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Home Range and Movements of Feral Cats on Mauna Kea, Hawai‘i

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Feral cats *Felis catus* in dry subalpine woodland of Mauna Kea, Hawai‘i, live in low density and exhibit some of the largest reported home ranges in the literature. While 95% fixed kernel home range estimates for three females averaged 772 ha, four males averaged 1 418 ha, and one male maintained a home range of 2 050 ha. Mean daily movement rates between sexes overlapped widely and did not differ significantly (P = 0.083). Log-transformed 95% kernel home ranges for males were significantly larger than those of females (P = 0.024), but 25% kernel home ranges for females were larger than those of males (P = 0.017). Moreover, log-transformed home ranges of males were also significantly larger than those of females in this and seven other studies from the Pacific region (P = 0.044). Feral cats present a major threat to endangered Hawaiian birds, but knowledge of their ecology can be used for management by optimizing trap spacing and creating buffer zones around conservation areas.

Key words: Daily movements, Feral cat, *Felis catus*, Hawai‘i, Home range

INTRODUCTION

FERAL cats *Felis catus* became abundant in forests of the Hawaiian Islands soon after their introduction in the late 1700s (King 1984; Rothschild 1893; Perkins 1903). They were subsequently reported to be notorious predators of birds that contributed to the decline and extinction of some Hawaiian species (Perkins 1903; Berger 1981; Ralph and van Riper 1985; Stone 1985; Snetsinger *et al.* 1994). In Hawai‘i, cats are currently important predators of terrestrial birds that nest near the ground (Kowalsky *et al.* 2002), and in trees (Hess *et al.* 2004). Cats are also important predators of colonial seabirds (Smith *et al.* 2002). Feral cats range throughout the Hawaiian Islands from high-density colonies near coastal areas where pets are frequently abandoned and fed by people (Winter 2003), to remote, low-density populations in montane forests and subalpine areas of Maui (Simons 1983) and Hawai‘i Island (Hu *et al.* 2001). Despite the long history of feral cats in Hawai‘i, there has been little research about their spatial arrangement or basic ecological organization, such as home range and movements.

Several studies have documented home range and movements in the Pacific region where introduced cats have established feral populations. Fitzgerald and Karl (1986) reported linear home ranges in the steep Orongorongo Valley of New Zealand. Konecny (1987) found the home ranges of male cats to be larger than those of females in the Gálapagos Islands; however, Norbury *et al.* (1998) found no difference in home range size between sexes for feral cats living in dry tussock grassland in New Zealand. Edwards *et al.* (2001) documented the largest home ranges (2210.5 ha) in semiarid woodland of central Australia. The only study of feral cat home ranges in Hawai‘i was from a wet montane forest on windward Mauna Kea, at Hakalau Forest National Wildlife Refuge (Hakalau), Hawai‘i Island (Smucker *et al.* 2000). These studies have contributed to the basic knowledge of the species, but have also provided information for better management of non-native predators and conservation of native fauna (Fitzgerald and Karl 1986).

The distribution and abundance of feral cats may be controlled by a number of factors including territorial behaviour, social inter-actions, or food resources. Marked differences between individuals may exist in landscape use patterns due to foraging, mate-seeking, denning, and rearing behaviours. The spatial arrangement of feral cats can be used to gauge the timing and spacing distance of control units (e.g., traps or poisoned baits), to understand the epidemiology of diseases, and to delineate the total area over which feral cats need to be controlled in order to remove resident animals and confine immigration to buffer zones on the perimeter of core conservation areas (Veitch 1985; Norbury 1998; Short *et al.* 1997; Edwards *et al.* 2001). Our objectives were to determine home range, territoriality, and daily movement rates of feral cats in the dry subalpine woodland of Mauna Kea, Hawai‘i, Island as part of a larger

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study of feral cats in Hawai‘i that included diseases (Danner *et al.* 2007), diet (Hess *et al.* 2007), and population genetics (Hansen *et al.*, 2007). The overall goal of this research was to provide basic information on the impacts of feral cats on native wildlife as well as strategic considerations for developing and improving control methodology.

