Eagles as indicators of ecosystem health: is the distribution of Martial Eagle nests in the Karoo influenced by variations in land-use and rangeland quality?

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ABSTRACT. The relationship is examined between the distribution of large eagles (particularly the Martial Eagle *Polemaetus bellicosus*) breeding on electricity transmission pylons in the central and southwestern Karoo, South Africa, and the general environmental health of commercially managed farmland. Hypothetically, eagle densities are depressed on poorly managed farms and healthy or inflated on well-managed properties. Eagle nests were surveyed by helicopter along a sample section of 1400 km of pylon line in July 2002, and ground surveys along a sub-section of about 640 km of pylons were conducted subsequently. Simple habitat evaluations were completed at every eagle nest visited, and every 5 km traveled along the pylon line during ground surveys, and included calculation of a Rangeland Health Index (RHI) that estimated the extent of veld degradation. The precise location of all eagle nests was recorded and coupled with information on breeding activity. GIS was used in all spatial data management and analysis. Eagle territories (containing up to four nests) were spatially simulated by plotting a circle with a 6 km radius around each active nest or the centre point between nests. The relative influence of variation in habitat quality on eagle distributions was assessed in terms of (i) the regularity/irregularity of spacing between territories, (ii) (landscape or macro-scale) discrepancies between the mean habitat composition of eagle territories (% surface area occupied by each habitat type) for a range of biotic and abiotic variables, and the mean habitat composition of an equivalent array of random plots, and (iii) (local or micro-scale) differences between habitat qualities (RHI and others) recorded at points within eagle territories and those recorded outside. A total of 112 eagle nests were located, comprising 83 eagle territories, mostly within the Nama and Succulent Karoo biomes. Eagle territories were generally irregularly distributed along the pylon line (P<0.025). Martial Eagles significantly favoured habitats with lower and/or less predictable winter rainfall (Bushmanland Nama Karoo, Upland Succulent Karoo) and lower primary productivity, while Tawny Eagles *Aquila rapax* preferred habitats with higher and/or more predictable summer rainfall (Eastern Mixed Nama Karoo, Upper Nama Karoo), and higher primary productivity. All eagles avoided areas of highest primary productivity and were absent from cultivated areas. Habitat assessments (including RHI values) within eagle territories were generally not significantly different to those recorded outside. However, eagle densities in areas stock with game (or game and domestic stock) were significantly higher than in areas stocked only with game (nearest neighbour distances, 7 km vs 12 km, P = 0.025). This study shows that (i) eagle distributions in the Karoo are subtly but significantly influenced by both macro- and micro-scale variation in habitat type and quality, (ii) that mismanagement of Karoo rangeland can impact on the welfare of eagle populations, and (iii) that the Martial Eagle is potentially suitable as an indicator of ecosystem integrity in the Karoo.
General ignorance of the fundamental influences of anthropogenic land transformation on ecosystem integrity stands as an obstacle to the successful conservation of African biodiversity (MacDonald 1989). Depleted populations of animal taxa outside of formally protected areas are an obvious manifestation of these influences, and yet the factors limiting these populations are often little studied. For example, many large African raptor species occur at very low densities outside of conservation areas (Aumann 1997, Herremans & Herremans-Tonnoeyr 2000). The incipient effects of habitat degradation on these eagle and vulture populations have been widely acknowledged (Brandl et al. 1985, Virani & Watson 1998, Barnes 2000, Herremans & Herremans-Tonnoeyr 2000) but remain poorly understood.

The Martial Eagle *Polemaetus bellicosus* is a large, Pan-African eagle species that is threatened across its range (Brown et al. 1982, del Hoyo et al. 1994). The South African population probably comprises less than 600 breeding pairs, mostly confined to conservation areas in the lowveld and Kalahari regions (Barnes 2000). The rarity of the Martial Eagle outside of extensive protected areas may be the result of widespread persecution of the species on privately owned land because of its reputation as a predator of domestic livestock (Brown 1991, Boshoff 1993). However, the relative importance of agriculture and ranching in degrading habitat (and depleting food resources) for Martial Eagles inhabiting non-conserved land has not yet been investigated.

The present study examines the relationship between the breeding distributions of large eagles (particularly Martial Eagle, but including Black Eagle *Aquila verreauxi* and Tawny Eagle *A. rapax*) in the central and southwestern Karoo, South Africa, and the general environmental health of commercially managed farmland in this region. The Karoo is a poorly conserved biome (Low & Rebelo
1996), and does not present the stark contrasts in large eagle densities that occur typically across game reserve boundaries in the savannas further north (e.g. Tarboton & Allan 1984, Aumann 1997). However, given that livestock grazing pressure in the Karoo is generally high, with an attendant loss of primary production (Dean & MacDonald 1994), there is likely to be considerable variation in the quality of the natural environment (depending on the management policies applied by each private landowner - Brandl et al. 1985, Joubert & Ryan 1999) that may be reflected in the distribution of eagle pairs. Hypothetically, eagle densities in the Karoo are depressed on poorly managed farms (with compromised ecological integrity - Milton et al. 1994), and healthy or inflated on well-managed properties.

