

**Martial Eagles and the national power grid in South Africa: the
implications of pylon-nesting for conservation
management**



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Submitted in fulfilment of the requirements for a degree of Master of Science

Acknowledgements

I would like to extend a thank you to Andrew Jenkins who initially supported my idea of developing a project focused on Martial Eagles nesting on the Eskom transmission network, as this topic has always been of great interest to me. Andrew graciously shared his data and ideas freely with me and for this I am extremely grateful. To Res Altwegg for agreeing to come on board my project as a statistical advisor. I have learnt a vast amount about the intricate workings of R and the complexity of habitat modelling, all of which were stowed away in a big black box with the name statistics printed on it in my mind. I really could not have done or believed I could have completed a project of this statistical complexity, especially since many models were run prior to settling on relatively manageable GLM models, without Res'' guidance. I would like to Thank Arjun Amar for supporting my project and including me in his raptor research group where I made invaluable research connections. I reaped the benefits of being able to swap ideas with other researchers struggling with similar project problems from being active within this group. For supporting my project financially with COE funding and always keeping an analytical eye on my progress.

I would like to extend thanks to the NRF for the free innovation scholarship awarded to me and to Bongiwe Ndamane for assisting me with the change of project. To the NRF Center of Excellence grant for funding my field work expenses. A very big thank you to the Bateleurs for sponsoring 2029km of fixed wing surveys and to Zelda Hudson for organising these flights and constant encouragement. Thank you to Ric Spear and Terence Weyer for flying over 1061km and 968.4km respectively on their own time with their own aircraft. I would like to extend a major thank you to IdeaWild for providing my project with a Celestron 100mm diameter and 22-66x100 optical zoom scope to make sure I could assess Martial Eagle nest occupancy on ground surveys without disturbing breeding eagles. To Alan Durant and Morris Verwey from Eskom and to Eskom for training me to drive under Eskom power lines and

giving me a key to drive the maintenance roads underneath these lines. A further thank you to Mr and Mrs Kruger, Gert their son and Mr and Mrs Maas for welcoming me into their homes, after a long day of driving servitudes roads under power lines alone.

A big thank you to my friends and family for supporting me through my thesis. Thank you mom and dad for always believing in me and supporting my interests in wildlife, letting me choose to study animals rather than securing your retirement by encouraging me to become a financial advisor, accountant or lawyer. Thanks mom for the constant emotional support and for taking me to the common to watch birds when I was younger. Thanks to my dad for checking through my thesis and correcting my awful dyslexia. A major thank you to Chris Laidler for being my secret supervisor, you taught me to code, helped write countless functions, taught me GIS and gave me advice, but most of all thank you for lending me your Land Rover Defender so I could accomplish my field work. Thanks to Gigi and Dennis Laidler for taking me into your home and showing a great interest in all my endeavours. A major thank you to Meg Murgatroyd my eagle friend, if it weren't for the hours spent with you and Black Eagles I may never have had the courage to believe in my passions and ultimately to convince academics it was a good idea to invest time and effort in a Martial Eagle study.



Abstract

Many large, sparsely distributed raptors are threatened by a host of anthropogenic factors, while a minority may actually benefit from some aspects of development and environmental change. Clarity on the size and trajectory of such populations is essential for effective conservation management, but can be difficult to achieve. One solution is to use multivariate habitat association models to derive critical estimates of distribution and abundance. The South African population of Martial Eagle *Polemaetus bellicosus* is currently estimated at <800 adult birds, with the bulk of the known population believed to be residing in the larger protected areas. However, Martial Eagles also build nests on pylons that support high voltage transmission lines running through the largely treeless, semiarid landscapes of the Karoo. The main aim of this study was to develop a better understanding of the environmental factors that influence Martial Eagle territory densities and locations along South African transmission lines, and thereby estimate the size of this population and its relative importance to the national conservation status of this globally threatened species.

I used habitat association models to describe Martial Eagle territory density in relation to eight environmental covariates. Models were first fitted to eagle territory data for the central Karoo regions, collected and pooled over the period 2002-2006, and then applied to predict the number of pairs present on each of three adjacent sections of unsurveyed line (northern, southern and eastern lines). Once these model predictions were verified by a series of aerial and ground surveys, I fitted the models to all the known Martial Eagle territory records for the transmission network and extrapolated from these back to the rest of the network using the fitted relationships. Ultimately, the models predicted 52 additional Martial Eagle territories on the remaining transmission network with a confidence interval ranging from 38 to 67 (based on models that explained up to 39 % of the total variance in terms of only two explanatory terms – rainfall and the proportion of cultivated land). I then examined the role of territoriality and social structure in the eagle population in determining the location and dispersion of pylon nests. To do this I used the location of active nests from the original central Karoo data and a similar number of randomly selected points. I then asked whether I could predict the nest locations from each of the eight environmental covariates and distance to its nearest conspecific active nest or its nearest nest of any other large eagle species. Using a logistic generalised linear model with regression splines for distance to nearest other nest, I found that Martial Eagles strongly avoid proximity to conspecific nests (mean distance to

conspecific nest = 28.2 km, range 2.5-167.1 km, $n = 306$). This result shows that minimum spacing should be considered in predicting the distribution of eagles on unsurveyed transmission lines. Lastly, I further investigated the geographical extent of pylon nesting in South African Martial Eagles, with particular focus on variation in the frequency of this behaviour in relation to biome-scale variation in the availability of trees as natural nest sites. To do this, I related Martial Eagle reporting rates generated by citizen-science bird atlas data to the density of transmission lines and biome types across South Africa. While these analyses yielded some suggestive results, such as significant positive and negative relationships between reporting rates and line density in the Desert ($P = 0.02$) *versus* the Savanna ($P < 0.001$) biomes respectively, data sparseness in arid areas and a generally low detection probability limited the conclusiveness of these results.

The refined habitat association models developed in this study predict that the South African transmission grid supports 130-159 breeding pairs of Martial Eagle. This figure has never been estimated or calculated before, and suggests that 36 % of the national breeding population could reside largely in the commercial ranchland and nest on man-made structures. This result, which is at odds with the generally held belief that the Martial Eagle is increasingly confined to large protected areas, has significant implications for the thinking around the conservation management of this globally threatened species.

Key words: Martial Eagle, power transmission network, habitat association model, environmental covariates, population size

Contents

Plagiarism Declaration	i
Acknowledgements	ii
Abstract	iv
Contents	vi
Chapter 1 : General Introduction	1
1.1 Raptors which benefit from human modified landscapes	2
1.2 Population size: establishing a baseline	4
1.3 The use of habitat association modelling to estimate population density	4
1.4 Conservation status of Martial Eagles	6
1.5 Martial Eagle as a study species	7
1.6 Key research questions	9
Chapter 2 : Exploring the drivers of Martial Eagle distribution and abundance on the transmission network	10
2.1 Introduction	10
2.1.1 Adaptation to a human modified landscape	10
2.1.2 Determining Martial Eagle habitat association relationships	11
2.1.3 Hypotheses	12
2.2 Methods	13
2.2.1 Study area	13
2.2.2 Eagle surveys	16
2.3 Data analysis	17
2.4 Results	35
2.4.1 Habitat association modelling: examining the predictors of Martial Eagle territory density on the transmission network	35
2.4.2 Applying the Habitat association model: predicting the number of Martial Eagle territories per line section of the transmission network	37
2.4.3 Refined habitat association model: predicting the density of Martial Eagle territories on the whole South African transmission network	40
2.4.4 Martial Eagle response to nearest neighbour	43
2.4.5 South African Bird Atlas Project 2 Martial Eagle reporting rate in relation to transmission line density	47
2.5 Discussion	50
2.5.1 Habitat association model: predicting the density of Martial Eagle territories on the whole South African transmission network	50
2.5.2 Martial Eagle distribution in response to nearest active territory	52

2.5.3	South African Bird Atlas Project 2 Martial Eagle reporting rate in relations to transmission line density	54
Chapter 3: Conclusions		57
3.1	The use of habitat association models in estimating population density of sparely distributed species	57
3.2	The importance of human modified environments in the sustainable conservation of scarce, wide-ranging species	58
3.3	Future work	59
References		63

Chapter 1 : General Introduction

Over the last century, many birds of prey across the globe have suffered sharp decreases in both range and numbers, coincident with a burgeoning human population (Newton 1979; Brandl *et al.* 1985; Herremans & Herremans-tonnoeyr 2000; Hudson & Bouwman 2007; Thiollay 2007a,b; Virani *et al.* 2011). These trends have prompted a concerted effort to understand the variables that naturally control raptor numbers, and to determine the key factors contributing to threaten populations (Newton 1979, a few of these include Booms *et al.* 2010; Cardador *et al.* 2011; Virani *et al.* 2011; Andrew & Mosher 2013; Buij *et al.* 2013; Cloete 2013; Krüger 2014).

Conservation-driven researchers relate population abundance to threats and their natural environment, as a means of assessing how these factors may limit animal populations. Direct survey and monitoring methods, or “citizen science” generated atlas data are used as a proxy for the relative abundance of an animal species (Robertson *et al.* 1995; Malan & Howells 2009). A major problem for conservation-driven research is the logistical and financial burden of monitoring animal populations which are widely and sparsely distributed (Gottschalk *et al.* 2005). An elegant solution is the extrapolation of species abundance data over broad temporal and physical landscape scales to understand how threats and the natural environment may affect an entire population’s abundance and thus conservation status. The most efficient and convenient methods to accomplish this is by means of increasingly sophisticated habitat association modelling techniques (Gottschalk *et al.* 2005; Altwegg *et al.* 2008).

The Martial Eagle *Polemaetus bellicosus* occurs in dry, open environments over much of sub-Saharan Africa. As the continent’s largest eagle, it has extremely large space requirements, and in many regions is now all, but confined to only the largest protected areas (Newton

1979; Van Zyl 1992; Herremans & Herremans-tonnoeyr 2000; Thiollay 2007 a,b). However, in South Africa this species has been using power transmission structures as surrogates for nest trees in the otherwise treeless Karoo region (Dean 1975; Boshoff 1993), and in doing so has possibly colonised extensive areas of private ranchland. This study builds on previous survey data for a sample of these pylon-nesting Martial Eagles (Machange *et al.* 2005; Jenkins *et al.* 2013) by using habitat association modelling to predict the wider distribution and abundance of Martial Eagles across the entire South African transmission network.

1.1 Raptors which benefit from human modified landscapes

Several raptor species have undoubtedly benefited from various forms of anthropogenic change (Bird *et al.* 1996; Curtis 2005), with the nature, extent and implications of these relationships spanning a wide spectrum.

The most extreme human modified environments are urban centres and perhaps the best example of a raptor species that has been able to exploit such drastically altered habitat is the Peregrine Falcon *Falco peregrines* (Bird *et al.* 1996). In many parts of the world the urban component of local Peregrine populations equals or even exceeds the number of rural pairs (Cade *et al.* 1996). Other successful urban nesting raptors include Eurasian Kestrel *Falco tinnunculus*, Black Sparrowhawk *Accipiter melanoleucus* Northern Goshawk *Accipiter gentilis*, Coopers Hawk *Accipiter cooperii*, Red Shouldered Hawk *Buteo lineatus*, Lesser Kestrel *Falco naumanni* and Mississippi Kite *Ictinia mississippiensis* (Bird *et al.* 1996; Rutz 2008; Altwegg *et al.* 2014; Martin *et al.* 2014; Sumasgutner *et al.* 2014). In most or all of these cases, the species affected are able to capitalize on both an abundance of urban-based prey and a ready availability of artificial nest structures.

Other instances of raptors apparently benefitting from anthropogenic change include the adoption of invasive alien vegetation as nesting habitat – for example in the last 80 years

Black Sparrowhawks *Accipiter melanoleucus* have expanded their range and increased their population size from 60 to 840 pairs in an area of South Africa in response to the spread of alien trees associated with commercial forestry (Malan & Robinson 2001). The Red-tailed Hawk *Buteo jamaicensis* has extended its range in the Western United States through the introduction of mesquite trees *Prosopis velutina*, which provide ideal nesting habitat (Gilmer 1983; Houston & Bechard 1983; Hobbs *et al.* 2006).

Similarly, some tree-nesting raptors have been recorded using electricity pylons and other man-made utility structures as nesting sites in otherwise relatively undisturbed but treeless environments (Infante & Peris 2003), and have increased in numbers and/or range as a result of such behaviour (Steenhof *et al.* 1993; Infante & Peris 2003). For example, the Red-tailed Hawk population of south-eastern Washington tripled in size after a power utility policy of removing nests from pylons was discontinued (Fitzner 1980), and the number of Osprey *Pandion haliaetus* pairs nesting along the Willamette River in Oregon increased from thirteen to seventy-eight over seventeen years after the installation of electricity pylons (Henny & Kaiser 1996).

In one important case, a population of the globally endangered Saker Falcon *Falco cherrug* was found to nest more frequently on artificial structures than natural ones in an area of Mongolia (Potapov *et al.* 2002; BirdLife International 2013a). Subsequent research has been directed at creating safe nesting opportunities for this species on power lines in order to mitigate other factors responsible for driving numbers down (Dixon *et al.* 2013).

In Southern Africa ten raptor species regularly use utility structures (mostly power pylons and telephone poles) as nesting sites (Malan & Howells 2009), of which the Martial Eagle is probably the rarest and most threatened (Machange 2003; Jenkins *et al.* 2013; Taylor In press 2015). Given that up to 60 pairs of these birds are known to reside on only a sample of the

pylons supporting South Africa's power transmission network (Jenkins *et al.* 2013), and in light of the significant conservation value of some pylon-bound raptor populations in other parts of the world, a reliable estimate of the number and distribution of Martial Eagle pairs dependent on utility structures in Southern Africa may be of paramount importance in securing the regional welfare of this iconic species.

1.2 Population size: establishing a baseline

Habitat degradation has been widely acknowledged to have a negative effect on many raptor populations (Brandl *et al.* 1985; Virani & Watson 1998; Barnes 2000; Herremans 2000), but biologists often struggle to empirically link hypothesized population limiting factors to measured abundances and distributions across national populations. Studies which hope to estimate population size and distribution have difficulty in matching the scale of the study sites to the scale at which limiting factors act (Newton 1998). This is especially true for large raptors that occur at low densities (Hustler & Howells 1987), and subsequently compromises our ability to manage for and conserve these taxa effectively.

The identification of resource selection functions may lead to the eventual determination of a baseline distribution and population abundance for species which occur at low densities (Boyce & McDonald 1999). These methods use habitat selection by animals, a behavioural process in which individuals either actively or passively select where they live (Southwood 1977).

1.3 The use of habitat association modelling to estimate population density

The South African national power utility (Eskom), provides important breeding structures for large eagles otherwise negatively impacted by human-induced landscape change (Brandl *et al.* 1985; Machange *et al.* 2005). However, the geographical extent to which electricity

pylons are used as nesting sites is not yet known. The use of satellite-based remote sensing applications which can be used in GIS analysis to provide quantitative categorisation of resource use by raptors at a large scale (Boyce & McDonald 1999; Gottschalk *et al.* 2005) is well suited to the problem of determining the distribution and abundance of large birds, specifically Martial Eagles using the South African power utilities. These GIS-based models have mostly been used for high-profile keystone and umbrella species, such as top predators, and have proved especially useful for regions where little is known about habitat use by animals as well as regions where human needs and the needs of animals clash (Gottschalk *et al.* 2005).

Such models have been used in conjunction with conservation programs in order to predict changes of the status of focal species in response to habitat change (Berry *et al.* 2002), and to identify suitable habitats in regions threatened by high levels of human disturbance (Early *et al.* 2008).

One such application of this modelling method was the estimation of the distribution of arctic Gyrfalcon *Falco rusticolus* nests. Major threats to this species include development issues (wind farm development) and global warming through vegetation and prey species changes (Booms *et al.* 2010). A spatially explicit model was created which predicted Gyrfalcon abundance and distribution throughout remote areas of Alaska (Booms *et al.* 2010). The model achieved a 67 % success rate in predicting the presence of Gyrfalcon nests, on the basis of a suite of directly (mapped sub-surface geology which determines the availability of nest cliffs), or indirectly (mapped distributions of vegetation types most likely to support high numbers of prey) correlated variables.

In another example, habitat modelling was used to understand the limiting factors in a forest population of the secretive Northern Goshawk *Accipiter gentilis*. Here the relationships

between the occurrence of goshawk nests, and tree and forest structural parameters is assessed (Reich *et al.* 2004). A predictive model illustrates that choice of nest location is probably constrained by territoriality within areas which meet the critical combination of structural criteria (Reich *et al.* 2004).

These two examples illustrate the power of habitat association models to use species-environment relationships in prediction of species' wider distribution and abundance. These models are particularly useful for guiding research efforts and advancing our ability to manage habitat for poorly understood, threatened raptor species (Gottschalk *et al.* 2005). Perhaps most importantly, these models highlight otherwise unknown areas that are most likely to support important breeding populations of target species, and which should be prioritised for future survey work (Garshelis 2000). This is especially true for the Martial Eagles which could potentially make use of a large portion of the >350 000km of power lines presently available in South Africa, which are logistically and financially impossible to survey directly.

1.4 Conservation status of Martial Eagles

The global IUCN list of threatened species considers Martial Eagle as Vulnerable with a declining population trend (BirdLife International 2013b), making this among the four most threatened African Eagles. The global population of Martial Eagles is thought to be in the tens of thousands (Ferguson-lees & Christie 2001), while the South African population is estimated at about 800 adult birds (Taylor In press 2015)

The threats that are believed to have caused the marked decrease in numbers over the last 50 to 60 years include: deliberate and incidental poisoning, habitat loss, reduction in available prey, pollution and collisions with power lines (BirdLife International 2013b). Within South Africa, a recent analysis using SABAP1 and 2 data showed that reporting rates had declined

by around 60 % over the last twenty years (Cloete 2013). Martial Eagle reporting rate declines were observed in the Kruger National Park (54 % decline) and the Kgalagadi Transfrontier Park (44 % decline), which were believed to be a stronghold for Martial Eagles. No significant declines were observed in the Western Cape or Northern Cape where a population of around 60 breeding Martial Eagles nest on the Eskom electricity pylons in the central Karoo region (Cloete 2013).

