


Habitat use by wandering pet cats (*Felis catus*) in a patchy urban environment

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Abstract

Pet cats (*Felis catus*) often have negative effects on wildlife. This is of growing concern in urban areas as these are increasingly becoming hotspots of native wildlife activity, and as the human population increases, so too does the pet cat population. To maintain biodiversity in urban areas, further knowledge on pet cat behaviour and impacts is required so that management strategies for pet cats are well informed and have public and government support. Here, we offer insights into the wandering activity of pet cats in a patchy urban—heavily vegetated landscape on the east coast of Australia. Our estimated pet cat movement ranges were generally larger than those previously observed in similar landscapes, as well as in more urbanized and rural habitats. Using GPS data loggers, we found that pet cats did not utilize vegetated spaces more than urban areas, nor did they prefer them relative to their availability. Half of our study cats selected urban habitats, whilst the other half displayed no selection or a slight preference for vegetated spaces; these cats had fewer barriers to overcome to reach them. We did not observe any large differences in movements or habitat use between day and night, but displacement distances and preference for vegetated space habitat were marginally lower at night. All pet cats monitored spent most of their time outside their houses. As both urban and vegetated spaces in patchy urban landscapes provide habitat for native wildlife, pet cat activity across both habitat types requires management action.

Key words: introduced species, home range, movement, management strategies, green space, nature preserve

Introduction

Domestic cats (*Felis catus*) are one of the most common pets globally [Growth from Knowledge (GfK) 2016], and the exponential growth of the human population equates to more pet cats generally living in urban areas in high densities (Legge et al. 2020a). It is common for owners to let pet cats roam freely or wander outside at designated times in order to live what they perceive to be a behaviourally enriched life (MacDonald, Milfont, and Gavin 2015; McLeod, Hine, and Bengsen 2015; Hall et al. 2016a), despite there being little evidence that this is a

requirement or even a benefit to these cats (Rochlitz 2005). High densities of free-roaming pet cats, fed by their owners, create the potential for hyper-predation on wildlife in urban areas, a situation in which usual predator-prey dynamics are decoupled and high rates of predation occur even at low prey densities (Woods, McDonald, and Harris 2003). There are many accounts of pet cats hunting native wildlife (e.g. Dickman and Newsome 2015), and creating further negative impacts through the transmission of viral, bacterial, fungal and parasitic diseases, especially the protozoan parasite *Toxoplasma gondii*, to both wildlife

and people (Day et al. 2012; Lepczyk, Lohr, and Duffy 2015; Legge et al. 2020b). Of further concern are the flow-on ecological impacts that can arise via competition between introduced and native predators (Bilney, Cooke, and White 2006) and prey stress responses to predator pressures (Fardell, Pavey, and Dickman 2020). As prey species navigate through ‘landscapes of fear’—areas of greater or lesser risk of predation (Laundre, Hernandez, and Ripple 2010) that may be created by the presence of cats (Mahlaba et al. 2017; Parsons et al. 2018) or their cues (faeces/urine/fur: Apfelbach et al. 2015), they may alter their feeding habits (Laundre, Hernandez, and Ripple 2010). Even if they escape predation, the effects of fear can negatively impact the reproductive success of prey species (Beckerman, Boots, and Gaston 2007; Bonnington, Gaston, and Evans 2013). Altered levels of stress or defensive behaviours can attract other predators or make prey more susceptible to them, thus increasing the risks to prey species still further (Preisser, Bolnick, and Benard 2005). An additional concern about wandering pet cats is that they may contribute to increased feral cat populations directly by not returning home, via breeding, or kitten abandonment (Jongman 2007). Furthermore, in areas where native felids are also present, there are risks of hybridization with pet cats and disease transmission from pet cats to native felids (Senn et al. 2019; Sieg et al. 2020).

The wandering activities of pet cats have long been known and although there is limited scientific support for such activities in specific conditions, as observed in New Zealand where the only native mammals were bats (Flux 2007, 2017), global increases in areas of urban sprawl that encompass green spaces or border nature reserves are increasing the potential impacts of pet cats. The diets of pet cats are dominated by native mammals in some forest-urban edge habitats, with native vertebrates still present in cat diets in urban habitats (Dickman 2009). Such impacts may only increase as wildlife are increasingly observed in urban habitats (Ives et al. 2016; Weller, Hoch, and Huang 2017), which gives the yards of houses surrounding green spaces, or bordering nature reserves, some conservation value (Rudd, Vala, and Schaefer 2002). Green spaces throughout urban sprawls, despite their often small size, are proven areas of environmental and biodiversity significance (Soanes et al. 2019). As native animals begin to adapt to urban sprawls, they can potentially alter their temporal activity (Gaynor et al. 2018). Indeed, we have encountered southern brown bandicoots, brown antechinus and short-beaked echidnas at urban properties or in the green spaces adjacent to them in the day during this study (pers. obs L. Fardell). To reduce encounter rates and the attendant negative impacts on wildlife from wandering pet cats in patchy urban, vegetated areas, appropriate management needs to be implemented (Legge et al. 2020a,b).

