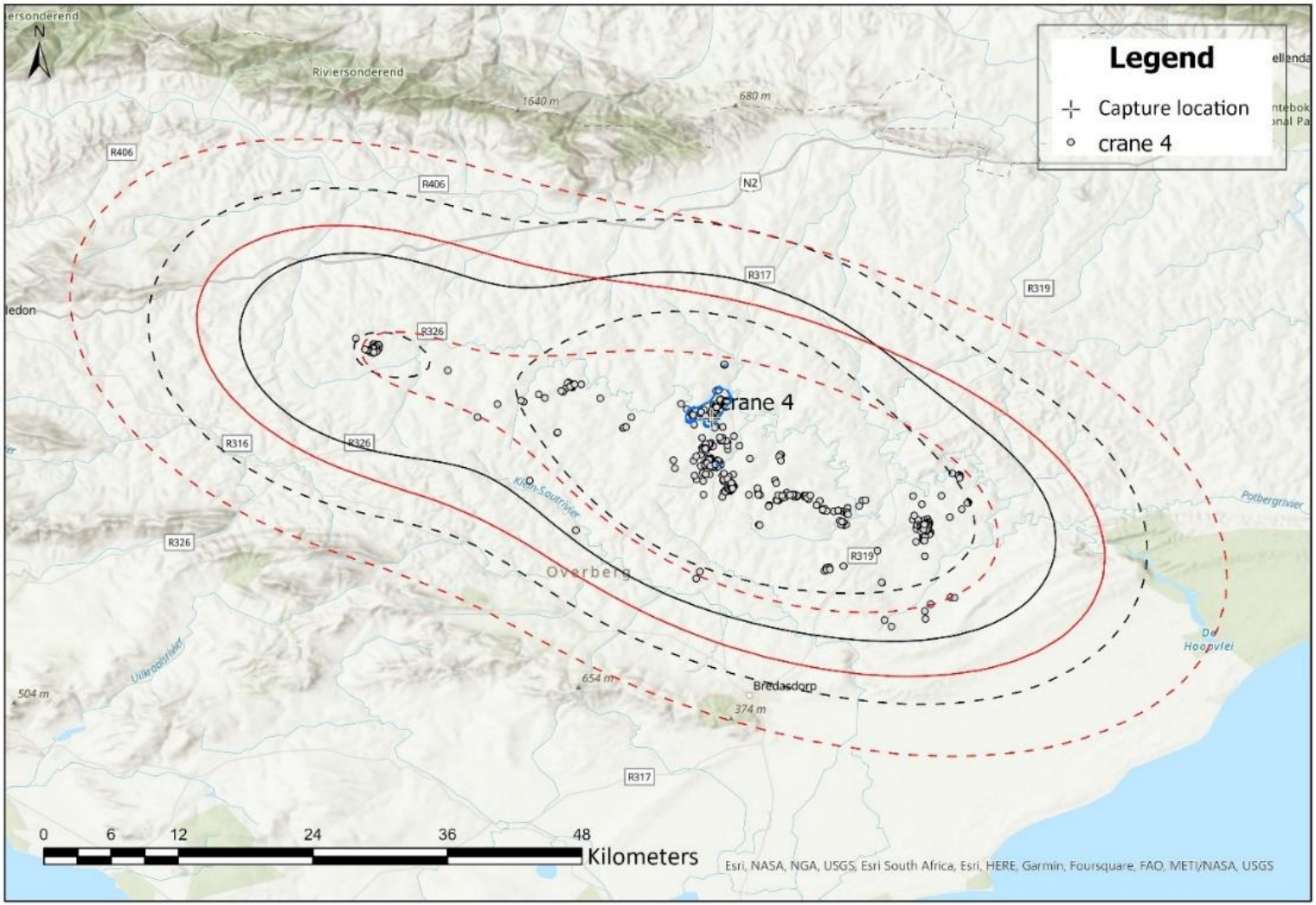
Supplementary Figure 9: Overall (black), summer (red) and winter (blue) 95% home ranges for two resident adult Blue Cranes in the Overberg. Crane 5 is a breeding adult, OV410 non-breeding. 95% confidence intervals of the home range estimates are indicated by dashed lines.



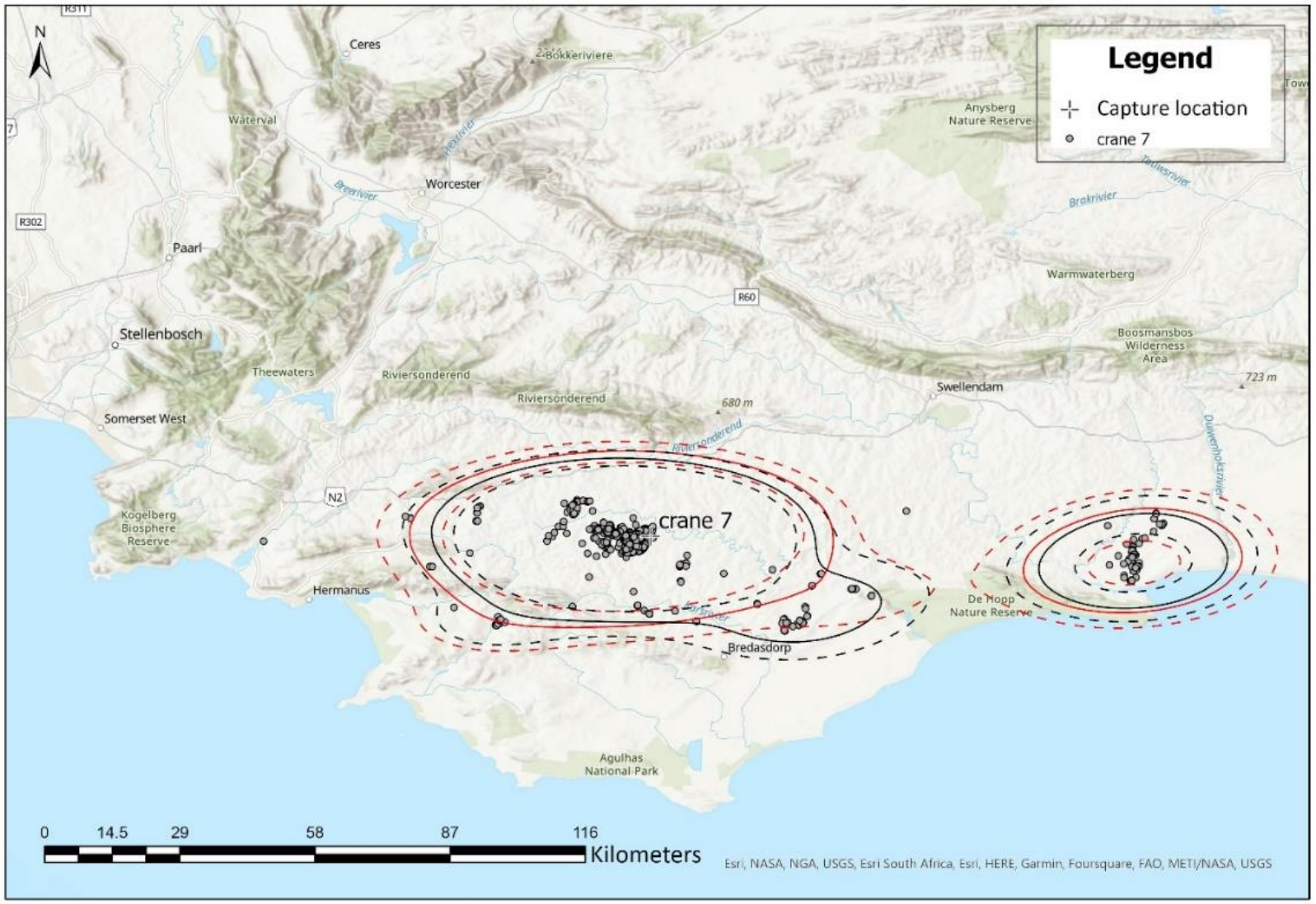
Supplementary Figure 10: Overall (black) and summer (red) 95% home ranges for resident non-breeding adult Blue Crane in the Overberg. 95% confidence intervals of the home range estimates are indicated by dashed lines.



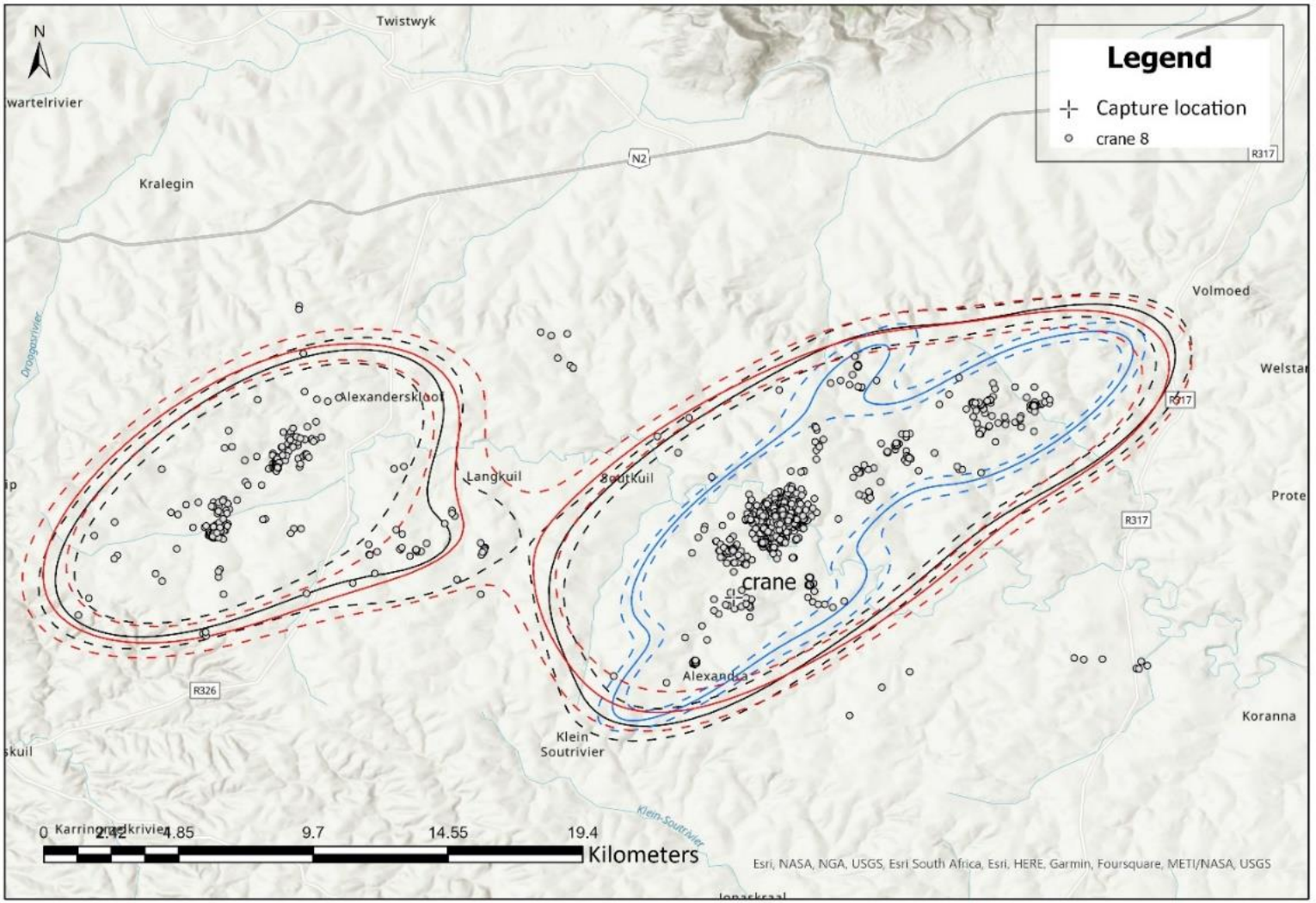
Supplementary Figure 11: Overall (black) and summer (red) 95% home ranges for regionally resident adult Blue Crane in the Overberg (breeding status unknown). 95% confidence intervals of the home range estimates are indicated by dashed lines.



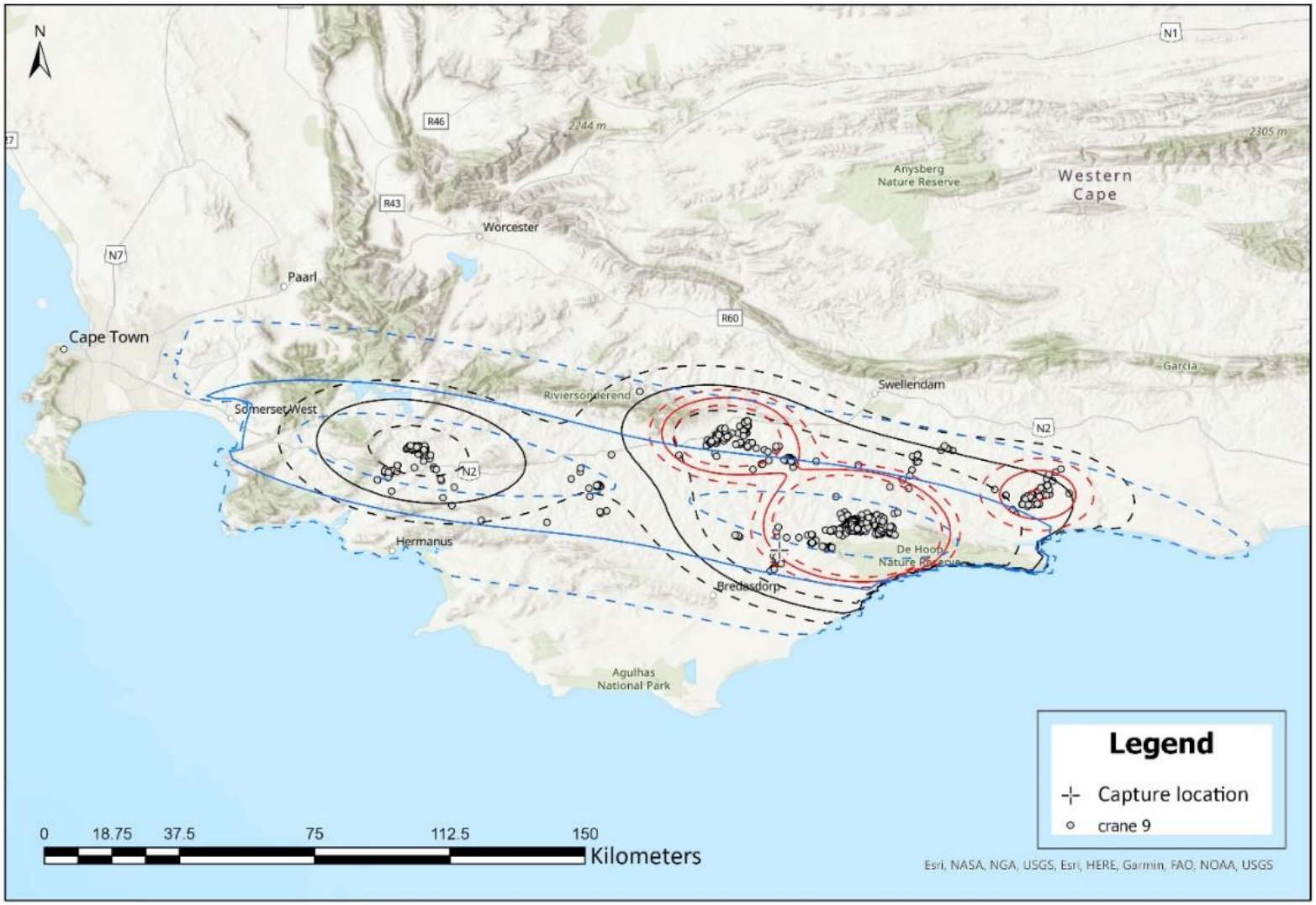
Supplementary Figure 12: Overall (black), winter (blue) and summer (red) 95% home ranges for resident intra-regionally moving juvenile Blue Crane in the Overberg. 95% confidence intervals of the home range estimates are indicated by dashed lines.



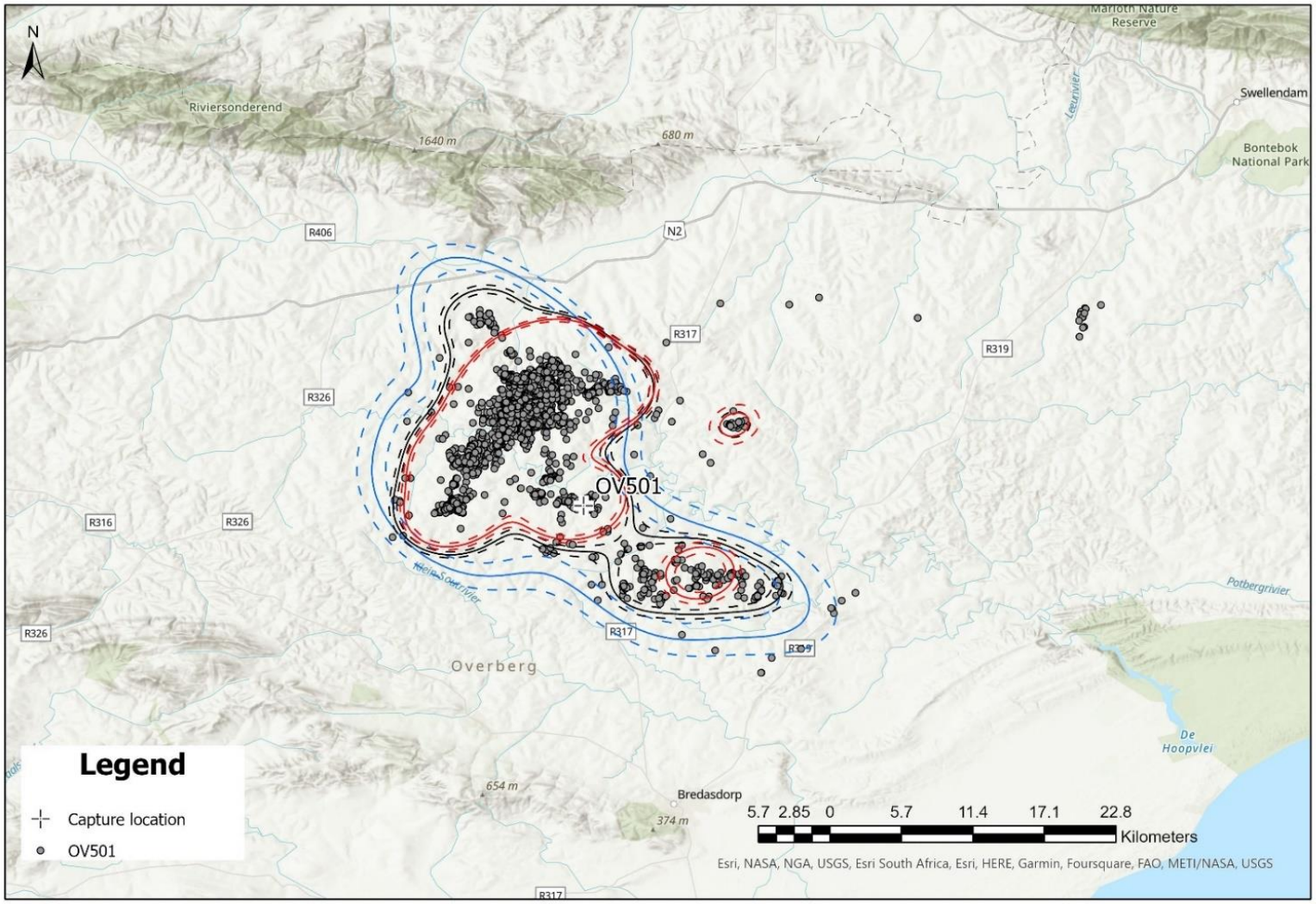
Supplementary Figure 13: Overall (black) and summer (red) 95% home ranges for a resident non-breeding Blue Crane making intra-regional movements in the Overberg. 95% confidence intervals of the home range estimates are indicated by dashed lines.



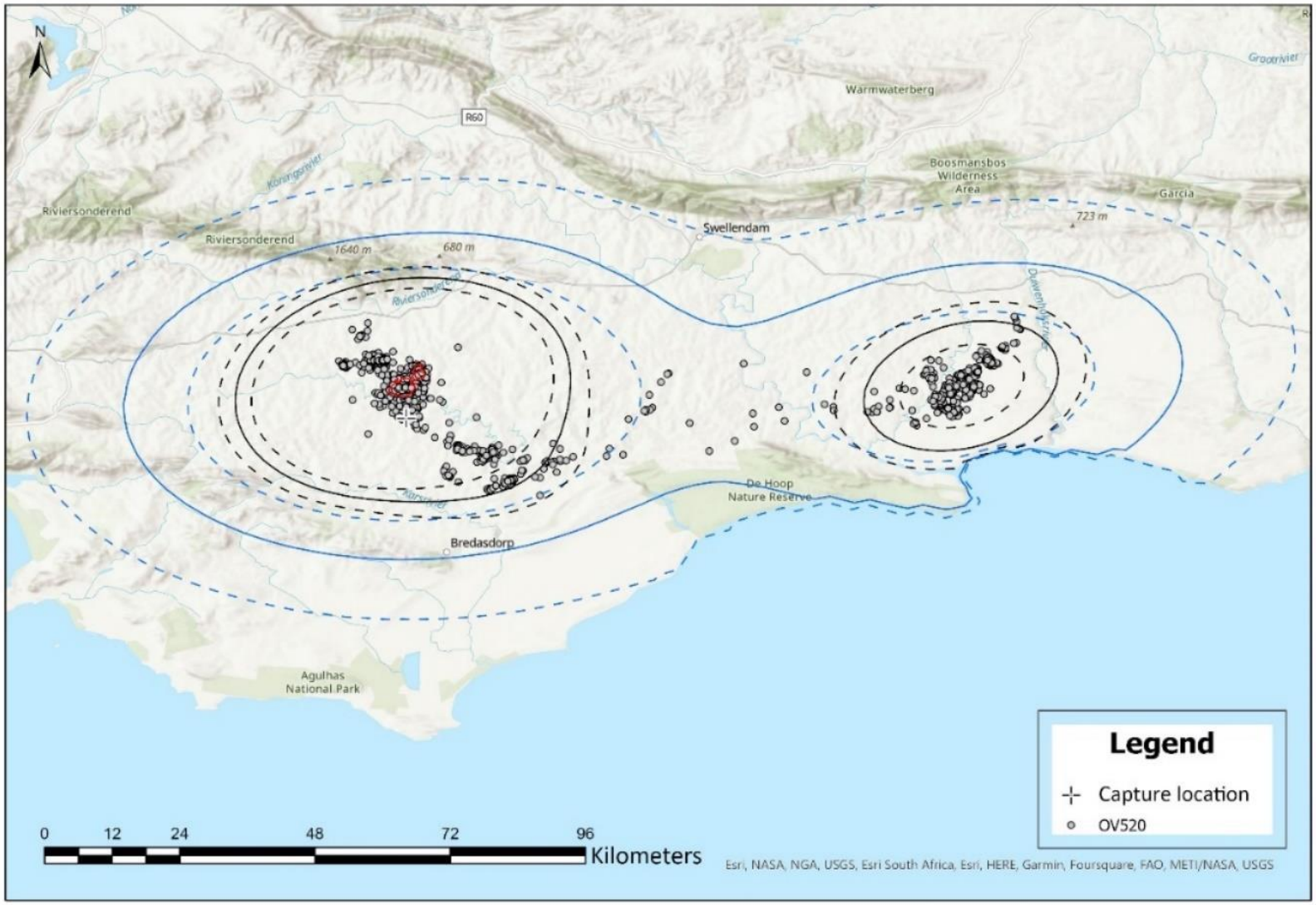
Supplementary Figure 14: Overall (black), winter (blue) and summer (red) 95% home ranges for regionally resident non-breeding Blue Crane in the Overberg. 95% confidence intervals of the home range estimates are indicated by dashed lines.