1.5 Martial Eagle as a study species

The Martial Eagle is a large, broad-winged raptor. In Southern African the Martial Eagle is widely but sparsely distributed over much of sub-Saharan Africa, from Senegal and Gambia in the east to Ethiopia and north-west Somalia and in the south to Namibia, Botswana and South Africa (Steyn 1982; Ferguson-lees & Christie 2001; Simmons 2005). Paired adults are generally resident within their extensive home ranges, and favour open woodland and fairly flat country, but can occur in mesic savanna, along forest edges and in open shrublands with wooded drainage lines (Brown 1970; Steyn 1982; Simmons 2005). The species is generally absent from heavily settled areas, mountainous regions and deserts (Steyn 1982; Boshoff 1997; Ferguson-lees & Christie 2001).

The species has very large home ranges. Preliminary data from five GPS-tagged Martial Eagles in Kruger National Park, South Africa suggest a mean home range of 113km² (Van Eeden unpublished data). Previous research suggests that, depending on habitat type, Martial Eagles were found to defend territories of 125km² up to 300km² in South and East Africa and in the most extreme cases 990km² in Hwange National Park, Zimbabwe (Brown 1970; Steyn 1982; Boshoff & Vernon 1980; Ferguson-lees & Christie 2001). Measured inter-nest distances are calculated at a mean of 19.2km, based on estimates from Kruger National Park and adjoining parks, the former Transvaal, the De Aar to Laingsberg region, Nylsvley,

Steenbok pan, Magalisberg, the southwest of Windhoek and Hwange National Park (Steyn 1982; Tarboton & Allan 1984; Hustler & Howells 1987; Boshoff 1993; Ferguson-lees & Christie 2001).

Martial Eagle pairs build a sturdy nest platform of sticks, with a diameter of 1.2-1.5m and a depth of up to 2m that they repeatedly use. The nest is lined with sprigs of green leaves when a breeding attempt is made (Steyn 1982; Ferguson-lees & Christie 2001). Nests are usually placed in a main fork or on the lateral branches of a large tree at a height of 6 to 20m (Steyn 1982; Tarboton & Allan 1984; Ferguson-lees & Christie 2001). A single egg is laid, between March and August in Southern Africa, with the highest proportion being laid in May and June (Boshoff & Vernon 1980; Steyn 1982; Tarboton & Allan 1984; Hustler & Howells 1987; Ferguson-lees & Christie 2001). The nestling period typically ranges from 90 to 109 days, and the chick may still be fed at the nest up to three months after leaving it (Boshoff & Vernon 1980; Steyn 1982; Tarboton & Allan 1984; Hustler & Howells 1987; Ferguson-lees & Christie 2001). The chick may stay in the area of the nest for 8-12 months (Steyn 1982; Ferguson-lees & Christie 2001). Breeding can be erratic and its cadence is known to be influenced by prey availability, post-nestling dependence and human disturbance (Steyn 1982; Hustler & Howells 1987; Boshoff 1993; Ferguson-lees & Christie 2001). If conditions are favourable breeding can occur biennially or annually (Simmons 2005).

Within the Karoo regions in South Africa, a breeding population of Martial Eagles nests on man-made structures in commercial ranchland (Dean 1975; Boshoff 1993; Machange *et al.* 2005; Jenkins *et al.* 2013). Martial Eagles build nests in steel lattice pylons supporting high voltage power lines running through what is a largely treeless, semiarid landscape. They may have even recently colonised large areas of the Karoo, supported by the expanding power transmission network (Dean 1975; Boshoff 1993). Given the species' current conservation

status, the apparent national decline, and the plethora of potential threats faced by Martial Eagles in the region generally, it is important to establish a baseline estimate of the number of Martial Eagle pairs resident on pylons nationally. If a substantial population is found to be using these artificial structures, and nesting in sometimes heavily modified environments, this would have significant implications for the thinking around the conservation management of this globally threatened species.

1.6 Key research questions

The main aim of this study was to estimate the size of the Martial Eagle population that uses the transmission network for breeding, by determining the environmental factors that regulate territory densities and locations along power lines using habitat association modelling. As a secondary aim, I consider the importance of territoriality, which is not directly accounted for in the previous habitat association modelling analysis, in addition to environmental covariates surrounding nest locations. As a tertiary supporting analysis I examine the effect of transmission line density on Martial Eagle prevalence, specifically in arid regions.

In summary, the primary research questions are as follows:

- How many pairs of Martial Eagles breed on the Eskom transmission network?
- Can the prediction of how many pairs of Martial Eagles breed on the Eskom transmission network be made using only a set of environmental covariates?
- Do environmental covariates and distance to other eagle nests explain variation in Martial Eagle nest localities?
- Does transmission line density have an effect on the Martial Eagle populations at the landscape level?

Chapter 2 : Exploring the drivers of Martial Eagle distribution and abundance on the transmission network

2.1 Introduction

Understanding species distributions over large geographical areas is critical for effective conservation management (Furness & Greenwood 1993; Wu & Smeins 2000). These data should ensure that sufficient research and conservation resources are deployed to regions where species are most threatened (Caughley 1994). However, the distributions of many species, and especially of those that typically occur at low densities and in remote areas, are often not well known (Peterson 2001; Pearce & Boyce 2006). Spatial modelling has been suggested as a method to extrapolate species distributions beyond areas of known presence (Booms *et al.* 2010). Spatial modelling is a cost effective method which uses available data (Booms *et al.* 2010). Currently there are few studies which employ spatial modelling techniques to predict the aggregate distribution and abundance of animal species that occur naturally at low densities. Studies which have successfully employed these methods include research on the arctic Gyrfalcon *Falco rusticolus* and Grey Wolf *Canis lupis* (Mladenoff *et al.* 1999; Booms *et al.* 2010).

2.1.1 Adaptation to a human modified landscape

The Martial Eagle is endemic to Africa and exhibits certain natural history traits that make it vulnerable to population decline (Steyn 1982; Boshoff 1997; Owens & Bennett 2000; Purvis *et al.* 2000; Simmons 2005; BirdLife International 2013b). Martial Eagles are large apex predators, which breed erratically and have one of the lowest natural densities of any bird species (Brown 1970; Newton 1979; Steyn 1982; van Zyl 1992; Ferguson-lees & Christie 2001), with adult birds occupying home ranges of up to 250-300km² (van Zyl 1992; Boshoff 1993). Occupancy of large home ranges has led to the poor understanding of habitat usage by

large eagles throughout their distribution range (Tarboton & Allan 1984; Fielding & Haworth 1995). Martial Eagles naturally occupy breeding territories within the Savanna Biome (Brown 1970; Steyn 1982; Simmons 2005), which is often prime habitat for stock farming. Mismanagement of farmlands can impact on the well-being of eagle populations, perhaps through soil erosion and associated overgrazing which may indirectly effect the distribution, abundance and accessibility of prey (Herremans 2000; Machange *et al.* 2005).

While it is apparent that some raptor species can withstand human influences on the environment, most of these do so by exploiting some critical aspect of localised anthropogenic change (Gilmer & Stewart 1983; Houston & Bechard 1983; Bird *et al.* 1996; Henny & Kaiser 1996; Tinkler 2000; Potapov *et al.* 2002; Hobbs *et al.* 2006; Rutz 2008; Altwegg *et al.* 2014; Sumasgutner *et al.* 2014). For example, Karoo Martial Eagles, Verreaux's Eagles *Aquila verreauxii* and Tawny Eagles *Aquila rapax* are more successful on well-managed properties, with minimal areas of land put to cultivation, and featuring a high proportion of indigenous game as stock (Machange *et al.* 2005).

2.1.2 Determining Martial Eagle habitat association relationships

Understanding resource use by raptors within disturbed and undisturbed habitats is important as it holds the key to determining which factors limit and which benefit breeding populations (Boyce & McDonald 1999; Gottschalk *et al.* 2005). Within a landscape natural environmental conditions can control raptor densities and usually cause raptors to seek out optimal breeding habitats (Hustler & Howells 1987;1990; Wichmann *et al.* 2003; Machange *et al.* 2005). In these suitable environments breeding pairs of raptors space themselves at a regular distance, presumably to minimize interference with neighbouring pairs (Newton 1979). This has been confirmed for most eagle species, including Wahlberg's Eagle *Aquila wahlbergi*, Golden

Eagle *Aquila chrysaetos*, Wedge-tailed Eagle *Aquila audax*, and Martial Eagle (Lockie 1964; Brown 1970; Leopold & Wolfe 1970; Tubbs 1974; Smeenk 1974).

Habitat association modelling can be a useful and cost effective means of refining relationships between animal distributions and natural and unnatural environmental covariates (Livingston & Todd 1990; Fielding & Haworth 1995; Bamford *et al.* 2009). In the present study, this approach is ideal for examining the influence of human disturbance factors on Martial Eagle distribution in South Africa, as well as to explore and define the relationships between eagles and natural environmental covariates. In addition, predictions from these models can be used to estimate the number of Martial Eagles nesting on the national transmission network.

2.1.3 Hypotheses

Based on the goals mentioned in section 1.6, I propose the following hypotheses about the drivers of Martial Eagle distribution and abundance on the South African transmission network which I will subsequently test in this chapter.

H1: *Densities* of Martial Eagle territories on the transmission network are strongly influenced by environmental, climatic and physiogeographic variables at the landscape scale and, by inference, predictive habitat association models based on these environmental covariates can accurately estimate the number of Martial Eagle territories on unsurveyed transmission lines

H2: The *location* and *dispersion* of Martial Eagle nest sites on the transmission network is influenced by environmental covariates surrounding each nest site as well as by the positioning of nearest neighbour eagle nests.

H3: Martial Eagles density in the treeless habitats of South Africa is positively correlated with the density of transmission lines.

2.2 Methods

2.2.1 Study area

2.2.1.1 Geographical description of multiple study sites on the Eskom power lines

Aerial surveys of eagle nests were conducted in the Karoo region on central transmission lines every year from 2002-2006 (Machange *et al.* 2005; Jenkins *et al.* 2013, Figure 2.1). Surveys extended from Koeberg, which is just north of Cape Town, in the southwest, to Kenhardt in the north and De Aar in the east (Figure 2.1).

I conducted additional surveys on the northern, southern and eastern transmission lines (Figure 2.1). Each of these study sites was used to verify predictions of Martial Eagle territory count by a set of habitat association models fitted to Martial Eagle territory data on the central line. Northern line surveys were conducted in the north of the country from Port Nolloth through Aggeneys to Kenhardt. The southern line surveys followed the transmission lines from Cape Town to Swellendam and on to George, then extended north to more arid regions of Beaufort West. Lastly the eastern line surveys were conducted from Heidelberg to Dealesville and continue through De Aar to Kuilfontein.

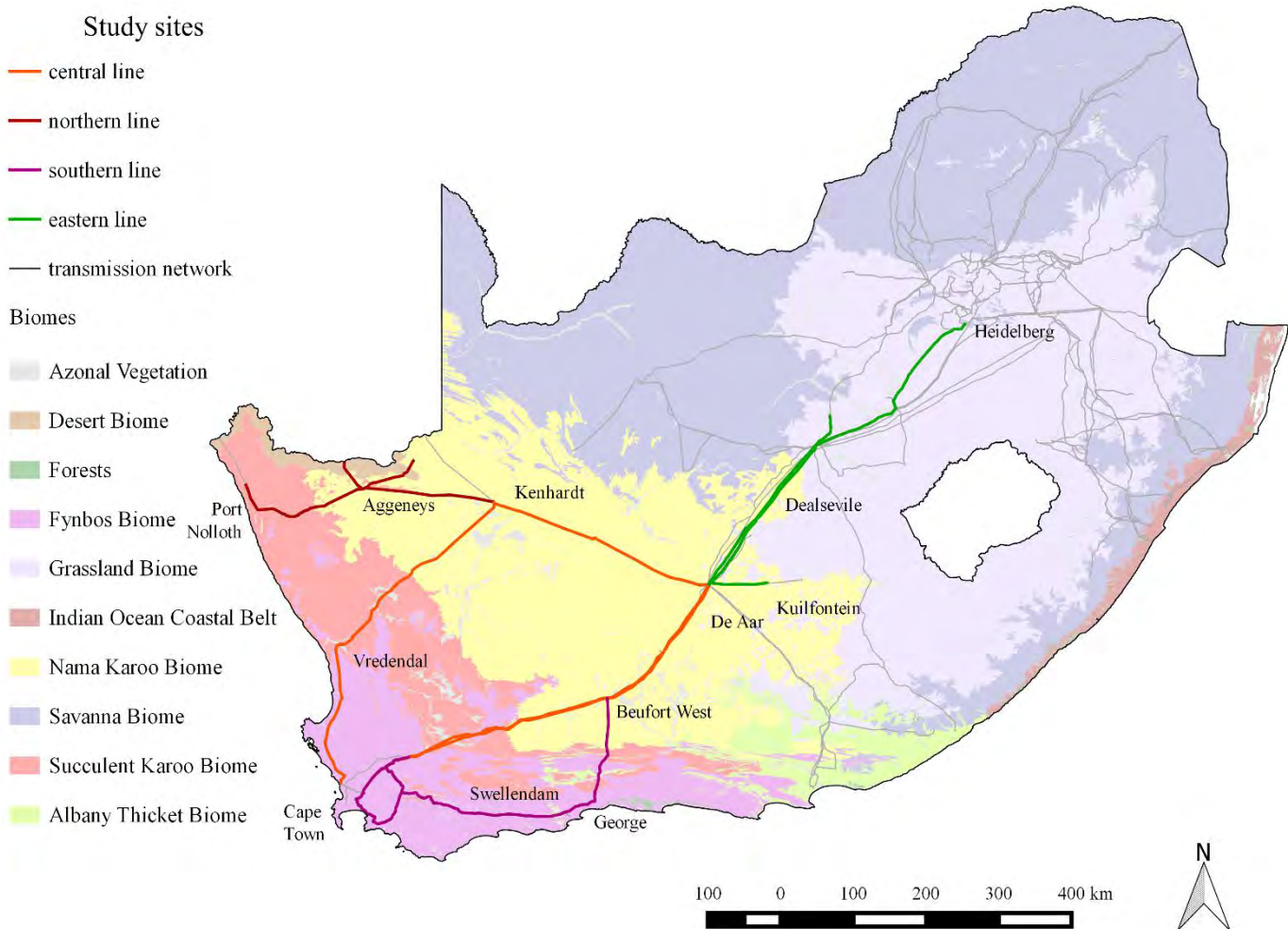


Figure 2.1: Map of South Africa highlighting the parts of the South African power transmission network that were surveyed for Martial Eagle nests in colour and the distribution of biomes across the country (taken from Mucina & Rutherford 2006). Grey lines are transmission lines that were not surveyed.

2.2.1.2 Environmental conditions surrounding surveyed lines

Land use (which in our study area comprises agriculture, livestock farming, degraded lands and urbanisation), vegetation cover, landscape morphology, primary productivity and rainfall were considered important for territory placement of Martial Eagles on the transmission network (Machange 2003). I therefore aimed to provide an adequate description of these characteristics in each of my study regions (Table 2.1).

Table 2.1 Environmental and land use characteristics (from Mucina & Rutherford 2006) of the five major biomes with which the selected study sites intersect

Biome ID	Lines within these biomes	Bare ground vegetation cover	Mean annual rainfall (mm)	Rainfall season	Mean annual temperature (°C)	Proportion of biome formally conserved	Range in altitude (m above sea level)	Dominant Land use threats
Nama Karoo	central, southern, northern & eastern line	intermediate	100-520	summer	16.7	0.7 %	1000-1400	stock farming
Succulent Karoo	central, southern & northern line	intermediate	100-200	winter	16.8	5.8 %	800	stock farming & agriculture
Desert	northern line	open	<200	winter	21.3	20 %	200-1000	semi-nomadic pastoral land use
Fynbos	central & southern line	dense	480	winter	14.8	50 % of mountain fynbos and 20 % low lying fynbos	80–200, mountain ranges 900-1900	agriculture & urbanisation
Grassland	eastern line	dense	500-700	summer	15.0	2.2 %	1500-2100	stock farming & agriculture

2.2.2 Eagle surveys

Martial Eagles build conspicuous nest platforms which are used repeatedly and can reach up to 2m in diameter and 1-1.3m in height (Simmons 2005). Nests are typically found in the waists of the pylon or above the towers conductors (Dean 1975) (Figure 2.2). Aerial nest searches and driven ground verification surveys to find these conspicuous nest platform locations were done originally by the „Electric Eagle Project“. These were flown annually from 2002-2006 for a sample of 1400 km of the central transmission line (Jenkins *et.al.* 2013, Figure 2.1). These surveys were conducted in the height of the eagle breeding season from mid-June to early July and mid-August in 2006.