Containment and exclusion or buffer zones are among the management options for reducing cat impacts on wildlife, but as their success depends on monitoring and penalties for non-compliance (Moore 2001), local governments can be reluctant to apply such measures. There is some incentive for managing pet cats, as urban biodiversity helps to fulfil people’s desire to live in environmentally enriched landscapes (United Nations 2014), with their proven health benefits (Astell-Burt, Feng, and Kolt 2014; Halonen et al. 2014; Kardan et al. 2015; Mitchell et al. 2015). Furthermore, surveys gauging community responses to pet cats have repeatedly shown that many people acknowledge cat-wildlife problems (Blair, Wescott, and Miller 2016; Hall et al. 2016a; Roetman et al. 2017; Travaglia and Miller 2018). The level of community recognition, however, may be relative to high endemic biodiversity, as Australia and New Zealand community

responses have been observed to be higher than in the UK, USA, China and Japan (Hall et al. 2016a). Despite any level of acknowledgement of cat-wildlife problems, social studies have also noted that implementing pet cat restrictions often still lacks public support (Roetman et al. 2017; Linklater et al. 2019). Local governing bodies, such as councils in Australia, for example, have shown interest in implementing regulations for pet cats (McCarthy 2005; RSPCA 2018; ACT Government 2019), and on occasions have succeeded [Eurobodalla Shire Council (ESC) 2018; Legge et al. 2020a; Read et al. 2020]. Research on pet cat movements and habitat use should provide useful insight to help garner more support to implement pet cat management.

The wandering activities of pet cats are highly variable (Hall et al. 2016b). Cat sex may be a source of this variation (Kikillus et al. 2017; Roetman et al. 2017), but its effect is inconsistent (Barratt 1997b; Meek 2003; Liliith, Calver, and Garkaklis 2008). Similarly, de-sexing can either markedly influence home range size (Kays et al. 2020), or have no influence (Hall et al. 2016b), whilst diurnal ranges may be both smaller than (Barratt 1997a; Roetman et al. 2017) or equal to nocturnal ranges (Kikillus et al. 2017). Pet cats in rural or farm areas also may have either larger (Liliith, Calver, and Garkaklis 2008) or smaller (Barratt 1997a) home ranges than their urban counterparts. In urban areas, however, housing density inversely affects pet cat range sizes, as low housing densities allow longer movements (Hall et al. 2016b; Hanmer, Thomas, and Fellowes 2017). One consistent result is that regularly fed pet cats still wander away from their homes and hunt, and regular husbandry and daily feeding by the owners does not affect range size when compared to cats given less human care and supplementary feeding (Hall et al. 2016b). This may be because domestic cats hunt even if satiated (Biben 1979).

Given the lack of clarity in previous research, here we aim to quantify the movements and habitat use of pet cats in an eastern Australian suburban area that contains multiple green spaces and corridors that connect them to surrounding nature reserves and conservation areas. We collectively term all of these features ‘vegetated spaces’, as they all comprise much native vegetation. Using GPS data loggers, we specifically investigated: (i) pet cat movements and range sizes, (ii) whether pet cats utilize the vegetated spaces and (iii) whether their movement patterns and habitat use differ by day and by night. As our sample size was small ($n=6$), we present our findings in relation to those from previous studies and use the results to suggest management options to reduce the potential impacts of pet cats on wildlife in the patchy urban environment.