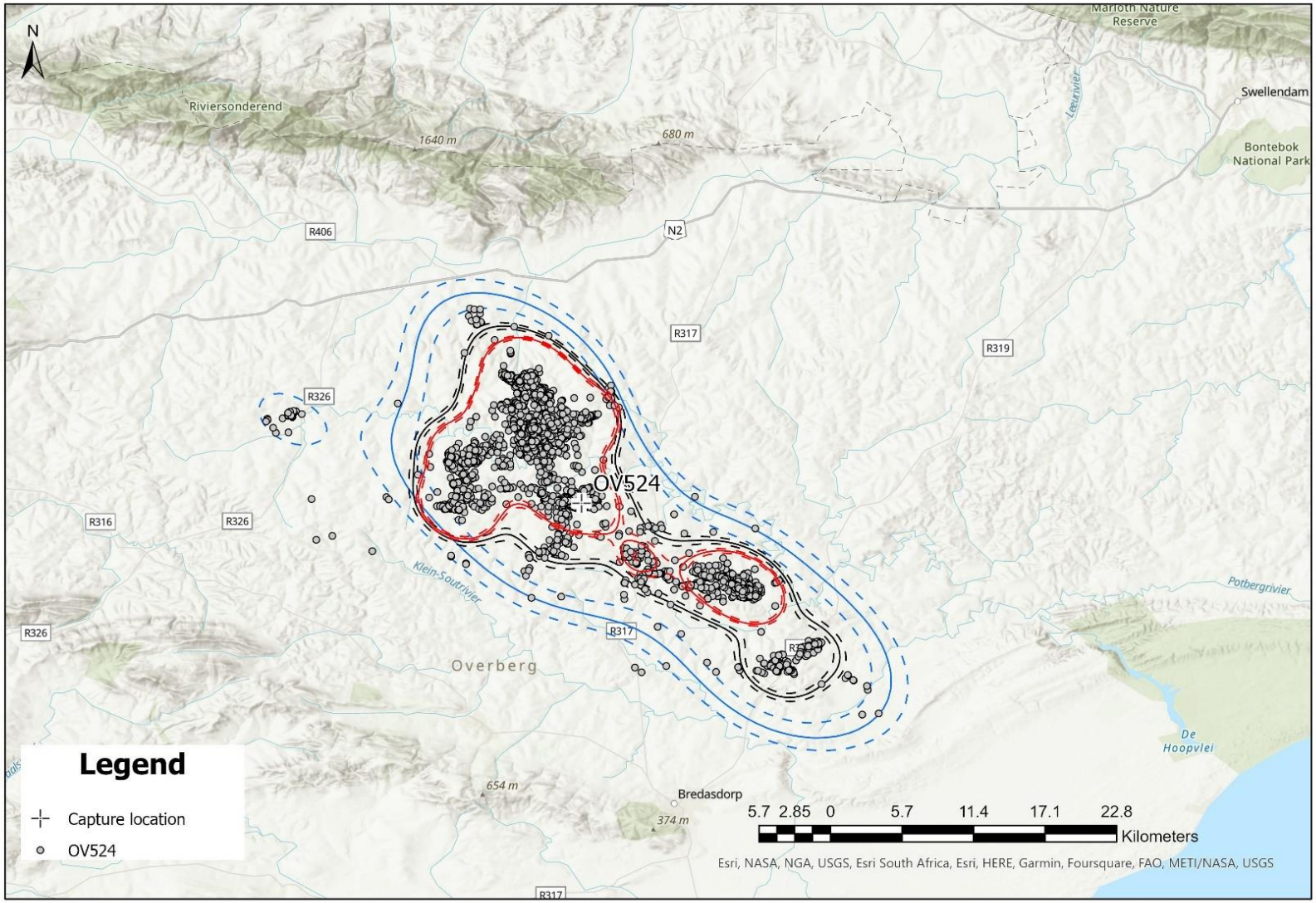
Supplementary Figure 15: Overall (black), winter (blue) and summer (red) 95% home ranges for a resident non-breeding Blue Crane making intra-regional movements in the Overberg. 95% confidence intervals of the home range estimates are indicated by dashed lines.



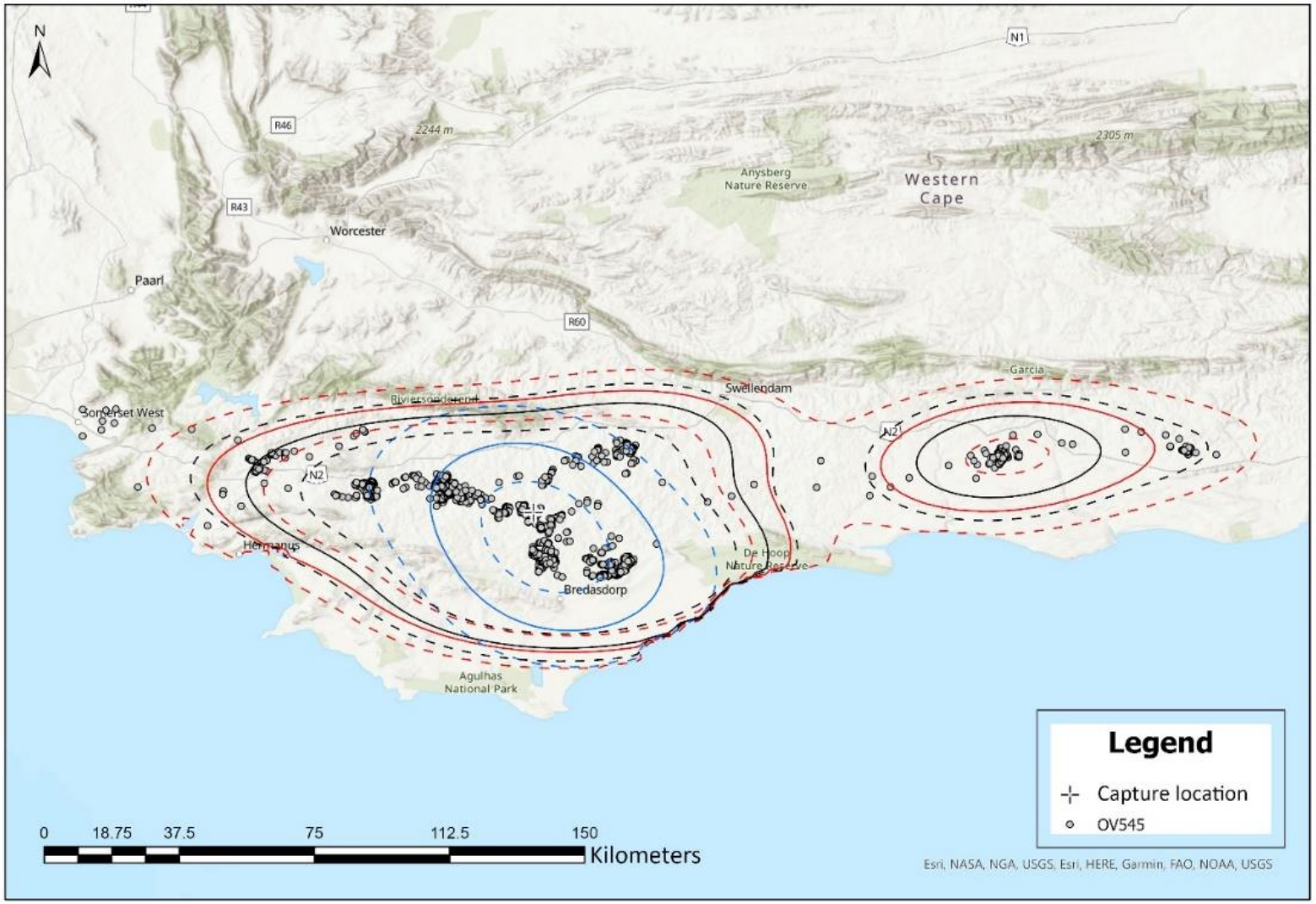
Supplementary Figure 16: Overall (black), summer (red) and winter (blue) 95% home ranges for a regionally resident Blue Crane in the Overberg (breeding status unknown). 95% confidence intervals of the home range estimates are indicated by dashed lines.



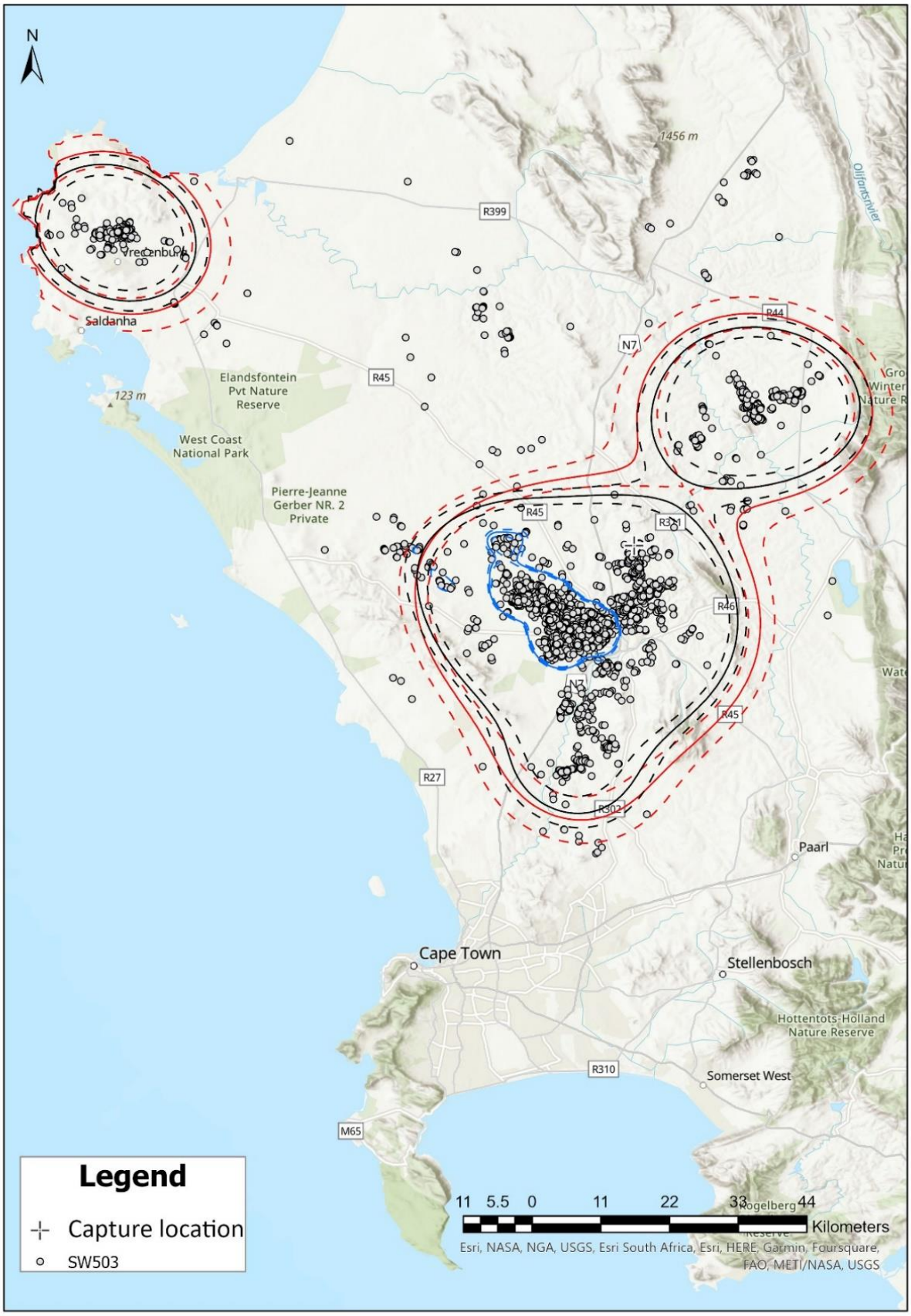
Supplementary Figure 17: Overall (black), summer (red) and winter (blue) 95% home ranges for a resident breeding Blue Crane in the Overberg, making intra-regional movements. 95% confidence intervals of the home range estimates are indicated by dashed lines.



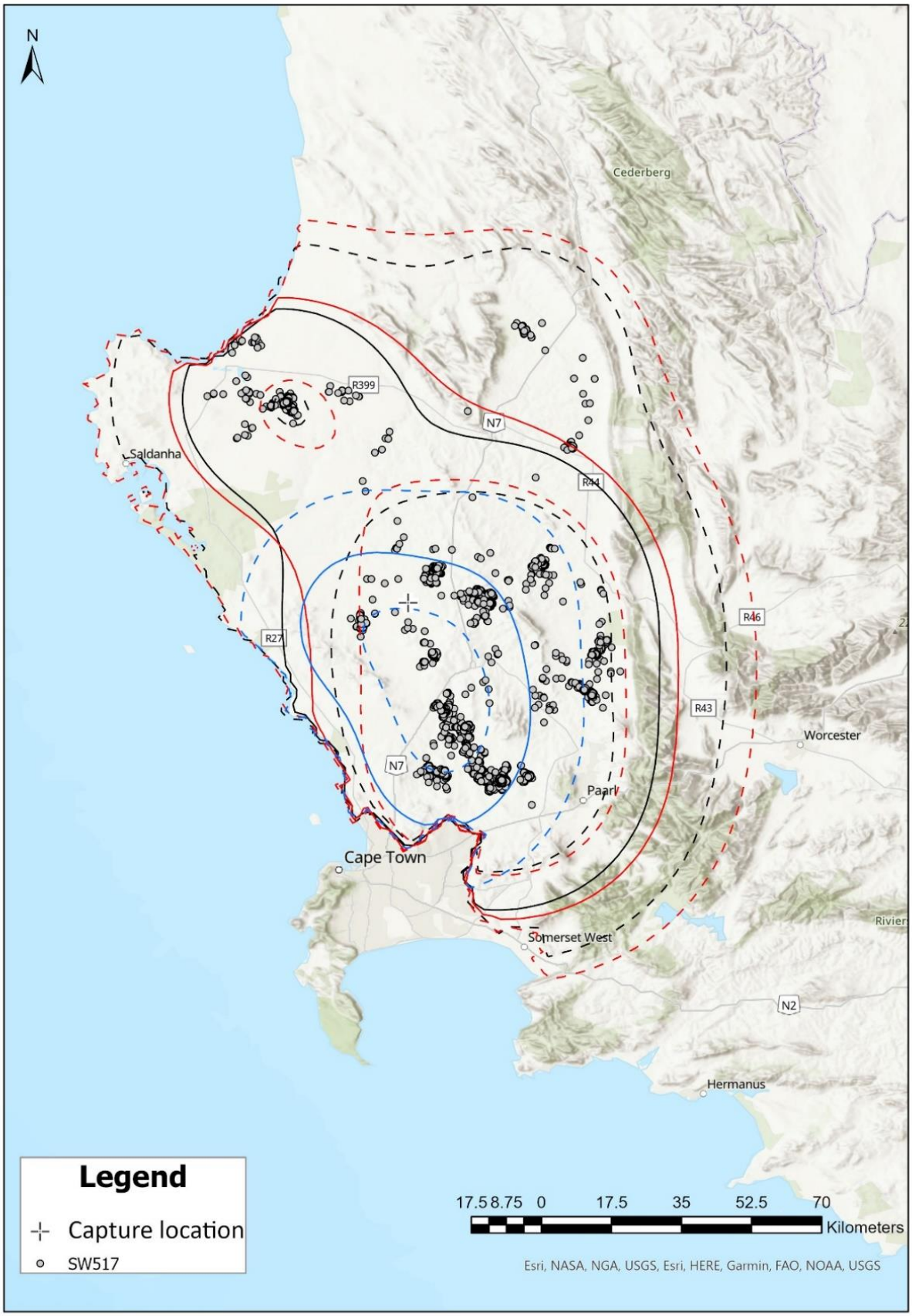
Supplementary Figure 18: Overall (black), summer (red) and winter (blue) 95% home ranges for a regionally resident Blue Crane in the Overberg, (breeding status unknown). 95% confidence intervals of the home range estimates are indicated by dashed lines.



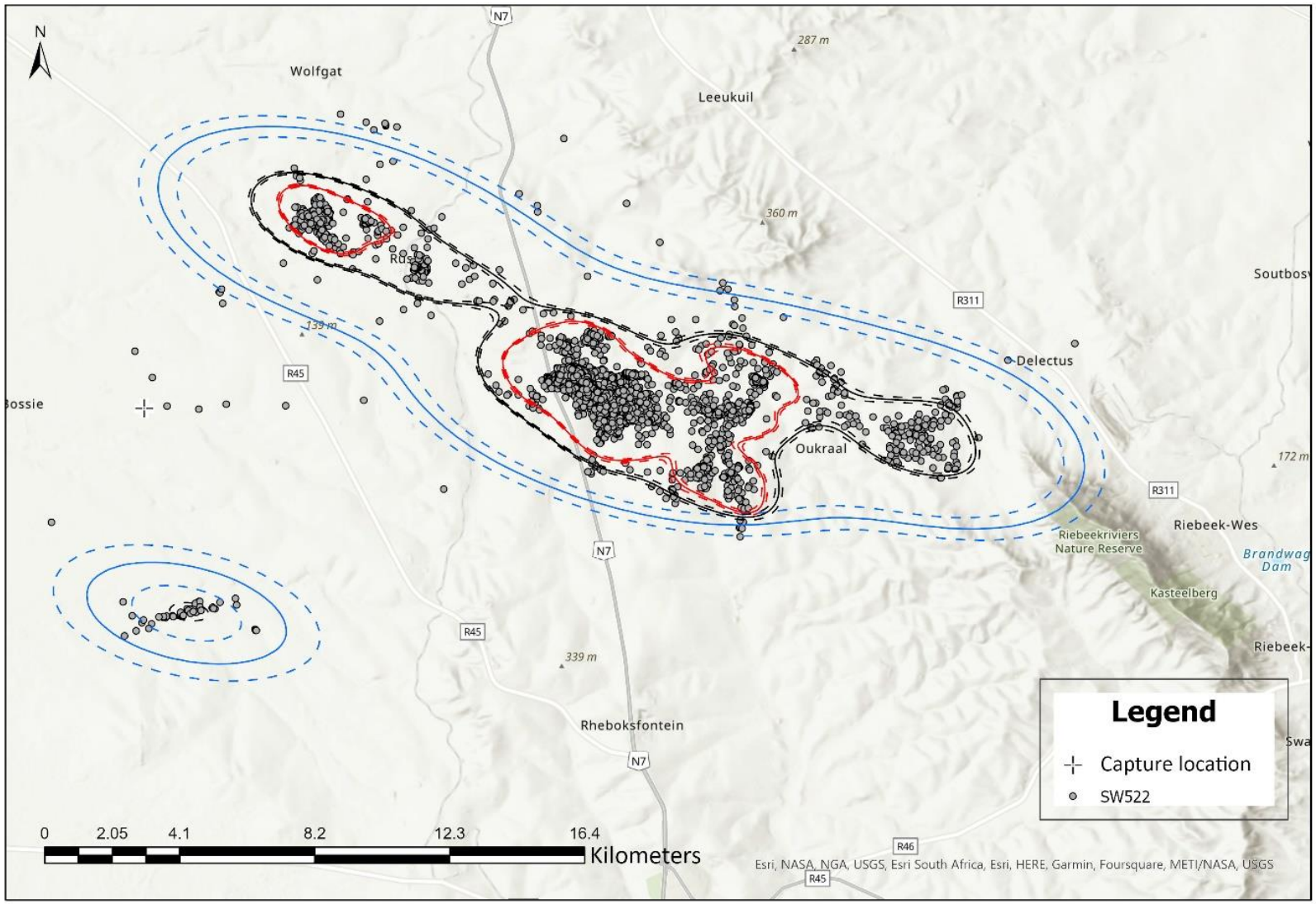
Supplementary Figure 19: Overall (black), summer (red) and winter (blue) 95% home ranges for a resident non-breeding Blue Crane, making intra-regional movements in the Overberg. 95% confidence intervals of the home range estimates are indicated by dashed lines.