This hypothesis is examined here in terms of the distribution of large eagle nests in pylon structures along electricity transmission lines in the Karoo in relation to measures of habitat quality at both local (micro-) and landscape (macro-) scale. Eagle nests in electricity pylons are relatively easy to locate and monitor (Boshoff 1993), allowing the study to cover a huge area of Karoo ranchland, and include information for a meaningful sample of nests across this area. Specifically, the study addresses the following key questions:

i) Are eagle nests (or territories) distributed regularly or irregularly along the surveyed transmission pylon lines (as an initial index of environmental sensitivity)?

ii) Does habitat composition – in terms of a range of digitally mapped biotic and abiotic variables – of (active and inactive) eagle territories differ significantly from the composition of a comparable sample of random plots?
iii) Are micro-scale measures of habitat quality within (active and inactive) eagle territories significantly different to those outside eagle territories?
METHODS

Study area

The study was conducted in the central and southwestern Karoo region of South Africa, including the entire south-central portion of the Nama Karoo Biome, the eastern half of the Succulent Karoo Biome, and the northern fringes of the Fynbos Biome (Fig. 1).

The two Karoo biomes share some plant and animal species but are generally regarded by botanists as clearly distinct (Dean 1995). Total annual rainfall in the Karoo ranges from <100 mm to about 600 mm. Areas with an average rainfall of < 200 mm are essentially deserts, producing less than one ton of dry plant material per hectare in most years (Milton & Dean 1996). Although rainfall has some regional pattern and predictability (e.g. predominantly summer or winter rainfall, increasing from west to east), it occurs erratically at any given location (Fahse et al. 1998). The Karoo generally features some degree of topographic relief. Flat plateaus, where the underlying bedrock is close to the surface, have very shallow soils. Plains that lie between ridges and hills usually have deep soils mixed with gravel and stones from nearby hill slopes (Milton & Dean 1996). There is little difference between the soils of the Succulent Karoo and Nama Karoo Biomes – both are lime-rich, weakly developed soils on rock (Low & Rebelo 1996).

The vegetation of the Nama Karoo has affinities with savanna vegetation (Gibbs Russell 1987), dominated by grassy, dwarf shrubland. Grasses tend to be more common in depressions and on sandy soils, and less abundant on clay-based soils. However, under conditions of overgrazing, many indigenous species may proliferate, including Threethorn *Rhigozum trichotomum*, Bitterbos *Chrisocoma ciliata* and Sweet Thorn *Acacia karoo*, and many grasses and other palatable species may be lost. Grazing rapidly increases the relative abundance of shrubs. The Prickly Pear *Opuntia*...
*aurantiaca* and Mesquite *Prosopis glandulosa* are the major alien invader species (Low & Rebelo, 1996). The grasses and shrubs are deciduous in response to rainfall events that occur mostly in summer. The rainfall varies between 100 and 520 mm per year. Absolute temperatures in the Nama Karoo range from $-5^\circ\text{C}$ (winter minimum) to $43^\circ\text{C}$ (summer maximum) (Milton & Dean 1990). Altitude ranges from 500-2 000 m above sea level (a.s.l.), with most of the biome falling between 1 000 and 1 400 m a.s.l. Less than 1% of the Nama Karoo is formally conserved (Low & Rebelo 1996).

The vegetation of most parts of the Succulent Karoo has some taxonomic affinities with the shrublands of the Cape Floral Kingdom. It is dominated by dwarf, succulent shrubs, of which the Vygies (*Mesembryanthemaceae*) and Stonecrops (*Crassulaceae*) are particularly important (Low & Rebelo 1996). There are few invasive alien plants in the biome, with only Rooikrans *Acacia cyclops* as a major problem in the southern coastal regions. Rainfall varies between 20 and 290 mm per year and falls mostly in winter. The temperature range is similar to that of the adjacent Nama Karoo, and during summer, temperatures in excess of $40^\circ\text{C}$ are common. Most of the biome covers a flat to gently undulating plain, with some hilly and “broken” veld. The altitude is mostly below 800 m a.s.l., but in the east it may reach up to 1 500 m a.s.l.. Less than 0.5% of the area of the Succulent Karoo Biome is formally conserved (Low & Rebelo 1996).

The Fynbos Biome comprises the highly diverse and unique Fynbos and Renosterveld vegetation groups (Low & Rebelo 1996). Renosterveld used to support herds of large ungulates but these are now mostly extinct in the region outside of conservation areas (Low & Rebelo 1996). By contrast, Fynbos is much richer in plant species, and holds most of the biome’s endemic amphibians, birds and mammals.
Figure 1. The location of the study area in the Western and Northern Cape Provinces, South Africa, showing the lay-out of the surveyed electricity transmission pylon lines in relation to biome type.
Soils (and hence plants) in the Fynbos Biome are nutrient-poor, and the region generally cannot sustain the densities of game or domestic stock that are characteristic of the Karoo (Low & Rebelo 1996).