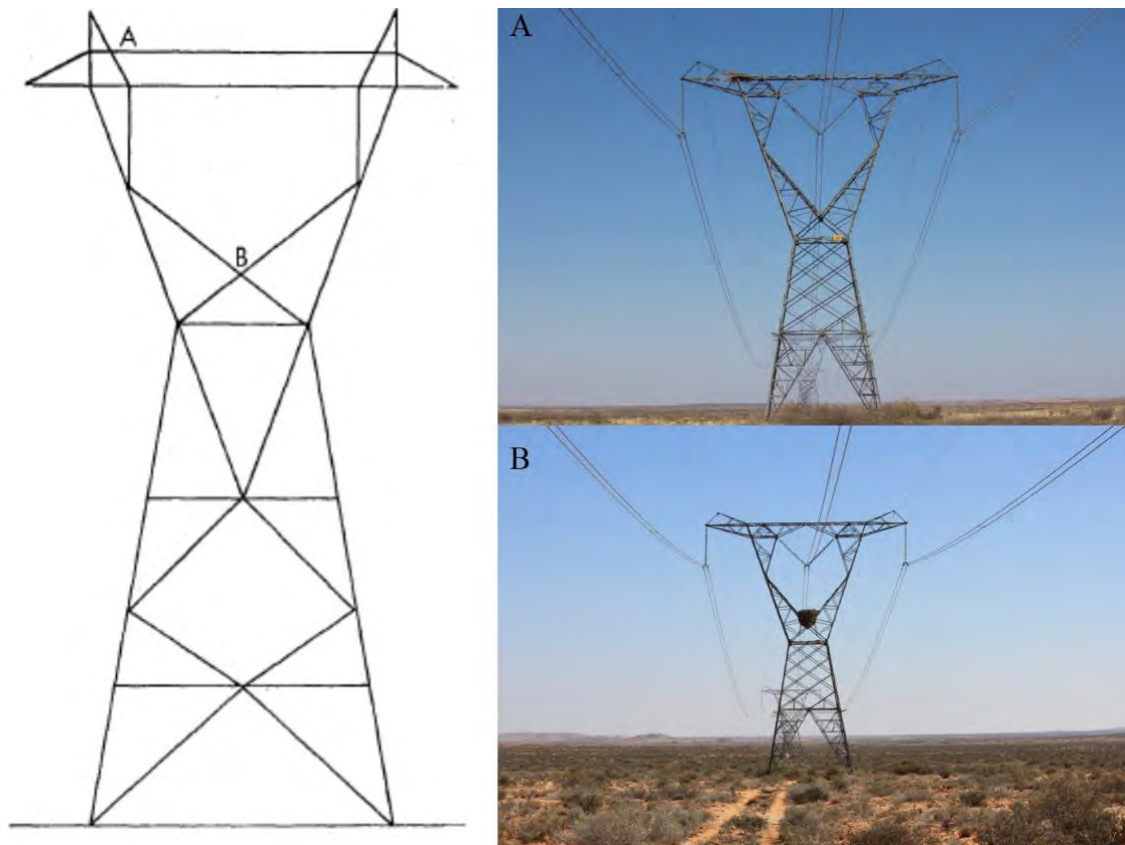


Figure 2.2: Schematic of high tension pylons illustrating nest positions A, over the conductors, and B, waist (Schematic taken from Dean 1975)

Verification surveys done during time of study (2014) consisted of aerial surveys, by light aircraft, of 777.81km of the southern line, 1080km of eastern line and ground surveys beneath 559km of the northern line. In addition ninety-five kilometres of the southern lines were driven to verify nest locations found during survey flights. These surveys were conducted between early August and September, which is considered the stage at which chicks could have already fledged, but are still largely dependent on the nest region.

During all surveys the breeding status (active / not used) and exact location of each nest was recorded, as well as the attendant species (Martial, Tawny or Verreaux's Eagle), and each aggregation of nests, thought to represent alternative structures within a single territory, was allocated to a territory number (Jenkins *et al.* 2013). My statistical analysis only includes territories that featured an active nest in at least one year over the period 2002-2006, or territories which included at least one nest structure and in which pairs of adult birds were seen.

To include the 2014 survey data into my statistical analysis a slightly different approach was needed. I included a nest and therefore the territory it belonged to even if this nest was not active, but signs of a previous breeding attempt such as white wash and prey remains were presents. Previously attended eagle species at these unused nests were identified by Jenkins through stick diameter and nest structure configuration. The rationale being that predictions of Martial Eagle territory count will be made based on a set of habitat association models built with territory data spanning five years (2002-2006), and so verification surveys should ideally have spanned multiple years of Martial Eagle territory occupancy.

2.3 Data analysis

I conducted my research using data only for the transmission lines (≥ 132 kV, Eskom 2013), including the following status categories: existing, commissioned and decommissioned, and

excluding the following status categories: designed, dismantled, invalid, planned or surveyed. I included decommissioned lines because although they are not electrified they can still provide nesting structures. Only 9 % of South African power lines are transmission lines ≥ 132 kV, which are lines typically supported by the largest pylon structures.

In the habitat association modelling analyses I used nest site as the centre point of each Martial Eagle territory. If a territory contained multiple nests, the mid-point on the transmission line between these nest locations was used. When I included territories with only one active nest site this nest was used as the centre point of the territory. Habitat association modelling used territory data, while models assessing Martial Eagle nest spacing (section 2.3.1.4) did not. In this case only active Martial, Tawny and Verreaux's Eagle nests from each year of „Electric Eagle Project“ survey were included in the analyses.

Eight environmental covariates were used to explain Martial Eagle territory density and nest dispersion on the transmission network, these included vegetation cover as well as climatic and physiogeographic variables. Vegetation cover is a category assigned to vegetation units in the South African vegetation book based on vegetation unit descriptions within this literature (Mucina & Rutherford 2006). A vegetation unit is assigned only one of the following three categories: either open vegetation cover if it is a vegetation unit which sparsely covers bare ground; intermediate vegetation cover if it is a vegetation unit which intermediately covers bare ground; or dense vegetation cover if it is a vegetation unit which almost completely covers bare ground. Only intermediate vegetation cover was used as one of the environmental covariates. Open vegetation cover is associated wholly with desert environments and these data were too sparse to be considered in habitat association modelling. Dense vegetation cover represents a directly opposing environment to that of intermediate vegetation cover and to avoid repetitiveness it was dismissed from models. Climatic and

physiogeographic environmental covariates used are obtained from Schulze (2007) (Table 2.2). These layers were created using remote sensing data gathered at a landscape scale. Lastly I wanted to use land use practices to explain Martial Eagle territory density and nest distribution on the transmission network. However I found little spatial variation in urban, degraded, water bodies, plantations and mine land cover covariates (obtained from National Land cover data set see Figure 2.3 H). Data for these covariates would therefore be of little use in explaining eagle territory densities and nest distributions in this particular data set. I therefore had to exclude them from all analyses. I only retained the proportion of cultivated land as a covariate.

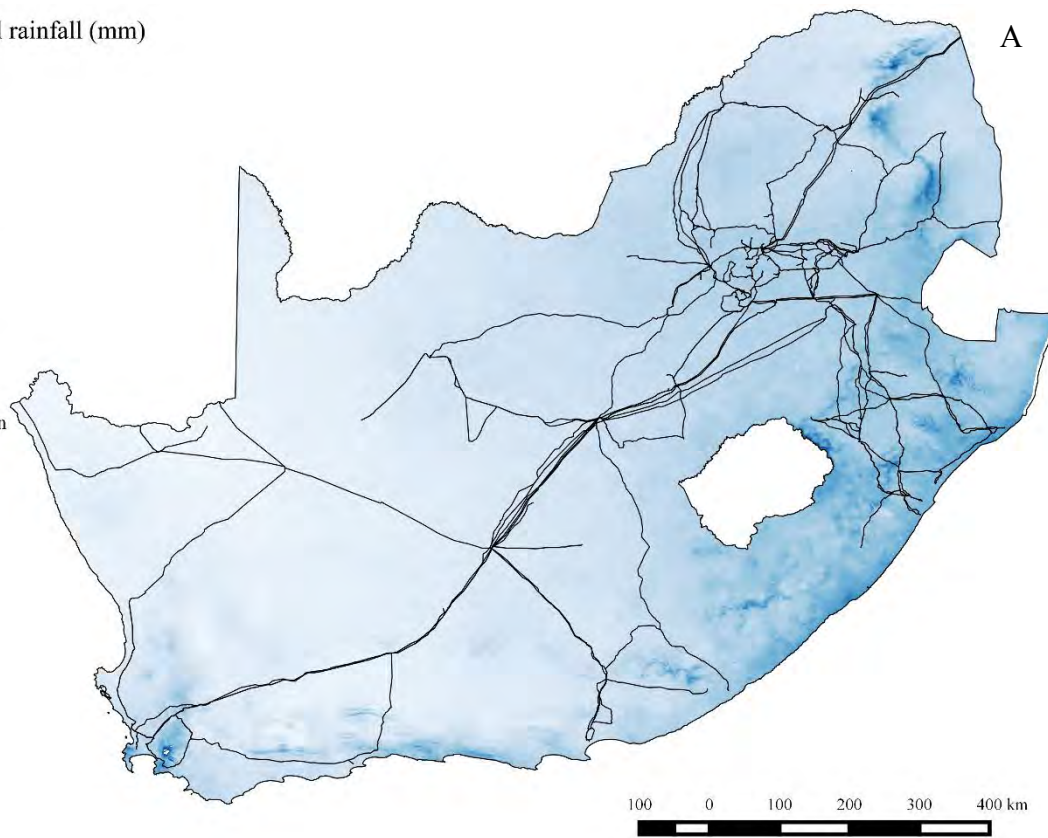
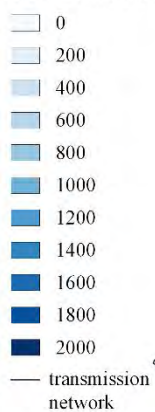
Table 2.2 Environmental and land use data layers used as covariates in habitat association modelling

Covariate	Metric measured in	Extracted as a	Model name	File type	Figure 2.2	Reference
Mean rainfall per annum	millimetres	mean	mrain	raster	A	Schulze & Lynch (2007)
Intermediate vegetation cover	an area of land covered intermediately by vegetation	proportion	minterm	polygon shapefile	B	Mucina & Rutherford (2006)
Average net natural primary productivity	tons per annum per hectare	mean	mavenpp	polygon shapefile	C	Schulze (2007)
Tree cover	percentage	mean	mtree	raster	D	Hansen <i>etal.</i> (2013)
Altitude	meters above sea level	mean	malt	raster	E	Schulze & Horan (2007)
Mean Temperature per annum	degrees Celsius	mean	mtemp	raster	F	Schulze & Maharaj (2007)
Flat ground	80 % of area covered by a gradient of <5 %	proportion	mRgr80 %	polygon shapefile	G	Schulze & Kruger (2007)
Cultivation	proportion of land	proportion	mcult	raster	H	Van den Berg <i>et al.</i> (2000)

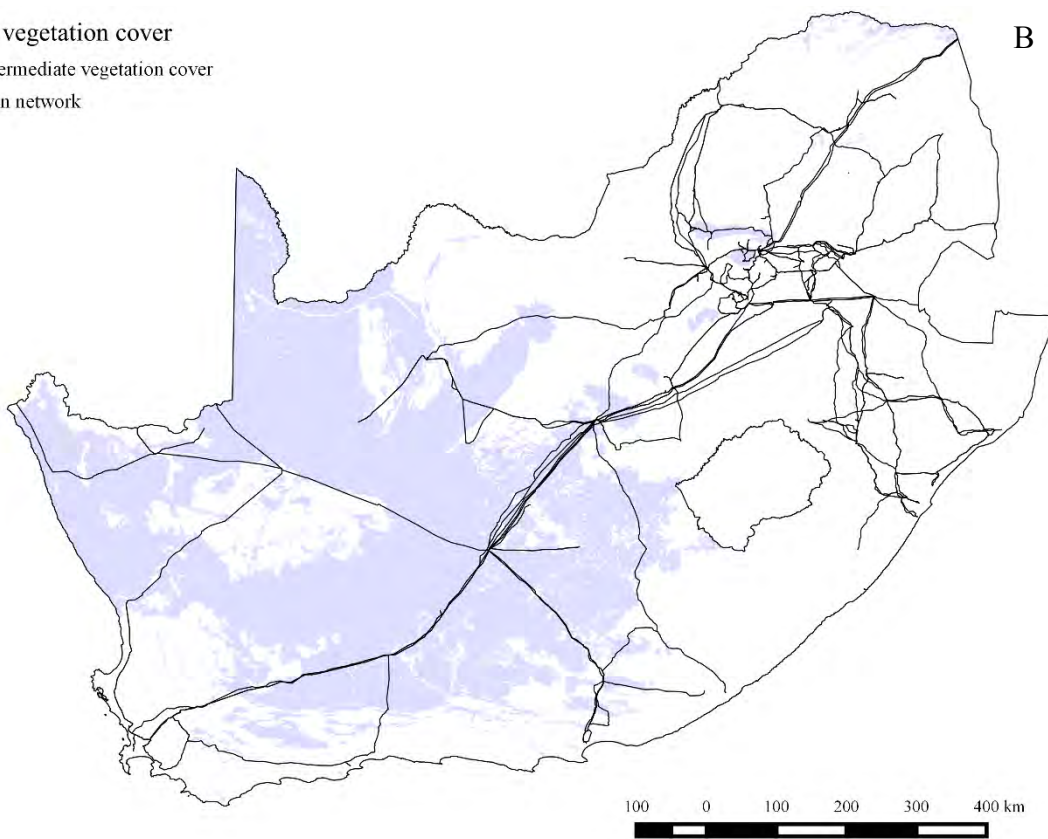
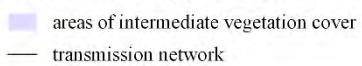
Many of the environmental covariates used in analyses were highly correlated. For example rainfall determines primary productivity, tree cover and, to a large extent, vegetation cover.

To deal with the problem of collinearity, I fitted univariate habitat association models, i.e. models describing Martial Eagle nests locations which included only one of these covariates at the time. For the refined habitat association models fitted to the larger data set, I allowed combinations of certain covariates only if I didn't expect them to correlate with each other (2.3.1.3). The sample size used to build the refined habitat association models was large enough to fit these slightly more complex models, but still small enough to create uncertainty surrounding which models should best described the variation in Martial Eagle territory placement. I therefore always based Martial Eagle territory density predictions on the whole set of habitat association models using Multi-Model Inference (MMI). In this way I avoid collinearity, but still account for all variables which could be affecting Martial Eagle territory density. MMI uses weighted averages across the entire set of habitat association model prediction equations to allow a prediction to be based on a group of models rather than a single best model (Burnham & Anderson 2002). The model name in Table 2.2 refers to the name of each of these habitat association models used to predict Martial Eagle territory density.

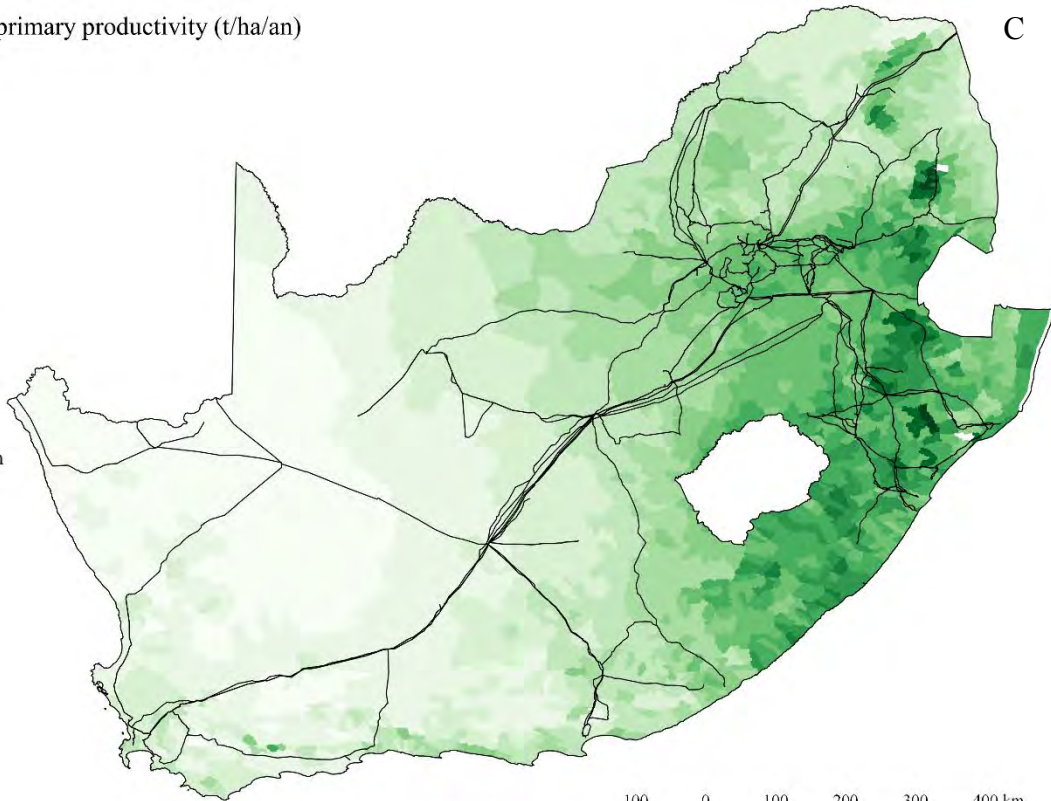
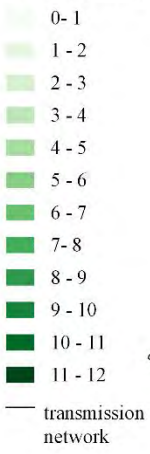
Mean annual rainfall (mm)