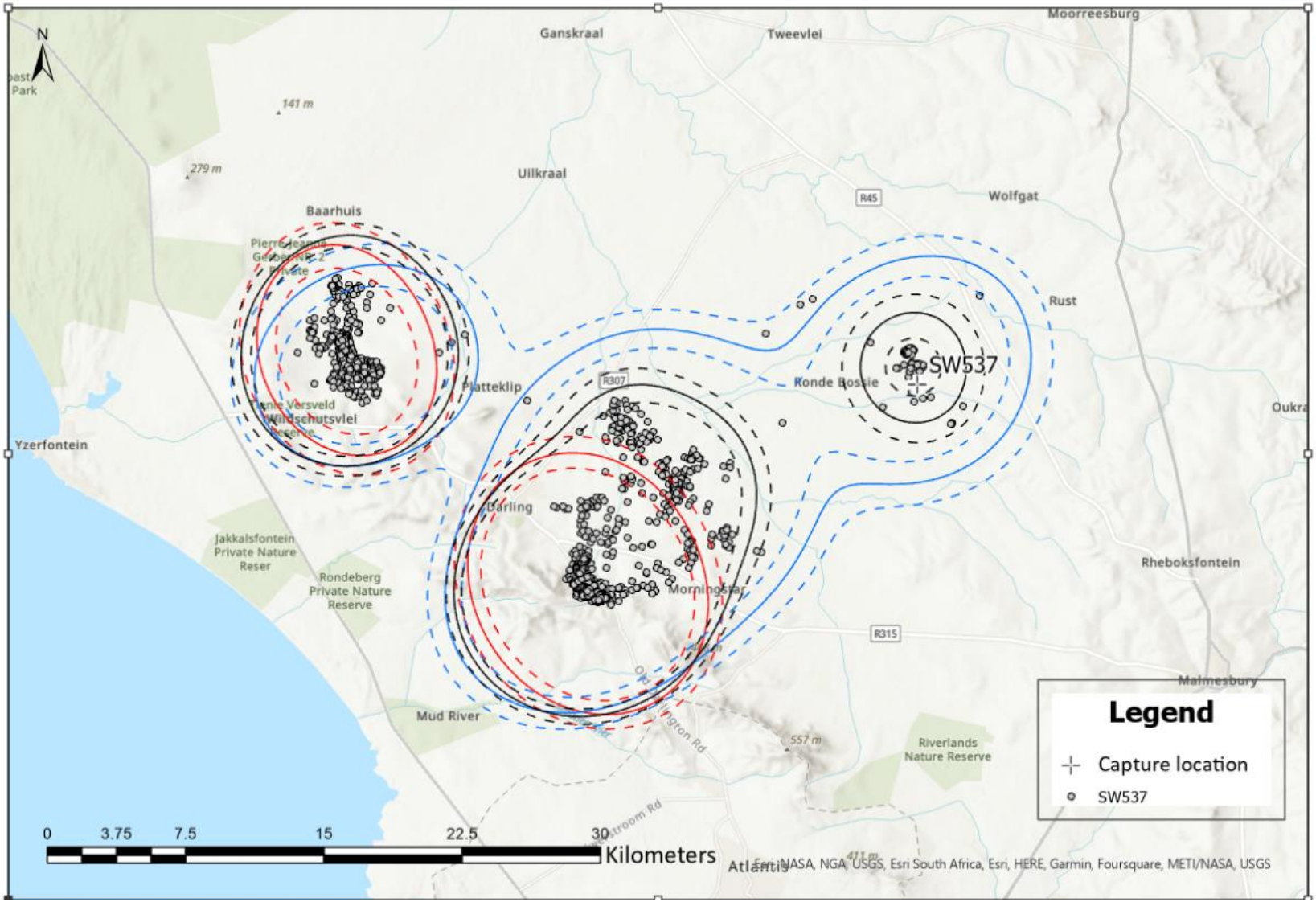
Supplementary Figure 20: Overall (black), summer (red) and winter (blue) 95% home ranges for a resident non-breeding Blue Crane, making intra-regional movements in the Swartland. 95% confidence intervals of the home range estimates are indicated by dashed lines.



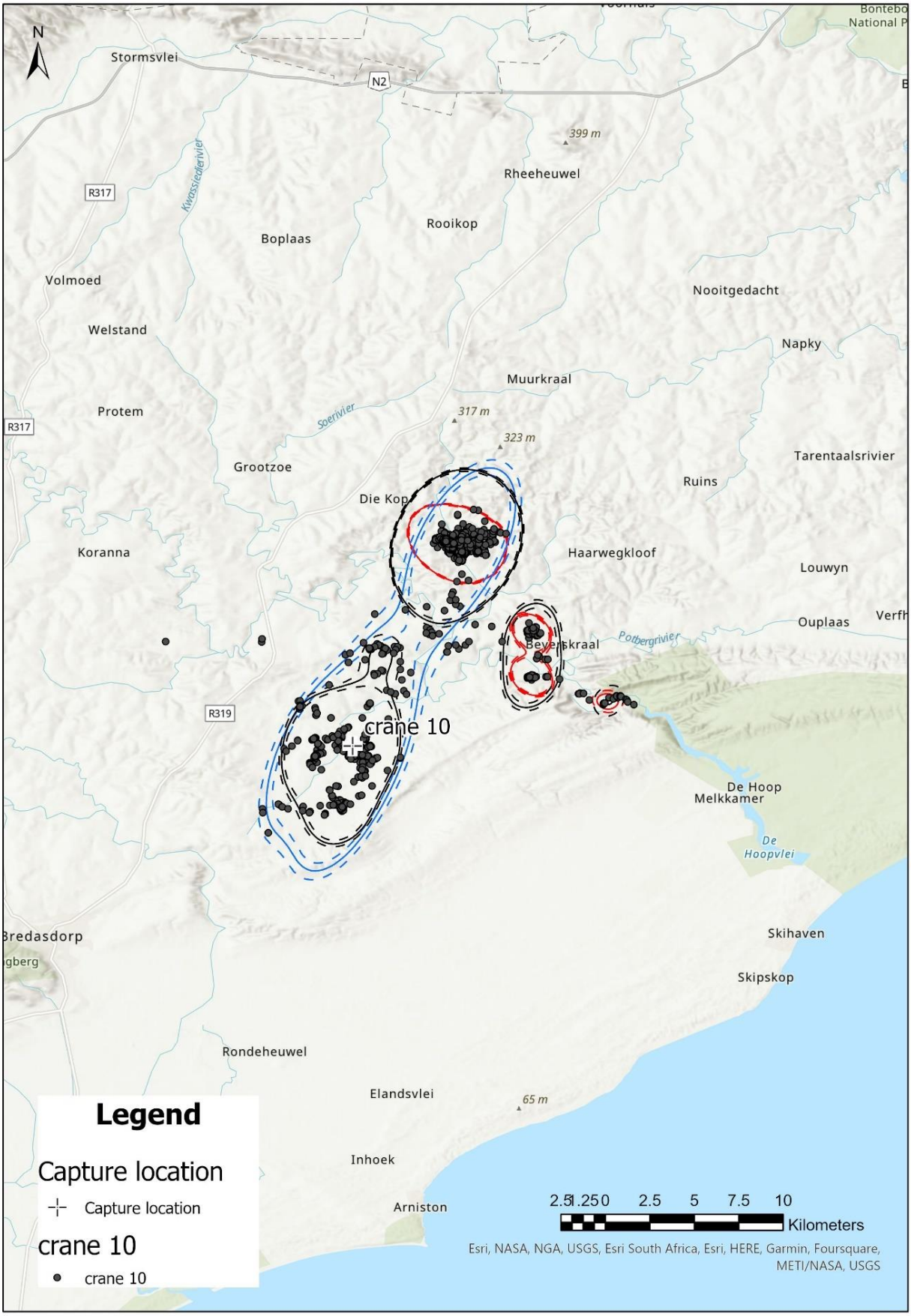
Supplementary Figure 21: Overall (black), summer (red) and winter (blue) 95% home ranges for a juvenile non-breeding resident Blue Crane, making intra-regional movements in the Swartland. 95% confidence intervals of the home range estimates are indicated by dashed lines.



Supplementary Figure 22: Overall (black), summer (red) and winter (blue) 95% home ranges for a regionally resident breeding Blue Crane in the Swartland. 95% confidence intervals of the home range estimates are indicated by dashed lines.



Supplementary Figure 23: Overall (black), summer (red) and winter (blue) 95% home ranges for a resident breeding Blue Crane in the Swartland. 95% confidence intervals of the home range estimates are indicated by dashed lines.



Supplementary Figure 24: Winter (blue) and summer (red) 95% home ranges for a regionally resident breeding Blue Crane in the Overberg. 95% confidence intervals of the home range estimates are indicated by dashed lines.

Chapter 5: Synthesis and Population Viability Analysis

As natural systems become increasingly transformed, more and more conservation will need to take place in altered landscapes. This adds a layer of complexity to conservation science and requires an understanding of the entire socio-ecological system. In this thesis I explore some of these questions, focusing on the Blue Crane *Anthropoides paradiseus*, whose stronghold is in the highly transformed Western Cape wheatlands of South Africa. This thesis arose out of concerns that this stronghold was an ecological trap for the species, and that their reliance on this habitat would affect the viability of the population. The aims of my thesis were to assess the state of the population, take stock of the primary threats, and gather information on the broader socio-economic system, through interviews with farmers.

In Chapter 2 I evaluated the population status and trends of Blue Crane across their range. Using aerial survey data, I estimated a population of approximately 51000 Blue Cranes in South Africa, with an range of 34000–68000. My analysis of Coordinated Avifaunal Roadcounts (CAR) and Southern African Bird Atlas projects (SABAP) indicate that the South African Blue Crane population has been generally increasing over

the last three decades. Across all CAR precincts, summer counts of Blue Cranes increased by 24% (95% CI 3.4–51%) between 2000 and 2019, and South African SABAP reporting rates increased by 6.3% between SABAP1 and SABAP2. However, in 2010, the population trend changed from positive to negative. Since 2011, across all CAR precincts, summer counts have declined by 19% (95% CI –31 to –5.2%), driven primarily by Overberg numbers declining by 22% between 2011 and 2019 (–37 to –1.9%). There are also indications that numbers are declining in the Karoo, with Northern Cape CAR counts declining by 49% (–71 to –17%) between 2011 and 2016. The information I present in Chapter 2 is key for assessing the Blue Crane on the IUCN Red List in terms of Categories A–D. To assess the Blue Crane against Category E, I run a Population Viability Analysis, drawing from data in Chapter 2, 4, Appendix 1 and the literature.

Assessing the conservation status of species

The IUCN Red List attempts to objectively assess the extinction risk to species, to allow conservationists to better direct their efforts (Mace et al. 2008; IUCN 2023). The IUCN first published lists of species at risk of extinction in the 1950s and began producing red lists in 1964 (Mace et al. 2008; IUCN 2023). These initial red lists were derived from subjective opinions, which caused much controversy (Mace et al. 2008). This led to the development of an objective and systematic set of categories and rules between 1984 and 2000, which are still in place today, although they have gone through some refinements (Mace et al. 2008; IUCN Standards and Petitions Committee 2019). The categories Extinct, Critically Endangered, Endangered, Vulnerable, Near Threatened and Least Concern, have become mainstreamed and universally recognised in the conservation community. These categories can be assigned based on five different criteria, namely population reduction (criteria A), range reduction (criteria B), small population size and decline (criteria C), small/restricted population (criteria D) or quantitative analysis (criteria E) e.g., probability of extinction based on viability analysis (IUCN Standards and Petitions Committee 2019).

These quantitative thresholds should mean that species are categorised objectively. There is however space for flexibility and judgement within the quantitative criteria, namely to account for lack of data (Collen et al. 2016; IUCN Standards and Petitions Committee 2019). This flexibility is where biases can arise in assessing species extinction risk (Hayward et al. 2015) and can lead to what has been described as a "crisis of legitimacy" (Campbell 2012, p. 367). These biases can be subconscious, namely through ambiguity or misunderstanding of the criteria, or conscious, where politics and agendas influence the red list process (Hayward et al. 2015). Conservation is by its nature a value-driven field, and human values and motives are inseparable from the science (Campbell 2012). Conscious biases arise when people with alternative agendas push to maintain or change a red-list categorisation, despite it not being supported by data.

Notable cases include the economically valuable Hawksbill Turtle *Eretmochelys imbricata* (Campbell 2012), the charismatic Snow Leopard *Panthera uncia* (Mallon & Jackson 2017) and Giant Panda *Ailuropoda melanoleuca* (Sills 2016). The Snow Leopard and Giant Panda case studies demonstrate biases within the conservation community, where experts are reluctant to down-list species, even though the data suggests that the population has recovered sufficiently, or new information shows that the species was not as threatened as originally thought (Campbell 2012; Hayward et al. 2015; Mallon & Jackson 2017). In these cases, the reluctance stems from concerns that down-listing a species will result in less attention and funding, and subsequently worsening of the species status (Mallon & Jackson 2017). The primary purpose of the Red List is assessing extinction risk. Conservation prioritisation is a separate process which should consider multiple other aspects such as local priorities, funding availability, potential for conservation success, etc. However, in practice many conservation prioritisation processes rely heavily on Red List Status. When conservation action is prioritised on Red List status, it operates predominantly within the reactive 'saving species from extinction' paradigm, and many species can fall into conservation traps. A conservation trap being where conservation action hinges on having a high threat status on the Red List, and therefore there is incentive to keep species on a higher threat status.

The IUCN has recognised this shortcoming with the Red List and has developed the Green Status of Species which looks more comprehensively at species recovery status, recovery potential and conservation dependence (Akcakaya et al. 2018). This metric was designed to assess conservation progress and success, providing a positive perspective, to compliment the negative, 'extinction risk' perspective provided by the Red List. Green Status defines recovery as viability and ecological function in each part of a species range (Akcakaya et al. 2018). The assessment starts off by defining what the fully recovered state looks like, then the species current condition is assessed in relation to this (Grace et al. 2021). This assessment is made for each part of the range based on four categories: Absent, Present, Viable, Functional, which are used to derive a species recovery score (Grace et al. 2021). The category "Functional" is an ambitious attempt to include ecological functioning as a goal in conservation, over and above ensuring viability of a population (Akcakaya et al. 2018; Grace et al. 2021). If there is enough information, the species can also be assessed on the following: Conservation Legacy (theorising the counter-factual status of a species had there been no conservation), Conservation Dependence (future status for the next 10 years if conservation stops), Conservation Gain (improvement possible with conservation over next 10 years) and Recovery Potential (degree to which species could recover over next 100 years with conservation) (Grace et al. 2021). Green Status assessments are published alongside the Red List status on the IUCN website, allowing both sets of information to be interpreted in conjunction.

As a charismatic species that has had decades of focused conservation action (Mirande & Harris 2019; Galloway-Griesel et al. 2022), the Blue Crane has not been exempt from these pitfalls to the Red List process. When Birdlife International proposed down-listing the species from Vulnerable to Near Threatened in 2019, the Endangered Wildlife Trust had concerns that this would adversely impact on conservation outcomes. This was not unfounded, because the EWT/Eskom strategic partnership uses the IUCN Red List status as one of the key factors to decide whether a powerline will be marked after an incident. Since powerline collisions are the main source of mortality for Blue Cranes, this could have knock on impacts on conservation progress. Through my PhD I provide a timely, comprehensive, and evidence-driven assessment of the status of the Blue Crane population to allow an objective assessment of both its extinction risk and recovery status, via the Red List and Green Status of Species.

Assessing the conservation status of Blue Crane: Red List

The Blue Crane is currently listed as Vulnerable globally, under Category A3cde+4cde (BirdLife International 2021a). These categories speak to current and projected declines (A3 + A4) over three generations due to decrease in range and/or habitat quality (c), actual/potential exploitation (d) and effects of pathogens, introduced taxa or pollutants (e). When Birdlife International proposed a down-listing in 2019, I used a basic analysis of the raw CAR data to motivate for it to be maintained at Vulnerable pending the conclusion of a full analysis in my PhD. Prior to this it was listed under category A3, projected declines only; category A4 was added with the preliminary evidence that the population is currently in decline.

The Blue Crane was assessed as Near Threatened on the South African regional Red List, category A2acde (Taylor et al. 2015) based on data which indicated a growing population at the time of the assessment (Hofmeyr 2012). Birdlife South Africa is currently doing a review of the regional Red List, and the below regional assessment will be used to inform this. In Namibia Blue Cranes were assessed as Critically Endangered, this declining and isolated population has a high probability of extinction (Simmons 2015).

Category B–D: Geographic range and population size

Geographic range is assessed by Extent of Occurrence (minimum polygon drawn around occurrence points) and Area of Occupancy (area within the extent of occurrence that is occupied) (IUCN Standards and Petitions Committee 2019). The Blue Crane's Extent of Occurrence (EOO) is 1 890 000 km^2 globally (BirdLife International 2021a) and 1 016 963 km^2 in South Africa (Birdlife South Africa, unpubl. data; produced for 2025 Regional Red List). Area of Occupancy in South Africa, assessed using a 2x2km grid with Birdlasser data, is 388 260 km^2 (Birdlife South Africa, unpubl. data; produced for 2025 Regional Red List). Therefore,

the Blue Crane does not meet the IUCN Red List thresholds to be assessed on Category B (Geographic Range < 20 000 km^2) (IUCN Standards and Petitions Committee 2019). Given the South African estimated population size of 51000, the Blue Crane does not meet the criteria to be assessed on Category C or D (Small Population size < 10 000, <1000 respectively) regionally, but would meet these criteria in Namibia, where the population is estimated at less than 50 birds (Namibia Crane Working Group 2020).

Category E: Quantitative Analysis

I used Vortex 10.5.5.0 (Lacy & Pollak 2021) to develop a baseline metapopulation model for the South African Blue Crane populations. I worked with the four core subpopulations, the grasslands, Karoo, Overberg and Swartland. I split the Overberg and Swartland as breeding success differs between these populations (Appendix 1). In line with IUCN Red List criteria, I ran the models for 100 years. The definition of extinction in the model was one sex remaining. I ran models for 1000 iterations. I did not specify any catastrophes in the model, or harvests/supplementations. I ran a population-based model as individual based models took over 12 hours to run and did not differ substantially from the population-based model.

Species description

There is no information available on in-breeding depression in Blue Cranes, therefore I modelled the population without this factor. I have no information on how survival and reproduction are correlated between subpopulations, so I set Environmental Variability correlation among populations at 0. I likewise set the correlation between reproduction and survival to 0, since the primary drivers affecting reproductive success (nest disturbance, predation, fence entanglements, drowning in water troughs) are different from the drivers affecting post-fledging survival (powerline collision, poisoning).

Dispersal

From Chapter 4 and van Velden et al. (2016a), we know that Blue Cranes in the Western Cape are mostly resident, and seldom move between populations. In addition, we know that breeding Blue Cranes often return to the same nest site each year (Allan 2005). Given this nest site fidelity, I expect adult (birds of breeding age) dispersal to be rare, and if individuals do move to other populations, they likely return within the year. Accordingly, I only consider juvenile and immature dispersal in the metapopulation model (i.e. cranes < 4 years old). There is no evidence to suggest that there are sex differences in dispersal, so I allow both sexes to disperse in the model. Blue Cranes undertaking long range movements are at higher risk of powerline collision (see Chapter 4), but I do not set a survival cost to dispersing, as this is accounted for in the juvenile survival/mortality estimates (Table 1).

There were no ringing records demonstrating dispersal between the Karoo (520 cranes ringed) and grasslands (118 cranes ringed) (FitzPatrick Institute of African Ornithology 2023), although anecdotally they are thought to migrate from the grasslands to the Karoo in the winter (Vernon et al. 1989). If this is the case, they likely return within the year, and this cannot be considered true dispersal, therefore I do not model dispersal between the Karoo and grasslands in the baseline model (Table 1).

There have been two records of Blue Crane dispersal from the Overberg to the Eastern Cape (Tracker OV514 in this study, a non-breeding adult of unknown age, a ringed crane (G22265) resighted at age 4, exact age of dispersal unknown) (van Velden et al. 2016a), and one record of a crane ringed (9A42379) in the Northern Cape and resighted in the Overberg at age 3 (696 Western Cape Blue Cranes ringed) (FitzPatrick Institute of African Ornithology 2023). The evidence is scant, and I do not model dispersal between the Karoo and Overberg or Swartland in the baseline model (Table 1).

Western Cape ringing data indicates that only 3.8% of Blue Cranes were recorded in both the Overberg and Swartland and 57% of chicks ringed return to their natal site as adults (van Velden et al. 2016a). In van Velden et al. (2016a)'s analysis, movements from the Swartland to the Overberg were twice as common (8 records) as the reverse (4 records). I therefore set juvenile dispersal, Swartland to Overberg to 4% and Overberg to Swartland at 2% (Table 1). I test the sensitivity of the model to dispersal by running a model with no dispersal and one with even dispersal (5%) between adjacent regions (Karoo and grasslands, Karoo and Overberg, Karoo and Swartland and Overberg and Swartland).

Reproductive System and Rates

Blue Cranes are long term monogamous breeders, that begin breeding at age four (Del Hoyo et al. 1996; Allan 2005). There is little data to support this however, so I test the sensitivity of the model to age of first breeding, testing ages three and five. Blue Cranes breed at most once per year and produce a maximum of two chicks (Allan 2005). I have received two anecdotal accounts of three chicks in the Overberg, but it appears to be very rare and could be pairs adopting another pair's young; I therefore set the maximum brood size to two. In the Karoo, the sex ratio of chicks is 50:50 (n = 12). In the Overberg and Swartland the ratio may be female biased in both regions 70:30 (Swartland n = 7, Overberg n = 7, see Chapter 4), however this is a very small sample size, so I modelled the population with a 50:50 sex ratio at birth (Table 1).

The oldest known ringed Blue Crane in the wild lived to 30 years old (ring: 972458), the next oldest records are 16 years old, which were still alive when sighted (rings: 9A20008, 9A20018) (FitzPatrick Institute of

African Ornithology 2023). I therefore set the maximum age in the model to 30, with no breeding senescence, since other crane species in captivity have been known to remain fertile until their death (Johnsgard 1983).

The parameter that I had greatest uncertainty about was % adult females breeding. In Vortex, this is defined as the proportion of females that successfully produce young (Lacy et al. 2021). But an alternative approach can be taken, where % adult females breeding is defined as the % of females that attempt to breed, the % success/failures are then specified in the distribution of broods (0 broods/1 brood) (Lacy et al. 2021) (Table 1). By defining % breeding as % that pair up prevents unsuccessful females from being paired up with a different male in the model (Lacy et al. 2021). For a long-term monogamous species like Blue Crane, it is useful to use the latter definition as cranes will often remain paired even if they fail in their breeding attempt (pers. obs). For Blue Crane I define breeding as pairing up. The issue is it is difficult to measure this at a population level. The last estimates for the Overberg were 28% of adults in pairs, 47% in the Karoo (Allan 1993) and 35% in the Mpumalanga grasslands (derived from Morrison 1998). These estimates are however outdated; for more recent estimates I draw from summer Coordinated Avifaunal Roadcounts to look at how many Blue Cranes are paired up (FitzPatrick Institute of African Ornithology 2020).

To calculate the % adult females breeding in the Overberg, I take an annual average and standard deviation of percentage of cranes paired up during summer CAR counts between 2010 and 2019, and for the other regions where data was sparser in recent years, I use data between 2010 and 2017 (Table 1). Blue Cranes can only be aged by plumage up until age 1, after this they come into their adult plumage. Vortex asks for proportion of adult (sexually mature = age four and up) females breeding, and since we cannot age Blue Cranes after age one, we can only look at the proportion paired out of the total population, which underestimates the adult proportion as it includes cranes age one to three. Other than underestimating % adult females breeding (as explained above), another source of error is that with these road counts taking place in January, some pairs could have bred early and already joined floater flocks. In addition, the timing of breeding differs between regions (Allan 2005), with Overberg and Swartland cranes driven by the timing of harvesting and Karoo and grasslands cranes thought to be driven by the timing of summer rains (BG Gibbons, EWT, pers. comm); this introduces an additional layer of uncertainty. Considering these uncertainties, I add 10, 15, 20, 30 and 40 percentage points to the % adult females paired up, to find which model best matches the observed trend.

The rest of the reproductive rate data is drawn from breeding monitoring data (Appendix 1; Table 1). I test the sensitivity of the model to variations in breeding success by adjusting the distribution of broods by –20, –10, 10 and 20 percentage points.