Methods

Site description

Whitebridge and Kahibah, both in the Lake Macquarie district of New South Wales, Australia, are urban communities that are interspersed with numerous green spaces, including corridors and large empty plots of state-owned (‘crown’) land. Many of these green spaces are remnant habitats consisting of wet and dry sclerophyll forests and rainforests that pre-date European disturbance and vegetation changes, and thus some of the vegetation communities are significant at national, regional or local levels (Department of Environment, Climate Change and Water (DECCW) 2010; Bell 2016). Both Whitebridge and Kahibah border Glenrock State Conservation Area (GSCA), which spans 534 ha along the coast and links to the large Awabakal Nature Reserve in the south. GSCA has a floristic diversity index of 72.26 species

per ha, placing it in the top five conservation areas in the Sydney basin [Department of Environment, Climate Change and Water (DECCW) 2010]. It hosts a diversity of birds, reptiles and mammals including five threatened bird species, and four threatened mammal species [Department of Environment, Climate Change and Water (DECCW) 2010]. High recreational value is placed on the GSCA as it hosts many tracks that are used by walkers, runners and mountain bikers, and often hosts competition events for such activities, each of which has the potential to alter wildlife activity (Gander and Ingold 1997; Frid and Dill 2002; Larson et al. 2016; Bleicher and Rosenzweig 2018). Additional problems for wildlife in this area may also arise from the prevalence of invasive species, including the feral domestic cat and the European red fox (*Vulpes vulpes*) [Lake Macquarie City Council (LMCC) 2012]. The area of Whitebridge is largely comprised of National Parks and Conservation Areas (49.49%), low-density environmental living (12.2%), low-density urban residential (16.01%), medium-density urban residential (5.84%) and recreation areas (5.48%), and has a population of 2612 people across 5 356 035 m². The area of Kahibah is largely comprised of medium-density urban residential (60.11%), low-density urban residential (18.19%), National Parks and Conservation Areas (13.62%) and recreation areas (6.68%), and has a population of 2464 people across 1 116 014 m². The Lake Macquarie district that encompasses these two suburbs is one of the fastest growing areas in the Hunter Region [Lake Macquarie City Council (LMCC) 2011], and as such management to preserve wildlife biodiversity under such pressures is imperative.

Pet cat monitoring

Recruitment of pet cats into the study was carried out primarily by sending requests to potential cat owners by a letter box drop to 400 houses within the study area in 2019. To further engage potential participants we also used word of mouth by participants, appearances on local radio and posters at vet clinics, local businesses and on social media. Six pet cats were recruited for this study using these methods. This project was conducted under animal ethics (2017/1275) and human ethics (2017/977) approval from the University of Sydney.

Each pet cat used in the study was fitted with a GPS data recorder (CatLog Gen 2™, Perthold Engineering LLC, USA) secured to a harness designed for cats, with safety break-away clips to facilitate escape if entangled. The GPS recorder sat on the back of the cat, below the shoulder blades to reduce interference with movement. The device, including the harness, weighs <5% of cat body weight (weight: 25 g; dimensions: 4.5 × 3.5 × 1.3 cm) and is powered by a rechargeable 800 mAh lithium battery. GPS records were programmed to be taken every 3 or 6 min if the position was not secured within 90 s. Measurements required a '3D position lock' of at least four different satellites to be read on any location at a time. The accuracy of the GPS data recorder was tested repeatedly under the conditions of inside, outside, under outside structures, outside in open areas and outside in vegetated areas. Deviations from known location were calculated in ArcMap Version 10.7 (ESRI 2019). Accuracy ranged between 0 and 10 m and was least accurate when inside. These findings align with the product's advertised accuracy range of 5–10 m, and with previous studies (Thomas, Baker, and Fellowes 2014). Cats were fitted with the device by L.L.F. and monitored for 30 min to ensure it did not affect the cat in any way. Accordingly, the initial first hour of fixes recorded for each cat were discarded from analyses, as this was considered an acclimatization period and not representative of their natural

movement activities. Owners were shown how to remove and re-attach the device if the cat at any time showed discomfort, although this did not occur. The device was attached to each pet cat for seven consecutive days. However, data were not recorded for the entire period for all individuals due to battery failures, which may be attributed to weak batteries, poor satellite communication requiring repeat connections or the amount of time spent under structures or dense vegetation. Dense vegetation cover causes rapid battery drain (Fischer et al. 2018), and built structures likely do so too. Location data were downloaded and converted for use in ArcMap Version 10.7 (ESRI 2019). The data were also uploaded to ZoaTrack.org, an animal telemetry data repository with analysis and visualization tools, to allow future studies on cat movements.