Intermediate vegetation cover

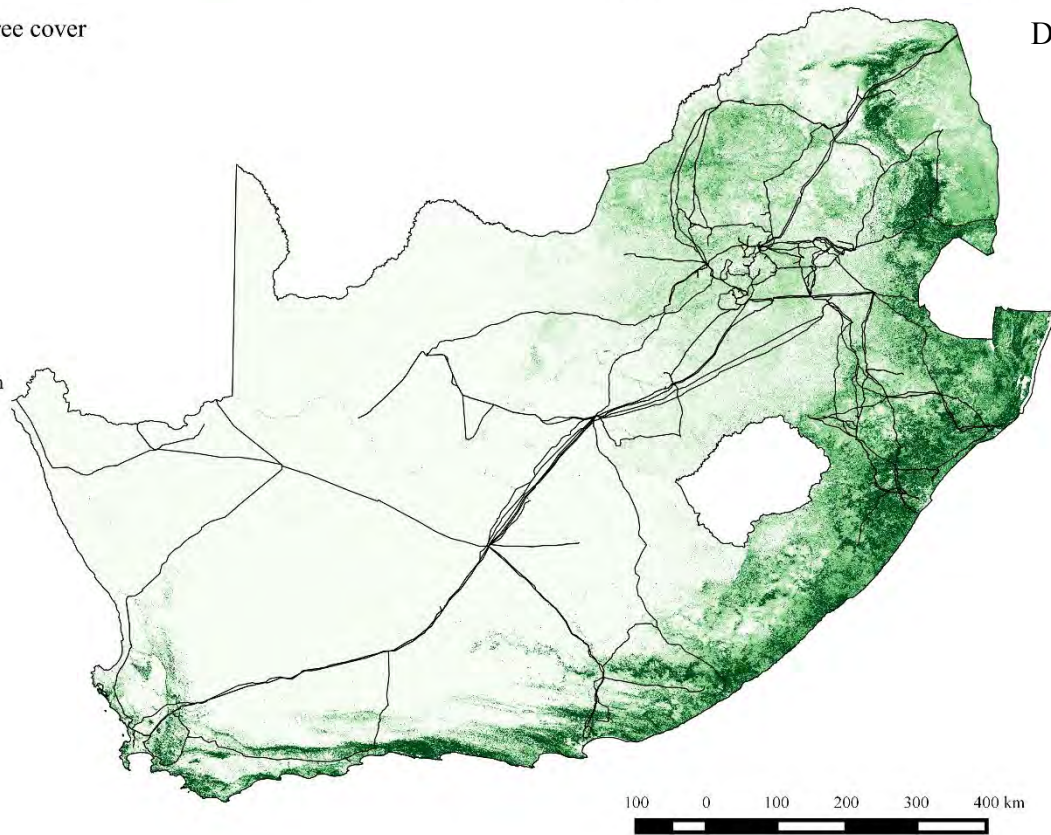
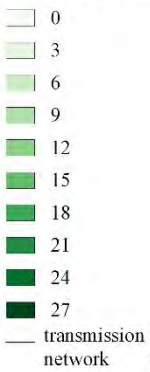


Average net primary productivity (t/ha/an)



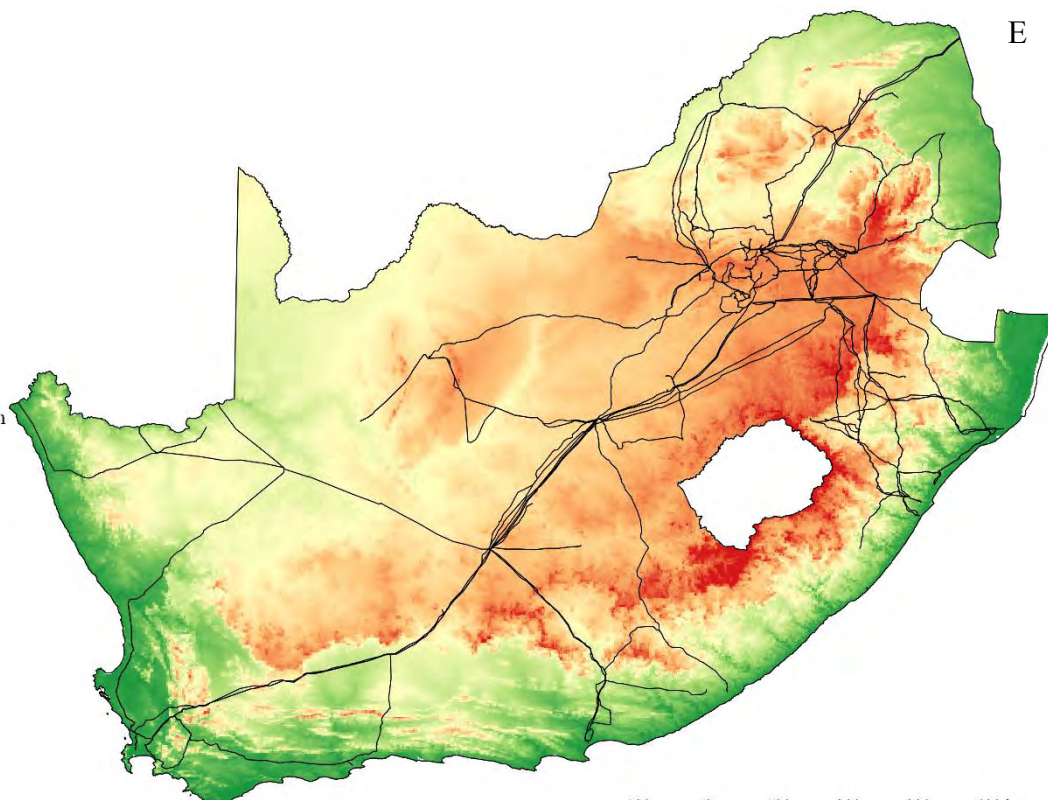
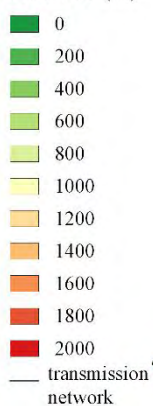
C

Percentage tree cover

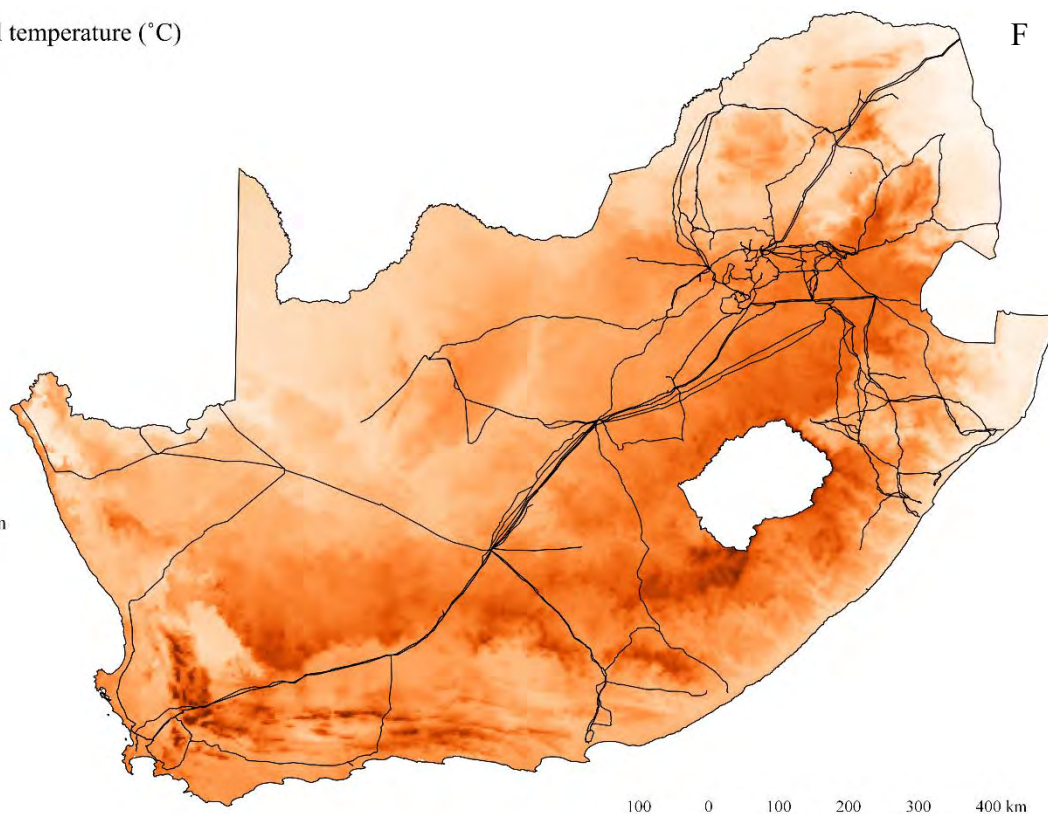
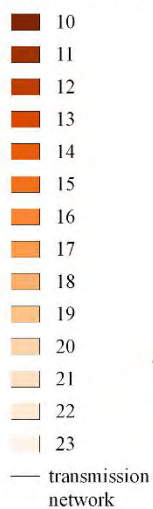


D

Altitude (m)

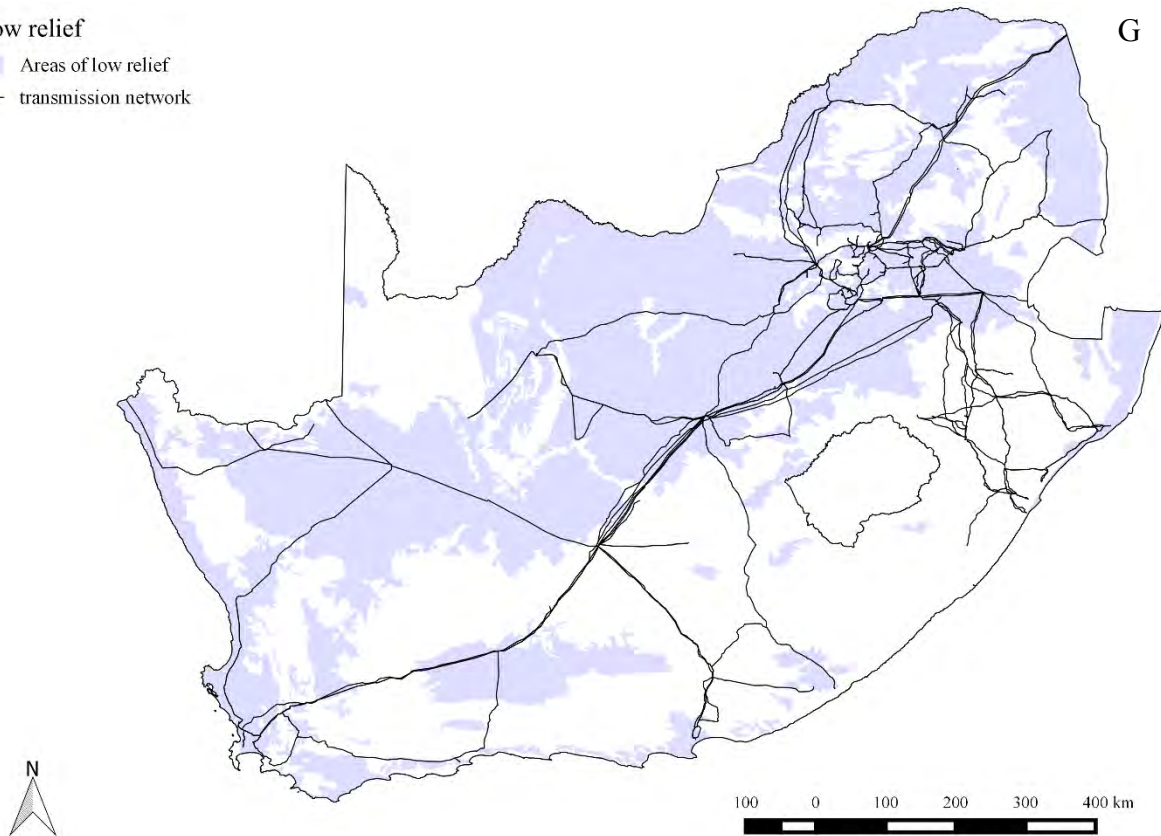


Mean annual temperature (°C)



Low relief

- Areas of low relief
- transmission network



National Land cover

- Natural
- Cultivated
- Degraded
- Urban
- Water bodies
- Plantations
- Mines
- transmission network

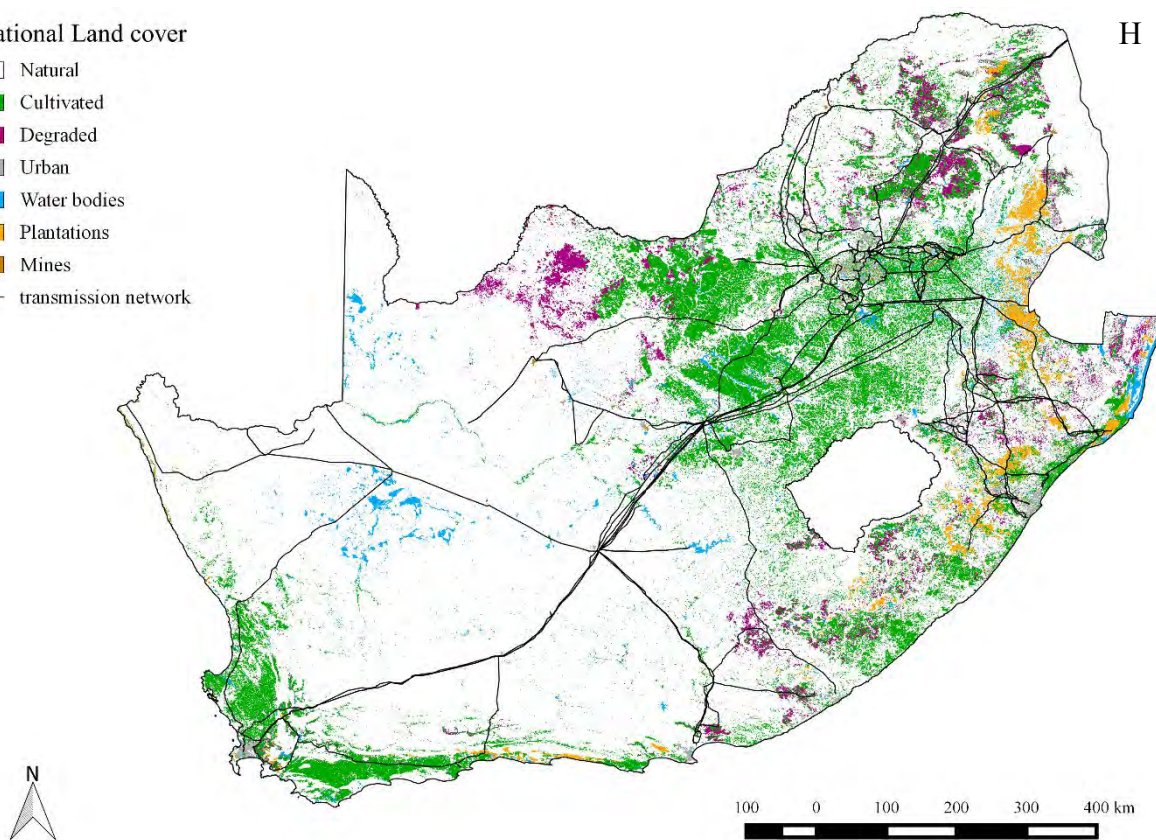







Figure 2.3: Maps showing the variation across South Africa of environmental variables considered important for Martial Eagle territory placement from A-H

2.3.1.1 *Habitat association modelling: examining predictors of Martial Eagle territory density on the transmission network*

I hypothesised that *densities* of Martial Eagle territories on the transmission network would be strongly influenced by environmental, climatic and physiogeographic variables (Table 2.2) at the landscape scale. I therefore examined the relationships between the number of Martial Eagle territories per central transmission line section and environmental covariates surrounding these line sections.

Prior data management steps were implemented first in order to test **H1**. These steps included the simplification of central transmission lines, dividing these lines into line sections, overlaying and tallying Martial Eagle territory count per line sections and extracting environmental covariates from buffered regions around each line section. To simplify the central lines I excluded substations and joined lines which travelled in and out of substations. I further simplified lines (see Figure 2.1) by excluding a line if it ran parallel within 2km of another line (minimum distance between active Martial Eagle nests) using QGIS (Quantum GIS Development Team 2014). This would result in only one transmission line running through a single Martial Eagle territory. To allow Martial Eagle territories count per line section to assume a Poisson distribution, I divided the simplified transmission lines into line sections of equal length (28km). I ran goodness of fit test exclusively for central line sections and this confirmed that the counts of territories per line section were well described by a Poisson distribution. To represent the landscape scale (as in López-López *et al.* 2005) 9km linear buffers were constructed around each of the simplified transmission line sections, resulting in 79 line sections for the central lines (see Figure 2.4). I then extracted environmental covariates (Table 2.2&Figure 2.3 A-H) within each of the individual buffer line section for inclusion in habitat association models (Figure 2.4).