Mortality Rates

In this project, I assessed the main source of mortality, powerline collision (Chapter 3) and I attempted to quantify fence entanglement rates (Appendix 2). Other causes of mortality include poisoning, which appears to happen infrequently (Verdoorn 2015; Overberg Crane Group 2022, 2023), and collision with wind turbines, which is relatively infrequent, eight Blue Cranes fatalities across 20 wind farms over four years; Perold et al. (2020).

In assessing % annual mortality, it is difficult to accurately extrapolate rates of powerline collision and fence entanglement to a population level, and I do not attempt to. I instead use survival estimates from ringing studies (Altwegg & Anderson 2009; van Velden et al. 2016a) and from the trackers I fitted in this study (Chapter 4). The immature survival estimates from the tracker data (84%) and van Velden et al. (2016a)'s study (87%) were similar, so I used the latter, as it is based off a larger sample size. There are no survival estimates for the grasslands, so I use the average of the Western Cape and Karoo data (Table 1). Mortality rates were calculated as 1 minus survival estimates (Table 1). I test the sensitivity of the model to mortality of different age stages by adjusting juvenile mortality by –10, –5, –2, 2, 5 and 10 percentage points, immature mortality by –5, –2, 2, and 5 and adult mortality by –2, –1, 1, and 2.

Initial Population Size and Carrying Capacity

I draw from Chapter 2 for population estimates (Table 1). There are no data available on current carrying capacity of these populations. The highest Blue Crane density in the Overberg was 10 years ago when the population was 22% higher than it is now, so I assume this was the carrying capacity (Table 1). The Swartland population may have already reached carrying capacity (the population trend levelled out in 2007 and has remained stable since), but the Blue Crane range is expanding up the west coast (according to SABAP data), beyond the scope of the CAR project, which is what I used to evaluate population trends. I therefore set the carrying capacity for this region at 10000. In the absence of evidence of a carrying capacity in the Karoo and grasslands, I set them at 20000 and 10000 respectively. Accurately estimating carrying capacity becomes more relevant when populations are increasing and reaching carrying capacity, which is currently not the case in the Karoo and grasslands.

Table 1: Summary of input parameters for baseline Blue Crane PVA in Vortex (Lacy & Pollak 2021).

	Overberg	Swartland	Karoo	Grasslands
Dispersal				
Age of dispersal		1–4		
% survival		100		
% dispersal (from source to destination)	0% to Karoo 2% to Swartland	4% to Overberg	0% to Overberg 0% to Grasslands	0% to Karoo
Reproductive System				
Age of first offspring		4		
Maximum lifespan		30		
Maximum age of reproduction		30		
Maximum no. broods per year		1		
Maximum no. progeny per brood		2		
Sex ratio		50/50		
Reproductive rates				
% adult females breeding (Model: CAR % paired)	27 (SD 4)	41 (SD 3)	25 (SD 6)	25 (SD 9)
Distribution of broods per year (%)				
0 broods	60	57	33	32
1 brood	40	43	67	68
Distribution of offspring per female per brood (%)				
1 offspring	63	81	55	60
2 offspring	37	19	45	40
Mortality rates (%)				
Age 0–1	40	40	47	44
Ages 1–4	13	13	27	20
Age 4+	5	5	4	4
Initial Population Size	25000	6000	16000	4000
Carrying Capacity (K)	30500	10000	20000	10000

Results of the Blue Crane Population Model

The Vortex models were sensitive to changes in the % adult females breeding. The base model using the % paired up from summer CAR counts produced an unrealistically pessimistic model, confirming that this % is an underestimate (Figure S1). The model which produces a trend closest to the observed trend over the last 10 years was the CAR % + 15 percentage points model (Figure 1), indicating that it is likely that 40–56% of adult Blue Cranes attempt to breed each year. The CAR % + 15 model has a deterministic growth rate of –0.02 at the metapopulation level (Table S1). The model predicts a 20% decline overall in the first 10 years, 24% decline in the Overberg, 23% in the Karoo, 6% in the grasslands and 7% in the Swartland, which is similar to the trends observed (Chapter 2). Over three generations, the population declines by 55%.

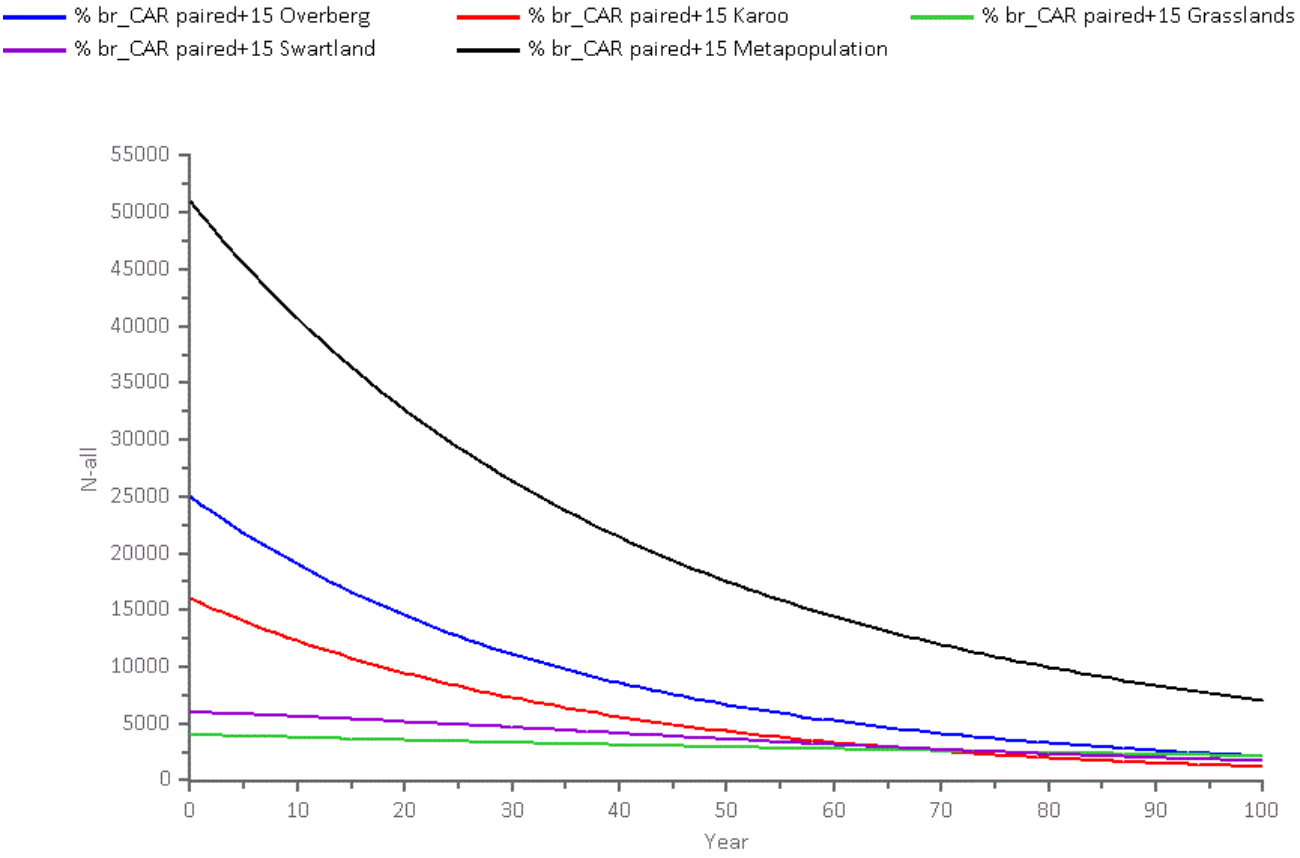


Figure 1: The number of individuals in the Blue Crane population, modelled over 100 years in the Overberg, Swartland, Karoo, grasslands and overall, in the metapopulation, based on the % breeding females from % cranes in pairs during summer CAR counts + 15 percentage points.

Adjustments to the dispersal parameter had very little impact on the trajectory of the model (Figure S2); therefore, I am confident with the parameters I have set for dispersal between the Overberg and Swartland, despite limited information (Table 1). Adjusting the age of first breeding to five produces a

similar model to the age four model, but adjusting to age three has a large impact, and produces a more optimistic model (Figure S3). The age of first breeding is an average, which means that for an average age of three, there would be some cranes breeding at two, which is highly unlikely. Therefore, models using age 4 or 5 are most plausible.

The model is highly sensitive to adjustments to the breeding success rate (Figure S4). Increasing breeding success rates by 20 percentage points across all populations results in an even population trend (Figure S4). The sensitivity of the model to adjustments in mortality is dependent on the age group (Figure S5–7). The model is most sensitive to adjustments in adult mortality (Figure S7), and least sensitive to adjustments to juvenile mortality (Figure S5). To produce an increasing population, I compared parameter values per region and adjusted those that tended to be lower compared to other regions. I increased Overberg and Swartland breeding success to 60 and 50% respectively. I reduce immature and juvenile mortality by 7 percentage points in the Karoo, 1 point in the Overberg and Swartland and 2 points in the grasslands. This model produces a slowly increasing population trend (Figure S8).

All models have a 0% probability of extinction in 100 years (Table S1). Based on these models, Blue Crane does not meet the criteria to be listed as Threatened on the IUCN Red List by Category E; extinction risk needs to be greater than 10% in 100 years to be listed as Vulnerable (IUCN Standards and Petitions Committee 2019). However, given the uncertainty in the % adult females breeding, and given how sensitive the model is to changes in this parameter, I would argue against using Category E for assessing Blue Crane on the Red List. For models to be useful for this purpose, we would need to gain a better understanding of % females breeding in this population, as well as a better understanding of carrying capacity, particularly in the Karoo and grasslands. The model is nonetheless useful in testing sensitivity to changes in Blue Crane population demographics.

Category A: Population size reduction in Blue Crane

Blue Crane can be assessed on either category A2 (observed decline), A3 (projected future decline) or A4 (both observed and projected decline). It would not be appropriate to list on category A1 (observed decline but reasons understood and ceased), as threats leading to their decline are continuing i.e. powerline collisions, fence entanglements, poisoning (Chapter 3, Appendix 2, Overberg Crane Group 2022, 2023). The Blue Crane has a published generation length of 12.5 years (BirdLife International 2021a), which was derived from a survival rate of 0.91 (Bird et al. 2020). Based on the actual adult survival (Chapter 4, van Velden et al. 2016a) which is higher, generation length calculated as 1/adult mortality + age of first breeding (IUCN Standards and Petitions Committee 2019) should be between 24 and 29 years. This

discrepancy should be discussed with the Red List authorities, but for this assessment I use the accepted generation length of 12.5 years from the last assessment. Species are assessed over the greater of 10 years or three generations (IUCN Standards and Petitions Committee 2019), which means that the Blue Crane is assessed over 37 years.

I used the CAR data to assess the Red List Status for Blue Crane, using category A4 (past population reduction, projected to continue into future) (Mace et al. 2008; IUCN Standards and Petitions Committee 2019). I used category A4, rather than A2 (population reduction observed over three generations), because the Blue Crane population trajectory changed from positive to negative in 2010 (Chapter 2), and this detail gets lost in the trend if assessing over three generations. Also, for most precincts, the CAR data does not date back three generations, at most, the data spans 27 years. Drawing from the population estimates and trends from this study (Chapter 2), I projected what the population estimate was in 2011, relative to the current estimate, and then assuming the population trend continues, I predict what the population estimate will be in three generations, 2011–2047.

Based on current population estimates (Chapter 2), the national population estimate is 51000 individuals. As per the Red List guidelines (IUCN Standards and Petitions Committee 2019), only mature individuals should be considered. Therefore, drawing from the PVA, I calculate the number of mature individuals for each sub-population, based on the % cranes paired during CAR plus 15 percentage points (Overberg 42% mature individuals, Swartland 56%, Karoo 40%, Grasslands 40%). This results in a population estimate of 21860 mature individuals. The national population has declined by 19% (95% CI –31 to –5.2%) over the last 9 years (2011–2019, as indicated by the CAR data; Chapter 2). This means that by extrapolating, prior to the decline, the rounded national population was 26013 (95% CI 22997–28637) mature individuals. Assuming the average annual rate of decline of 2.1% (95% CI –3.4 to –0.6%) between 2011 and 2019 continues, then between 2011 and 2047 (i.e., for 37 years/three generations), the population will decline by 53% (95% CI –19 to –72%).

If this were to occur, the Blue Crane would meet the criteria for listing as Endangered (50–80% decline) (IUCN Standards and Petitions Committee 2019). However, there is considerable uncertainty in the CAR data, and at the lower end of the 95% confidence interval, the Blue Crane would only be listed as Near Threatened. Considering the overall increases in SABAP reporting rates and uncertainty in the CAR data, I recommend taking a middle ground and listing Blue Crane as Vulnerable. These findings provide additional support for the 2020 global Red List assessment revision of Blue Crane (BirdLife International 2021a). For the ongoing South African Red List assessment, I advise up-listing from Near Threatened to Vulnerable.

Why are Blue Cranes declining?

When a population is in decline, at the simplest level, it indicates that the death rate exceeds the birth rate, or that emigration exceeds immigration. There is no evidence that significant emigration is taking place from the Overberg (Chapter 4, van Velden et al. 2016a), or from the Western Cape wheatlands as a whole, and it is unlikely that this is driving a declining population trend in this region. In the Karoo and grasslands we have limited knowledge of Blue Crane movements, so I cannot exclude this mechanism as a driver of current observed declining and increasing trends respectively (Chapter 2; Galloway-Griesel et al. 2022). Satellite tracking of Blue Cranes in the Karoo and grasslands, as well as ringing (with pro-active efforts to resight), would advance our understanding of movement patterns within and between these populations.

Assuming negligible migration out of the Western Cape wheatlands, my results indicate that the Blue Crane mortality rate in the Western Cape exceeds the birth rate. Blue Crane annual survival is fairly high in the Western Cape wheatlands. Annual survival rates of breeding cranes were 0.95 (95% CI 0.71–0.99) and non-breeding cranes 0.85 (0.61–0.95) (Chapter 4), which is similar or higher than estimates from the Karoo (age 2–3: 0.73, age 4+: 0.96) when the population was stable/increasing (Altwegg & Anderson 2009). The primary causes of mortality for fully-grown Blue Cranes are powerline collision and fence entanglement, with stochastic events such as poisoning (Verdoorn 2015; Overberg Crane Group 2022, 2023), disease outbreaks and predation also contributing. In this thesis I quantified Blue Crane powerline collision rates, in three core regions: the Swartland (0.08 cranes/km/year, 95% CI 0.02–0.17), Overberg (0.05, 95% CI 0.02–0.08) and Karoo (0.18, 95% CI 0.13–0.24) (Chapter 3). These, and fence entanglement rates, which farmers estimated at 0.8 cranes/per farm/per year in the Overberg, and 0.1 cranes in the Swartland (Appendix 2) are not insignificant and need to be addressed. However, there are no indications that mortality rates are higher than they used to be; if anything, my research indicates that Overberg powerline collision rates have decreased since 2008 (Shaw et al. 2010b) (Chapter 3).

There is however evidence that recruitment of juveniles is lower than it used to be; the proportion of juveniles in wintering flocks, 4.0% (Appendix 1) is half of what it was in the Overberg in the late 80s and early 90s (8.8%; Allan 1993). Juvenile recruitment is similarly low in the Swartland, 3.6% (Appendix 1). The current recruitment rate is also 2–3 times lower than what was recorded in other cranes species (Allan 1993). In addition, breeding productivity is lower in the Western Cape wheatlands than the rest of the country (Appendix 1). Only 40% of Overberg pairs and 43% of Swartland pairs fledge at least one chick per year, compared to 67–68% of grasslands and Karoo pairs (Appendix 1). This points to depressed breeding

productivity as the reason for the recent declining trend in the Overberg. It is not yet clear why breeding productivity and recruitment is lower. A preliminary study (Bouwer 2023) of Blue Crane nest success in the western Overberg in 2021/22, found that crude hatching success is not significantly different to what it was in 2003, when the population was increasing (Bidwell 2004). These two studies are snapshots, but if they represent the general trend in hatching success, I deduce that lower Blue Crane recruitment is not driven by nest failure rates prior to hatching. Further research may provide clues as to what the mechanisms were that tipped the population trajectory, and what the primary drivers of lower recruitment are. However, I would argue that we must be careful not to continue "counting the books, while the library burns" (Lindenmayer et al. 2013, p. 549), and rather use the evidence we have at hand to implement conservation action, alongside continued monitoring to facilitate adaptive management.

Are the Western Cape wheatlands an ecological trap for Blue Cranes?

The key overarching question of this thesis was whether the Western Cape wheatlands are an ecological trap for Blue Cranes. The key indicators of an ecological trap are high abundance and low reproductive output, evidence that an animal preferentially selects for the trap, and that the population is not viable (Battin 2004; Kautz & Gardiner 2019). There is evidence that Blue Cranes meet the first three indicators of an ecological trap in the Western Cape wheatlands; they occur in high abundance, compared to the rest of their range (Chapter 2) and have low breeding success (Appendix 1) despite selecting for this habitat (Chapter 2). There is however no indication that this subpopulation is not currently viable.

From the Population Viability Analysis, there is a 0% chance of the Blue Crane going extinct in 100 years in the Overberg or Swartland (Table S1). Another way of assessing a species viability is by using the concept of minimum viable population size. There is much debate over this concept, and there have been many attempts to develop rules of thumb for minimum population size (Reed et al. 2003; Traill et al. 2007; Flather et al. 2011). One of the most widely used thresholds was a population which exceeds 5000 adult individuals, a review has since found limited support for this however (Flather et al. 2011). An estimate from a meta-analysis of bird populations indicates a lower threshold of some 3742 birds (Traill et al. 2007). Based on this, the Blue Crane can currently be considered viable in the Western Cape wheatlands, and based off the PVA will remain viable for the next 100 years.

However, it is less clear whether this population would remain viable, if there was a major change to the agricultural landscape or a new emerging threat. Interviews with farmers (Appendix 2), conversations with agricultural researchers (Johan Strass, Western Cape Department of Agriculture, pers. comm) and studies (Bradley et al. 2012; Estes et al. 2013) do not indicate a fundamental shift to the agricultural habitat in the

Western Cape wheatlands in response to climate change or socio-economic change. The threats of powerline collisions (Chapter 3), fence entanglements (Appendix 2), poisoning (Appendix 2) and breeding disturbance (Appendix 1) are ongoing. There were concerns that wind energy developments could become a significant threat but so far there have been relatively few Blue Crane collisions with wind turbines (Perold et al. 2020). This may be because Blue Cranes are relatively sedentary (Chapter 4), and generally undertake short flights, below turbine height, although this is based on anecdotal observations and further investigation on flight heights are needed. It is also possible that wind turbines to date have not been built in areas which pose a high collision risk to Blue Cranes, or that post construction monitoring has not been done for long enough. The Overberg is one of the South African government's designated priority areas for renewable energy development (Renewable Energy Development Zone), and as new facilities are built, the impact on Blue Cranes should be closely monitored. The impact of renewable energy infrastructure on Blue Cranes may be uncertain, or minimal, but we do know that the associated increase in powerline infrastructure will impact Blue Crane, and this needs to be minimised and mitigated through optimal powerline placement and line marking (Chapter 3). In addition, the hotter and drier conditions predicted by climate change models are likely to impact breeding success in Blue Cranes (Bouwer 2023; discussed in Appendix 1) and result in fewer seasonal water bodies, which are used for roosting sites by Blue Cranes. In conclusion, the Western Cape wheatlands do not currently meet all the criteria to be considered an ecological trap for Blue Cranes, but if the population becomes non-viable, the criteria would be met.

Assessing Blue Crane conservation progress: Green Status of Species

Considering the concerns around the Western Cape wheatlands population, we must not lose sight of the recovery of the Blue Crane population over the last 20–30 years (Chapter 2). The IUCN has developed a tool, called the Green Status of Species, which assesses recovery. In 2020 I was asked to take part in the final testing phase of the Green Status of Species, prior to its launch in 2021 (Grace et al. 2021). Together with Mike and Ann Scott I assessed the Blue Crane (Craig et al. 2021). Above I outline the various aspects of a Green Status Assessment. In short, each subpopulation is assessed as either Absent, Present, Viable or Functional (Grace et al. 2021). I define a viable population using the Minimum Viable Population size concept (as discussed above) – from this we consider only the South Africa subpopulations to be viable, the Namibian one is not as it is fewer than 50 birds (Namibia Crane Working Group 2019, 2020) and there is very little chance of immigration from South Africa (Craig 2017).

I had difficulty in defining what makes a viable Blue Crane population functional. Akcakaya et al. (2018, p. 1130) define it as follows: "A fully recovered species exhibits the full range of its ecological interactions,

functions, and other roles in the ecosystem". I settled on a functional population as one which forms large flocks in winter (> 20 cranes), consistently and at several sites across the range. I theorised that this behaviour was an indicator of cranes occurring at sufficient densities to fulfil basic functions such as pairing with a mate and breeding. Pairs and pre-breeders perform courtship dances in these flocks, which likely play an important role in pair bonding and the social functioning. In the next revision of the Green Status, I would consider making this indicator more specific and revise the definition of a large flock to be more than 50 birds. Based on this definition, I classify the Western Cape and Karoo populations as functional, and the grasslands as viable, but as possibly functional in the upper levels of uncertainty. Another ecological function to consider would be Blue Crane's role in the food chain, although there is little information on this. In agricultural areas they seem to feed mainly on waste grains (Allan & Ryan 1996; Archibald et al. 2020), whereas in their natural habitat their diet comprises of insects, seeds, and small vertebrates (Archibald et al. 2020).

The outcome of the Green Status assessment was that overall, the Blue Crane has a Species Recovery Score of 75%, which falls into the category Moderately Depleted (with the maximum being 100% for a fully recovered species) (Craig et al. 2021; Grace et al. 2021). In addition, our assessment puts Blue Crane as having a high Conservation Legacy, and medium Conservation Dependence, Conservation Gain and Recovery Potential (Craig et al. 2021). There have been decades of focused Blue Crane conservation efforts, which is captured in this Green Status Assessment (Mirande & Harris 2019; Shaw et al. 2021). These conservation efforts include: powerline mitigation, landowner engagement to raise awareness and foster custodianship, interventions to reduce nest disturbance, protection of land through biodiversity stewardship and research and monitoring (Mirande & Harris 2019; Shaw et al. 2021). A paper linked these conservation efforts in the grasslands (KwaZulu-Natal) to increases in crane numbers (Galloway-Griesel et al. 2022), which provides further support. For the full details of the assessment see Craig et al. (2021).

As it stands, I found the Green Status Assessment process somewhat subjective, as it relies primarily on choosing four categories (Absent, Present, Viable or Functional) to assess species. This is less rigorous and quantifiable, than the current Red List category criteria. The Red List had similar issues in its infancy (Mace et al. 2008), and the Green Status will no doubt evolve and develop as the Red List has.

How can we secure the future for Blue Cranes?