STUDY AREA

Study area was located in subalpine woodland on Hawai‘i Island on the West Slope of Mauna Kea (19° 49' N, 155° 36' W), a dormant volcano. Subalpine woodland occurs between 1 750–3 000 m elevation. Overall canopy cover averaged 30% and canopy height was generally short (3–8 m) with interspersed lower-stature shrubs and larger areas of shrublands. Dominant trees include Māmane *Sophora chrysophylla* and Naio *Myoporum sandwicense* and extensive shrublands are dominated by Pūkiawe *Leptecophylla tameiameiae*, and ‘A‘ali‘i *Dodonaea viscosa*. The semi-arid aspect of subalpine woodland is due to severely drained volcanic substrates and rain shadow effects. Rainfall averaged 511 mm and temperature averaged 11.1° ± 1.5° C annually (Juvik *et al.* 1993). There are no natural sources of perennial standing water in the study area.

METHODS

Since feral cats are difficult to observe, we calibrated 35–37g Holohil Systems Ltd. model MI-2 radio transmitters with AOR AR8200 digital receivers to determine location accuracy during close-range tracking. We simulated cat behaviour by handling transmitter collars both in motion and motionless at < 0.5 m height through vegetation. Observers that did not know the true location of transmitters monitored the receiver’s LCD signal meter and achieved approximately 50 m accuracy. We maintained this distance during tracking to avoid disturbing the subjects.

We captured seven male and three female cats, anaesthetized them with methoxyfluorane, and fitted them with transmitters. Cats were allowed to fully recover in traps and were not tracked for ≥ 1 d after release. Six male cats were fitted with transmitters in July 1999. One cat (M-4) was opportunistically recaptured after 14 mo and fitted with a new transmitter to extend data collection. Three females and one additional male cat were fitted with transmitters in September 2000. The weight of males ranged from 2.4–3.65 kg, (mean = 2.99 kg), while females ranged from 1.75–2.2 kg (mean = 1.86 kg). All cats were adults, based on dentition. We recorded ≤ 3 locations per cat per day with Garmin GPS 12 (Lenexa, Kansas, USA) global positioning system receivers. Cats were periodically tracked on consecutive days to determine daily movements. Data collection ended in February 2002.

To investigate the temporal autocorrelation of observations, we calculated t2/r2 statistics for a range of minimum times between observations (Swihart and Slade 1985; 1986). A minimum separation of 2.85 d was needed to achieve quasi-independent observations. We excluded data points that were taken ≤ 2.85 d after the first observation, and points that were ≤ 2.85 d after subsequent observations. We calculated 95%, 50%, and 25% fixed kernel (Worton 1995) home ranges using the animal movement extension (Hooge and Eichenlaub 1997) for ArcView GIS (ESRI 1999). We used least squares cross-validation to estimate a kernel smoothing parameter for each cat, and used the median value (378 m) for all cats to produce the final home range estimate as recommended by Seaman and Powell (1996). We then examined the effect of reduced sample size on kernel home range estimates with 1 000 bootstrap minimum convex polygons (MCP) from the remaining locations using the animal movement extension (Hooge and Eichenlaub 1997). We plotted MCP area against sample size to determine if sufficient observations existed to stabilize MCP area. We compared log-transformed 95% and 25% kernel home range estimates between sexes and the simple mean rate of speed (m/d) between all successive observations with *t*-tests. We also compared log-transformed home range estimates between sexes with seven other published studies from the Pacific region.

RESULTS

Fixed kernel home range estimates were determined to be reliable for seven of the 10 subjects through bootstrap minimum convex polygon analysis. Estimates of 95% fixed kernel home ranges for these seven cats ranged from 610–2 050 ha and averaged 1 418 ha for males and 772 ha for females (Table 1). Excluding points to achieve quasi-independence resulted in an average increase of 28% in the 50% core activity areas, although overall 95% kernel home ranges were smaller when compared to analyses using all observations. Log-transformed 95% kernel home ranges for males were significantly larger than those of females (Equal variance 2-sample t-test; DF = 5, t = -3.20, P = 0.024), but 25% kernel home ranges of females were larger than those of males (DF = 5, t = 3.53, P = 0.017; Figs 1–2). Female F-3 raised two litters of kittens during the study and had the smallest home range and daily movement rates. F-2 had two core 25% activity areas and males M-2, M-4, and M-5 had multiple 50% activity areas. M-1 exhibited sequentially clustered observations separated by 14.8 km and was therefore treated as having two separate home ranges, although sample size was insufficient for reliable kernel estimates for either home range. M-3 periodically travelled from the West to the North Slope of Mauna Kea, making a 45 km roundtrip in a 2-week period, but had insufficient sample size for reliable kernel estimate. Mean daily movement rates between sexes overlapped widely and did not differ significantly (Unequal variance 2-sample t-test; DF = 6, t = -2.08, P = 0.083). Log-transformed home ranges for males were significantly larger than those of females in this and seven other studies from the Pacific region (DF = 12, t = -2.25, P = 0.044; Table 2).