Buffered transmission line sections (28 km x 18 km)

-  central line
-  northern line
-  southern line
-  eastern line
-  transmission network

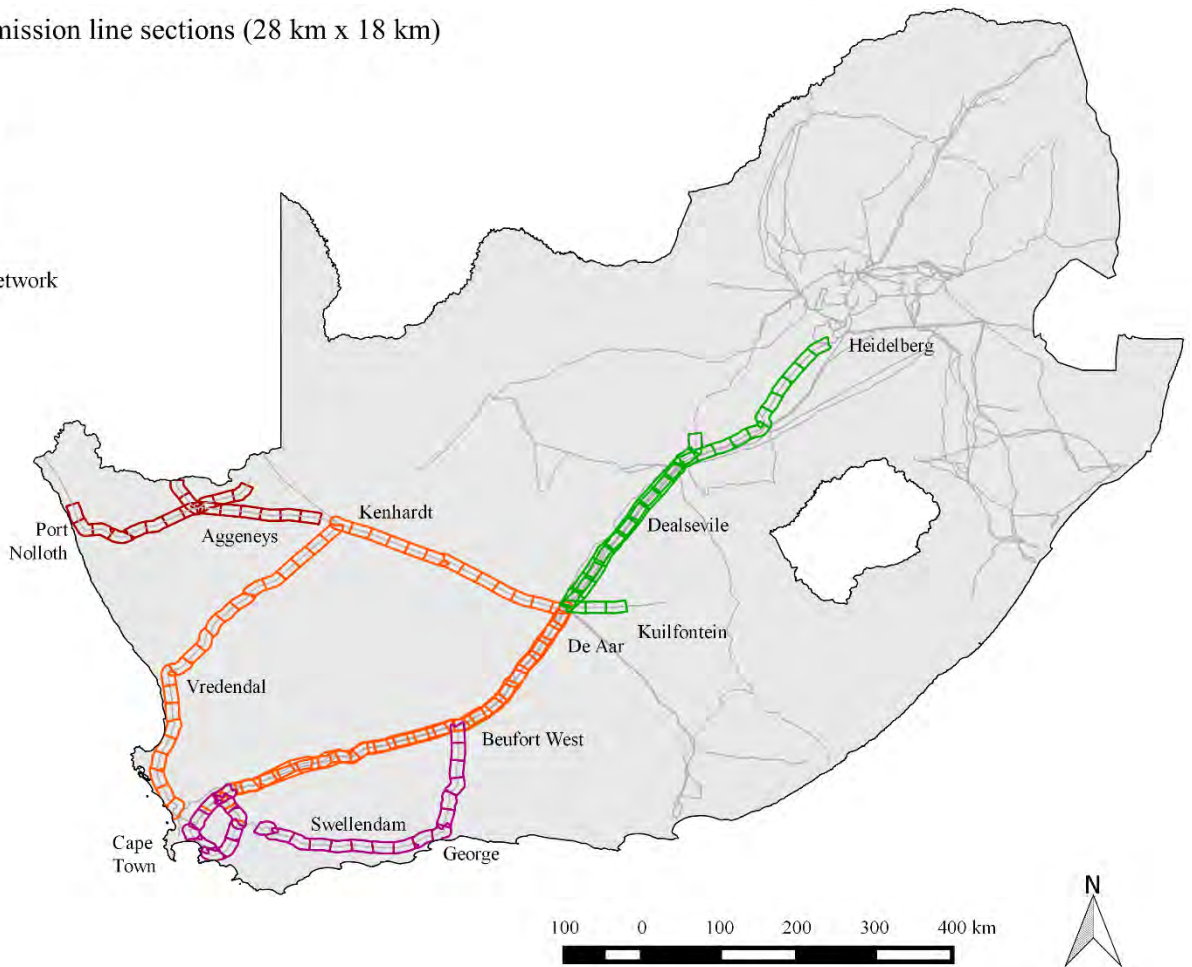


Figure 2.4 Buffered transmission line sections (28km x 18 km buffers) from which environmental covariate data are extracted and Martial Eagle territories are tallied per line section. Predictions of Martial Eagle territory abundance were later made through application of habitat association models for the 28km line sections of the northern, southern and eastern lines respectively.

Once these prior data management steps were implemented, I used Generalised Linear Models (GLM) with Poisson errors and log link functions in R package „stats“ function „glm“ (R Development Core Team 2014) to examine the ability of extracted environmental covariates to explain the variation in Martial Eagle territory count per line section. I modelled each covariate individually to minimise model complexity and avoid over-fitting. This led to eight habitat association models describing Martial Eagle territory density (count) on each of the central transmission line sections, which I compared using Akaike’s Information Criterion (AIC).

2.3.1.2 *Applying the habitat association model: predicting the number of Martial Eagle territories per line section of the transmission network*

Environmental covariate data were extracted for line sections of previously unsurveyed, northern, southern and eastern lines (Figure 2.4) using the same prior data-management steps described in 2.3.1.1. Based on these covariates and the models fitted to the central lines, I then predicted the number of Martial Eagle territories for each unsurveyed line section using the weighted averages of predicted territory counts. I used Akaike weights for the weighted predictions (Burnham and Anderson 2002). The unconditional standard errors were calculated following methods described in Burnham & Anderson (2002) in R (R Development Core Team 2014).

Predictions of Martial Eagle territory count were verified through direct survey (section 2.2.2). On a per line section basis prediction accuracy was quantified by the percentage of observed Martial Eagle territory count which fell within each section's prediction error. I also summed the predictions per line and verified if the summed observed territory count fell within prediction errors. I used a parametric bootstrap method to calculate the 95% prediction interval for the total number of predicted Martial Eagle territories for each of the three lines based on one thousand simulated predictions. For each simulation I generated an observation for each line section, where that observation was drawn from a Poisson distribution with mean equal to the line section prediction. I used the 95 % confidence interval which ranged between the 2.5th percentile and the 97.5th percentile of these simulated values, as reported in Table 2.4. I did investigate creating prediction intervals through a more complex method, which allowed for uncertainty in the original prediction for each line section. This was done by simulating a mean for each line section for each prediction. The mean was drawn from a normal distribution with standard deviation equal to the original prediction standard error.

Results from the simple and complex methods were equivalent and therefore results from the simple method are reported.

2.3.1.3 *Refined habitat association model: predicting the density of Martial Eagle territories on the whole South African transmission network*

In order to satisfy the main aim of my research, to determine the number of Martial Eagle territories on the whole of the South African transmission network, I fitted a new set of refined habitat association models to the combined data from the central, north, south and eastern lines. I extracted covariate data following the steps outlined in section 2.4.1 for all transmission lines across the country (13048 km, the grey lines in Figure 2.4).

The sample size from which refined habitat association models were built was larger and therefore allowed the fitting of slightly more complex models. Since a previous study found cultivation, rainfall and primary productivity to be the most important covariates in determining Martial Eagle territory placement (Machange *et al.* 2005), I allowed a combination of cultivation and rainfall as an additional habitat association model. I expected all environmental covariates to be fairly correlated and so didn't allow any further environmental covariate combinations. As in section 2.3.1.2 I calculated model-averaged predictions for the rest of the transmission lines from the nine newly refined habitat association models.

I summed predictions across all unsurveyed transmission line sections and calculated associated confidence intervals using methods in section 2.3.1.2. I tallied the number of Martial Eagle territories expected for the entire South African transmission network by combing the number of known Martial Eagle territories on the central, northern, southern and eastern lines with the predicted number of Martial Eagle territories for the rest of the transmission network.

2.3.1.4 *Martial Eagle distribution in response to nearest neighbour*

In the previous analysis, Martial Eagle territory density was predicted for the transmission network only, using a set of environmental covariates. This analysis provided no information on territory or nest placement within line sections. More specifically, territory or nest placement in relation to other eagle nests, was not examined in this analysis. I therefore next examined the *location* and *dispersion* of Martial Eagle nests on the transmission network in terms of the influence of environmental covariates surrounding each nest site, as well as the positioning of nearest neighbouring eagle nests (**H2**). I used this analysis to estimate a threshold minimum distance at which Martial Eagle nests can be placed. The results from this investigation were applied to original and refined habitat association model predictions, to establish the maximum number of Martial Eagle territories allowed in a single 28km line section.

Two analyses were performed to test **H2**. In both these investigations, I determined which environmental covariate surrounding Martial Eagle nests best explained eagle nest distribution on the transmission network. In combination with this I used a measure of Martial Eagle dispersion. The difference between the two analyses are that in analysis one minimum distances between Martial Eagle nests were used as a measure of nest dispersion and in analysis two minimum distances between Martial Eagle nests and any other eagles nests i.e. distance to closest Martial, Tawny, or Verreaux's Eagle nests were used as a measure of nest dispersion.

I used Martial, Tawny, and Verreaux Eagle nest location data from the 2002-2006 eagle surveys and calculated the distance between each active Martial Eagle nest and the closest active Martial Eagle nest to it (analysis one) (Jenkins *et al.* 2013). For analysis two I calculated the distance between each active Martial Eagle nest and the closest Martial,

Tawny, or Verreaux's Eagle nest to it. Distances were calculated separately for each year of survey and later amalgamated into one data set. For both analyses I generated a set of random points, equal to the number of active Martial Eagle nests in each year along the transmission lines. I then calculated the distance between each active Martial Eagle nest and the closest random point in each year. Environmental covariate data (Table 2.2) were extracted from a buffer circle of 3km around both active Martial Eagle nests and random points. Similarly to the previous habitat association modelling, models included only one of the eight environmental covariates and of the logarithm of distance to nearest Martial Eagle nest as a second covariate. This resulted in eight different habitat association models.

The response was binary (Martial Eagle nest versus random point) and I used a logit link function to examine the effect of the covariates on the response. Because I expected a non-linear effect (threshold) of distance to nearest eagle nest, I added this covariate as a regression spline with three knots. The environmental covariates were entered as regular linear covariates. All models are fitted using the maximum likelihood method of the `,gam` function of the package `,mgcv` (Wood 2000) in the program R (R Development Core Team 2014) and I selected the best model using AIC.

2.3.1.5 South African Bird Atlas Project 2 Martial Eagle reporting rate in relation to transmission line density.

To investigate my hypothesis (**H3**) that Martial Eagles density in the open habitats of South Africa were positively related to the density of transmission lines, I used South African Bird Atlas Project 2 (SABAP2) data obtained from the Avian Demography Unit at the University of Cape Town. These data are citizen science national survey data which consist of checklists of all bird species encountered in a particular grid cell during a survey. SABAP2 was initiated in 2007 and is currently ongoing. Bird species records are collected at a 5' × 5' (pentad) scale, which I aggregated to the Quarter-degree (QDS) resolution (approx. 26 x 27km). This scale

better corresponds to the Martial Eagles' use of the landscape (van Zyl 1992). Data were collected in each pentad for at least two hours of intense birding and over a period of up to 5 days (Boshoff 1997; <http://saba2.adu.org>). All vetted records submitted until 31st July 2014 are included in this investigation (checklists were submitted for 93 % of all the QDS cells in South Africa).

I use the proportion of checklists that reported Martial Eagles per QDS cell, called reporting rate, as a measure of abundance (Robertson *et al.* 1995). The explanatory variables used to investigate **H3** were transmission line length (km) and biome identity within each QDS cell. I also fitted the interaction between these variables because I expected the effect of transmission line length to depend on biome. Transmission line length (km) and biome identity were extracted for each QDS cell in QGIS (Quantum GIS Development Team 2014).

I treated the number of checklists that reported Martial Eagles as a binomial response with sample size equal to the total number of checklists submitted for a particular grid cell. I used a Generalised Linear Model (GLM) with a logit link function implemented in R (R Development Core Team 2014) using package „stats“ function „glm“.

2.4 Results

2.4.1 Habitat association modelling: examining the predictors of Martial Eagle territory density on the transmission network

The statistics for each of the eight habitat association models are shown in Table 2.3. Half of the relationships between Martial Eagle territory count and environmental covariates were negative, namely rainfall, primary productivity, tree cover and cultivation. While the other half of these relationships were positive, including intermediate vegetation cover, temperature, altitude and area covered by low to no slopes (Table 2.3). Four of the covariates had appreciably higher Akaike weights than the others, and their relationships with Martial Eagle territory count are shown in Figure 2.5. The proportion of deviance explained by the best model was 27 % which is acceptable for a model with a single explanatory variable.

Table 2.3: Individual habitat association model statistics, illustrating which models are given the highest weights in MMI predictions and the nature of each relationship between Martial Eagle territory count and environmental covariate data. Each generalised linear model has only one explanatory covariate see Table 2.2 where each of these is described in detail.

Models	No. of parameters	Delta AIC	Akaike weight	Coefficient	P value	Standard error	Prop. of deviance explained by model
mrain	2	0.00	0.68	-0.01	<0.001	0.00	0.27
mavenpp	2	1.84	0.27	-1.18	<0.001	0.29	0.25
mtemp	2	6.63	0.02	0.38	<0.001	0.10	0.19
mtree	2	7.51.	0.01	-0.45	0.07	0.25	0.18
mcult	2	10.33	0.00	-4.02	0.01	1.58	0.14
mRgr80	2	16.05	0.00	0.79	0.03	0.36	0.07
mopen	2	19.48	0.00	0.47	0.17	0.35	0.02
malt	2	21.95	0.00	-0.00	0.00	0.61	0.00

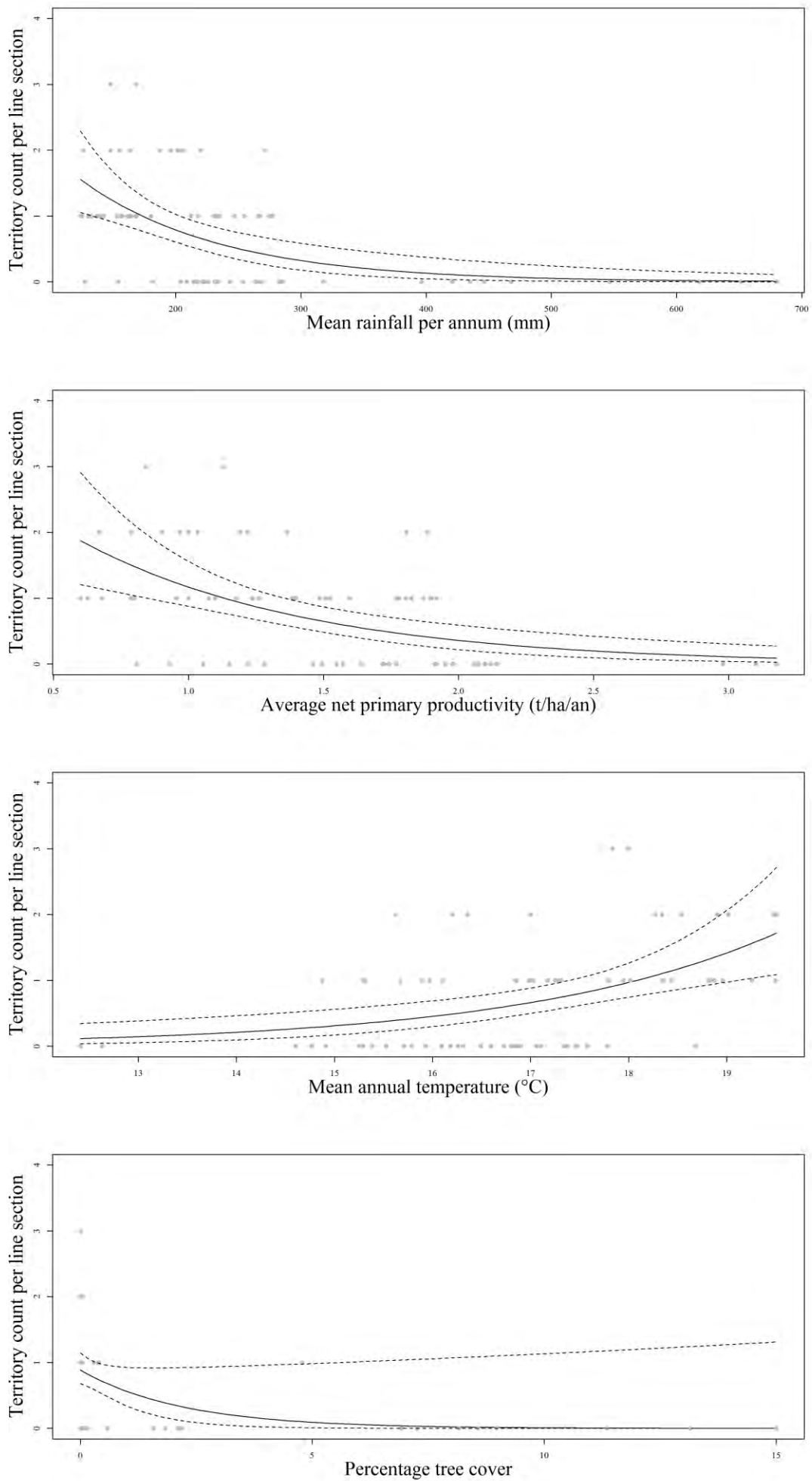


Figure 2.5 GLM habitat association model fits for four of the best models explaining Martial Eagle territory density on the central line. Dotted lines represent confidence intervals

2.4.2 Applying the Habitat association model: predicting the number of Martial Eagle territories per line section of the transmission network

Rainfall was the best model with the lowest Akaike weight (Table 2.3). Sixty-eight percent of the final Martial Eagle territory count prediction for each of the three unsurveyed lines was therefore based on this model. Predictions for the southern line were the most accurate, with predictions for the northern and eastern lines being fairly inaccurate (Table 2.4). Fourteen northern line sections and eastern line sections had poor predictions, while five southern line sections had poor predictions since the number of observed Martial Eagle territories on each of these line sections fell outside of prediction confidence intervals (Figure 2.6-Figure 2.7). This translated into 26 %, 81 % and 60 % of observational data falling within prediction confidence intervals for the northern, southern and eastern line sections respectively. The habitat association models therefore performed relatively well when predicting Martial Eagle territory density for unsurveyed lines.