The Blue Crane population has proved to be adaptable in the face of landscape change, moving into the Western Cape wheatlands and establishing a stronghold in this human-modified landscape has been their saving grace. Unfortunately, there are now indications that the Western Cape wheatlands are becoming an

ecological trap for Blue Cranes. Fortunately, through my research, the research of others before me (Allan 1993; Aucamp 1993; Morrison 1998; Kotoane 2003; Bidwell 2004; McCann et al. 2007; Altwegg & Anderson 2009; Mmonoa 2009; Shaw et al. 2010b; Smith et al. 2016; van Velden et al. 2016a; van Velden et al. 2016b; Davis 2018; Young & Harrison 2020; Shaw et al. 2021; Bouwer 2023), and decades of crane conservation work (Davis 2010; Austin et al. 2018; Mirande & Harris 2019; Galloway-Griesel et al. 2022), we have a strong knowledge foundation on which to build a conservation plan for the species. A Population and Habitat Assessment is underway, led by the EWT and supported by the Conservation Planning Specialist Group, which will result in a comprehensive conservation plan for the species. To conclude this thesis, I make some provisional recommendations, based on the findings on my research. These will be further interrogated and developed through the conservation planning process.

In the Western Cape wheatlands, the indication is that poor breeding productivity and recruitment is driving the decline in the population. Several interventions could improve recruitment in the Western Cape wheatlands (at the nest and chick phases), many of which have been done in the past (Mirande & Harris 2019). Prior to 2010, Overberg Crane Group and EWT field officers were active in the region, identifying nests during harvesting and encouraging and assisting farmers with putting up rocks and flags to make them visible to farmers operating machinery. To reduce chick drownings in water troughs, field workers would liaise with farmers to place rocks in the trough so that chicks could climb out.

The legacy of this work is still evident, with many farmers aware of these issues, but few still take measures to mitigate them. Further exacerbating the problem, the new generation of farmers are farming in an increasingly intensified and commercialised way (Appendix 2). In this context, they struggle to prioritise interventions for Blue Cranes, without assistance and encouragement from conservation workers. Similarly, with fence entanglements, Birdlife South Africa have released guidelines on how to make fences safer for birds (Birdlife South Africa 2019), but there needs to be consistent engagement with farmers to implement these measures. Even then, changing or removing fences may not be a viable option for farmers, in which case it will be important to respond to fence entanglement injuries. If cranes are removed promptly from fences, and their injuries treated appropriately and swiftly, many can be released. This requires a conservation presence in the landscape, so that landowners know who to contact for assistance. It also requires skilled rehabilitation capacity, which is an issue in the Overberg, where there are few facilities able to take Blue Cranes, given the additional permitting needed for housing species on the Threatened or Protected Species List (South Africa 2007a), and the time, skills and facilities needed to rehabilitate large, long-legged birds. Reducing breeding failure due to human impacts will be particularly

important in the face of climate change, as research indicates that higher temperatures may further reduce nest success (Bouwer 2023), which would compound poor breeding productivity rates.

In conjunction with these interventions, I recommend that breeding monitoring is continued in the Overberg and Swartland to serve as an indicator for the effectiveness of interventions. Breeding sites need to be checked at least monthly; when sites are visited less frequently, it is easy to miss key events. Breeding monitoring can be made more efficient by engaging with landowners and asking them to send regular updates. Breeding and/or recruitment monitoring should also be resumed in the Karoo and grasslands, where the last comprehensive breeding monitoring was done more than 10 years ago (Appendix 1). In long-lived species, the impact of low breeding productivity on the population is typically gradual, and it takes a while for the impact on the population trend to become evident (Kuussaari et al. 2009). Gathering information on breeding productivity and recruitment can serve as an early warning sign that the population is in decline.

In addition to improving Blue Crane breeding productivity and recruitment in the Western Cape wheatlands, it will be important to ensure that mortality rates of fully grown birds remain stable or is reduced. The primary source of this mortality is collision with powerlines (Chapter 3). The EWT-Eskom Strategic Partnership and researchers (Kotoane 2003; Shaw et al. 2010a; Shaw et al. 2010b; Shaw 2013) have made significant strides in understanding and mitigating powerline collisions, through line marking (Shaw et al. 2021). Line-marking should be prioritised as a conservation intervention, especially powerlines around waterbodies which are high risk for Blue Cranes (Chapter 3).

Mitigating powerline collisions will have the greatest impact on the survival rates of non-breeding/immature Blue Cranes. In Chapter 4 I found that non-breeding cranes moved significantly farther per day than breeding cranes. As a result, non-breeding cranes are at greater risk of powerline collision (Chapter 4). In the Karoo, where immature survival rates are lower than in the Western Cape, mitigating powerlines could be especially impactful, in turning the negative population trend around. Raising immature survival ensures that greater numbers of Blue Cranes reach breeding age and have a chance to reproduce.

Mitigating stochastic events such as poisoning and disease will also be important for conserving Blue Cranes. I am not aware of any mass mortalities of Blue Crane due to disease, but diseases such as avian flu have impacted other crane species, for example at least 5000 Eurasian Cranes died of avian flu at a migration stopover in Hula Valley, Israel (The Wildlife Society 2022). The spread of disease could be accelerated in agricultural areas where cranes congregate in large numbers e.g., sheep feedlots (Austin et

al. 2018). There should be a response plan in place, should a disease outbreak occur. During farmer interviews I learnt that rodenticide use is widespread in the Western Cape wheatlands, to reduce rodent damage to crops (Appendix 2). Rodenticide use is legal, but some baits can be attractive to non-target species, such as Blue Cranes. A few farmers also mentioned the occasional illegal use of poison to kill birds like geese, game birds and sometimes cranes, to mitigate crop damage, particularly in the growing season (Appendix 2). Blue Cranes seldom cause crop damage in the Western Cape wheatlands, although they are known to be a problem on sweet lupin in the Swartland (van Velden et al. 2016b). Occasionally farmers complain when Blue Cranes aggregate in large numbers at sheep feed troughs, and on irrigated lucerne lands in the Karoo. This is a significant risk in the Karoo, where flocks on lucerne lands can number over 1000 individuals (Chapter 2). A mass poisoning event on one of these fields could be very serious. We do not know what the farmer sentiments are in the areas such as Orania and Grassridge Dam, where there are these large winter flocks (Chapter 2); it would be valuable to visit these communities and assess attitudes towards Blue Cranes. To combat the risks of poisoning, it would be beneficial to have a greater conservation presence in this landscape, having conservation staff working with farmers to find alternative solutions for mitigating crop damage and encouraging people to use rodenticide responsibly. I recommend developing a poison response plan (Kenya Wildlife Service 2018), so that when poisoning events occur, people can respond swiftly, treat surviving animals, collect evidence, and decontaminate the scene so that the impact is minimised, and perpetrators can be prosecuted.

Lastly, every conservation plan needs a comprehensive monitoring plan to accompany it, so that the impacts of interventions are clear. Comprehensive, population wide, long-term monitoring can be expensive, time consuming and difficult to fund. Monitoring which requires some sensitivity and species expertise e.g., breeding monitoring, needs to be done by trained conservation staff. However, simple counts and recording presence/absence can be outsourced to the public, via citizen science projects such as CAR counts and SABAP. Unfortunately, participation in CAR has declined in the last 5 years, which limited my investigation into recent Blue Crane trends (Chapter 2). These projects used to fall under the Animal Demography Unit, which closed in 2018. The project website and data are now managed by the FitzPatrick Institute of African Ornithology, but there is limited capacity for the implementation of this project, which is mainly done by volunteers. At the start of the CAR project there were dedicated staff who coordinated the project and gave regular feedback to citizen scientists, which encouraged participation; this is now greatly reduced. The CAR project has incredible potential to serve as a country-wide Blue Crane monitoring tool. It would be valuable to feedback to the CAR participants on a regular basis, to encourage them, particularly in the current economic climate, where high fuel prices can discourage people from

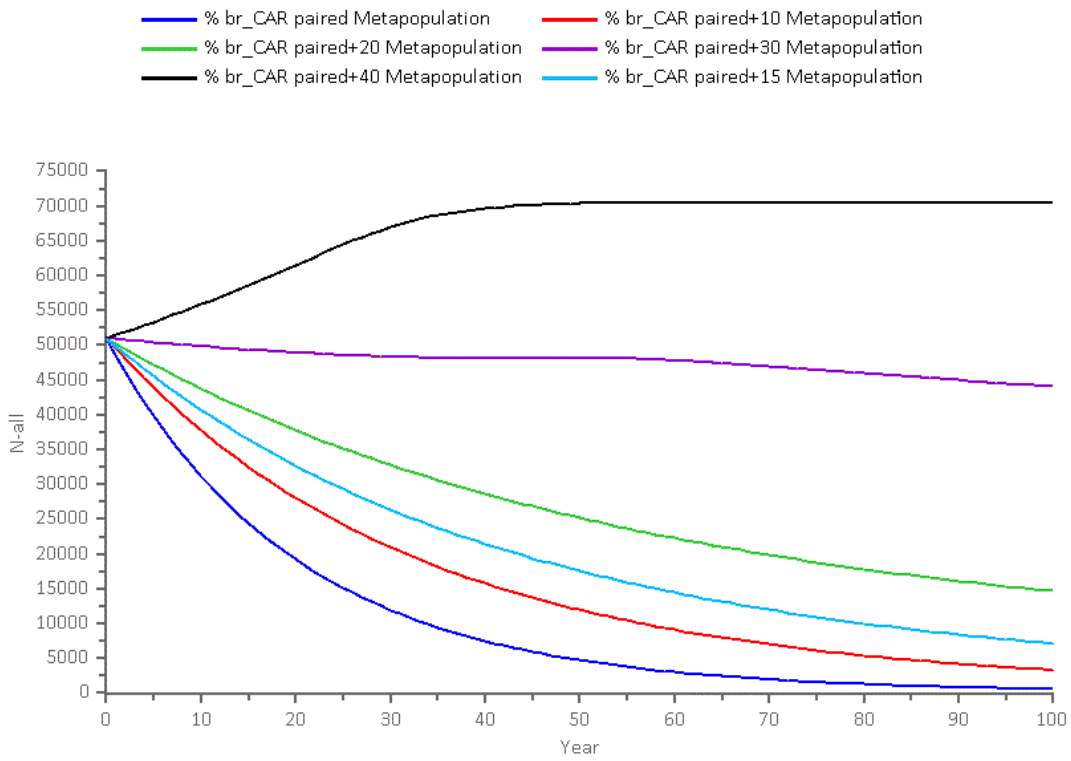
doing counts. It would also be useful to develop an app to make data collection and entry simpler and more user friendly. For example, the Birdlasser app, has allowed the SABAP project to grow substantially, despite facing many of the same challenges faced by CAR. An app would appeal to the younger generation and could potentially bring in a new cohort of counters into the project. The CAR and SABAP projects, would complement insights from expert monitoring e.g., breeding monitoring, flock monitoring and aerial survey counts.

The case of the Blue Crane highlights the complexities in conserving species in transformed landscapes. The species expansion into agricultural habitats aided their recovery, but in the last 10 years, this recovery has faltered. Intensively managed agricultural landscapes are in continual flux, and certain shifts can lead to them becoming ecological traps for species, hampering conservation progress. The silver lining is that species that reside in these landscapes have proven to be adaptable to change, so through a thorough understanding of the species and landscape, conservation action can turn the trend around. With an evidence driven, cross cutting and adaptive approach, there is hope for renewed recovery of the Blue Crane population, as well as other species that have persisted in the Anthropocene.

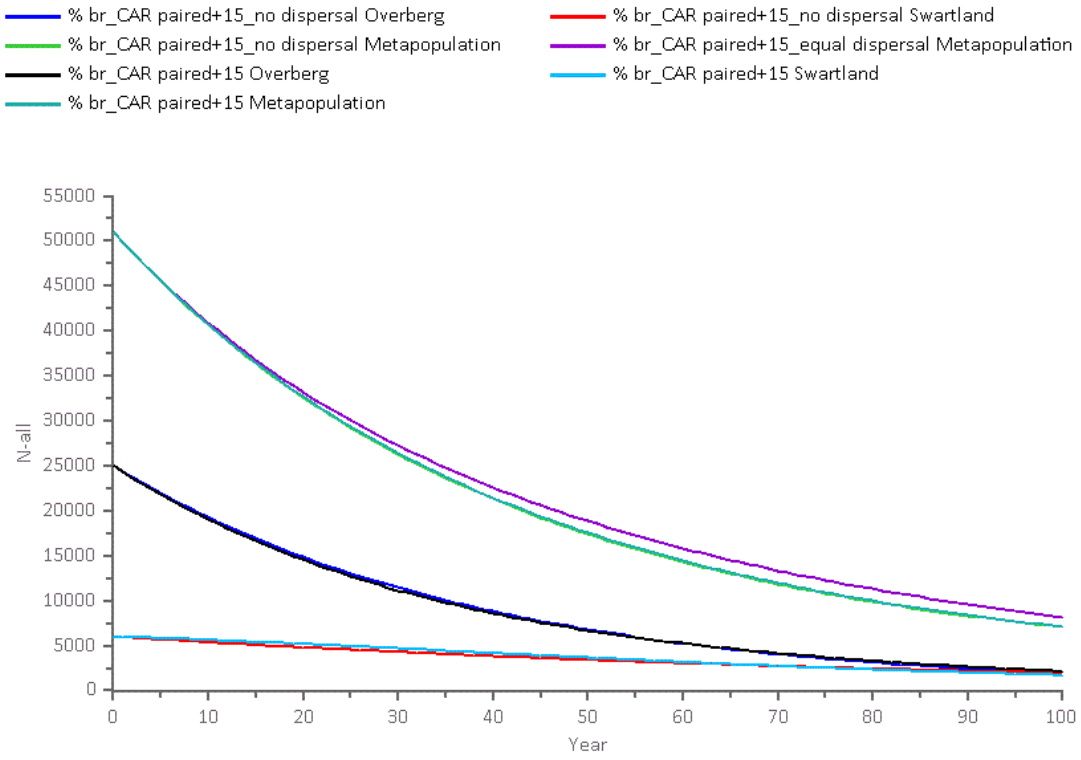
Supplementary Materials

Supplementary Table 1: The outputs of a Vortex population model for Blue Crane, over 100 years, to one significant figure.

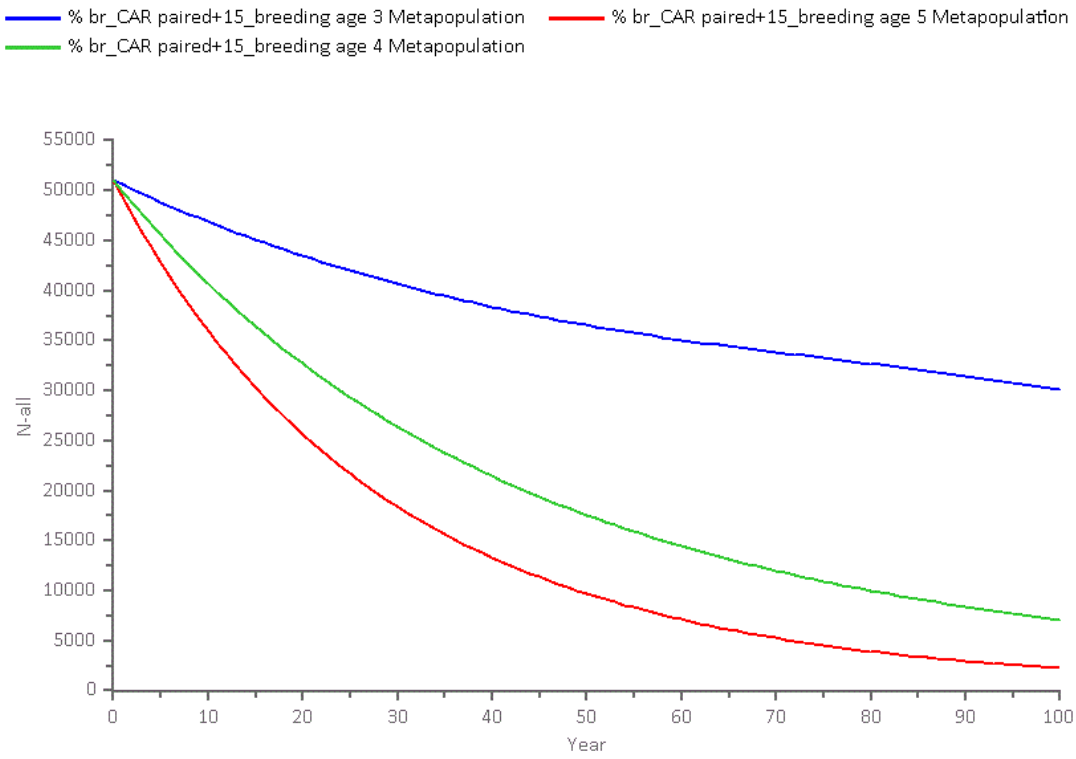
Scenario	CAR % paired + 15				
Population	Overberg	Karoo	Grasslands	Swartland	Metapopulation
Deterministic Growth Rate (r)	–0.03	–0.03	–0.006	–0.01	–0.02
Stochastic Growth Rate (r)	–0.03	–0.03	–0.006	–0.01	–0.02
SD(r)	0.006	0.01	0.02	0.005	0.006
Probability of Extinction	0	0	0	0	0
Number of extant individuals (N)	2098	1159	2151	1673	7080
SD(N)	101	103	320	61	363



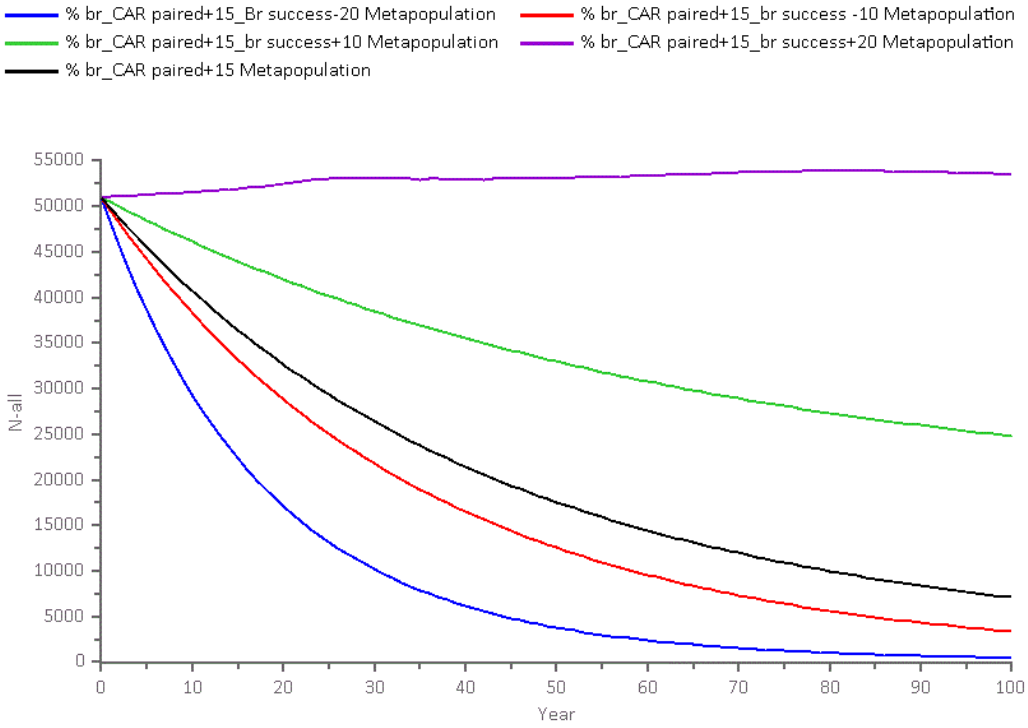
Supplementary Figure 1: The modelled number of Blue Cranes in the metapopulation over 100 years, based on variations in the % adult females breeding, adding 10, 15, 20, 30 and 40 percentage points to the base figure.



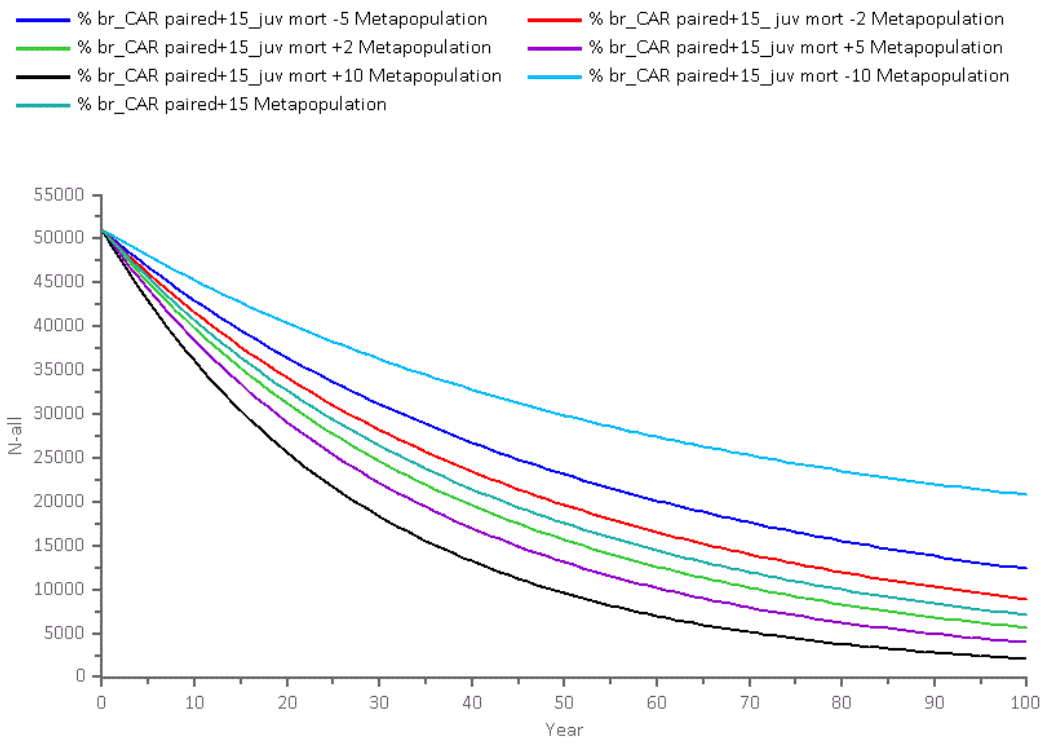
Supplementary Figure 2: The modelled number of Blue Cranes in the metapopulation and each subpopulation over 100 years, based on variations in dispersal: no dispersal and 5% dispersal between all adjacent subpopulations.