Data analysis

Home range size

Outliers were removed from the data by using a speed filter in ZoaTrack prior to analysis (Dwyer et al. 2015). The likely maximum transit speed for pet cats we selected was 12.6 km/h, as domestic cat movement ranges between low and high speeds of 2.5–4.5 m/s (Kim et al. 2014). To measure forays to the furthest locations tracked and the spaces they encompassed, we used a 100% minimum convex polygon (MCP) (Worton 1995). This potential full range of tracked movement is hereafter referred to as the MCP 100 range. To account for the actual movements and the difference in the density of fixes taken from different locations, the utilization distribution was estimated using fixed kernel density estimation (KUD) at both 95% and 50% isopleths to determine the likely home and core range areas, respectively (Seaman and Powell 1996). The estimated home range and core range areas for the duration of the observation period are hereafter referred to as the KUD 95 and KUD 50 ranges, respectively. The MCP 100 area (ha) was plotted against the number of fixes to visually examine whether cat home ranges reached an asymptote during the study period. If the MCP 100 area plateaued during the study we assumed that enough fixes had been collected to adequately describe that individuals' home range. Similarly, KUD area (ha) was plotted at 10% isopleth increments to confirm that the 50% isopleth (KUD 50) described the core range of the cats tracked during our study. To determine the maximum linear distance travelled from home, displacement was also calculated for each fix. Range and displacement calculations were made via ZoaTrack (Dwyer et al. 2015), which utilizes the 'adehabitatHR' package (Calenge 2006) in the program R (R Development Core Team 2019). Each dataset was analysed as a whole and for both day and night fixes only, which were determined by local daily sunrise and sunset times.

Habitat use

Habitats within the estimated ranges were classified into two types: (i) urban, which included roads, any built structure and connected fenced-in yard areas and (ii) vegetated space, which included vegetated areas that were state conservation areas, nature reserves and green space: corridors, crown land and parks, including open grass sporting ovals surrounded by large native trees. Roads were included in the urban classification and not considered a hindrance to movement, as only two main roads were within the wider range available to all of the cats studied, and only one was within each cat's range. These roads were considered 'busy' within the middle of the morning peak traffic period (7–9 am) and the first 3 h of the afternoon peak traffic period (3–6 pm). Traffic during the remaining peak period

hours was classified as 'medium' with the remaining periods classified as 'light'. Incidental observations during the study revealed that the roads did not act as barriers to native wildlife in these areas (pers. obs L. Fardell).

Habitats were mapped using ArcMap 10.7 (ESRI 2019). Habitat use was then assessed within the MCP 100, KUD 95 and KUD 50 ranges by day, by night and for each 24 h period by calculating the percentage of the home range area and number of fixes falling within each habitat type for each of the range measures. We used Jacobs' index (Jacobs 1974) to calculate habitat use relative to availability in the wider area (within a 370-m radius from each cat's house; see below). Jacobs' index is calculated as $D = (r - p)/(r + p - 2rp)$, where r is the proportion of a habitat type utilized, p is the proportion of the habitat type available in the wider area and D is habitat type preference/avoidance in relation to potential habitat availability. Complete preference = +1, complete avoidance = -1 and no selection = 0 (Jacobs 1974). We used a 370-m radius from each cat's house to determine habitat availability in the wider area (p), based on the maximum linear distance that pet cats moved from their home in our study, which was within the suggested buffer zone range from previous studies (Lilith, Calver, and Garkaklis 2008; Thomas, Baker, and Fellowes 2014).

Statistical analyses

Day and night effects on maximum distance travelled, MCP 100, KUD 95 and KUD 50 ranges, as well as on the area size, preference for and frequency of use of each habitat type across the three range measures, were assessed using paired Wilcoxon signed ranks tests. Differences between urban and vegetated space: area in each range, frequency of use in each range and habitat preference in each range were also assessed using paired Wilcoxon signed ranks tests. This non-parametric method was used as data were not normally distributed, and the day and night, and urban and vegetated space detections were repeated measures on each cat. Tests were performed in R (R Development Core Team 2019) using the 'wilcox.test' function from the base package and the 'wilcoxsign_test' function from the 'coin' package (Hothorn et al. 2006).

Results

Of the six cats tracked during the study, two (Tess and Tiger) lived together and were neighbours to a third tracked cat (Daeng) (Fig. 1B). These three cats were known by their owners to interact regularly as there was no fence between the properties. Together, the two properties created a large, open grass and vegetated area that contained many large native trees and bordered a green space corridor with a creek, between which there was no fence. Another two cats, Cairo and Monty, were known by their owners to frequently interact as they lived across the road from one another (Fig. 1D). Their street had green space corridors both at the end of the street and behind it (Fig. 1A). GSCA was located adjacent to their homes, past two rows of houses and a two-lane road (Fig. 1A). The sixth cat, CoCo, lived across a single lane road from a green space corridor area that contained a wide 16 km long recreational path, which was heavily utilized by people (Fig. 1C). All the green space corridors surrounding the properties connected to GSCA (Fig. 1A).