Urbanization and agriculture are minimal in the Karoo. Most of the region is used for ranching, mainly of small domestic livestock, such as Merino and Dorper sheep and Angora goats, but also of indigenous stock such as ostriches (Dean 1995) and small antelope species such as Springbuck (*Antidorcas marsupialis*) and Gemsbuck (*Oryx gazella*). Ranching can be commensurate with conservation, but recommended stocking rates are frequently exceeded and much of the Karoo is chronically overgrazed (MacDonald 1989). For example, the entire Karoo and adjacent Eastern Cape agricultural regions are stocked at 130% of their safe carrying capacities (Roux & Van der Vyver 1988).

**Eagle surveys**

A sample section of about 1400 km of 400kV electricity transmission pylon line, extending from Koeberg in the southwest, to Kenhardt in the north and De Aar in the east, was surveyed by helicopter in early July 2002. The exact location of all large eagle nests (mostly Martial Eagles, but also including Black Eagle and Tawny Eagle sites) observed was recorded using a Global Positioning System (GPS) and coupled with information on observed eagle breeding activity. Ground surveys that followed the initial aerial survey were carried out between July and October-November 2002. About 640 km of Eskom servitude (tracks that run under all transmission lines to allow access for maintenance activities) were driven during these ground surveys, and about half of the eagle territories included in the total surveyed population were re-visited and examined more closely.
Pairs of large eagles often build more than one nest structure, and alternate between nests in successive breeding attempts. (e.g. Martial Eagle territories may contain up to seven nests – Steyn 1982). In this study, where multiple nest structures were located in short sections of pylon line these were considered to be alternate nests within a single eagle territory. Once identified, eagle territories were classified either as active (including a nest containing either an egg or a nestling) or inactive (possibly occupied by a pair of eagles, but no absolute signs of breeding were recorded). Once plotted in a GIS (using ArcView software), the spatial extent of each eagle territory was simulated by a circle centred on either the active nest or the centre point on the line between alternate nests in inactive territories. The radius of the circle was set at 6 km, determined as approximately half the overall average inter-nest distance recorded for Martial, Black and Tawny Eagles in southern Africa (Tarboton & Allan 1984, Gargett 1990, Herholdt et al. 1996), and deemed to adequately simulate the average territory size occupied by pairs of these species in the region.

The pattern of spacing between eagle territories was examined as an indication of the degree of sensitivity to extrinsic, environmental variables, with regular or even spacing reflecting a lack of sensitivity (with eagle distributions determined primarily by intrinsic factors), irregular or uneven spacing reflecting a measure of sensitivity (perhaps to local or micro-scale variation in habitat quality), and clumped spacing reflecting pronounced sensitivity (to landscape or macro-scale variation in habitat quality). To test the null hypothesis that territories along the transmission lines were randomly or irregularly spaced, a randomisation analysis was performed using 500 iterations. The standard distribution was used as the statistic to measure the pattern of dispersion of eagle territories. The observed standard deviation (around the mean distance between the centre points of adjacent territories) was compared with the
empirical frequency distribution of standard deviations derived from the randomisations. The P-value was derived from the standard deviation of the number of observations, that is less than or equal to the standard deviation of the randomisation divided by the number of iterations. Using a two-tail test with \( \alpha = 0.05 \), it was expected that, if \( 0.025 < P < 0.975 \) accept the \( H_0 \); if \( P < 0.025 \), eagle distribution is uniform and if \( P > 0.975 \), eagle distribution is clustered or clumped (Zar 1996).

**Eagles and habitats at the macro-scale**

Eagle habitat preferences at the landscape or macro-scale were examined by comparing habitat composition (in terms of the percentage area covered by each habitat category) within eagle territories with habitat composition within an equivalent array of random plots with the same shape and surface area.

ArcView GIS analysis was aided by extensions and scripts downloaded from ESRI (www.esri.com). Six broad-scale habitat variables, that describe general biotic and abiotic attributes of both the natural and modified environment, were selected according to availability and relevance to this analysis. These were vegetation type (Department of Environmental Affairs & Tourism, Cape Town), landscape morphology (Fairbanks, *et al.* 2000), soils (surface soil characteristics and topsoil textures, Institute of Soil, Climate and Water, Pretoria), primary productivity (Department of Agricultural Engineering, University of Natal, Pietermaritzburg), land-cover (ARC / SCIR, Pretoria, Thompson 1999) and rainfall (Department of Agricultural Engineering, University of Natal, Pietermaritzburg). These GIS coverages were overlaid on eagle territory distributions and the distributions of random or selected random plots using the Albers Equal-Area Conic projection (Spheroid: Clarke 1880).
Randomization tests (Manly 1991, Zar 1996) were used to test the null hypothesis that the habitat composition of eagle territories did not differ from random. An ArcView extension ‘Random Point Generator v. 1.1’ was used to generate 500 random points along the transmission pylon line. Each point was expanded to a circle with a 6 km radius to simulate an eagle territory, with the resulting compliment of random plots representing all possible random rearrangements of eagle territories along the line. The habitat composition of all the eagle territories and of each random plot, in terms of the proportion of the total surface area occupied by each habitat parameter, was calculated for each of the different GIS coverages used. The mean habitat composition of a random sample of random plots ($N =$ the number of eagle territories, all plots were available for selection more than once) was then calculated and compared with the mean habitat composition of eagle territories, and counters for upper and lower tail were updated according to:

Left tail counter $+ 1$ if random proportion $\leq$ observed proportion

Right tail counter $+ 1$ if random proportion $\geq$ observed proportion

This process was repeated for 500 samples of random plots and, ultimately, each habitat parameter was scored plus (+) or minus (-) according to the calculated probability that the observed proportion either exceeded or was less than the average random proportion.

Note that the soil coverage used in the overlay analysis did not completely cover the entire study site, leaving part of study area with two martial eagle nests uncovered. Therefore these two nests were excluded from the analysis.

**Eagles and habitats at the micro-scale**

All stretches of servitude driven during ground surveys served as transects through the landscape. Every 5 km traveled along the transmission lines, and at every eagle nest
visited, a simple assessment of habitat quality was conducted. This included the calculation of a ‘Rangeland Health Index’ (RHI), based on criteria developed by Milton et al. (1998), as a measure of the level of impact on the environment of grazing and disturbance. Parameters contributing to the RHI were:

(a) Forage Value: What percentage (scored 1-5) of the vegetation was palatable to livestock, and what proportion poisonous or unpalatable?

(b) Grazing Intensity: How severely (scored 1-5) were the canopies of palatable plants browsed?

(c) Disturbance Indicators: How prevalent (scored 1-5) were alien, annual or mat-forming plants?

(d) Soil and habitat health: How prevalent (scored 1-5) were positive (mulch, animal diggings, fertile patches, shade plants, living crust) vs negative (rills, pedestals, terraces, mineral crust, exposed roots) signs of soil and habitat health? How well covered and bound was the topsoil by vegetation (the percentage of vegetation cover was estimated along a 50 x 4 m foot transect extended perpendicular to the servitude through a representative patch of habitat)?

The final RHI value was calculated as the sum of the four scores (a + b + c + d), and used to categorize veld condition as either excellent (score 18 - 20), good (score 13 - 17), intermediate (score 8 - 12) and poor (score < 8).

The degree to which eagle distributions were influenced by local or micro-scale variation in habitat quality was determined by comparing RHI and percentage vegetation cover values measured at nests or at least within the plotted areas of each eagle territory, with those that were measured away from nests and outside eagle
territories. Non-parametric Mann-Witney $U$ tests were used to statistically evaluate these comparisons.

The type of livestock present in the general area was also recorded in the course of each habitat assessment. Stock types were summarised into two groups: domestic stock (sheep, goats, cattle) and mixed stock (game or game and domestic stock). Each eagle territory in which habitat assessments were conducted was assigned to the appropriate stock type. In cases where more than one assessment was conducted in a single territory and stock types varied between assessments, the most inclusive type (mixed stock) was assigned. The ratio of active:inactive territories, and the density of eagle pairs (in terms of nearest neighbour distance (NND)) was then examined relative to stock type.
RESULTS
A total of 117 large eagle nests (94 Martial Eagle nests, 14 Tawny Eagle nests and 9 Black Eagle nests) (Table 1) were plotted, coupled with basic information on the structure placement and usage of each nest (Fig. 2). From these, 83 eagle territories were identified. Fifty-six (67%) contained a single nest structure, 21 (25%) contained two nests, 5 (6%) contained three nests, and one territory contained four nests. Sixty-four territories (77% of the total) were located within the Nama Karoo Biome (at an average linear density of 7.2 territories per 100 km of transmission pylon line), 15 (18%) were located in the Succulent Karoo (6.2 territories per 100 km of line), and 4 (5%) were located in the Fynbos Biome (2.2 territories per 100 km of line).

All subsequent analyses were conducted using data for all eagle territories together, and Martial and Tawny Eagle territories separately. The sample of Black Eagle nests obtained was considered too small to yield biologically meaningful results.

Table 1. Numbers of active and inactive large eagle nests and territories recorded along Eskom transmission lines in the central and southwestern Karoo.

<table>
<thead>
<tr>
<th>Species</th>
<th>No. nests</th>
<th>No. territories</th>
<th>No. active territories</th>
<th>No. inactive territories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martial Eagle</td>
<td>94</td>
<td>62</td>
<td>34</td>
<td>28</td>
</tr>
<tr>
<td>Black Eagle</td>
<td>9</td>
<td>8</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Tawny Eagle</td>
<td>14</td>
<td>13</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>TOTAL</td>
<td>117</td>
<td>83</td>
<td>48</td>
<td>35</td>
</tr>
</tbody>
</table>
Spacing of eagle territories
All eagle territories were spaced irregularly (or randomly) along the pylon lines (Table 2), except active Tawny Eagle territories that were restricted to (or clustered within) a stretch of only 280 km (20%) of the total sample distance (Fig. 2, Table 2), and were regularly (or non-randomly) spaced within this restricted range (Table 2).