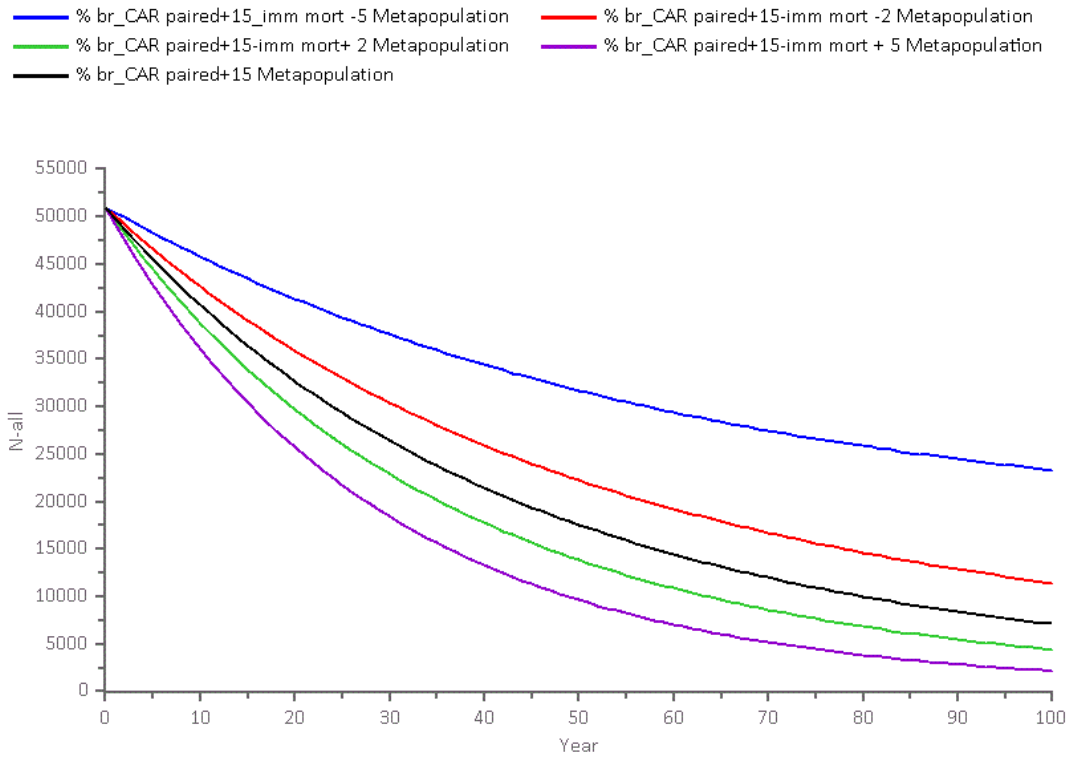
Supplementary Figure 3: The modelled number of Blue Cranes in the metapopulation over 100 years, based on variations in the average age of first breeding, age 3, 4 and 5.



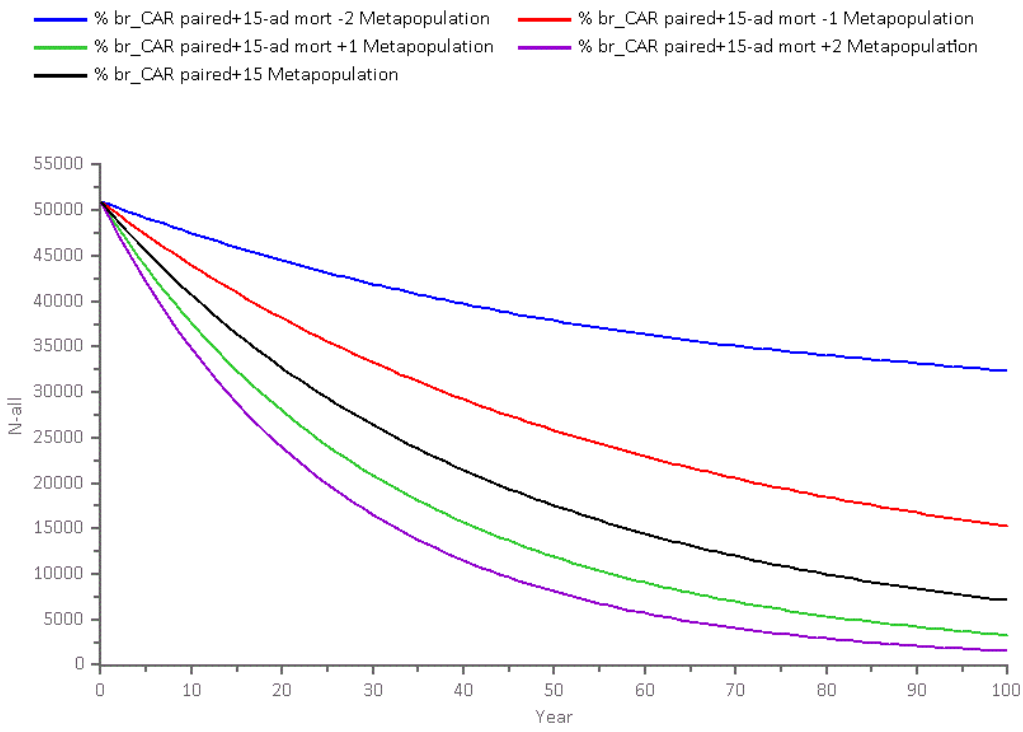
Supplementary Figure 4: The modelled number of Blue Cranes in the metapopulation over 100 years, based on variations in breeding success, adding –10, –20, 10, and 20 percentage points to the base figure.



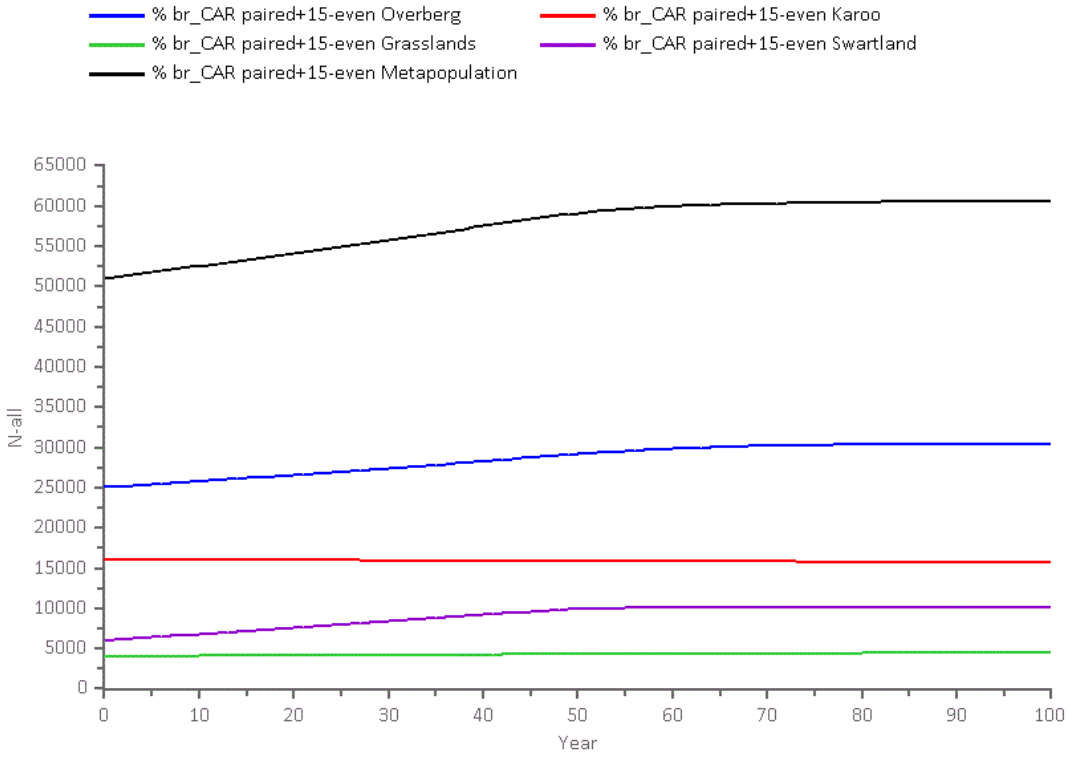
Supplementary Figure 5: The modelled number of Blue Cranes in the metapopulation over 100 years, based on variations in juvenile mortality, adding –10, –5, –2, 2, 5 and 10 percentage points to the base figure.



Supplementary Figure 6: The modelled number of Blue Cranes in the metapopulation over 100 years, based on variations in immature mortality, adding –5, –2, 2, and 5 percentage points to the base figure.



Supplementary Figure 7: The modelled number of Blue Cranes in the metapopulation over 100 years, based on variations in adult mortality, adding –2, –1, 1, and 2 percentage points to the base figure.



Supplementary Figure 8: The modelled number of Blue Cranes in the metapopulation and subpopulation over 100 years, with juvenile and immature mortality adjustments in all subpopulations and breeding success adjustments in the Overberg and Swartland, to produce a positive growth rate.

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Appendix 1: Blue Crane Breeding Productivity and Recruitment

Abstract

Assessing population extinction risk requires a comprehensive understanding of key demographic parameters. This study focuses on Blue Cranes *Anthropoides paradiseus*, a long-term monogamous species, occurring namely in the eastern grasslands, Karoo and Western Cape wheatlands (Overberg and Swartland) of South Africa. The species has been declining in the Western Cape, with the reasons being uncertain. In this study I evaluate breeding productivity and recruitment across their range. I used breeding monitoring data collected by Endangered Wildlife Trust field staff between 2011 and 2021 to assess breeding productivity, and winter flock monitoring data to evaluate juvenile recruitment in the Western Cape. Between 2019 and 2021, the percentage of juveniles in winter flocks was on average 4.0% (range = 2.8–5%) in the Overberg, and 3.6% (3.4–4.0%) in the Swartland. This is more than two times lower than it was in the Overberg 30 years ago. Breeding success is higher in the grasslands (68% of pairs fledge chicks, range = 39–90%, n = 95) and Karoo (67%, range = 56–82%, n = 90), than in the Overberg (40%, range = 36–46%, n = 100) and Swartland 43% (39–50%, n = 63). Swartland pairs fledge two chicks (as opposed to one) half as often as Overberg, grasslands, and Karoo pairs. These are the first data presented on Blue Crane breeding rates in the Swartland, so it is not possible to compare to the past. It is possible that breeding rates are lower because Swartland summers are drier, compared to the rest of the country. These data point to low breeding productivity and recruitment as the reason for the declining population in the Western Cape wheatlands. It would be beneficial to implement interventions which improve breeding productivity and juvenile survival.

Introduction

Key demographic parameters for assessing population extinction risk are population size, fecundity, survival, immigration, and emigration, as well as age structure (Mace et al. 2008; Volis & Deng 2019). In this study I assess Blue Crane *Anthropoides paradiseus* fecundity, as part of a broader assessment of the conservation status of the species. Blue Cranes are a long-term monogamous species, breeding once a year, with pairs beginning to nest from September (Allan 2005). They usually lay 2 eggs, which both parents incubate for 29–30 days (Allan 2005). Once hatched, it takes approximately 12 weeks for chicks to become flighted, and pairs may remain on territory with their chicks for a further 2 months, before joining winter flocks (Allan 2005). Juveniles can be distinguished from adults up until 1 year old, as they lack the long tertial feathers and have a less bulbous head than older cranes (Allan 2005) (Figure 1).

The proportion of juveniles in winter is useful for assessing recruitment into the population. In winter, the proportion of juveniles in Overberg winter flocks ranged between 6.5% and 8.8%, in the Karoo: 13.2–18% (Allan 1993) and the Mpumalanga grasslands: 24.1% (Morrison 1998). In the Overberg, pairs fledged on average 1.06 chicks per year (Aucamp 1993), substantially higher than estimates from Steenkampsberg (Mpumalanga): 0.49 (Morrison 1998) and from the Eastern Cape: 0.25 (Vernon 1991). These estimates date back more than 20 years, and it is possible that there have been changes, especially as the Overberg population has declined (Chapter 2). Here I present updated estimates of breeding productivity (fledglings/pair) for the Karoo, eastern grasslands and Overberg and present the first estimates of breeding productivity for the Swartland. I also give revised estimates of annual juvenile recruitment into the Western Cape wheatlands population.

Figure 1: A juvenile Blue Crane (centre) with its parents, showing the short tertial feathers and less bulbous head shape (Photograph: Ciming Mei).

Methods

I calculated the proportion of juveniles in Western Cape flocks in the over-wintering period to assess annual recruitment of juveniles into the population in the Western Cape. For this I used ad-hoc flock sighting data collected between 1 May and 30 September during 2019–2022 (n = 303 flocks). Blue Crane habitat in the Western Cape is fairly open (Chapter 1), and Blue Cranes are habituated to people in vehicles, therefore I was able to get close enough to differentiate first year birds (juveniles) from older birds (termed adults, even though they include some pre-breeding birds, given that Blue Cranes only start breeding once they are 3–5 years old (Del Hoyo et al. 1996).

Endangered Wildlife Trust field staff follow a standard protocol when monitoring breeding cranes (Endangered Wildlife Trust 2022). Breeding sites are identified when a pair is holding territory at the beginning of the season. Sites are visited at least twice (beginning of season to describe breeding site and end to record outcome i.e., number of fledglings), but usually more. Each breeding site was visited on average 3 (SD 0.5) times throughout the season. The average number of nest site visits did not differ substantially among the four different field officers (range 2.4–3.8 visits per season), since field officers are region specific, this means that visitation rates were comparable across regions.

In the Western Cape I use breeding site monitoring data collected in the Overberg and Swartland between 2018 and 2021, in the grasslands the most recent data was from 2009–2011 and 2013, and in the Karoo between 2009 and 2011 (Figure 2). To calculate the success rates per region, I divided the number of pairs that fledged chicks by the number of pairs monitored for each breeding season and then calculated an average annual success rate across years. This included pairs that held territory but were not seen with a clutch or chicks because site visits were infrequent and thus it was possible to miss clutches that failed. Therefore, I assumed that all pairs that were recorded holding territory during the breeding season made an attempt to breed, even if eggs or chicks were not recorded during a site visit.

I ran a Poisson Generalized Linear Model (GLM) on the breeding data, modelling number of fledglings (0, 1 or 2) per breeding site monitored, as a function of region (Swartland, Overberg, Karoo, Grasslands). To account for the uncertainty around pairs holding territory but not being seen with eggs or chicks, I ran two models. The first model I included all pairs monitored (as above) which gives a conservative breeding productivity estimate as it accounts for both pairs that nested and failed (before the field worker could record it) as well as pairs that held territory but never nested (which would generally be excluded from calculations of breeding productivity). The second model I only included pairs that were confirmed to have

nested (seen with a clutch and/or chicks), which over-estimates breeding productivity. The true breeding productivity estimate likely sits somewhere between these two models.

From these models I got the annual fledging rate for each region by back-transforming (exponentiating) the log estimate for the base category (intercept), and for the other categories back-transforming the intercept + region estimate. I calculated confidence intervals by: exp (Estimate + 1.96 * Standard Error). I then subset the data by region (Karoo, Overberg, Swartland and Grasslands), and ran Poisson GLMs per region to explore whether the number of fledglings differed by year. Data analysis was done in R 4.2.0 (R Core Team 2022).

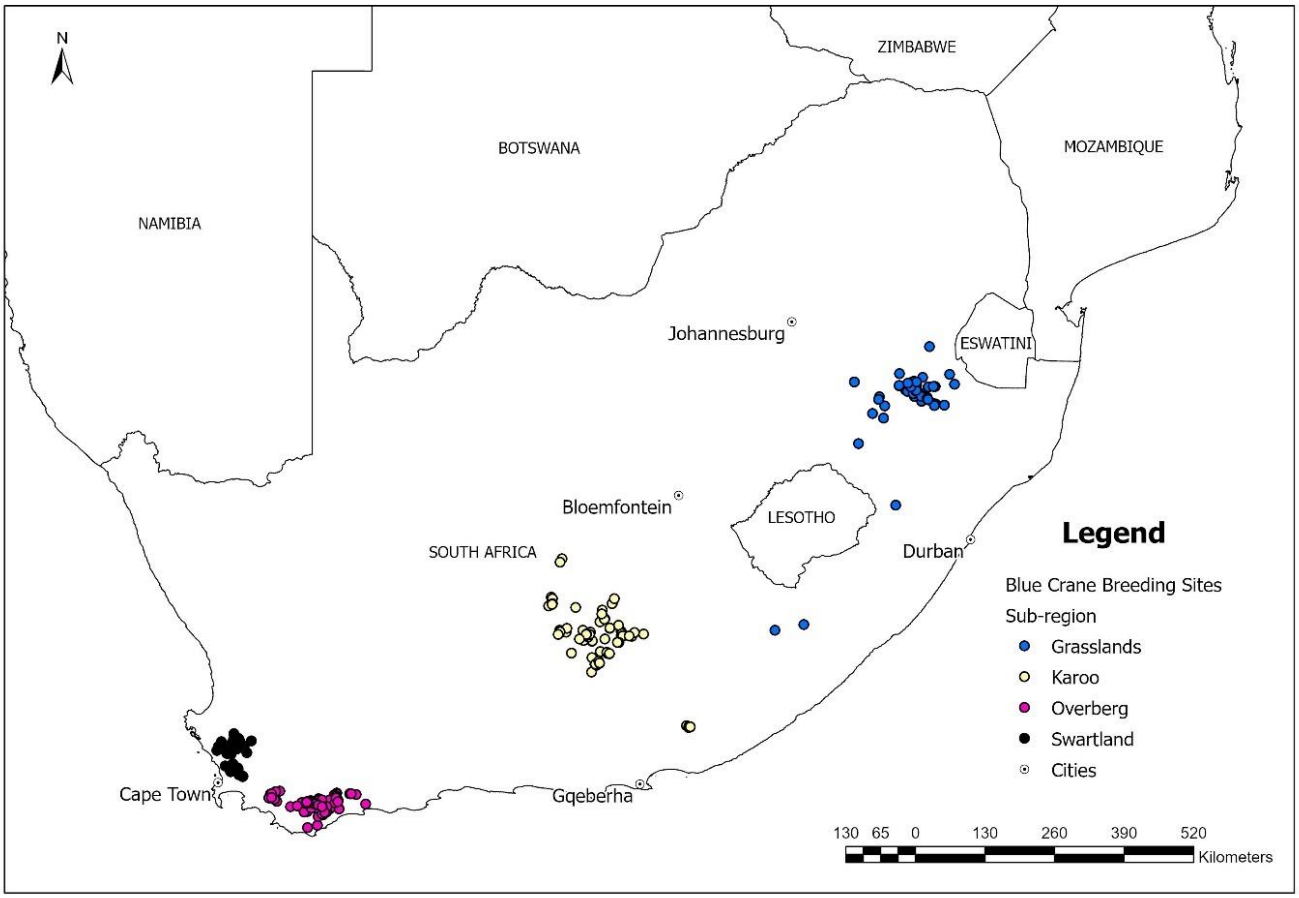

Figure 2: Locations of breeding sites used to determine breeding productivity in grasslands, Karoo, Overberg and Swartland.

Results & Discussion

Between 2019 and 2021, the percentage of juveniles in winter flocks was on average 4.0% (range = 2.8–5%) in the Overberg, and 3.6% (3.4–4.0%) in the Swartland. This is more than two times lower than it was

in the Overberg 30 years ago, more than three times lower than it was in the Karoo (1988–1993) (Allan 1993), and 6 times lower than in the Steenkampsberg region of the grasslands (Morrison 1998).

In the grasslands an average of 68% of pairs fledge chicks each year (range = 39–90%, n = 95), and 67% of Karoo pairs (range = 56–82%, n = 90). In the Western Cape wheatlands this was lower, Overberg pairs fledged chicks 40% of the time (range = 36–46%, n = 100) and Swartland 43% (39–50%, n = 63). This is lower than data from 1989–1993 (Allan 1993), when 60% of Overberg pairs fledged chicks. By contrast, in the Karoo annual success rates tended to be higher, than 53% in 1989–1993 (Allan 1993).

In the Western Cape wheatlands, Overberg breeding pairs fledge two chicks (as opposed to one) twice as often as in the Swartland (Table 1). Compared to 1989–1993, the distribution of fledglings (1 vs 2 chicks) is very similar to what it was 30 years ago in the Overberg: 2 fledglings = 31% (range 12–48%) (derived from Allan 1993) and 31% (derived from Aucamp 1993) (Table 1). Likewise in the grasslands, the proportion of pairs fledging two chicks is the same as historical rates: 40% (1982–1990, n = 10; Allan 1993), or similar: 54% (n = 35) (derived from Morrison 1998) (Table 1). In the Karoo however, there are now more than three times as many pairs fledging two chicks, compared to 1987–1993 (13%, n = 23; Allan 1993) (Table 1). However, the sample sizes from past research were small and may not have been representative.

Table 1: The average % distribution of number of fledglings fledged per successful pair, for the grasslands, Karoo, Overberg and Swartland.

Region	Number of fledglings per pair (%) (SD)	
	1	2
Grasslands	60 (5)	40 (5)
Karoo	55 (8)	45 (8)
Overberg	63 (10)	37 (10)
Swartland	81 (6)	19 (6)

Considering all monitored pairs, breeding success as a function of year did not differ significantly ($p < 0.05$) in the Overberg, Swartland or grasslands, but did differ in the Karoo, with breeding success lowest in the 2011/2012 season (0.6 fledglings per pair, Estimate = –0.5, SE = 0.25, $p = 0.04$). If I exclude pairs that held territory but weren't seen nesting, breeding success did not differ significantly between years in any of the regions ($p > 0.05$).

Annual breeding productivity, modelled as a co-variate of region, was not significantly different ($p > 0.05$) between the grasslands and Karoo, in either model (Table 2), but was significantly lower in the Swartland in both models (Table 2). Breeding productivity in the grasslands was 1.5 times higher than estimates from

Wakkerstroom (1994–2003, Ramke, unpubl data in Allan 2005) and twice as high as estimates from Steenkampsberg (Morrison 1998), indicating a potential improvement in Blue Crane breeding success in this region.

There are no historical breeding data from the Swartland, so mine is the first estimate of breeding productivity for this region. Allan (1993) collected data on Karoo Blue Crane clutch size, brood size and post-fledging recruitment rates, but did not collect data on fledgling rate per pair per year, so the rate I present here is also novel for this region.

In the Overberg, breeding success was significantly lower ($p < 0.05$) than in the Karoo and grasslands when considering all monitored pairs (Table 2). When including only pairs that were confirmed to have nested, breeding productivity was still lower, but this difference was not significant (Table 2). In my study the annual productivity estimates for the Overberg are lower than they were in 1992/3: 1.06 fledglings/pair (Aucamp 1993) but are higher than unpublished estimates from Overberg Crane Group monitoring data 1999–2009 (n=73): 0.3 (SD 0.6) (Vicky Hudson & Kevin Shaw, CapeNature, unpubl data).