DISCUSSION

Mean home ranges of feral cats on Mauna Kea were the largest reported among seven other studies from the Pacific region for females (mean = 80.1% larger) and the second largest for males (mean = 56.1% larger; Table 2). We found that home ranges of male feral cats on Mauna Kea were 60% larger, and females were 71% larger than those reported from Hakalau, which is approximately 25 km in distance from our study site (Smucker *et al.* 2000). Moreover, home ranges of males were also significantly larger than those of females throughout the Pacific region.

Although Konecny (1987), Jones and Coman (1982), and Norbury *et al.* (1998) used minimum convex polygon analyses, the larger home ranges on Mauna Kea represents more than a methodological discrepancy. Home ranges were comparably sized in the environment most similar to Mauna Kea; semi-arid woodland of the Northern Territory of Australia (Edwards *et al.* 2001). Edwards *et al.* (2001) and Smucker *et al.* (2000) also based their estimates

Table 1. Fixed kernel home range estimates (ha) and mean daily movement rates of feral cats (*Felis catus*) on the West Slope of Mauna Kea, Hawai'i, 1998–2001. Non-independent observations were eliminated based on estimated average of 2.85 days to quasi-independence. Home range was calculated by the median least square cross validation (LSCV) smoothing parameter (H) value of 378.

ID	Days to Quasi-Independence	Observations n (all)	n (2.85)	LSCV H	Home Range (ha) 95%	50%	25%	Mean Distance (m/day)
M-1	0.25	26	9[a]	600	637	55	24	—
M-1	0.05	30	8[a]	298	428	60	26	4521.5
M-2	0.04	66	29	416	1167	98	37	6014.3
M-3	4.00	70	18[a]	399	739	80	29	4901.4
M-4	6.65	179	43	542	2050	152	29	153.7
M-5	0.05	112	46	358	1279	116	32	109.8
M-6	1.00	19	6[a]	386	432	80	24	90.9
M-7	8.00	73	30	428	1176	84	32	124.9
F-1	4.95	135	31	291	875	169	61	108.6
F-2	1.70	130	27	292	831	202	58	112.4
F-3	6.90	183	44	195	610	100	39	183.7

[a]Insufficient observations for reliable home range estimate.

Table 2. Comparison of home range estimates from the West Slope of Mauna Kea, Hawai'i, with seven other published studies from the Pacific region. Percent by which Mauna Kea home range was > another study area = $(1 - (HR_{study\ x}/HR_{Mauna\ Kea}))*100$.

Habitat and Location	Home Range Size (ha) F	M	Percent Mauna Kea > by F	M
Subalpine woodland, Mauna Kea, Hawai'i	772	1418	—	—
Victorian Mallee, South-eastern Australia[a]	170	620	78.0%	56.3%
Orongorongo Valley, North Island, NZ[b]	80	140	89.6%	90.1%
Galápagos Islands[c]	82	304	89.4%	78.6%
Dry tussock grassland, South Island, NZ[d]	225	225	70.9%	84.1%
Open forest, New South Wales, Australia[e]	140	288	81.9%	79.7%
Wet montane forest, Hakalau, Hawai'i[f]	223	574	71.1%	59.5%
Semi-arid woodland, Central Australia[g]	—	2211	—	-55.9%
Mean	241.7	722.4	80.1%	56.1%

[a]Jones and Coman (1982); [b]Fitzgerald and Karl (1986); [c]Konecny (1987); [d]Norbury *et al.* (1998) ; [e]Molsher *et al*. (2005); [f]Smucker *et al.* (2000); [g]Edwards *et al.* (2001)