Table 2. Mean distances (± 1 standard deviation) between eagle territories along the sampled transmission pylon line, with results of randomization tests to determine patterns of dispersion or spacing of territories. Statistically significant values are marked with an asterisk.

<table>
<thead>
<tr>
<th></th>
<th>No. territories</th>
<th>Mean distance (km)</th>
<th>P</th>
<th>Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>All eagle territories</td>
<td>83</td>
<td>17.4±0.0</td>
<td>0.166</td>
<td>Irregular</td>
</tr>
<tr>
<td>All active eagle territories</td>
<td>48</td>
<td>48.3±3.3</td>
<td>0.096</td>
<td>Irregular</td>
</tr>
<tr>
<td>All inactive eagle territories</td>
<td>35</td>
<td>37.7±1.1</td>
<td>0.070</td>
<td>Irregular</td>
</tr>
<tr>
<td>All Martial eagle territories</td>
<td>62</td>
<td>31.2±1.1</td>
<td>0.124</td>
<td>Irregular</td>
</tr>
<tr>
<td>Active Martial Eagle territories</td>
<td>34</td>
<td>52.0±4.4</td>
<td>0.068</td>
<td>Irregular</td>
</tr>
<tr>
<td>Inactive Martial eagle territories</td>
<td>28</td>
<td>51.3±6.6</td>
<td>0.056</td>
<td>Irregular</td>
</tr>
<tr>
<td>All Tawny Eagle territories</td>
<td>13</td>
<td>47.6±6.6</td>
<td>0.026</td>
<td>Irregular</td>
</tr>
<tr>
<td>Active Tawny Eagle territories</td>
<td>8</td>
<td>80.3±7.7</td>
<td>0.016*</td>
<td>Regular</td>
</tr>
</tbody>
</table>
Figure 2. Distribution of large eagle nests along Eskom transmission pylon lines in the central and southwestern Karoo.
**Broad-scale assessment of habitat composition**

*Vegetation types*

The Bushmanland and Nama Karoo variants were the most widely occurring vegetation types in eagle territories (Fig. 3). In terms of the entire sample, Central Lower Nama Karoo was significantly less prevalent in eagle territories than in random plots (rejected, $P = 0.022$), and Upper Nama Karoo was significantly more prevalent in eagle territories than in random plots (selected, $P = 0.024$) (Appendix 1, Fig. 3). Martial Eagles selected Bushmanland Nama Karoo ($P = 0.016$), while Upland Succulent Karoo was characteristic of (or ‘selected’ in) inactive Martial Eagle territories ($P<0.001$). Tawny Eagles selected Eastern Mixed Nama Karoo ($P = 0.018$) and Upper Nama Karoo ($P<0.001$). All other vegetation types were used randomly.

![Figure 3](chart.png)

**Figure 3.** Mean proportions of different vegetation types present in eagle territories vs random plots along transmission pylon lines in the central and southwestern Karoo.
**Landscape morphology**

Generally, eagle territories were distributed randomly relative to landscape morphology (Appendix 2) although, for the entire sample, moderately undulating plains were rejected ($P = 0.014$), Martial Eagles selected slightly irregular plains ($P = 0.018$), Tawny Eagles rejected plains ($P = 0.022$) and selected slightly irregular plains ($P = 0.014$), and active Tawny Eagles selected lowlands and hills ($P = 0.020$) (Appendix 2).

**Surface soil characteristics**

All eagle territories combined, all active territories, and all active Martial Eagle and Tawny Eagle territories were distributed randomly relative to the distribution of surface soil characteristics (Appendix 3), while rocky substrates ($P = 0.004$) and coarse desert pavements ($P = 0.004$) were characteristic of inactive eagle territories, and inactive Martial Eagle territories respectively.

**Topsoil textural characteristics**

All eagle territories were randomly distributed relative to the distribution of topsoil textural characteristics (Appendix 4).

**Primary productivity**

Generally, eagle territories were non-randomly distributed relative to the distribution of primary productivity (Appendix 5, Fig. 4). Martial Eagles and Tawny Eagles showed a marked difference in selection/rejection patterns of more productive vs less productive habitats: Martial Eagles selected less productive habitats ($P<0.001$) and rejected more productive habitats, while Tawny Eagles selected moderately productive habitats ($P<0.001$) (Appendix 5). Interestingly, all eagles combined avoided areas with highest primary productivity ($P<0.001$).
Figure 4. Mean proportions of different levels of primary productivity (tonnes/hectare) present in eagle territories vs random plots along transmission pylon lines in the central and southwestern Karoo.