Overberg breeding productivity has varied over time, but the mechanisms driving this variation are not clear. The reasons for nest failure in the Overberg include predation, infertile eggs, nest destruction by machinery and nest disturbance (Bidwell 2004; Bouwer 2023). Farmers harvest wheat in October/November and leave it to dry in wind rows before collecting. Blue Cranes that nest between cutting and collecting may lose their clutch if the eggs are crushed when farmers bring machinery back in to pick up the cut wheat.

A recent study (Bouwer 2023) demonstrated that crude hatching success (% pairs that hatch at least one egg) was similar in 2021/22 and 2022/23 compared to 2003/04 (Bidwell 2004), in the western Overberg. Bouwer (2023) found that higher maximum air temperatures and longer time spent off the nest were significant predictors of clutch failure. In 50% of cases, clutch failure was due to predation, mainly by Pied Crows *Corvus albus* (Bouwer 2023). Pairs that spent more time off the nest were more likely to lose their clutch to predation (Bouwer 2023). In this way, disturbance causing parents to leave the nest, increases the risk of predation.

These research studies have improved our understanding of the mechanisms of nest failure, which can guide interventions. Less is known about the rates and reasons for chick mortality; our current understanding is based on anecdotal reports from farmers and personal observations of fence

entanglements, drownings in water troughs, leg abnormalities or starvation (Chapter 4). There is scope for a focused research project to gain clarity on these issues.

For the Swartland, it is not possible to compare current breeding productivity to past breeding success as we do not have the data. It might be that Swartland breeding productivity has always been limited by drier summers compared to the Overberg, which has higher rainfall in summer, particularly in the east (South African Weather Service 2023). Blue Crane chicks need access to water such as a farm dam within walking distance of the nest. In the Swartland, many dams dry out in summer, particularly in drought years.

The two different models (all pairs vs. pairs that confirmed nested) produced similar breeding productivity estimates for the grasslands and Karoo (Table 2), but in the Overberg and Swartland the estimates were quite different, a difference of 0.26 and 0.16 fledglings/pair respectively (Table 2). This suggests that a greater proportion of Overberg and Swartland pairs hold territory but do not nest, compared to the other regions, or that nests more often fail before field workers record them, in the Overberg and Swartland. Given the coarse resolution of these data, it is not possible to elucidate the reasons behind this difference.

The findings in this study point to lower breeding productivity and recruitment for Blue Crane in the Western Cape wheatlands. This is concerning for this stronghold population and might explain why numbers in the Overberg have been declining for the last decade (Chapter 2). It would be beneficial to implement interventions which improve breeding productivity, such as engaging with landowners to reduce nest disturbance and promoting chick-safe water troughs (stacking rocks to allow chicks to climb out).

Table 2: Model coefficients for the two models of Blue Crane breeding productivity across four regions, fledging rate as per the model and the sample size for each region.

Region	Overberg	Swartland	Karoo	Grasslands
Model: All monitored pairs				
Estimate	–0.55	–0.62	0.05	–0.05
SE	0.17	0.21	0.15	0.11
p	0.001	0.002	0.72	0.61
n	100	63	90	95
Fledglings/pair (95% CI)	0.55 (0.42–0.80)	0.48 (0.34–0.75)	1 (0.79–1.55)	0.95 (0.86–1.30)
Model: Pairs that nested				
Estimate	–0.22	–0.46	0.01	0.01
SE	0.17	0.12	0.15	0.11
p	0.2	0.03	0.94	0.91
n	70	50	88	89
Fledglings/pair (95% CI)	0.81 (0.57–1.12)	0.64 (0.42–0.95)	1.02 (0.76–1.35)	1.01 (0.82–1.24)

Appendix 2: Farmer Views on Agricultural Change and Blue Cranes in the Western Cape Wheatlands

Abstract

Conservation of species residing on privately-owned agricultural land requires a holistic understanding of landowner views and the agricultural system. In the Western Cape Blue Cranes *Anthropoides paradiseus* occur on intensively farmed agricultural land, and therefore the population is impacted by farmer decisions. I conducted interviews with farmers in the Overberg (n = 20) and Swartland (17) in June 2019 and June 2021, to understand climate change adaptation strategies, agricultural change and attitudes to Blue Cranes and their conservation. The main agricultural change in the last few decades has been a switch to minimum till, or conservation farming, a trend which is to increase, as it was cited by farmers as their main climate change adaptation strategy. Minimum till is one of three pillars of conservation agriculture, which are minimum soil disturbance, maintaining soil organic cover (leaving stubble on the land or cover crops) and using crop rotation. Many of these practices should benefit cranes, although increased reliance on chemicals for weed and pest control may be detrimental. Many farmers experience crop damage from rodents and geese, and the use of rodenticide to control rodents is widespread. Some farmers are aware of poison being used for geese in their area, despite it being illegal. A greater conservation presence is needed in this landscape to curb these practices, and to encourage responsible pest control. Overall, the interviewed farmers had positive attitudes towards Blue Cranes on their farms, 62% of farmers got the highest possible attitude score for these attitude statements. Despite this positive attitude, overall farmer attitudes towards Blue Crane conservation initiatives were only mildly positive, mainly because most farmers believe that Blue Cranes are doing well in the area. This information can guide future conservation approaches; it is possible that a more integrated approach, where interventions have multiple goals, could be effective. For example, assisting farmers find solutions for crop damage by geese and rodents, would be beneficial to farmers and biodiversity, including cranes.

Introduction

Conservation of species residing on privately-owned agricultural land requires a holistic understanding of landowner views and the agricultural system. In the Western Cape Blue Cranes *Anthropoides paradiseus* mostly occur on intensively farmed agricultural land. Crops such as wheat, barley, oats and canola are planted for harvest in rotation with nitrogen fixing plants such as lucerne, medics and lupins, used for grazing small stock. The Western Cape is a winter rainfall area, so crops are sown in autumn, they grow

over winter and are harvested in October/November. Blue Cranes prefer short vegetation; in these landscapes they are found in pastures, harvested crop fields and early-stage crop fields, but avoid mature crops as they are too tall (Chapter 2). On some crop fields at certain times of year there is potential for crane/farmer conflict. A study exploring the issue of cranes and crop damage through farmers interviews found Overberg farmers to be more tolerant of cranes, than Swartland farmers, largely due to Blue Cranes damaging sweet lupin plants, which are more commonly planted in the Swartland (van Velden et al. 2016b). These interviews touched briefly on the topic of climate change and found that 60% of Swartland farmers reported shorter, later or lower rain during winter, and 40% of Overberg farmers reported more intense rainfall, shorter rainfall or higher temperatures (van Velden et al. 2016b). To gain further insights into these issues, I conducted interviews with farmers in the Overberg and Swartland, to understand climate change adaptation strategies, agricultural change and attitudes to Blue Cranes and their conservation.

Methods

To gather insights into the agricultural context, agricultural change and climate change adaptation I conducted interviews with 20 Overberg and 17 Swartland farmers in June 2019 and June 2021, under human ethics clearance number FSREC 57 – 2019. All participants read and signed an informed consent form (S1), and all data were anonymised (farmer names and farm names were not attached to the surveys). Farmers had the choice of being interviewed in Afrikaans or English; 86% chose to be speak in Afrikaans or a mixture of the two. Most interviews were with one participant, but in three cases I interviewed two people at once (farmer and wife, or co-owners).

Interviews typically lasted one hour, and took place mainly at the farmer's house, except for one which was over the phone. I used a snowball recruitment technique, starting with farmers I knew, or was introduced to, and then recruiting new participants by asking participants to refer me to other farmers who might be prepared to be interviewed. The initial survey in 2019 included 59 questions (S2), but this was reduced/refined in 2021 to 43 questions (S3). The survey included a mixture of open-ended and close ended questions and statements with a Likert scale to assess attitudes towards Blue Cranes (S2 & S3). The scale was designed to assess farmer attitudes to Blue Cranes on their farm (3 statements, S3: Questions 33, 35, 37), and attitudes to the conservation of Blue Crane in the Overberg and Swartland (3 statements, S3: Questions 31, 34, 36). The Likert statements had three possible answers (disagree: –1, neutral: 0, agree 1). To summarise attitudes, I summed the numbered responses for the three questions to assess whether the overall attitude was positive or negative, and the strength of the attitude e.g. –3 would be a strongly

negative attitude, whereas –1 would be a weakly negative attitude, and 3 is a strongly positive attitude. Since the statements assessing attitudes to Blue Cranes on farms were worded negatively (e.g. “Blue Cranes are becoming too numerous in the Western Cape”), I multiplied these scores by –1 to reverse the score, so that positive scores indicated positive attitudes. I then averaged the scores per farmer for each region.

I used NVivo software to categorise the answers to open-ended questions into themes, relating to agricultural change, drought, climate change and challenges in farming. I chose four topics *a priori* to code themes within: “Agricultural change, past to present” (v1 Questions 22 & 25/v2 Questions 21 & 24), “Observed climate change” (v1 Questions 30–32/v2 Question 29), “Climate change adaptation strategies (v1 Questions 29–32/v2 Questions 28 & 30), and “Future agricultural change” (v1 Questions 23 & 26/v2 Questions 22 &25).

Results & Discussion

Overall, the interviewed farmers had positive attitudes towards Blue Cranes on their farms (average score = 2.1), 62% of farmers got the highest possible attitude score for these attitude statements (a score of 3). Only 11% of farmers had a negative attitude towards Blue Crane, and this was mildly negative. Reasons given for negative attitudes towards Blue Cranes were that they created disturbance at their sheep feed troughs and damaged lupin crops, which is consistent with findings by van Velden et al. (2016b). Despite this positive attitude, overall farmer attitudes towards Blue Crane conservation initiatives were only mildly positive (average score: 0.9, where range is –3 to 3). The reasons cited for negative attitudes to Blue Crane conservation (16% of farmers interviewed) were that Blue Cranes do well in the area, nothing harms them, and that there were other species that were scarcer. Reasons cited in support of Blue Crane conservation presence is that it is good to know what is going on, awareness is needed, and advice on how to handle crane damage would be useful. This information can guide future conservation approaches; it is possible that a more integrated approach, where interventions have multiple goals, could be effective. For example, assisting farmers find solutions for crop damage by geese and rodents, would be beneficial to farmers and biodiversity, including cranes.

In the Overberg, 10 out of 16 farmers (who answered this question) had seen Blue Cranes entangled in fences in the last 2 years, compared to 6 out of 15 farmers in the Swartland. Overberg farmers reported an average rate of fence entanglement of 0.8 cranes on their farm per year, compared to 0.1 cranes per farm per year in the Swartland. This is the first attempt to estimate fence entanglement rates in Blue Cranes. One farmer in the Swartland reported that they had regrettably poisoned two Blue Cranes when targeting

francolins with poison baits. Three other farmers said that they have heard of farmers using poison to limit crop damage by geese and guineafowls, but also Blue Cranes when congregated in large flocks on new crops. Using poison to kill birds is illegal (with a few exceptions), as it involves the use of insecticides off-label, and in the case of Blue Cranes, involves killing a threatened and protected species, both of which contravene the South African National Management Biodiversity Act Threatened or Protected Species Regulations (2007) and the Western Cape Nature Conservation Laws (2000). In the last two years two Blue Crane poisoning cases have been reported in the Overberg (Overberg Crane Group 2022, 2023), but it is likely that many other cases are not being reported. A greater conservation presence is needed in this landscape to curb these practices.

The use of rodenticide for rodents, used appropriately, is legal, and this practice was commonplace amongst the farmers interviewed, for the prevention of crop damage. Rodent baits can be attractive to birds, including Blue Cranes, depending on the types of baits used e.g., grain, and where they are set e.g. on the ground or in the burrow. One farmer said they took measures to ensure that birds could not reach rodent baits (plastic boxes with mouse sized holes). Several farmers use owl boxes for rodent control, but many said owls alone were not sufficient to control rodent populations. There is a great need to find alternative solutions for crop damage (by birds and rodents in the Overberg and Swartland), and to encourage responsible poison use by farmers.

Among farmers interviewed, the most commonly perceived change in agriculture in the last few decades, was the use of minimum till practices, technology and precision farming (Table 1). Minimum till is one of three pillars of conservation agriculture, which are minimum soil disturbance, maintaining soil organic cover (leaving stubble on the land or cover crops) and using crop rotation (Swanepoel et al. 2017). These practices are done to conserve soil fertility and moisture, improve yields and secure carbon in the soil (Swanepoel et al. 2017). Prior to conservation agriculture, farmers would till before planting and after harvesting to control weeds and pests, and many farmers would burn the stubble after harvesting. With conservation agriculture, farmers rely more on chemical treatments to control weeds and pests. Interest in and uptake of conservation agricultural practices have increased over the last 20 years (Swanepoel et al. 2017; Smith 2021; Strauss et al. 2021). In 2021 the adoption rate in the Western Cape is at 51%, up from 36% in 2015 (Swanepoel et al. 2017; Smith 2021; Strauss et al. 2021). It seems likely that conservation agricultural practices have been beneficial for Blue Cranes. Habitat is provided through the use of pastures in crop rotation and less tilling/burning in crop fields likely benefits breeding cranes (Cunningham et al. 2004; Holland 2004; Bedano et al. 2016). Increased organic cover in stubble fields increases macroinvertebrates in the soil, which cranes would eat, along with fallen grains (Cunningham et al. 2004;

Holland 2004; Bedano et al. 2016). The increased use of agrochemicals might be detrimental to cranes (e.g. macaques in Malaysian palm oil plantations; Holzner et al. 2024), but we do not know what impact this has. We do not know how or whether conservation agriculture has contributed to Blue Crane population trends in the Western Cape wheatlands. Blue Crane numbers were increasing steadily when conservation agriculture first took off, in the late 1990s (Strauss et al. 2021), but the increasing trend began to taper off (Swartland) and decline (Overberg) (Chapter 2) as conservation agriculture became mainstreamed in the 2010s. It is highly likely that the uptake of conservation agriculture will continue to increase, and we need to understand how these practices impact Blue Cranes. The organisation Conservation Evidence (Williams et al. 2020b) reviewed studies (in Europe and the USA) on the impact of reduced tillage on farmland bird communities, and found mixed results, but reduced tillage typically supports higher nesting densities of ground nesting birds than regular tillage (Basore et al. 1986; Lokemoen & Beiser 1997; Field et al. 2010).

When asked about future change in agriculture, 15 farmers raised the issue of land reform, 14 predicted that technology will become more relevant in the future and 10 raised the issue of climate change (Table 1). When asked specifically about climate change, the most commonly observed response was that the winters had become shorter, and the rain was arriving later (Table 1). In terms of climate change adaptation, the most common strategy/planned strategy would be to rely on new cultivars, technology (e.g. smart seeders that measure carbon and moisture while planting) and to use minimum till strategies to save moisture in the soil (Table 1). Ten farmers indicated that having good livestock feed reserves is important when conditions are drier to ensure adequate grazing. For this reason, 6 farmers indicated that to adapt to drier conditions they would plant more crops and reduce their livestock component (Table 1). However, nine farmers said they would do the opposite, i.e., diversify their income and reduce risk by increasing their livestock component or other income streams such as tourism (Table 1).

One emerging trend in the Overberg, where there is more summer rainfall, is the use of summer cover crops (e.g. sorghum, teff) (Strauss et al. 2019). A tall crop such as sorghum would not be suitable for Blue Cranes, so if these crops became widespread, they could reduce available breeding habitat. However, overall, there are no indications from farmers, agricultural researchers (Johan Strass, Western Cape Department of Agriculture, pers. comm), or the literature (Bradley et al. 2012; Estes et al. 2013) that the Western Cape agricultural system will change fundamentally in the face of climate change, or socio-economic change. In turn this would mean that the agricultural habitat that Blue Cranes depend on is secure, provided agricultural practices are in alignment with Blue Crane conservation.

Table 1: Quantification of themes identified under each topic during qualitative interviews, including all 37 interviews.

Themes	Number of times themes mentioned in interviews
Agricultural change: past to present	
Climate change more of an issue	5
Crime & security more of an issue	4
Livestock operations have intensified	4
Farming has intensified/scaled up	5
Farmers have less livestock, sow more	6
More use of minimum-till	27
Farmers are more conservation aware	6
Farmers have more financial pressure	8
There has been no change	3
There has been socio-political change	8
More technology, precision farming	10
Observed climate change	
Drier	2
Hotter	2
Later rain, shorter rainy season	12
Rain more intense	2
Variability	2
Climate Change Adaptation Strategies	
Companion crop/cover crop	3
Cultivars/technology	13
Diversify-mixture of livestock, crops, tourism	4
Increase cash crops, reduce livestock	4
Continuous cropping	1
Irrigation	1
Become less intensive/move to livestock (rather than crops)	5
Sow less hectares	3
Minimum till	11
Move to a different crop	1
Plant later	4
Reduce livestock	2
Stock up on livestock feed	10
Time lambing later so there is enough grazing	1
Future agricultural change	
Amalgamate farms/mega farmers	1
Climate change will become of an issue	10
Conservation & environmental concerns will become more relevant	5
Crime	2
Financial pressure will intensify	7
Labour challenges will intensify	4

More chemicals will be used	2
Farmers will sow more crops/ have less livestock	4
There will be more diseases & weeds	1
Farmers will have more livestock & be less intensive	1
Will be more minimum till	9
Will move away from minimum till	1
Politics & land reform will become an issue	15
Farming will scale up	5
Farming will stay the same	1
Technology will increase	14
Tourism will become more relevant	1

Supplementary Materials

S1: Informed consent form: Afrikaans

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Ingeligte Vrywillige Toestemming om deel te neem aan Navorsingstudie

Projek Titel: Bloukraanvoel en Landbou.

Uitnodiging om deel te neem, en voordele: U word uitgenooi om deel te neem aan 'n navorsingsstudie wat met Wes-Kaapse boere gedoen is. Die doelwit is om huidige en toekomstige boerderypraktyke in die Wes-Kaap beter te verstaan. Ek glo dat u boerdery ervarings 'n waardevolle bron van inligting sal wees. Ons sal hierdie inligting gebruik om te voorspel hoe Bloukraanvoëls kan aanpas by veranderinge in hul omgewing. Deur u unieke kennis van die landskap te gebruik, kan ons meer ingeligte besluite neem oor hoe om Suid-Afrika se nasionale voël te bewaar.
Prosedures: Tydens hierdie studie sal u gevra word om u gedagtes oor boerdery in die Wes-Kaap en u ervarings met voëls op u plaas te deel.
Opname: Met u toestemming mag ons moontlik die onderhoud klankbaan opneem as deel van die studie. Dit is sodat die navorser kan terug verwys en die onderhoud akkuraat kan neerskryf. Niemand behalwe vir die navorser sal na die opname luister nie. Wanneer die klank afgeskryf word, sal dit met 'n nommer aangeteken word, dus dit is heeltemal anoniem. As u nie wil opgeneem word nie, dui dit asseblief aan in die spasie onder aan die bladsy.
Vrywaring / Onttrekking: U deelname is heeltemal vrywillig; u mag weier om deel te neem, en u mag enige tyd terugtrek sonder om 'n rede en sonder enige vooroordeel of straf teen u te stel. Indien u kies om te onttrek, verbind die navorser om nie enige van die inligting wat u verskaf het, te gebruik sonder u toestemming nie.
Vertroulikheid: Alle inligting wat in hierdie studie ingesamel word, sal privaat gehou word. U sal nie op naam of deur u plaasnaam geïdentifiseer word nie. As u in die navorsingspublikasies aangehaal word, sal u naam of plaasnaam nie gebruik word nie. Op hierdie manier word enigiets wat u sê, vertroulik gehou (net aan ons bekend) en anoniem (in enige publikasies wat hierdie navorsing volg).
Om hierdie vorm te teken beteken die volgende:
Deur hierdie toestemmingsvorm te teken, stem u in om deel te neem aan hierdie navorsingsstudie. Die doel, prosedures wat gebruik gaan word, asook die moontlike risiko's en voordele van u deelname, is mondelings aan u verduidelik, met behulp van hierdie vorm. Weiering om enige tyd aan hierdie studie deel te neem of te onttrek, sal op geen manier ‘n effek op u hê nie. U is vry om my te kontak, om vrae te vra of verdere inligting te versoek, te enige tyd gedurende hierdie navorsing.

Ek stem in om deel te neem aan hierdie studie (tick ‘n boks) ☐ Ja ☐ Nee_____ (Voorletters)
Ek stem in vir die onderhoud om opgeneem te word ☐ Ja ☐ Nee_____ (Voorletters)
Ek stem in om anoniem in webwerwe en publikasies vir navorsingsdoeleindes aangehaal te word (Voorletters) ☐ Ja ☐ Nee_____

_____	_____	_____
Naam van deelnemer	Handtekening van deelnemer	Datum
_____	_____	_____
Naam van navorser	Handtekening van navorser	Datum

S2: Survey used for farmer interviews: Version 1 used in 2019 (changed/deleted questions in grey along with reason)

Region:	Interview no.	Gender:
Interviewer:	Interview Language:	Date:
Recording number:	Place of interview:	Method of recruitment:
What year were you born?	Time start	Time end

1.) Ek besit / bestuur / huur / of is a gedeeltelike eienaar
What is your position on the farm? (manager/owner/part-owner)

2.) Watter jaar het u hier begin boer?
What year did you start farming here?

If owner:

3.) Het u die plaas ge-erf?
Did you inherit the farm?

If inherited:

4.) Hoe lank is die plaas in u familie se besit?
How long has it been owned by your family?

5.) Gee asb vir ons n aanduiding van die persentasie van verskillende grond gebruik op die plaas - gebruik die tabel hieronder
Please give us a breakdown of the percentage of each land-use on your farm

Land use / Grond gebruik	% van die hele plaas van elke tipe grond gebruik % of whole farm of each land use
Graan gewasse (gars/rog/ koring/ hawe) Cereals (barley/rye/wheat/oats)	
Kanola / Canola	
Droë lande - nie besproei nie/ Dryland pasture (not irrigated)	
Besproeide grond/ Irrigated pasture	

Ongebruikte lande/ Fallow	
Groente/Vegetables	
Wingerde/Vineyards	
Ander – spesifiseer asb	

6.) Hoe groot is die plaas in hektaar?
What is the size of the farm in hectares?

7.) Is dit die enigste plaas wat aan u behoort?
Is this your only property?

8.) Huur u van 'n ander boer of grond eienaar ? Of huur u aan 'n ander boer ?
Are you renting out property to another landowner? Or do you rent property from an adjacent landowner?

9.) Watter rotasie sisteem volg u?
What rotation system do you follow?

If plant grain:

10.) Watter metode gebruik u om graan te plant - wees asb spesifiek.
What method do you use to plant grain? (*if clarification is needed, use examples: by planter, or broadcasting*)

11.) Boer u met vee of met wild? Watter soort?
Do you farm with livestock or game? What type?

12.) Het u Bloukraanvoëls op u plaas?
Do you have Blue Cranes on your farm?

13.) Sien u net broei pare of net swerms of sien u beide swerms en broei pare?
Do you see breeding pairs only, flocks only or both breeding pairs and flocks?