Table 2.4: Survey verification data as represented by observed Martial Eagle territory count and the predicted Martial Eagle territory count for the northern, southern and eastern lines through habitat association modelling

	southern lines		northern lines			eastern line		
	Lower CI	Upper CI	Lower CI	Upper CI	Lower CI	Upper CI		
Prediction	2	6	23	35	2	6	11	
Observation.	4		13			15		6
Observation -prediction.	-2		-22			-5		

*CI is Confidence interval

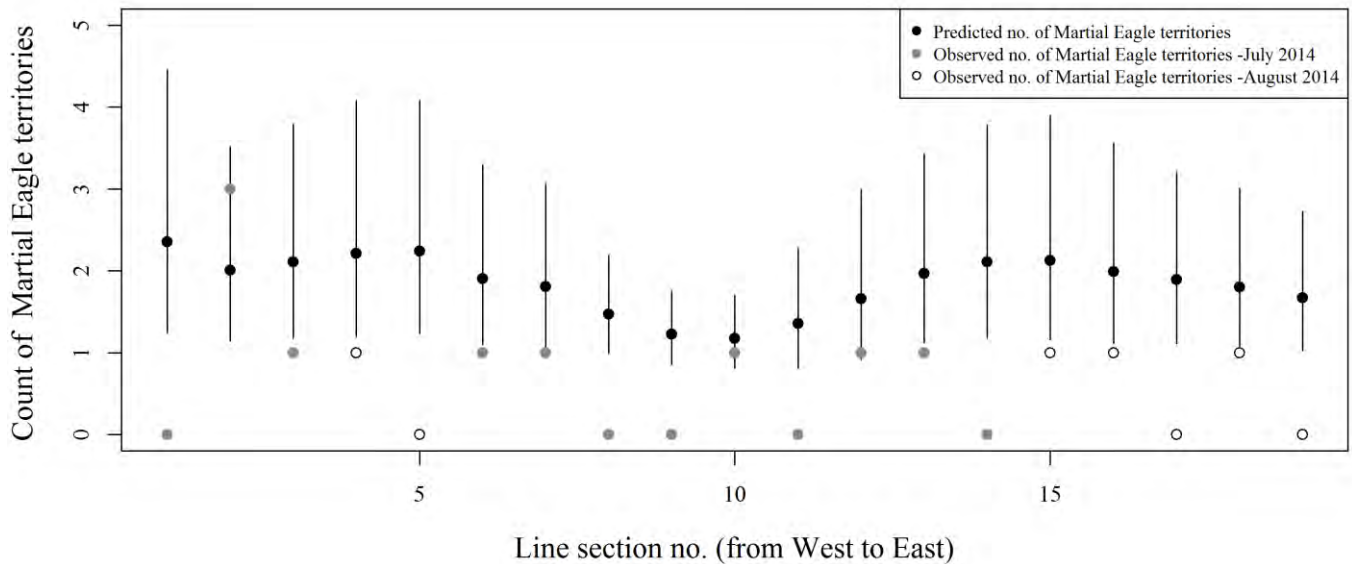


Figure 2.6 Count of observed and predicted Martial Eagle territories per 28km northern line section, the bars represent +/- 2 standard errors

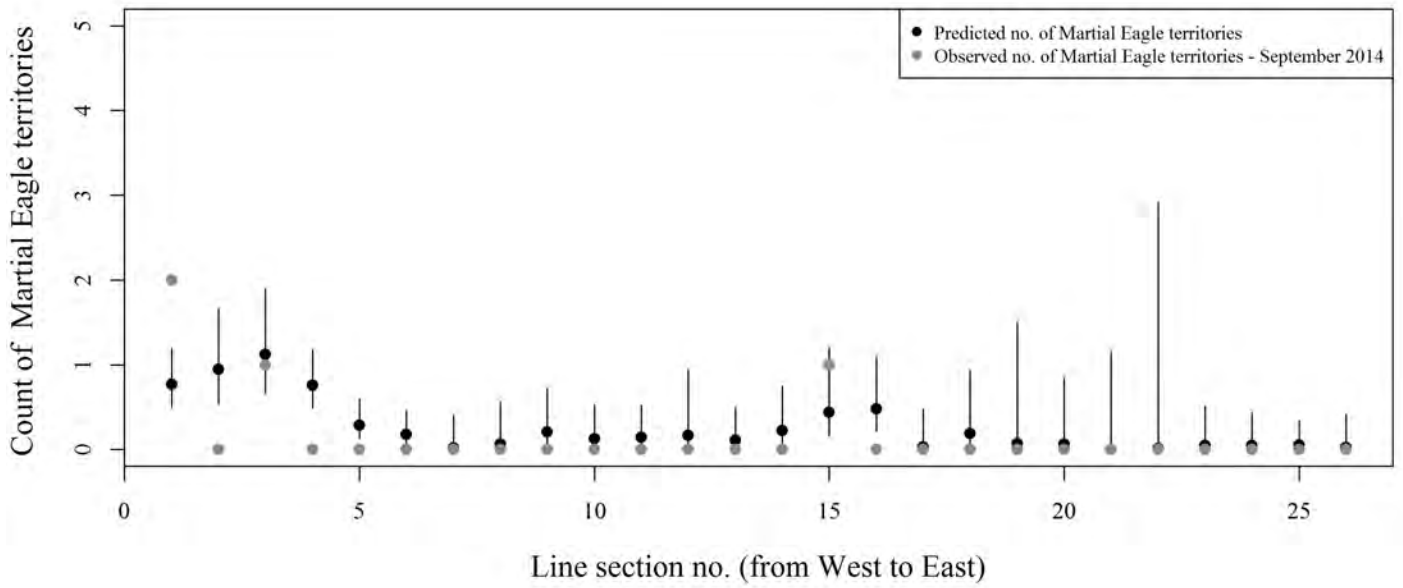


Figure 2.8 Count of observed and predicted Martial Eagle territories per 28km southern line section, the bars represent ± 2 standard errors

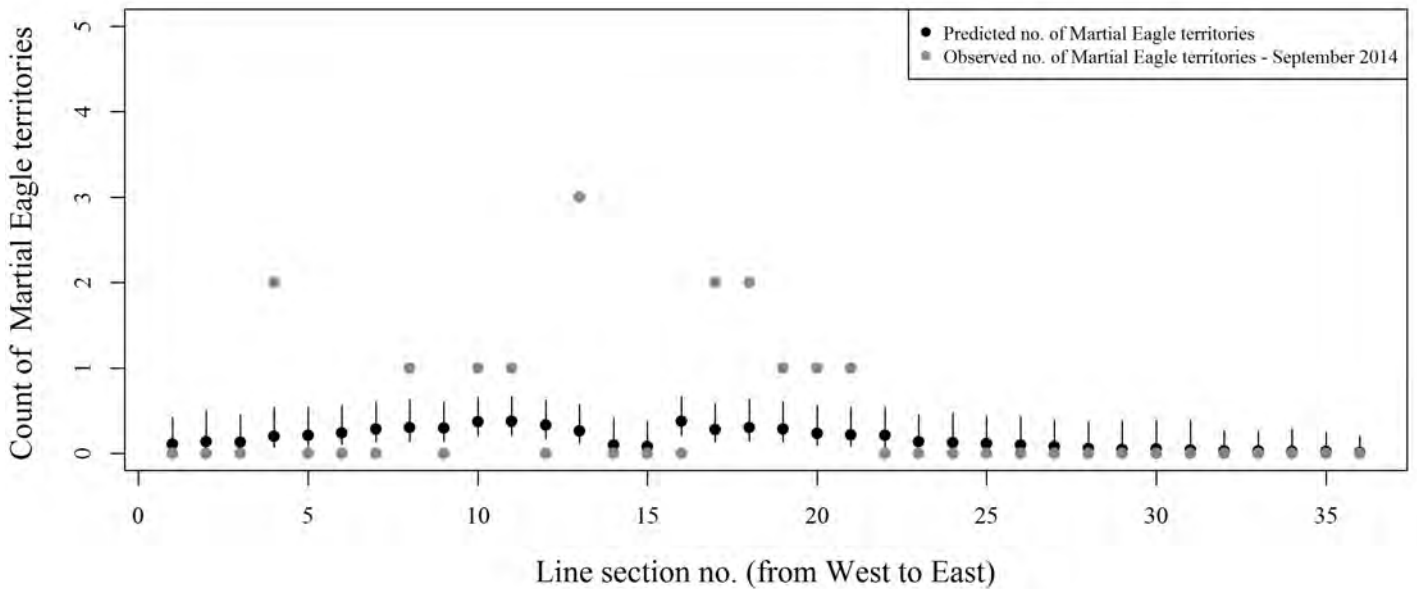


Figure 2.7 Count of observed and predicted Martial Eagle territories per 28km eastern line section, the bars represent ± 2 standard errors

2.4.3 Refined habitat association model: predicting the density of Martial Eagle territories on the whole South African transmission network

The refined habitat association models yielded a similar result to the original habitat association models as the nature of relationships remained the same (Table 2.3 & Table 2.5).

The model contributing most to the predictions was *mculttrain*. This model had both cultivation and rainfall as explanatory variables of Martial Eagle territory count and had appreciably higher Akaike weight than any of the other models (Figure 2.10). In section 2.4.1 primary productivity was the best model, but with the inclusion of more Martial Eagle territory data from a wider range of environments, rainfall and cultivation emerged as the best predictors of Martial Eagle territory density (Table 2.5). The proportion of deviance explained by the models was satisfactory and the best habitat association model explained 39 % of the variation in Martial Eagle territory density (Table 2.5).

Individual lines section predictions summed to a total of 52 Martial Eagle territories for the remaining transmission lines unsurveyed for Martial Eagle territories, with a lower confidence limit of 38 territories and an upper confidence limit of 67 territories. In combination with the 92 Martial Eagle territories found during the two survey periods, this predicted figure yields an overall estimate of the Martial Eagle population resident on South Africa's national transmission grid to be 144 within an upper confidence limit of 159 territories and a lower confidence limit 130 territories (Figure 2.11).

Table 2.5: Individual refined habitat association model statistics, illustrating which models are given the highest weights in MMI predictions and the nature of each relationship between Martial Eagle territory count and environmental covariate data. Each generalised linear model has only one explanatory covariate see Table 2.2 where each of these is described in detail.

Models	No. of parameters	Delta AIC	Akaike weight	Coefficient	P value	Standard error	Prop. of deviance explained by model
mcultrain	3	0	0.95	rainfall cultivation	-0.01 -3.5	0 1.47	0.39
mrain	2	6.87	0.03	-0.01	0	0	0.33
mcult	2	8.39	0.01	-6.62	0	1.5	0.32
mtree	2	17.39	0	-0.52	0	0.17	0.27
mavenpp	2	18.15	0	-0.96	0	0.18	0.26
mtemp	2	35.55	0	0.47	0	0.1	0.15
mopen	2	42.88	0	1.13	0	0.31	0.1
malt	2	55.86	0	0	0.16	0	0.01
mRgr80	2	56.68	0	0.31	0.27	0.28	0.01

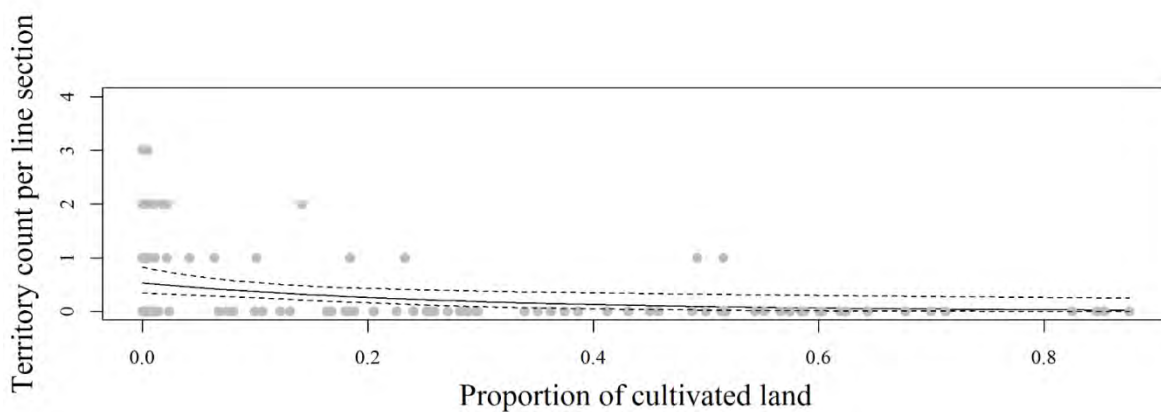
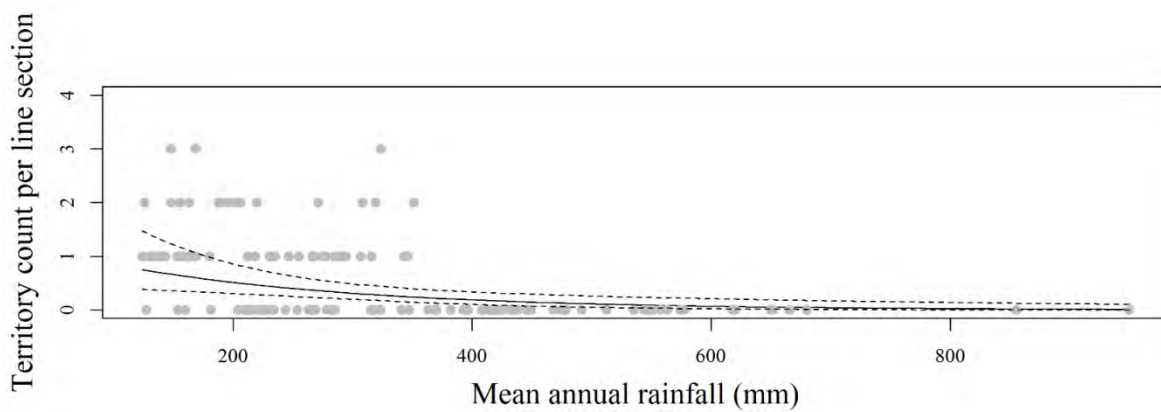


Figure 2.10 GLM habitat association model fit for the best model explaining Martial Eagle territory density on the central, northern, southern and eastern lines. The relationship between Martial Eagle territory count and rainfall is calculated at mean cultivation and the relationship between Martial Eagle territory count and cultivation is calculated at mean rainfall. Modelled separately rainfall and cultivation GLM (mrain and mcult) curves follow the same trajectory as presented in this figure. The dotted lines represent the confidence intervals.

Distribution of Martial Eagle territories

No. of observed territories

- 0
- 1
- 2
- 3

No. of predicted territories

- 0-0.1
- 0.1-0.2
- 0.2-0.3
- 0.3-0.4
- 0.4-0.5
- 0.5-0.6
- 0.6-0.7
- 0.7-0.8
- 0.8-0.9

Percentage tree cover

- 0
- 3
- 7
- 10
- 14
- 17
- 21
- 24
- 27

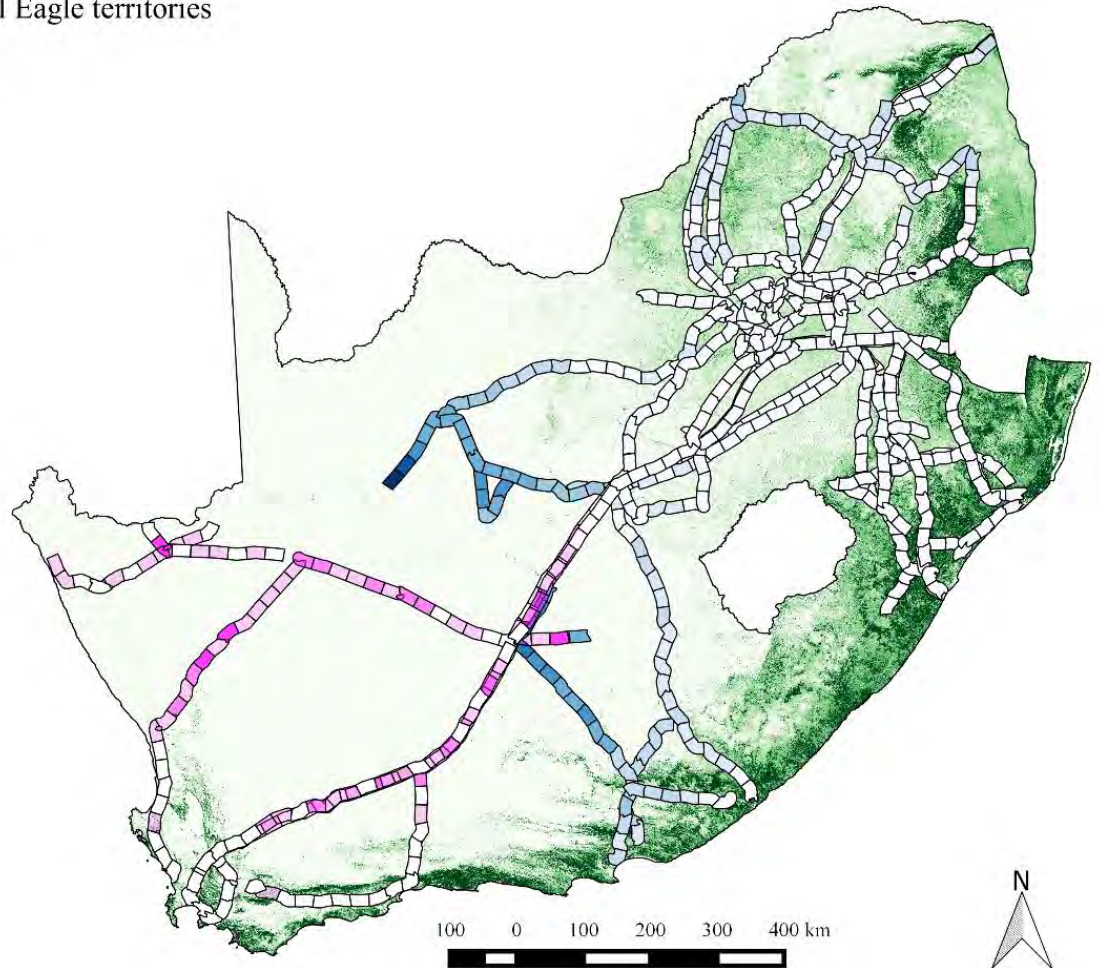


Figure 2.11: Observed and predicted Martial Eagle territory counts per 28km section of transmission line, in relation to percentage tree cover, to illustrate that higher territory densities of Martial Eagles occur in areas of low tree cover, even though tree cover was not the most heavily weighted model in MMI.