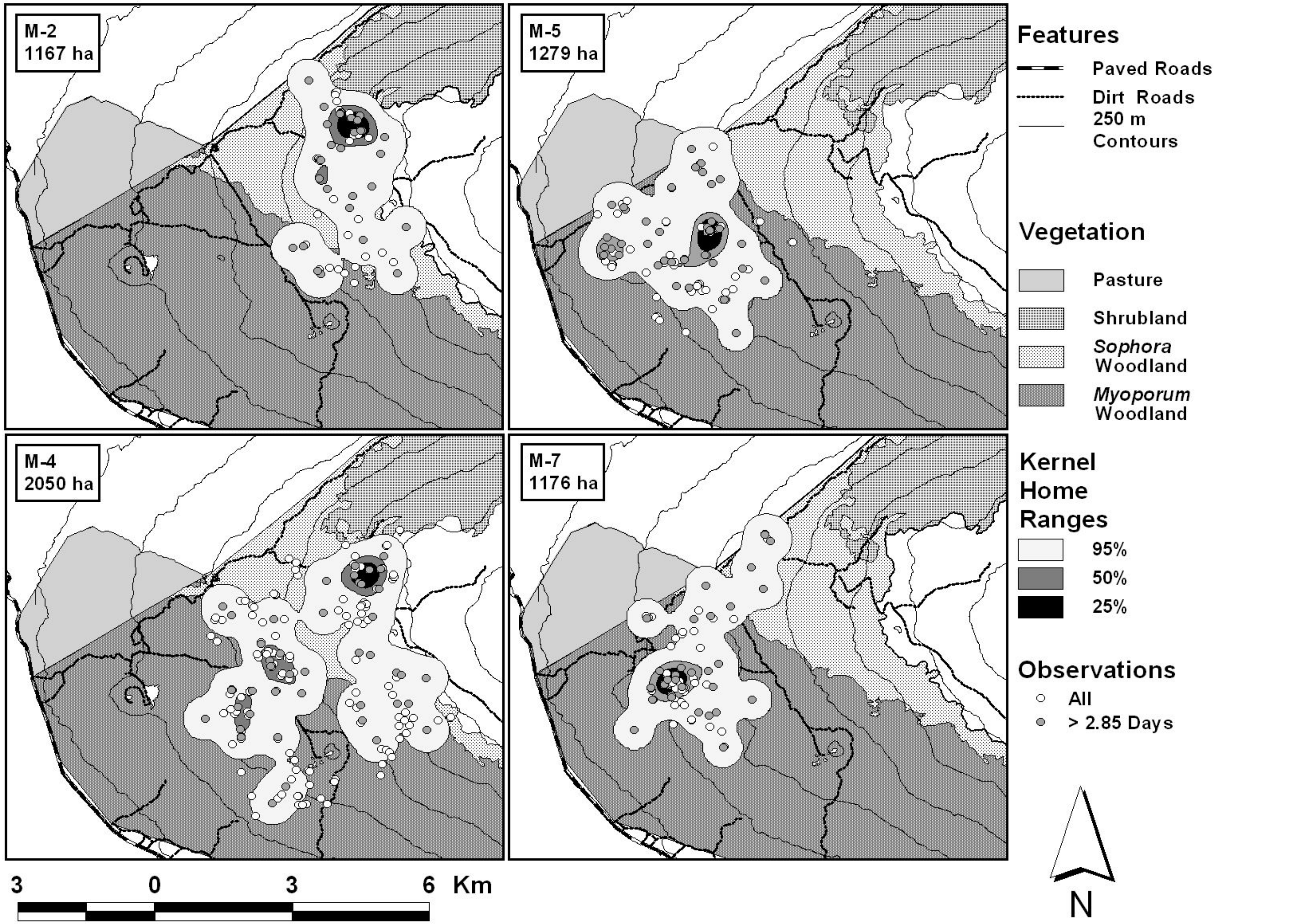

Fig. 1. Telemetry observations and fixed kernel home ranges of male feral cats on the West Slope of Mauna Kea, island of Hawai'i 1998–2001. Non-independent observations were eliminated based on estimated average of 2.85 days to quasi-independence.