Movements of the cats were tracked for 4–7 consecutive 24-h periods during winter–spring 2019 in the southern hemisphere, with a maximum of 3 weeks difference between the first and last cats tracked. As only minimal climatic change was observed during this period, with no rain events, seasonal conditions

were not considered to be a driver of pet cat movement behaviours. On average, 288 detections were taken per pet cat per 24-h period, giving a total of 10 373 detections (Table 1). All pet cats had been neutered prior to the study; four were female and two were male (Table 1). Three cats were aged 1.5–3 years, and the other three 12–19 years (Table 1). Husbandry was similar across all pet cats, as they were all fed a wet meal every afternoon–evening and had cat biscuits left out for daily access from the morning. All pet cats were allowed to roam freely both inside and outside their houses during the study period, although three owners noted that their cats were frequently inside at night from around 9–10 pm until sunrise. However, tracking results showed that this was not always the case.

Movements and range sizes

The maximum linear displacement distance travelled from home by a pet cat was 370 m, which occurred during a daytime period (Table 1). The maximum linear displacement distance from home was marginally (average 6–7 m) less by night than by day ($Z = 1.95$, $P = 0.05$). However, the MCP 100, KUD 95 and KUD 50 range areas were no different in size between day and night (Fig. 2 and Supplementary Table S2). The MCP 100 area varied the most (6.98–12.86 ha, median: 6 ha) and was considerably larger than the KUD 95 area that was 21.5% of the MCP 100 range size but had less variance (0.70–2.49 ha, median: 1.36). The KUD 50 range area was the smallest, being 10% of the KUD 95 range size, and varied the least (0.02–0.24 ha, median: 0.15). Asymptotes occurred for each pet cat's full range of detections (MCP 100), confirming that home ranges were indeed defined reliably in the observation period (Supplementary Fig. S1). Similarly, visual plots of KUDs at isopleth increments of 10 confirmed that the 50% isopleth adequately described the cats' core ranges (KUD 50) during the observation period (Supplementary Fig. S2).

Habitat use

The percentages of fixes that were actually inside each pet cat's house in the MCP 100 range were a small fraction of the total urban fixes: Coco = 6%, Daeng = 6%, Tiger = 5%, Tess = 11%, Cairo = 23% and Monty = 30%. More fixes were taken in urban habitats than in vegetated spaces and there was greater area of urban habitats compared to vegetated spaces within all range estimates for all cats (Fig. 3 and Supplementary Table S1). However, there was a smaller area of urban habitat in the MCP 100 range than in the KUD 95 range for all cats (Fig. 3) except for CoCo, who had more fixes in and a greater area of urban habitat across her MCP 100 range compared to that in her KUD 95 range (Table 1). The KUD 50 ranges occurred exclusively in urban habitat for all cats (Fig. 3) except Tiger, who utilized the habitats at a ratio of ~83:17 of urban to vegetated space habitat area and fixes in Table 1. No significant differences were found between day and night for the area of each habitat type used or the number of fixes in each habitat within the MCP 100, KUD 95 and KUD 50 ranges (Supplementary Table S2).

Within the potential pet cat movement range of 370 m radius from their houses, Cairo and Monty had the most area of vegetated space habitats potentially available to them (52% and 55% of the area, respectively), followed by CoCo (25% vegetated space), then Tiger, Tess and Daeng (14%, 14% and 13% vegetated space, respectively). Based on Jacobs' index, three cats (Cairo, Monty and CoCo) showed a preference for urban habitats relative to habitat availability across all range measures (Table 1).