Land-cover
All eagles, and all Martial Eagles, rejected cultivated land classes (P<0.001, P = 0.008) and selected shrubland and low Fynbos (P<0.001, P = 0.002) (Appendix 6), while Tawny Eagle territories were randomly distributed relative to the distribution of land cover classes.

Mean annual rainfall
Again, Martial Eagles and Tawny Eagles showed a marked difference in selection/rejection patterns of higher vs lower rainfall areas: Martial Eagles selected lower rainfall habitats (P = 0.006) and rejected higher rainfall areas, while Tawny
Eagles selected higher rainfall habitats ($P = 0.010$) and rejected lower rainfall areas ($P = 0.022$) (Appendix 7).

**Micro-scale assessment of habitat quality**

Eight sections of the transmission pylon line were surveyed on the ground. A total of 118 habitat assessments, with associated RHI and percentage vegetation cover values, were completed at points along the pylon lines. Of this total, 88 assessments were conducted at eagle nests or within plotted eagle territories, and 30 were conducted at points outside of plotted eagle territories.

Most (76%) RHI values measured fell into the intermediate category, with 6% scored as poor, 18% scored as good and 0% scored as excellent. In all cases, mean RHI and percentage vegetation cover figures within eagle territories were not significantly different to those measured outside eagle territories (Table 3).

**Table 3.** Statistical comparison (Mann-Witney U test) of mean percentage vegetation cover values ($\pm 1$ standard deviation) measured within vs outside of eagle territories.

<table>
<thead>
<tr>
<th>No. habitat assessments</th>
<th>% Cover</th>
<th>U</th>
<th>Adjusted Z</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>All eagle territories</td>
<td>34.2±16.1</td>
<td>1231.0</td>
<td>0.195</td>
<td>0.846</td>
</tr>
<tr>
<td>Active eagle territories</td>
<td>32.7±15.7</td>
<td>951.0</td>
<td>-0.276</td>
<td>0.783</td>
</tr>
<tr>
<td>Inactive eagle territories</td>
<td>37.7±15.5</td>
<td>305.5</td>
<td>1.221</td>
<td>0.228</td>
</tr>
<tr>
<td>All Martial Eagle territories</td>
<td>34.7±16.2</td>
<td>1081.0</td>
<td>0.351</td>
<td>0.726</td>
</tr>
<tr>
<td>Active Martial Eagle territories</td>
<td>32.8±15.9</td>
<td>778.5</td>
<td>-0.311</td>
<td>0.756</td>
</tr>
<tr>
<td>Inactive Martial Eagle territories</td>
<td>38.6±15.8</td>
<td>270.0</td>
<td>1.395</td>
<td>0.163</td>
</tr>
<tr>
<td>All Tawny Eagle territories</td>
<td>36.0±16.4</td>
<td>245.5</td>
<td>0.633</td>
<td>0.527</td>
</tr>
<tr>
<td>Active Tawny Eagle territories</td>
<td>32.9±14.2</td>
<td>243.5</td>
<td>0.068</td>
<td>0.946</td>
</tr>
<tr>
<td>Areas outside all eagle territories</td>
<td>32.5±14.3</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Generally, there were no significant differences in RHI and percentage vegetation cover values between all active and inactive eagle territories (RHI: active territories 10.7±2.1 vs inactive territories 10.7±1.6, \( Z = 0.131, P = 0.896 \); percentage cover: active territories 32.8±15.8 vs inactive territories 37.7±15.5, \( Z = -1.881, P = 0.060 \)) and in RHI values between active and inactive Martial Eagle territories (active territories 11.1±2.0 vs inactive territories 10.7±1.6, \( Z = 0.861, P = 0.389 \)), but percentage vegetation cover was significantly lower in active Martial Eagle territories than in inactive Martial Eagle territories (active territories 32.9±16.0 vs inactive territories 38.6±15.8, \( Z = -1.990, P = 0.047 \), Fig. 5).

![Box plot of percentage vegetation cover in active vs inactive Martial Eagle territories](image)

**Figure 5.** Comparison of percentage vegetation cover values in active vs inactive Martial Eagle (ME) territories.

Habitat assessments were conducted within 54 (65%) of the eagle territories plotted. In terms of the stock observed and recorded in these assessments, 63% of
eagle territories were located on ranchland dominated by domestic stock, and 37% were located on farms with a mixture of domestic stock and game (Table 4).

Table 4. The number of eagle territories in areas with domestic and/or mixed stock.

<table>
<thead>
<tr>
<th>Stock type</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>h</th>
</tr>
</thead>
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<tr>
<td>Domestic</td>
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<td>24</td>
<td>10</td>
<td>29</td>
<td>21</td>
<td>8</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
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<td>16</td>
<td>4</td>
<td>11</td>
<td>8</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Unknown</td>
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<td>8</td>
<td>21</td>
<td>22</td>
<td>5</td>
<td>17</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
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<td>48</td>
<td>35</td>
<td>62</td>
<td>34</td>
<td>28</td>
<td>13</td>
<td>8</td>
</tr>
</tbody>
</table>

a = All eagle territories; b = All active eagle territories; c = All inactive eagle territories; d = All Martial Eagle Territories; e = Active Martial Eagle territories; f = Inactive Martial Eagle territories; g = All Tawny Eagle territories; h = Active Tawny Eagle territories.