2.4.4 Martial Eagle response to nearest neighbour

Analysis one and two showed that individual Martial Eagle nest positions responded to both natural environmental covariates surrounding each nest and minimum distance to nearest neighbouring eagle nest. When rainfall was included as the single environmental covariate used to explain Martial Eagle nest dispersion, these models performed best in both analyses

(Table 2.6 & Table 2.7). I therefore only report results from these models. Distance to nearest active Martial Eagle nest was a strong predictor for nest locations (Figure 2.12). If a locus was within 10km of an active Martial Eagle nest the probability of the position being that of another active Martial Eagle nest site dropped rapidly. In addition the probability of a point being an active Martial Eagle nest site (rather than a random point) was increased if the locus fell within a region of 200-300 mm of rainfall, while rainfall above 300mm resulted in a rapidly diminishing probability (Spline process: $\mu_{\text{min distance}} = 28.16\text{km}$, $\chi^2 = 12.82$, $df = 2$, $p\text{-value} = 0.0016$, Linear process: $\mu_{\text{rain}} = 185.85\text{mm/an}$, coefficient. = -0.010 , $se = 0.0022$, $p\text{-value} < 0.001$, $n = 306$ Martial Eagle nests, Figure 2.12, **Error! Reference source not found.** & Table 2.6). In analysis two, the same result was found, although at a lower tolerance level. If a locus was within 8km of an active Martial, Tawny or Verreaux's Eagle nest the probability of the position being that of another active Martial Eagle nest site dropped rapidly. In addition the exact same result was found for analysis two considering rainfall. (Spline process: $\mu_{\text{min distance}} = 23.46\text{km}$, $\chi^2 = 7.41$, $df = 2$, $p\text{-value} = 0.025$, Linear process: $\mu_{\text{rain}} = 185.85\text{mm/an}$, coefficient. = -0.010 , $se = 0.0022$, $p\text{-value} < 0.001$, $n = 306$ Martial Eagle nests, Figure 2.14, **Error! Reference source not found.** & Table 2.7).

In order to determine which Martial Eagle nest dispersion measure was the best driver of Martial Eagle nest location, I compared the AIC values of the best models in each analyses. The best model was one which incorporated only Martial Eagle nests as a measure of dispersion and rainfall (Table 2.6 & Table 2.7). This result that Martial Eagle nests are affected by the placement of neighbouring Martial Eagle nest was used in habitat association models. The minimum distance between Martial Eagle nests was used to calculate how many Martial Eagles could realistically fit into a 28km line section. Minimum distance was 2 km and so all habitat association model predictions and confidence intervals were capped if they exceeded 15 eagle territories per 28 km of transmission line section. This did not need to be

implemented as habitat association prediction and confidence intervals were always well below 15 eagle territories.

Table 2.6 Environmental covariate selection for model with distance to nearest Martial Eagle nest.

Environmental covariate	No. of parameters	Delta AIC	AIC	Coefficient	P value	Standard error (s.e)
Rainfall	3	0.00	352.48	0.01	<0.001	0
Tree cover	3	5.56	358.04	-1.74	0.01	0.64
Average primary productivity	3	6.66	359.14	-1.38	3.63	0.27
Cultivation	3	15.34	367.82	-5.56	<0.001	1.65
Temperature	3	23.35	375.83	0.39	<0.001	0.11
Low slope	3	29.96	382.43	0.82	0.01	0.30
Altitude	3	34.93	387.41	0	0.15	0
Intermediate vegetation cover	3	37.17	389.65	-0.03	0.91	0.28

Table 2.7 Environmental covariate selection for model with distance to nearest Martial Eagle, Verraux's Eagle or Tawny Eagle nest.

Environmental covariate	No. of parameters	Delta AIC	AIC	Coefficient	P value	Standard error
Rainfall	3	0.00	374.25	-0.01	<0.001	0
Tree cover	3	3.32	377.56	-1.86	0.01	0.75
Average primary productivity	3	5.67	379.91	-1.35	<0.001	0.26
Intermediate vegetation cover	3	23.38	397.62	-0.07	0.80	0.27
Cultivation	3	16.84	391.09	-5.69	0.02	1.82
Temperature	3	24.26	398.50	0.38	<0.001	0.10
Low slope	3	30.85	405.10	0.80	<0.001	0.28
Altitude	3	37.39	411.64	0	0.19	0

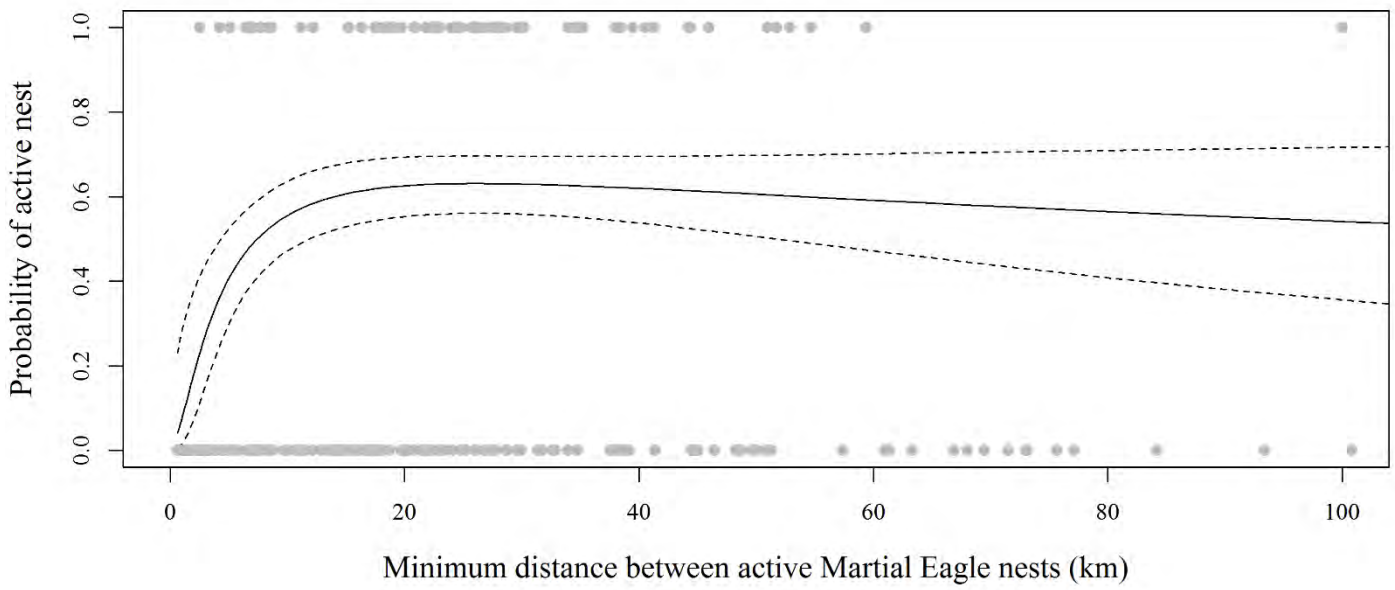


Figure 2.12: Probability of a Martial Eagle nest being active nest and not a random point given minimum distance to nearest Martial Eagle nest at a mean annual rainfall

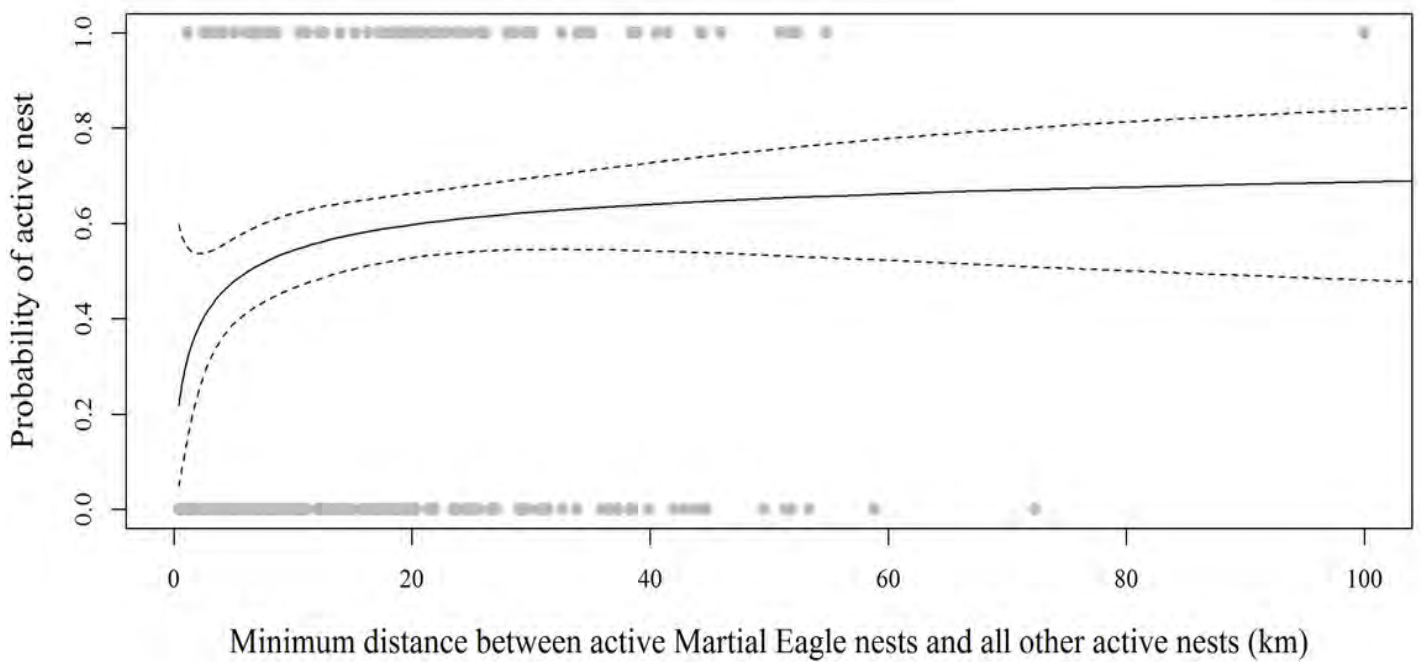


Figure 2.13: Probability of a Martial Eagle nest being active and not a random point given minimum distance to nearest eagle nests at a mean annual rainfall

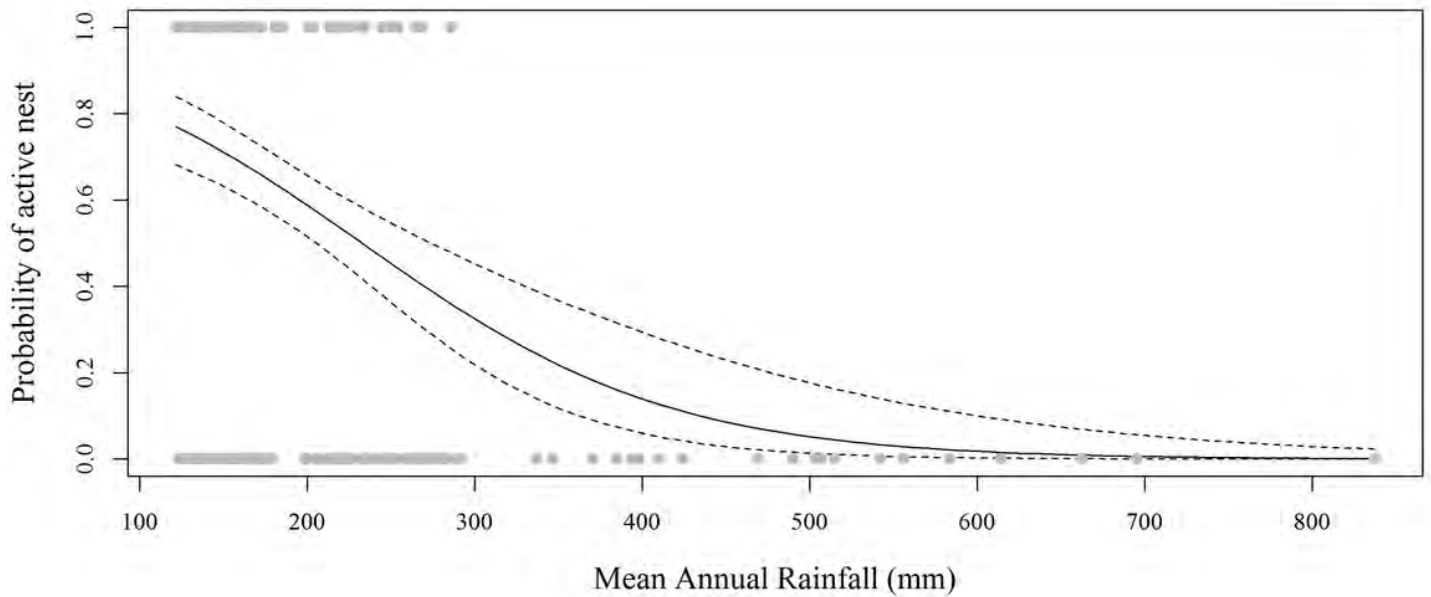


Figure 2.14 Probability of a Martial Eagle nest being active and not a random point given mean annual rainfall surrounding each Martial Eagle nest at a mean distance.

2.4.5 South African Bird Atlas Project 2 Martial Eagle reporting rate in relation to transmission line density

A strong negative relationship (coefficient = -0.013, s.e = 0.00072, p-value < 0.001, n=1843 QDS cells) emerged between the proportion of Martial Eagle detections and transmission line length within each QDS cell. However, the interaction between transmission line length and biome was also significant. Transmission line density had a positive effect on the proportion of Martial Eagle detections per QDS cell within the Desert Biome (est. coeff=0.063, s.e = 0.027, p-value= 0.023) and a negative effect on the proportion of Martial Eagle detections per QDS in the Savanna Biome (est. coeff = -0.016, s.e=0.0046, p-value <0.001). Additionally nonsignificant negative effects emerged between proportion of Martial Eagle detections per QDS and all remaining biomes. Interestingly, relatively few QDS cells surrounding the surveyed transmission lines have a high Martial Eagle reporting rate (Figure 2.15). There are very few QDS cells which have a high density of power lines and a high Martial Eagle

reporting rate. Figure 2.15 additionally shows that many of the Martial Eagles occupying known nest sites on the transmission lines have not been reported by SABAP2 atlasing.

SABAP2 Martial Eagle reporting rate

transmission line length (km)

- 0 - 67
- 67 - 135
- 135 - 203
- 203 - 271
- 271 - 339

Martial Eagle reporting rate

- 0.2
- 0.4
- 0.6
- 0.8
- 1.0

Biome

- Azonal Vegetation
- Desert Biome
- Forests
- Fynbos Biome
- Grassland Biome
- Indian Ocean Coastal Belt
- Nama-Karoo Biome
- Savanna Biome
- Succulent Karoo Biome
- Albany Thicket Biome
- Martial Eagle territories
- transmission network

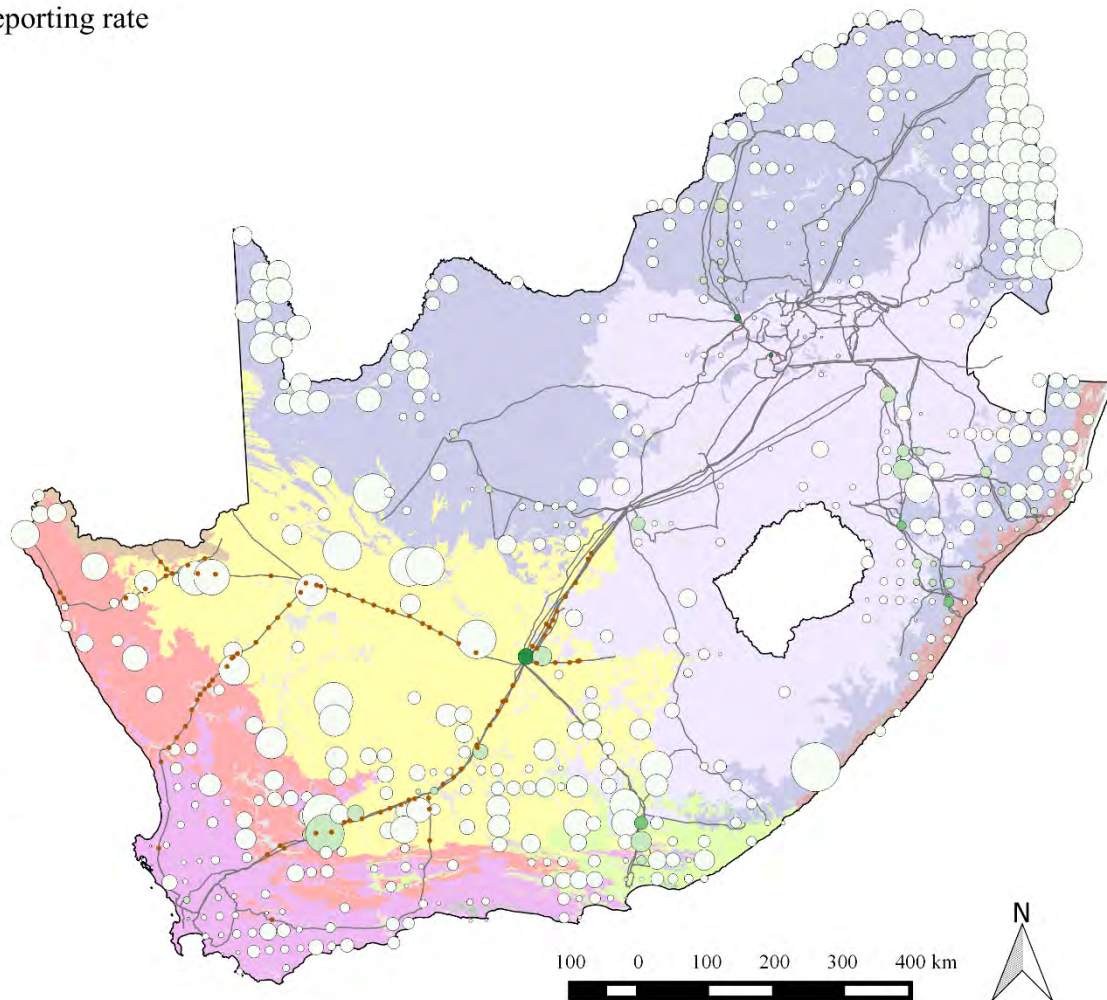


Figure 2.15 Weighted SABAP2 reporting rates for Martial Eagles in relation to biome and the distribution of the national transmission grid.