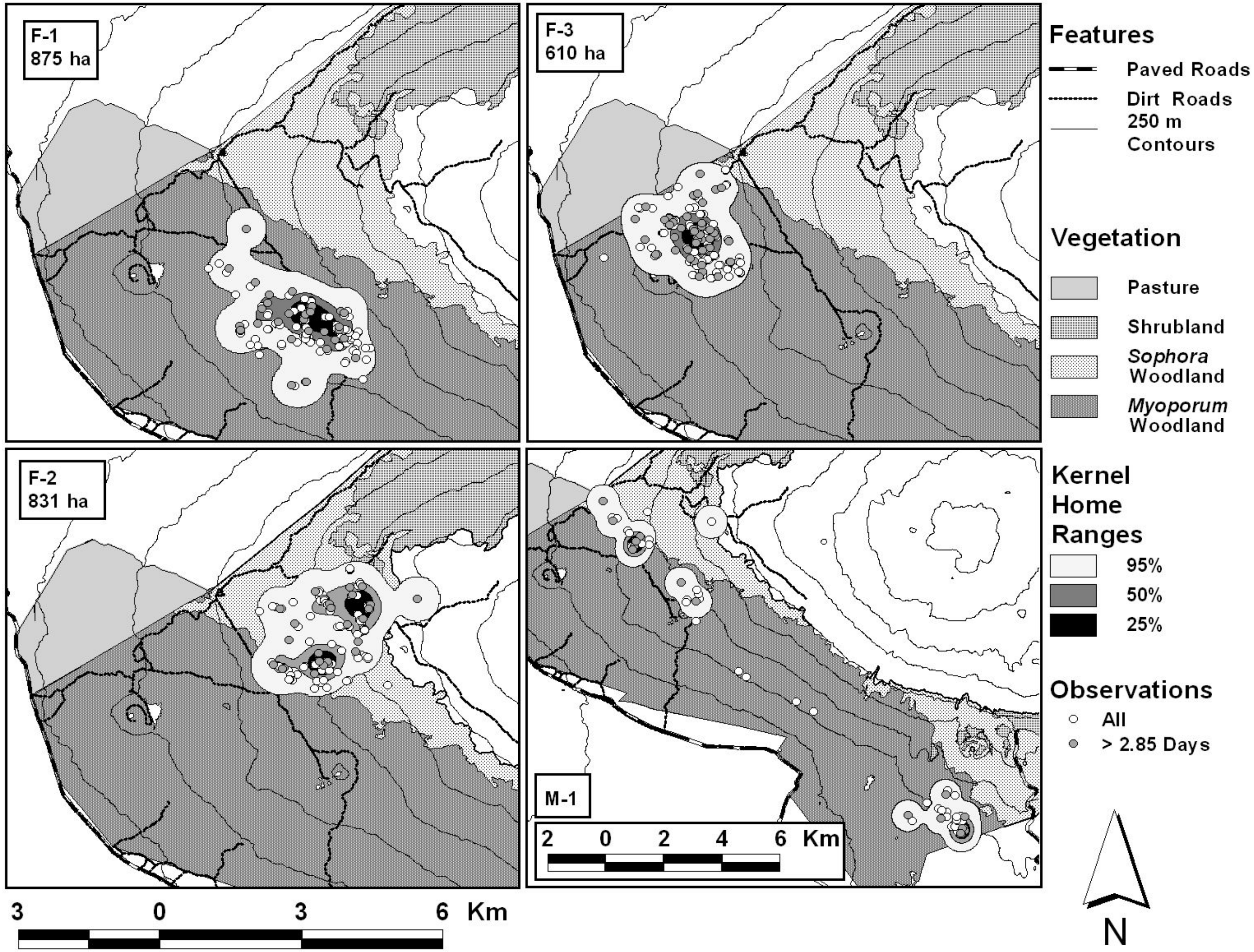

Fig. 2. Telemetry observations and fixed kernel home ranges of three female and one male feral cat on the West Slope of Mauna Kea, island of Hawai'i 1998–2001. Non-independent observations were eliminated based on estimated average of 2.85 days to quasi-independence.

on kernel methodology, but our estimates of overall home ranges may be comparatively smaller in area because we eliminated non-independent points. No other studies explicitly accounted for the independence of locations; however, Norbury *et al.* (1998) examined the effect of sample size on home range estimates and found that home range size began to stabilize after about 10 locations. We found that subjects with ≤ 18 locations did not provide reliable home range estimates. Only two of five subjects in the Smucker *et al.* (2000) study had > 18 locations, therefore sample sizes may have been inadequate, resulting in underestimation of true home range size.