Overall, the proportion of eagle pairs breeding (80%) in areas stocked with game (mixed stock) tended to be higher than in exclusively sheep or goat farming areas (about 71%) although this difference was not statistically significant ($\chi^2 = 0.659, P = 0.19$, Table 4). However, the density of eagle pairs (in terms of the distance between nearest neighbouring territories) was significantly higher in game or mixed farming areas than in areas with domestic stock only (Fig. 6).
Figure 6. Comparison of nearest neighbour distances (NND) between large eagle territories in areas predominated by domestic livestock vs areas with both domestic stock and game (mixed stock) (mean NND in domestic livestock areas = 12.0±9.12 km (n = 34 territories), mean NND in mixed livestock areas = 7.0±4.78 km (n = 20 territories), t = 2.30, df = 54, P = 0.025).
DISCUSSION

Nest spacing and sensitivity to habitat variation

Over 60 Martial Eagle territories were located and monitored in this study, constituting more than 10% of the estimated South African population of this species (Barnes 2000). This emphasises the importance of the Karoo in the conservation of Martial Eagles nationally (and globally), and the significance of fully understanding the relationship between the welfare of eagle populations and the management practices and attitudes of private landowners in this poorly conserved environment.

The irregular distribution of eagle territories along transmission pylon lines in the Karoo (Table 2) suggests sensitivity to relatively fine-scale measures of habitat quality. In particular, Martial Eagles were found along the entire length of surveyed line (Fig. 2), but the spacing between territories and active nests varied subtly and unpredictably throughout. This could indicate that the density of eagle pairs is affected by localised variation in the availability of essential resources – either nest sites or food (Newton 1979). Given that nest site availability (in terms of the number and quality of pylon structures present) is effectively uniform along the line, differences in the eagle prey base are more strongly implicated. Hence, either staple prey taxa (hares, small antelope, viverrids – Boshoff et al. 1990) are patchily distributed, or they are more or less susceptible to eagle predation in different habitats with different cover conditions. Alternatively, eagle populations may be impacted by farm-to-farm variation in the intensity of persecution by landowners. However, this may be more likely to affect the distribution of active vs inactive territories (rather than all territories collectively), with inactive (and unoccupied) territories resulting from conflict between formerly active eagle pairs and eagle-unfriendly farmers (e.g. Brown 1991).
Eagle distributions and habitats at the landscape scale

The various GIS coverages used in this aspect of the study were considered to be representative of a cross-section of essential biotic and abiotic parameters that might affect the quality of eagle habitat, and hence the distribution of eagle territories. Most of the variables used are not in any way reflective of the effects of land management, largely because no such data were available. However, assessment of the sensitivity of large eagles to natural, landscape-scale biogeography is essential to understanding superimposed sensitivity to habitat modification.

At some level, eagles were non-randomly distributed relative to all of the habitat variables used (Appendices 1-7). Interpretation of these data was often confounded by general lack of discernible pattern, but some meaningful results emerged.

Martial Eagles apparently favoured habitats with lower and/or less predictable winter rainfall (e.g. Bushmanland Nama Karoo, Upland Succulent Karoo – Appendix 1, Low & Rebelo 1996) and lower primary productivity (Fig. 4), while Tawny Eagles (on the basis of a relatively small sample size) preferred habitats with higher and/or more predictable summer rainfall (e.g. Eastern Mixed Nama Karoo, Upper Nama Karoo), and higher primary productivity. All eagles avoided areas of highest primary productivity. In terms of human impacts, eagles selected both poorly conserved/heavily grazed habitats (e.g. Upper Nama Karoo, Bushmanland Nama Karoo, Eastern Mixed Nama Karoo), and well conserved/lightly grazed habitats (e.g. Upland Succulent Karoo) (Low & Rebelo 1996), but were conspicuously absent from cultivated areas (Appendices 1 & 6).

These results only partly concur with previous studies of African eagle distributions (mostly conducted in tropical savannas), that have clearly shown that (i) large eagles occur at markedly lower densities outside of protected areas (Gargett
1977, Tarboton & Allan 1984, Aumann 1997, Herremans & Herremans-Tonnoeyr 2000), and (ii) that within a given environment, large eagles (including Martial Eagles) favour areas of higher productivity and higher rainfall (Hustler & Howells 1989, 1990, Wichmann et al. In press). These differences, and particularly the persistence of Martial Eagles in drier, less productive environments, can probably best be explained in terms of the relatively homogeneous nature of Karoo shrublands, and the relatively unpredictable rainfall regime that sustains them. In such areas, while primary productivity and rainfall in combination may directly and positively influence the abundance of large eagle prey (Nel 1983, Kerley 1992), they may also affect vegetation cover (and hence the accessibility of key prey taxa – e.g. Gargett 1977) more profoundly than in more mesic habitats. These effects, in turn, are either dampened or exaggerated by grazing pressure (Landsberg et al. 2002), and the complex, dynamic and ongoing interaction of these multiple factors probably ultimately controls foraging conditions for Karoo eagles. The coarse scale of the mapping used in this study, and the simplicity of the analyses conducted, were not suited to detecting such subtle and complex relationships, and these warrant further investigation.