2.5 Discussion

2.5.1 Habitat association model: predicting the density of Martial Eagle territories on the whole South African transmission network

Based on the number of Martial Eagle pairs nesting on the national transmission grid, the results of this study indicate that eagles nesting on transmission lines could well be as numerous, as the combined populations of the Kruger National and Kgalagadi Transfrontier Parks. These parks were previously believed to be the remaining strongholds for this species (Tarboton & Allan 1984).

The current estimate of the national Martial Eagle population was calculated through combining the nesting densities of Martial Eagles in six previous designated regions of South Africa (Taylor In press 2015). Having taken into account the decline in Martial Eagles since 1984, the population was estimated to be approximately 800 adult birds (Taylor In press 2015). Assuming a gender balanced population, the findings of this research indicate that 36 % of the national breeding population resides on man-made structures in commercial ranchland.

In order to estimate the population of Martial Eagles nesting on the national transmission grid, habitat association models were used. These models were used to test the hypothesis that densities of Martial Eagle territories on the transmission network are influenced by environmental climatic and physiogeographic variables, at the landscape scale (**H1**). This hypothesis is substantiated by both original and refined habitat association models, which satisfactorily explained the variation in Martial Eagle territory density on the transmission lines (Table 2.3 & Table 2.5). The environmental covariates used in habitat association modelling were chosen, based on the finding of a previous study and these expected

relationships have remained consistent between the two study periods (Machange *et al.* 2005). The main aim of this study was not to provide a definitive test for factors driving Martial Eagle territory density on the transmission network, or even to fully understand these; but rather an attempt to use and test a set of likely drivers which provide an estimate of the Martial Eagle territory density on the transmission network.

Verification of original habitat association models may provide further insight into the ability of the environmental covariate data to track Martial Eagle territory density on the transmission lines. The discrepancy between the observed number of Martial Eagle territories and the predicted number of territories for all lines is discussed, in terms of environmental covariate rainfall. Predictions were primarily based on this model (Table 2.4 & Table 2.3).

Predicted Martial Eagle territory counts for the northern line were not accurate and too high (Table 2.4). Habitat association models expect that rainfall should translate into high Martial Eagle territory counts, because of a negative linear relationship (Table 2.3). Logically this negative linear relationship should break down in regions of very low rainfall, as they probably would not have enough vegetative material to support large enough prey to sustain an eagle population. The northern line is surrounded by rainfall which is identical to the lowest rainfall surrounding the central lines. This rainfall supports many eagle territories on the central line, but not on the northern line (Figure 2.3 C). Hence the over-prediction of Martial Eagle territories for the northern lines is indicative of the collapse of this negative linear relationship (Figure 2.5). The same phenomenon is observed with under estimation of eagle territories for the eastern lines. Here the rainfall is not considered low enough to support as many eagles as it does.

The predicted Martial Eagle territory count for the southern line was accurate. This result is due to similar rainfall conditions surrounding both the central and southern lines. Predictions

for line sections 1-4 and 15-16 of the southern line are elevated (Figure 2.7 C), because of this relationship.

Both original and refined habitat association models performed well, because a satisfactory amount of variation within Martial Eagle territory density on the transmission lines was explained through the eight environmental covariates chosen (Table 2.5). In addition the majority of predictions made by original habitat association models were accurate, despite the homogenous nature of the Karoo environment, on which these models were based. Prediction made by Booms *et al.* 2010 of Gyrfalcon nest occurrence were accurate 67 % of the time, when assessed with independent nest data. When predictions from original habitat association models were assessed with independent data, they proved accurate up to 81 % of the time. Based on all these rationale and the variety of different environments covered by refined habitat association models, predictions from these models are likely to give a true reflection of Martial Eagle territory count for unsurveyed transmission lines. Verification surveys for refined habitat association models do, however, need to be performed especially within open/more treed habitats, to allow direct testing of the influence of tree availability on the selection of power pylons as nesting substrata.

2.5.2 Martial Eagle distribution in response to nearest active territory

The location and dispersion of Martial Eagle nests on the transmission network has been found to be influenced by environmental covariates surrounding each nest, as well as the positioning of nearest neighbouring eagle nests. This supports the *location* and *dispersion* of Martial Eagle nest sites on the transmission network should be influenced by environmental covariates surrounding each nest site as well as by the positioning of nearest neighbouring eagle nests (**H2**). These findings are congruent with previous studies, which found that for

species occupying exclusive home ranges, territoriality can be an important disperser in optimal habitats (Newton 1979).

Overall the best model which explained Martial Eagle nest dispersion on the transmission lines had similar explanatory variables, as models set to explain the nest occupancy of Booted Eagles *Hieraaetus pennatus*. In Murcia, Spain, nest dispersion of Booted Eagles was related to intraspecific nearest neighbour distances and two habitat variables (Martínez *et al.* 2006). These findings are described as a consequence of competition (Solonen 1993; Hakkarainen *et al.* 2004) and are congruent with the theory that Martial Eagles nest at low densities with large distances between nest sites (Newton 1979; van Zyl 1992; Boshoff 1993; Herholdt & Kemp 1997).

My results confirm that nest placement between eagles of different species to be an important disperser of Martial Eagle nests. Previous research has not detailed the effects of conspecific and other eagles' species nest placement on the dispersion of Martial Eagle nest sites. A previous study in the Kgalagadi Transfrontier Park illustrated that Martial Eagles and Bateleurs show similar habitat preferences (Herholdt & Kemp 1997), while another study found that all transmission line eagle territories including Martial Eagles were irregularly spaced (Machange *et al.* 2005).

Many other studies have also shown that choice of nest location is most often driven by the availability of high quality habitats, within areas constrained by neighbouring territories (Katzner *et al.* 2005; Klaver *et al.* 2012). This seems the case for transmission line nesting Martial Eagles, although the abundance of pylons suggests that nest site availability should not be a limiting factor (Boshoff 1993). The large spatial requirements of Martial Eagles may cause space to be the limiting factor.

2.5.3 South African Bird Atlas Project 2 Martial Eagle reporting rate in relation to transmission line density

I examined whether the substantial population of Martial Eagles nesting on the transmission network are large enough to noticeably affect the probability of encountering Martial Eagles in the low tree cover regions of the country. If that was the case, I would have expected a more positive relationship between transmission line density and Martial Eagle reporting rate in arid areas compared to more mesic, tree-covered areas. The main result from this analysis was a largely negative relationship between transmission line length and proportion of checklists reporting Martial Eagles (**Error! Reference source not found.**). However the interaction between biome and transmission line length was significant because of a locally positive relationship between transmission line length and Martial Eagle reporting rate in the Desert Biome. Thus **H3** is partially confirmed as the results are consistent with the hypothesis that transmission line density increases Martial Eagle density within low tree cover environments such as the Desert biome. The generally negative relationship between transmission line density and Martial Eagle reporting rate throughout all other biomes is probably a result of transmission line density positively associating with other variables. These include cultivated areas and to a certain extent human development which Martial Eagles have been shown to avoid (though the latter is not investigated within the current study). Neither of these land use practices seem to affect the Desert Biome as drastically due to its extreme aridity and uniformity (Jürgens *et al.* 2006).

Reporting rate are sometimes interpreted as a measure of population density (Robertson *et al.* 1995; Huntley & Barnard 2012). However in my case, the reporting rate reflects the probability that a typical birder will encounter a Martial Eagle, which may only loosely be related to population density. Reporting rate are affected by a number of factors including what part of a grid cell is accessible to the public or the location of popular birding

destinations in relation to where the eagles occur (Figure 2.15). The arid areas are furthermore poorly sampled, which introduces a large observation uncertainty. Nevertheless, across the country, reporting rates seem to reflect Martial Eagle population densities relatively well. For example the low reporting rates along the southern lines and in the Swartland section of the central lines do seem to reflect low eagle densities, found during eagle surveys (Figure 2.15). In addition the high reporting rates in Kruger and Kgalagadi also correlate with known high eagle densities within these regions. How well reporting rates reflect actual Martial Eagle densities at finer scales is unclear and I would currently not recommend SABAP2 as a monitoring tool for this Martial Eagle population.

In conclusion, Martial Eagles most likely use electricity pylons under the transmission network as nesting tree surrogates in regions of low tree cover. The density of this eagle population is mostly influenced by rainfall and tree cover, while dispersion is affected by the Martial Eagles' territorial and social structure. Using these relationships, a substantial population was found to nest on electricity pylons as tree surrogates, in a largely human altered landscape. This result is at odds with the generally held belief that the Martial Eagle is increasingly confined to large protected areas and has significant implications for the thinking around the conservation management of this globally threatened species.

Although this study highlights the benefits derived from power lines by large bodied birds such as the Martial Eagle, power lines have the potential to increase mortality rates of raptors and bustard populations (Jenkins *et al.* 2010; Rollan *et al.* 2010). Nesting on electricity pylons may therefore presents a double edged sword providing nesting structures but causing fatalities due to electrocution and collisions. However Lehman *et al.* 2007 stipulates that electrocution of large eagles on transmission lines are very rare. Determining how such mortality affects the Martial Eagle transmission line populations stability as well as the

effects of major threats on the population, will provide an indication of the viability of this population into the future. Currently this is not possible as detailed demographic data, for this species does not exist. There is therefore a chance that the power-line breeding population is a sink population that relies on immigration from protected areas.

Ultimately with the ever burgeoning human population, the future of Martial Eagles is likely to become increasingly dependent on private land owners and stakeholders as more of South Africa is lost to anthropogenic change (Brandl *et al.* 1985; Herremans 2000; Barnes 2000; Anderson & Kruger 2004; Hudson & Bouwman 2007; Thiollay 2007; Virani *et al.* 2011). In this regard the national utility company will play a critical role in future welfare of the transmission line eagle population (Fitzner 1980).

Chapter 3: Conclusions

3.1 The use of habitat association models in estimating population density of sparsely distributed species

Rare, sparsely distributed animals present many challenges for conservation biologist and resource managers because they tend not to be highly habitat specific, and they often move long distances and occupy large home ranges (Mladenoff *et al.* 1999). This makes it increasingly difficult and expensive to estimate population size and effectively monitor population trajectory into the future (Gottschalk *et al.* 2005). One solution is to use multivariate habitat association models to derive critical estimates of distribution and abundance based on relatively small samples of field data (Gottschalk *et al.* 2005).

Application of these models to estimate the population density of Martial Eagles nesting on the South African power transmission network proved to be highly successful. The large spatial requirements of this species allowed the use of readily available, coarse-scale climatic and physiogeographic environmental data to estimate the habitat requirements of this species (Mladenoff *et al.* 1999; Gottschalk *et al.* 2005). The models were also particularly effective because of the linearized dispersion of the study population, which made accurate density predictions easier to achieve and verify. Lastly, the use of models provided a reliable estimate of population size and distribution on a national scale, which otherwise would have been financially and logistically impossible to derive from direct survey and monitoring methods (Tarboton & Allan 1984; Fielding & Haworth 1995).

Although only few studies to date have applied habitat association models to predict densities of such widely and thinly dispersed apex predators, they have become increasingly prevalent in smaller scale population studies since the 1990s (Gottschalk *et al.* 2005). Hopefully the

success of these methods in the current study will encourage their use in other conservation-driven studies of threatened raptor populations.

3.2 The importance of human modified environments in the sustainable conservation of scarce, wide-ranging species

Many large, sparsely distributed raptors are threatened by a host of anthropogenic factors, but a minority may actually benefit from some aspects of development and environmental change. While it is apparent that some raptor species can withstand human influences on the environment, most of these do so by exploiting some critical aspect of localised anthropogenic change (Tinkler 2000; Potapov *et al.* 2002; Hobbs *et al.* 2006; Rutz 2008; Altwegg *et al.* 2014; Sumasgutner *et al.* 2014).

The Karoo population of Martial Eagles is another example of the value of resilience and adaptability. Perhaps in excess of 36% of the South African population of this highly threatened species is resident in unprotected farmland, primarily because of the availability and utility of power pylons as artificial nesting sites, suggesting that effective conservation management of the Martial Eagle in South Africa depends at least as much on the actions and decisions of Eskom and Karoo landowners, as it does on maintaining the ecological integrity of the country's network of nature reserves. This notion is further endorsed by recent tracking data which reveal that Martial Eagles based in the Kruger National Park frequently range well beyond the boundaries of this huge reserve (R. van Eeden, unpublished data). Ultimately, the long-term survival of wide-ranging predators such as Martial Eagle, Grey Wolf, and others, may well prove beyond the scope of formal protection in pristine habitat (Peterson 1988; Fritts & Carbyn 1995; Mech *et al.* 1995; Anderson & Kruger 2004), and will require that both people and animals adapt to and accommodate each other in the context of a more sustainable approach to commercial land use (Mladenoff *et al.* 1999).

3.3 Future work

While the present study largely succeeded in achieving its main objectives, the data used and analyses completed were not without limitations, and there is clearly scope available to refine the models and improve the estimate of Martial Eagle population size and distribution.

The key aspects of the study requiring further work are:

1. *Update and extend sample surveys*: The sample survey data used in this study were considered adequate to deliver worthwhile results, but expansion and consolidation of these surveys would probably yield more accurate outcomes. Ideally, the surveys should be expanded to include sample sections of (i) transmission line in less open/more treed habitats, to allow direct testing of the influence of tree availability on the selection of power pylons as nesting substrata, (ii) the higher voltage distribution lines (33-110 kV), to determine the extent to which these smaller support structures are used as nest sites, and (iii) the larger trees in major drainage lines and/or plantations within the Karoo biome, to determine the extent to which Martial Eagles occur and breed in these habitats without depending on utility structures. It may be possible to make some, relatively inexpensive progress in all three of these additional avenues of study by using the popular media to solicit information on nest sites from landowners and managers across the country. Further, samples of the central Karoo transmission lines should be re-surveyed to confirm that nests and territories located on these lines in the 2000s are still present and occupied today.
2. Previous research on Martial Eagles using the central Karoo transmission lines (Jenkins *et al.* 2013) suggested that the distribution of nests was influenced by the relative availability of different designs of transmission pylon, with eagles showing a significant preference for nest-building in one of the three main installed

configurations. It proved impossible to obtain good information on the numbers and distribution of the various pylon types present on each line, and to include this information in my analyses, in the time available for this study. For the sake of completeness, this factor should be integrated into any revision of the models presented here.

3. The next critical step in determining the real value of the pylon-nesting to Martial Eagle conservation is to initiate a long-term, demographic study of a subset of the population defined here. Only by establishing the stability and viability of this population—expressed in terms of estimates of both productivity and survival—will it be possible to fully ascertain the role that transmission lines may be playing in sustaining the broader regional and national populations. Such research— involving ongoing nest monitoring, and tagging and tracking of both adults and dispersing young—is currently underway on Martial Eagles resident in protected savanna areas in north-eastern South Africa (van Eeden pers. comm.), and directly comparable work in the Karoo would be highly instructive.

In addition to the further research requirements listed above, the present study also yields a number of clear, applied conservation and management recommendations, including:

1. The long-term welfare of the Karoo pylon-nesting population of Martial Eagles is entirely and directly dependent on the attitude adopted by the power utility Eskom in accommodating these birds. Martial and other large eagle nests on Eskom structures are known to be a source of line faulting which can have a significant negative (and costly) effect on the company's quality of supply (Jenkins *et al.* 2013). Equally, eagles may be disturbed by Eskom maintenance activities and new-build projects, and killed in both electrocution on and collision with power infrastructure. While it is

entirely possible to manage the interface between eagles and industry to the benefit of both, this requires a high level of commitment by the utility to protecting the eagles, including training field staff and line managers in the relevant best practice.

2. The outcomes of this study should be considered in planning and assessing the impacts of new transmission line developments, both from the point of view of the disturbance of eagle nests on nearby existing lines, and in terms of the possible expansion of the Martial Eagle breeding population on to sections of new line. While the latter is almost certainly a positive eventuality for eagle conservation wherever it occurs, the issue of eagle-related line faulting should be managed pro-actively, preferably by including structures on newly-built pylons to encourage nest-building and roosting below the conductors (Jenkins *et al.* 2013).

Pylon-nesting Martial Eagles are widely exposed to the attitudes of private, small-stock farmers, and could be heavily persecuted as result (Boshoff & Vernon 1980; Steyn 1982; Tarboton & Allan 1984; Barnes 2000; Anderson & Kruger 2004). It is therefore important that education and awareness programs tailored towards these groups, are strongly driven in the future (Boshoff & Vernon 1980; Steyn 1982; Tarboton & Allan 1984; Barnes 2000; Anderson & Kruger 2004).

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