14.) Gedurende watter seisoen is hulle op die plaas?
What season/s do you see them?

15.) Dink u die Swartland Bloukraanvoël populasie in besig om te verhoog, of te verminder, of bly hulle die selfde? Hoekom?

Do you think the Blue Crane population in the Swartland is increasing/decreasing or staying the same? Why?

16.) Bloukraanvoël verstrengel soms in heinings, het dit al op u plaas voorgekom?

Sometimes Blue Crane get caught in fences, have you seen this on your farm?

17.) Indien Ja, hoeveel Bloukraanvoëls het u op heinings in die afgelope twee jaar gevind?

If yes: How many Blue Cranes have you found stuck on fences in the past 2 years?

18.) Oor die algemeen hoeveel vee water krippe het u op die plaas?

Approximately how many livestock water troughs do you have?

19.) Hoeveel van die krippe het heel jaar water?

Approximately how many have water throughout the year?

20.) Kry u enige natuurbewaring raad of ondersteuning in u area (bv. Regerings departement of Nie vir-wins-organisasie)

Do you get any nature conservation support or advice (govt. or NGO) in your area?

21.) Is u tans betrokke by bewarings aktiwiteite op u plaas? (bv uitwissing van indringer plante, die voogdyskap program of beskerming van Renosterveld)

Are you involved in any conservation activities on your farm? Such as stewardship, Renosterveld protection, alien clearing?

22.) Hoe boer u verskillend van die vorige geslag?

How is the way you farm different to how the previous generation farmed?

23.) Hoe dink u sal die volgende geslag anders as u boer?

How do you think farming methods of the next generation will be different to yours?

24.) Wat is die hoof uitdagings vir u as n boer?

What are the main challenges that you face as a farmer?

25.) Hoe verskil die van uitdagings wat die vorige geslag het?

How do these differ from the challenges faced by the previous generation of farmers?

26.) Wat dink u sal die uitdagings wees vir die volgende geslag?

What challenges do you think the next generation of farmers will face?

27.) Wanneer laas het u droogte op die plaas gehad. Hoe lank was die droogte gewees?

When did you last experience drought on your farm? How long did it last?

28.) Hoe het dit u geaffekteer?

How did it affect you?

29.) Gedurende 'n soortgelyke droogte sou u boerdery praktyke verander?

If there was another drought like that, how would you adjust your farming?

30.) Indien winter reënval permanent laer word , hoe sou u boerdery praktyke verander ?

If winter rainfall was to be permanently lower, how would you adjust your farming?

31.) Indien toekomstige reën later en later in die seisoen val , hoe sou u boerdery praktyke verander?

If the rain was to always arrive later how would you adjust your farming?

32.) Indien die reënval seisoen permanent korter word, hoe sou u boerdery praktyke verander?

If the rainy season was to become permanently shorter, how would you adjust your farming?

these three questions are repetitive- got a lot of the same answers. Rather ask "Have you noticed any climate changes" and "how would you adapt your farming practices for them"

Attitude statements (Disagree, Neutral, Agree)

33.) Ek dink dat die Overberg en Swartland 'n belangrike rol speel in die bewaring van voëls

I think farms in the Overberg & Swartland play an important role in conserving birds

34.) Overberg en Swartland plase is meer effektief om voëls te beskerm in vergelyking met formeel beskermde gebiede

Overberg and Swartland farms are more effective in conserving birds in comparison to protected areas

35.) Ek dink voëls kan beter habitat in beskermde gebiede vind

I think birds can find better habitat in protected areas, than on Overberg & Swartland farms

These questions are too general and confusing to participants- delete and focus just on cranes

36.) Overberg en Swartland plase speel 'n belangrike rol in die voortbestaan van die Bloukraanvoël populasie.

Overberg & Swartland farms play an important role in sustaining the Blue Crane population

37.) Ek dink die Bloukraanvoël populasie in die Wes Kaap stabiel is

*I think the Blue Crane population in the Western Cape is stable -**remove reptetitive***

38.) Ek dink meer fondse en werk moet gerig word om Bloukraanvoëls in hulle natuurlike habitat (Karoo en grasveld) te bewaar as om hulle in die Overberg en Swartland te probeer bewaar.

I think more money and effort should go into conserving Blue Cranes in natural habitat (like the Karoo and grasslands), than into conserving them on Swartland & Overberg farmlands

39.) Ek sal graag meer Bloukraanvoëls op my plaas wil sien

I would like to see more Blue Cranes on my farm

40.) Ek dink dit beter om fondse te spandeer om spesies wat skaarser is as die Bloukraanvoël te beskerm

I think it would be better to spend money on conserving species that are rarer than the Blue Crane

41.) Bloukraanvoëls word te veel in die Wes Kaap

Blue Cranes are becoming too numerous in the Western Cape

42.) Ek dink meer fondse en werk moet gerig wees op die bewaring van Bloukraanvoëls in die Overberg en Swartland.

I think more money and effort should go into conserving Blue Cranes in the Overberg & Swartland

43.) Bloukraanvoëls op my grond maak dit moeiliker vir my om 'n wins op die plaas te maak

The Blue Cranes on my land make it harder for me to make a profit from farming

44.) Ek is bekommerd dat Bloukraanvoëls in die toekoms sal uitsterf

I am concerned that Blue Cranes may go extinct in the future

45.) Bloukraanvoëls het nie 'n impak op my boerdery nie

*Blue Cranes **do not** impact my farming practice- **remove repetititve (irritates participants)***

46.) Ek sou verkies dat daar minder Bloukraanvoëls op my grond moet wees.
I would prefer it if there were fewer Blue Cranes on my farm

47.) Het u probleme gehad met voëls wat skade op die plaas aanrig? Rather say animals (many farmers are bringing up gerbil problems, make question broader to capture this)
Have you had any problems with birds causing damage on your farm?

48.) Watter sort voëls doen die meeste skade, en in watter volgorde?
What birds do the most damage, and in what order?

49.) Wat beskadig hulle? Hoe veroorsaak hulle skade?
What do they damage? And how do they cause damage?

50.) Watter metodes gebruik u om die skade te vermy of te verminder?
What methods do you use to prevent or minimise these damages?

51.) Watter metode werk die beste?
*Which method works the best? – **remove repetitive***

52.) Voer Bloukraanvoëls by u voerbakke?
Do Blue Cranes feed at your livestock feed troughs? (*only ask if not mentioned above*)

If they have crop damage:

In Amerika is daar 'n produk onder die handelsnaam Avipel. Dit bevat 'n bestanddeel genaamd anthraquinone wat die voël laat naar voel as dit ingeneem word. Dit word dus gebruik om plante of saad een keer per seisoen te behandel in a spuit formaat om weiding te ontmoedig. Studies het bewys dat dit hoogs doeltreffend is om voëls af te skrik. Teen oestyd het die bestanddeel ontbind en is nie meer te bespeur in die oes nie. Die bestanddeel het geen permanente newe werking op voëls of die oes nie.
In the US there is a product called Avipel, developed from a non-lethal substance called anthraquinone, which causes digestive discomfort in birds which discourages them from feeding on plants sprayed with it. It is either coated on seeds, to deter birds eating sown seeds or used once per season as a foliar spray to deter grazing. Studies have shown it to be effective in reducing bird herbivory on various crops and seeds. Studies have also shown that by harvest time the concentration of the chemical on the plant is negligible, therefore it is unlikely to affect palatability of the crop to livestock or people.

53.) Stel u belang om hierdie produk te probeer?

Would you be interested in trying this product? Rather say buying

54.) Vir watter soort gewasse?

For which crops?

55.) Hoeveel is u bereid om vir die produk te betaal per hektaar?

How much would you be willing to pay per hectare for this product?

Remove- farmers found hard to answer and limited value to question

Ask only if comfortable

56.) Dink u dat u dalk die plaas in die nabye toekoms sal verkoop?

Do you have plans to sell the farm in the near future?

57.) Indien wel , in hoeveel weke / maande / jare se tyd.

If yes…When do you plan to sell?

58.) Wat motiveer u om dit te verkoop of laat dink aan verkoop?

What has influenced your decision to sell?

Remove these questions - made farmers uneasy

59.) Stel u belang om die uitslae van die navorsing te ontvang?

Are you interested in getting a copy of the research results?

S3: Survey used for farmer interviews version 2 (used in 2021)

Region:	Interview no.	Gender:
Interviewer:	Interview Language:	Date:
Recording number:	Place of interview:	Method of recruitment:
What year were you born?	Time start	Time end

Farming/farmer context

1.) Ek besit / bestuur / huur / of is a gedeeltelike eienaar

What is your position on the farm? (manager/owner/part-owner)

2.) Watter jaar het u hier begin boer?

What year did you start farming here?

If owner:

3.) Is dit 'n familieplaas? Het u die plaas ge-erf?

Is this a family farm? i.e. did you inherit the farm?

If inherited:

4.) Hoe lank is die plaas in u familie se besit?

How long has it been owned by your family?

5.) Hoe groot is die plaas in hektaar?

What is the size of the farm in hectares?

6.) Is dit die enigste plaas wat aan u behoort?

Is this your only property?

7.) Huur u van 'n ander boer of grond eienaar ? Of huur u aan 'n ander boer ?

Are you renting out property to another landowner? Or do you rent property from an adjacent landowner?

8.) Gee asb vir ons n aanduiding van die persentasie van verskillende grond gebruik op die plaas - gebruik die tabel hieronder

Please give us a breakdown of the percentage of each land-use on your farm

Land use / Grond gebruik	% van die hele plaas van elke tipe grond gebruik % of whole farm of each land use
Graan gewasse (gars/rog/ koring/ hawe) Cereals (barley/rye/wheat/oats)	
Kanola / Canola	
Droë lande - nie besproei nie/ Dryland pasture (not irrigated)	
Besproeide grond/ Irrigated pasture	
Ongebruikte lande/ Fallow	
Groente/Vegetables	
Wingerde/Vineyards	
Ander – spesifiseer asb	

9.) Watter rotasie sisteem volg u?

What rotation system do you follow?

10.) Boer u met vee of met wild? Watter soort?

Do you farm with livestock or game? What type?

Blue Cranes on the farm

11.) Het u Bloukraanvoëls op u plaas?

Do you have Blue Cranes on your farm?

12.) Sien u net broei pare, of net swerms of sien u beide swerms en broei pare?

Do you see breeding pairs only, flocks only or both breeding pairs and flocks?

13.) Dink u die Swartland Bloukraanvoël populasie in besig om te verhoog, of te verminder, of bly hulle die selfde?

Do you think the Blue Crane population in the Swartland is increasing/decreasing or staying the same? Hoekom/Why?

14.) Bloukraanvoël verstrengel soms in heinings, het dit al op u plaas voorgekom?

Sometimes Blue Crane get caught in fences, have you seen this on your farm?

15.) Indien Ja, hoeveel Bloukraanvoëls het u op heinings in die afgelope twee jaar gevind?

If yes: *How many Blue Cranes have you found stuck on fences in the past 2 years?*

16.) Voer Bloukraanvoëls by u voerbakke?

Do Blue Cranes feed at your livestock feed troughs?

17.) Oor die algemeen hoeveel vee **water** krippe het u op die plaas?

*Approximately how many livestock **water** troughs do you have?*

18.) Hoeveel van die krippe het heel jaar water?

Approximately how many have water throughout the year?

19.) Kry u enige natuurbewaring raad of ondersteuning in u area?

Do you get any nature conservation support or advice in your area?

20.) Is u tans betrokke by natuur bewarings aktiwiteite op u plaas?

Are you involved in any nature conservation activities on your farm?

Changes in agriculture

21.) Hoe boer u verskillend van die vorige geslag?

How is the way you farm different to how the previous generation farmed?

22.) Hoe dink u sal die volgende geslag anders as u boer?

How do you think farming methods of the next generation will be different to yours?

23.) Wat is die hoof uitdagings vir u as n boer?

What are the main challenges that you face as a farmer?

24.) Hoe verskil die van uitdagings wat die vorige geslag het?

How do these differ from the challenges faced by the previous generation of farmers?

25.) Wat dink u sal die uitdagings wees vir die volgende geslag?

What challenges do you think the next generation of farmers will face?

26.) Wanneer laas het u droogte op die plaas gehad. Hoe lank was die droogte gewees?

When did you last experience drought on your farm? How long did it last?

27.) Hoe het dit u geaffekteer?

How did it affect you?

28.) Gedurende ‘n soortgelyke droogte sou u boerdery praktyke verander?
If there was another drought like that, how would you adjust your farming?

29.) Het u enige langtermynveranderinge in die klimaat in u streek opgemerk?
Have you noticed any long term changes in the climate in your region?

30.) Hoe het dit u boerdery beïnvloed?
How has this affected your farming operations?

Attitudes to cranes (Disagree, Neutral, Agree)

31.) Overberg en Swartland plase speel ‘n belangrike rol in die voortbestaan van die Bloukraanvoël populasie.
Overberg & Swartland farms play an important role in sustaining the Blue Crane population

32.) Ek dink meer fondse en werk moet gerig word om Bloukraanvoëls in hulle natuurlike habitat (Karoo en grasveld) te bewaar as om hulle in die Overberg en Swartland te probeer bewaar.
I think more money and effort should go into conserving Blue Cranes in natural habitat (like the Karoo and grasslands), than into conserving them on Swartland & Overberg farmlands

33.) Bloukraanvoëls word te veel in die Wes Kaap
Blue Cranes are becoming too numerous in the Western Cape

34.) Ek dink meer fondse en werk moet gerig wees op die bewaring van Bloukraanvoëls in die Overberg en Swartland.
I think more money and effort should go into conserving Blue Cranes in the Overberg & Swartland

35.) Bloukraanvoëls op my grond maak dit moeiliker vir my om ‘n wins op die plaas te maak
The Blue Cranes on my land make it harder for me to make a profit from farming

36.) Ek is bekommerd dat Bloukraanvoëls in die toekoms sal uitsterf
I am concerned that Blue Cranes may go extinct in the future

37.) Ek sou verkies dat daar minder Bloukraanvoëls op my grond moet wees.
I would prefer it if there were fewer Blue Cranes on my farm

Problem animals

38.) Het u probleme gehad met diere wat skade op die plaas aanrig?
Have you had any problems with animals causing damage on your farm?

39.) Watter sort diere doen die meeste skade, en in watter volgorde?
What animals do the most damage, and in what order?

40.) Wat beskadig hulle? Hoe veroorsaak hulle skade?
What do they damage? And how do they cause damage?

41.) Watter metodes gebruik u om die skade te vermy of te verminder?
What methods do you use to prevent or minimise these damages?

If they have crop damage:

In Amerika is daar 'n produk onder die handelsnaam Avipel. Dit bevat 'n bestanddeel genaamd anthraquinone wat die voël laat naar voel as dit ingeneem word. Dit word dus gebruik om plante of saad een keer per seisoen te behandel in a spuit formaat om weiding te ontmoedig. Studies het bewys dat dit hoogs doeltreffend is om voëls af te skrik. Teen oestyd het die bestanddeel ontbind en is nie meer te bespeur in die oes nie. Die bestanddeel het geen permanente newe werking op voëls of die oes nie.
In the US there is a product called Avipel, developed from a non-lethal substance called anthraquinone, which causes digestive discomfort in birds which discourages them from feeding on plants sprayed with it. It is either coated on seeds, to deter birds eating sown seeds or used once per season as a foliar spray to deter grazing. Studies have shown it to be effective in reducing bird herbivory on various crops and seeds. Studies have also shown that by harvest time the concentration of the chemical on the plant is negligible, therefore it is unlikely to affect palatability of the crop to livestock or people.

42.) Stel u belang om hierdie produk te koop?
Would you be interested in buying this product?

43.) Vir watter soort gewasse?
For which crops?

44.) Stel u belang om die uitslae van die navorsing te ontvang?
Are you interested in getting a copy of the research results?

Appendix 3: Ethics Approvals

Science Faculty Animal Ethics Committee
Chair: Dr Dawood Hattas
Private Bag X03, Rhodes Gift, 7701, South Africa
Room 4.03, HW Pearson Building, Upper Campus, UCT, Rondebosch, 7701, South Africa
Tel: +27 (0) 21 6502443
Chair E-mail: dawood.hattas@uct.ac.za
Submissions & General Correspondence: sfaec@vula.uct.ac.za

22 May 2020

Dear Prof. Peter Ryan

Approval for use of animals in research/teaching: 2020/V6/PR/A1

I am pleased to inform you that the Science Animal Ethics Committee (SFAEC) has *conditionally/unconditionally* approved your research/teaching protocol for the study entitled **Understanding how scavenger bias affects power line collision estimates in the Western Cape and Nama Karoo.**

Such approval is applicable only to the number and types of animals, and the proposed activities, that are detailed in your protocol. Approval is valid for the specified duration of a project or for the time period specified on the relevant permit(s) from conservation authorities, with a maximum of three years, after which a new application/protocol (listing the original approval number) must be submitted.

Such approval is also subject to the submission of relevant permits from conservation authorities within 60 days, if not already provided. Should any permits expire and be renewed during the execution of the project, you are required to submit a copy thereof to the SFAEC. Should there be any changes to the numbers and types of animals to be used, participants and/or procedures to be followed, you must obtain further written approval from the SFAEC.

Please also note that the SFAEC expects lised participants of approved studies to take an active role in monitoring study animal welfare, and to take necessary actions when problems are encountered. In the event that symptoms of unanticipated physiological or behavioural stress are manifested, the approved animal use procedures must cease immediately and the Chair of the SFAEC must be informed. Should the applicants plan to proceed further, a Protocol Amendment Form will need to be submitted that must clearly state any changes to the animal usage procedures, how these have been modified to prevent recurrence of stress to the study animals, and the details of how animal welfare will be monitored.

The SFAEC has the right to request progress reports and/or final reports on any teaching or research activities that are approved. These reports may include details of animal usage, animal welfare observations, adherence to protocol-outlined procedures and results achieved compared to animal usage. The SFAEC is also obliged to respond to any complaints relating to animal welfare from members of UCT, or problems identified during occasional and unannounced inspection of animal housing facilities and/or operational procedures. In the event of deviations from protocols that are deemed to be serious, the SFAEC may withdraw approval,order the immediate cessation of any teaching or research activity, and refer the matter to the Senate Animal Ethics Committee for further investigation, as outlined in the Standard Operating Procedures on the SFAEC website.

Please use the following animal ethics clearance number for all publications and reports relating to this work, as well as in possible renewals and any correspondence with the committee: **2020/V6/PR/A1**. A copy of this approval letter should also be displayed in any animal holding facilities (if applicable).

Best wishes

Signed by candidate

Dawood Hattas
Chair: SFAEC

ENDANGERED WILDLIFE TRUST
Protecting forever, together.

Endangered Wildlife Trust Ethics Committee
(EWTEC)

OUTCOME OF APPLICATION TO USE ANIMALS FOR RESEARCH OR CONSERVATION PURPOSES

Project title	Satellite tracking of Africa's four crane species as part of a global 1000 cranes tracking project
Ethics clearance number	EWTEC2018_005
EWT programme	African Crane Conservation Programme
Researcher/Principal Investigator	Matt Becker

Species	Blue Crane (*Anthropoides paradiseus*)	Grey Crowned Crane (*Balearica regulorum*)	Wattled Crane (*Bugeranus carunculatus*)	Black Crowned Crane (*Balearica pavonina*)
Sample size	20	110	60	30
Approval period	December 2018 – December 2019			

Kindly take note of the following:

- *The applicant is required to complete an annual progress report that will be due on 31 January 2019.*
- *Should there be any unexpected adverse effects on individuals, or changes in procedure/s, please submit details to the EWTEC using the respective approved forms.*

Application outcome	APPROVED
Date	2018/05/12
EWTEC Chair Signature	Signed by candidate

Science Faculty Animal Ethics Committee
Chair: Dr Dawood Hattas
Private Bag X03, Rhodes Gift, 7701, South Africa
Room 4.03, HW Pearson Building, Upper Campus, UCT, Rondebosch, 7701, South Africa
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Chair E-mail: dawood.hattas@uct.ac.za
Submissions & General Correspondence: sfaec@vula.uct.ac.za

22 May 2020

Dear Prof. Peter Ryan

Approval for use of animals in research/teaching: 2020/V7/PR/A1

I am pleased to inform you that the Science Animal Ethics Committee (SFAEC) has *conditionally/unconditionally* approved your research/teaching protocol for the study entitled **Investigating movements and landscape use of Blue Cranes in the Western Cape and Karoo.**

Such approval is applicable only to the number and types of animals, and the proposed activities, that are detailed in your protocol. Approval is valid for the specified duration of a project or for the time period specified on the relevant permit(s) from conservation authorities, with a maximum of three years, after which a new application/protocol (listing the original approval number) must be submitted.

Such approval is also subject to the submission of relevant permits from conservation authorities within 60 days, if not already provided. Should any permits expire and be renewed during the execution of the project, you are required to submit a copy thereof to the SFAEC. Should there be any changes to the numbers and types of animals to be used, participants and/or procedures to be followed, you must obtain further written approval from the SFAEC.

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The SFAEC has the right to request progress reports and/or final reports on any teaching or research activities that are approved. These reports may include details of animal usage, animal welfare observations, adherence to protocol-outlined procedures and results achieved compared to animal usage. The SFAEC is also obliged to respond to any complaints relating to animal welfare from members of UCT, or problems identified during occasional and unannounced inspection of animal housing facilities and/or operational procedures. In the event of deviations from protocols that are deemed to be serious, the SFAEC may withdraw approval,order the immediate cessation of any teaching or research activity, and refer the matter to the Senate Animal Ethics Committee for further investigation, as outlined in the Standard Operating Procedures on the SFAEC website.

Please use the following animal ethics clearance number for all publications and reports relating to this work, as well as in possible renewals and any correspondence with the committee: **2020/V7/PR/A1**. A copy of this approval letter should also be displayed in any animal holding facilities (if applicable).

Best wishes

Signed by candidate

Dawood Hattas
Chair: SFAEC

UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

Faculty of Science
University of Cape Town
Rondebosch
South Africa 7701

E-mail: shari.daya@uct.ac.za
Tel: 021 650-2880

11 June 2019

Ms Christie Anne Craig
Department of Biological Science

RE: Assessing the long term viability of Blue Cranes on the farms in the Western Cape

Dear Ms Christie Anne Craig

I am pleased to inform you that the Faculty of Science Research Ethics Committee has approved the above-named application for research ethics clearance, subject to the conditions listed below.

- Implement the measures described in your application to ensure that the process of your research is ethically sound; and
- Uphold ethical principles throughout all stages of the research, responding appropriately to unanticipated issues: please contact me if you need advice on ethical issues that arise.

Your approval code is: **FSREC 57 - 2019**

I wish you success in your research.

Yours sincerely

Signed by candidate

Dr Shari Daya
Chair: Faculty of Science Research Ethics Committee

cc. Professor Peter Ryan (supervisor)