We found some evidence that the spatial arrangement and low density of feral cats on Mauna Kea was tied to social organization. There were strong differences between sexes in home range size, which we attributed primarily to mate-seeking behaviour in males, and denning behaviour in females. Although females on Mauna Kea occupied large areas relative to other study locations, their overall mean home ranges were only 54% as large as males, but their core activity areas were larger than those of males indicating they may use smaller areas more intensively while males use larger areas more extensively. Because mean daily movements on Mauna Kea did not differ between sexes, this indicates that males did not always return to the same location on a daily basis, whereas females may have been tied to a central location. Konecny (1987) also found differences between sexes and that female cats with kittens occupied extremely restricted ranges. Norbury *et al.* (1998) and Molsher (2005), however, found no difference between sexes in home range for cats in dry tussock grassland in New Zealand and central-western New South Wales, Australia, respectively. The relative sizes of male and female home ranges may differ among these study environments due to the breeding frequency of females and the mate-seeking and foraging behaviours of males in different habitats.

In studies where food sources were abundant and concentrated, a large degree of spatial overlap occurred between male cat home ranges, but activity centres were discrete and encounters with conspecifics were rare (Konecny 1987; Short *et al*. 1997). Smucker *et al.* (2000) reported that male home ranges had minimal overlap in montane forest at Hakalau. In subalpine Mauna Kea, however, male cat home ranges overlapped extensively, including the 25% core activity areas of M-2 and M-4. There was no apparent seasonal pattern to home range overlap; however, the range of M-4 extended to lower elevation primarily during March–August 2001, and subsequently returned to higher elevation. Evidence for territorial encounters between males on Mauna Kea comes from the prevalence of Feline Immunodeficiency Virus (FIV) which is primarily transmitted by biting and scratching (Yamamoto *et al.* 1988). While 17% of 39 males from Mauna Kea tested positive for FIV, all 29 females were negative (Danner *et al.* 2007). Overall female home ranges on Mauna Kea overlapped only slightly, and core activity areas did not overlap.

Feral cats are wide-ranging predators with negative effects on the native fauna throughout the Pacific region (Dickman 1996). Hansen *et al.* (2007) estimated that 17.6% of cats per generation on Mauna Loa, primarily males, had migrated > 53 km from Mauna Kea. There is evidence that feral cats in Hawai‘i prey on endangered forest birds (Laut *et al.* 2003; Hess *et al.* 2004) as well as nesting seabirds (Smith *et al.* 2002; Hess *et al.* 2007). Male cats tend to be more wide-ranging than females and may therefore encounter more endangered birds while foraging. For example, the mean home range of male cats on Mauna Kea represents more than 10% of the entire range (140 km^2) occupied by the endangered Hawaiian finch, the Palila (*Loxioides bailleui*) (Scott *et al.* 1986). Because male home ranges were also non-exclusive, Palila may be simultaneously exposed to predation by several different individual cats.

Trap spacing should account for minimum daily movements and differences between sexes in home range. The radius of a circular area equivalent to the home range of female feral cats on Mauna Kea is 1 568 m and males is 2 125 m. Cats may be expected to encounter traps at some point in time when traps are spaced less than these distances, however, daily movements may be used to dictate minimum spacing between transects during short-term (2–3 d) trapping sessions. Most subjects made daily movements > 100 m. The implications of large home ranges in male cats is that large trapping areas are needed to confine immigration to buffer zones on the perimeter of endangered species habitat in this environment in Hawai‘i. Other considerations are also important for effective trapping programmes. Short *et al*. (2002) found that feral cats that did not use rubbish dumps were more likely to be caught in concealed foot-hold traps than cage traps. No such human subsidies currently exist within the range of cats on the West Slope of Mauna Kea.

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