**Eagles and rangeland quality**
The lack of any obvious correlation between the distribution of large eagle territories and the condition of rangeland surveyed in this study suggests that eagles are generally insensitive to the quality of land management in the Karoo. However, this result should be qualified in terms of the degree of variation observed in the Rangeland Health Index and percentage vegetation cover figures obtained. While some extremes were recorded, the majority of assessments yielded intermediate values, and reflected the predominantly poor or indifferent condition of the areas
evaluated. Once again, this relative homogeneity of the Karoo environment, even at the micro-scale, could mask responsiveness in the eagle population to rangeland health, and require that variation in habitat quality be more accurately assessed. This could entail more extensive sampling, or refinement of the assessment procedure to include parameters more directly pertinent to eagles and eagle resources. For example, the significant correlation between Martial Eagle breeding activity and the extent of vegetative cover (Fig. 3) suggests that the dynamic between prey abundance and the availability of protective cover might be a fruitful avenue for further investigation.

The strong positive relationship between the density of eagle territories and the presence or absence of game on ranchland in the Karoo (Fig. 4) mirrors more extreme contrasts in both eagle and game densities observed across conservation area boundaries in Afrotropical savannas (Tarboton & Allan 1984, Brandl et al. 1985, Aumann 1997), and is arguably the most significant finding of this study. Although game-dominated farms did not obviously feature better quality veld than those with domestic stock only, herds of indigenous antelope evidently interact with the Karoo environment in a subtly different way, that is beneficial (or less detrimental) to large eagle populations, even at excessive stocking rates. Hence stock type may be more significant in affecting the general health of commercially managed Karoo rangeland, and indirectly the density and performance of local eagle populations, than stocking rates or grazing regimes per se.

Persecution vs habitat loss?
Depletion of large eagle populations in ranchland has been attributed mainly to high levels of persecution in many studies (e.g. Davies 1999, Kenward 1999, Pedrini & Sergio 2001). The Martial Eagle is widely regarded as a small-stock predator in the
Karoo, and may be the most severely persecuted raptor in the region (Boshoff &
Vernon 1980). Consequently, the detrimental effects of inflated rates of adult
mortality cannot be discounted as an important factor limiting the distribution and
success of breeding pairs. For example, relatively healthy eagle populations in areas
stocked with game may simply reflect the fact that game farmers are less inclined to
attribute stock losses to eagles (Anderson 2000), so eagles are probably less heavily
persecuted in game farming areas. Further, quantitative studies on the relationship
between eagle densities in the Karoo and levels of direct persecution by farmers are
urgently required.

However, the process of rangeland modification and degradation (primarily by
overgrazing) must impact on eagle populations, at least indirectly by affecting the
distribution, abundance and accessibility of prey. Grazing by domestic livestock is
shaping landscapes in many regions of the world (Settele et al. 1998). In South
Africa, rangelands have been consistently overstocked since at least the 1930’s
(Downing 1978). In semi-arid rangelands, this situation is associated with accelerated
rates of soil erosion and reductions in faunal biomass as a consequence of
desertification, impaired productivity and the competitive effects of domestic
livestock (Osem et al. 2002). Various studies on Karoo rangeland management have
shown that overgrazing, and over-selective grazing, by domestic stock, result in the
loss of plant cover and diversity, and reduced secondary production (Bosch 1989,

This study has clearly shown that, even in the relatively homogeneous
conditions that prevail in the Karoo, eagle distributions are subtly but significantly
influenced by both macro- and micro-scale variation in habitat type and quality, and
that mismanagement of Karoo rangeland can impact on the welfare of eagle populations.

**Eagles as indicators of habitat health**
As widespread, conspicuous and mobile organisms, birds often serve as valuable and sensitive indicators of environmental change (Furness *et al.* 1993, Carrete *et al.* 2002), and measures of raptor species distribution and abundance have served as functional indices of habitat health (Robinson & Wilcove 1989). The Martial Eagle is potentially suitable as an indicator of ecosystem integrity in the Karoo. It is a large and obvious species, widely distributed and relatively easy to monitor, particularly where pairs breed on electricity pylons. As a predator of small to medium-sized mammals and large birds and reptiles, the Martial Eagle operates at the apex of the local food pyramid, and is well placed to detect and respond to imbalances at subordinate producer and consumer levels (Watson 1991, Wichmann *et al.* In press). Evidence presented here suggests that the species may indeed be sensitive to such imbalances.
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