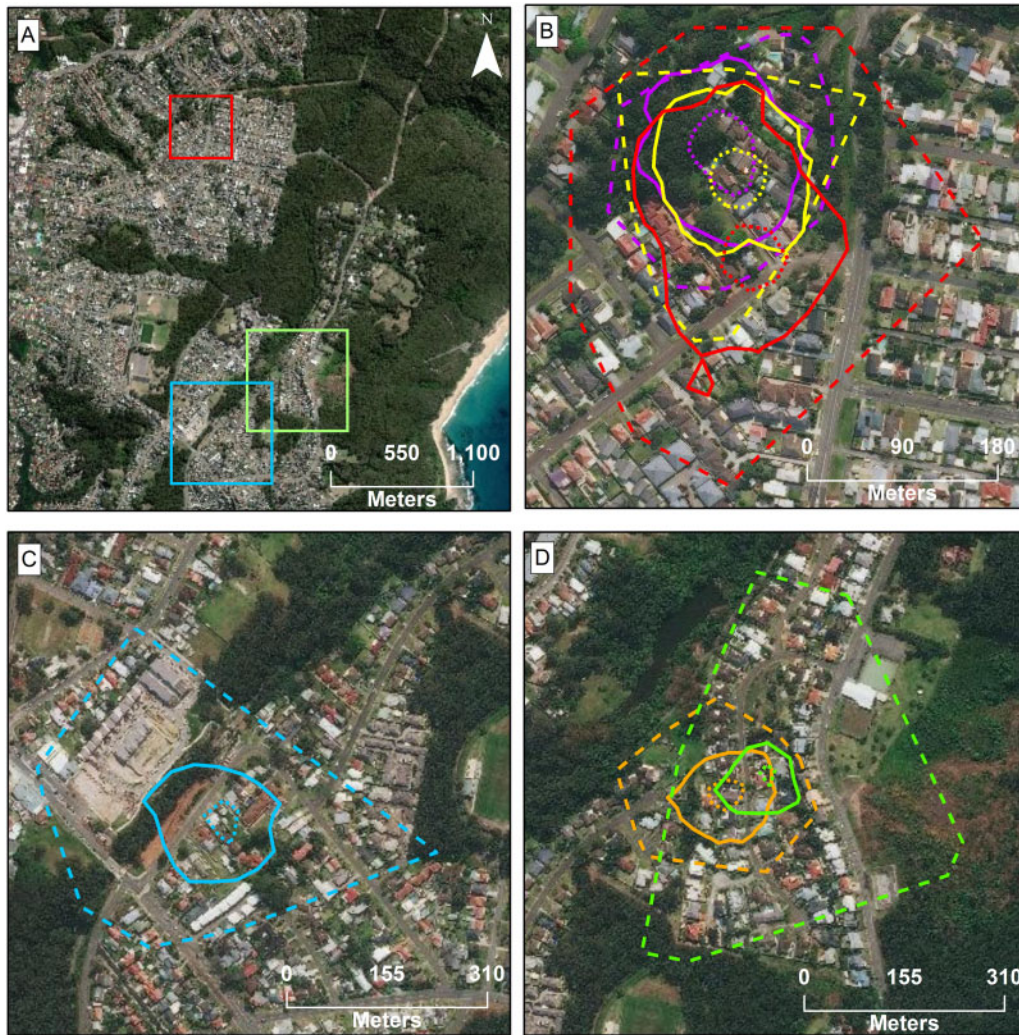


Figure 1: The MCP 100 (outer, dashed line), KUD 95 (middle, solid line) and KUD 50 (inner, dotted line) ranges for (B) Daeng (red), Tess (yellow), Tiger (purple); (C) CoCo (blue); and (D) Monty (green) and Cairo (orange) within the patchy urban study area of Kahibah and Whitebridge, NSW, Australia (A). The green space corridors surrounding the areas of study link up to GSCA to the east (A). In map A, the red square is the area of map B, the blue square is the area of map C and the green square is the area of map D. Background world imagery sourced from (ESRI 2019).

Within her KUD 95 range, however, CoCo showed less of a preference and more even habitat use. Monty did not utilize the vegetated space habitats relative to their availability within his home and core ranges, moving exclusively through urban habitats and visiting vegetated spaces irregularly on forays (Table 1 and Fig. 1). The remaining three cats (Daeng, Tess and Tiger) exhibited little preference for habitat type, showing only a slight preference for vegetated spaces in proportion to availability in their MCP 100 and KUD 95 ranges (Table 1). The cats' KUD 50 ranges, however, showed a preference for urban habitat relative to availability, except Tiger, who had a slight preference for vegetated space over the urban habitat that was potentially available (Table 1 and Fig. 1). When combined, the cats showed little preference for habitat type relative to availability, although it tended to be slightly lower for vegetated space compared to urban habitats across the MCP 100 and KUD 95 ranges when assessed by day, night and the combined periods (Fig. 4 and Supplementary Table S1). Night time KUD 95 range use was exceptional in that cats preferred urban habitats (Fig. 4). The KUD 50 ranges across day, night and combined all strongly favoured urban habitats (Fig. 4 and Supplementary Table S1). Within the

MCP 100, KUD 95 and KUD 50 ranges, there was no difference in indices of urban or vegetated space habitat preference, individually, when comparing day to night time measures (Supplementary Table S2).

Discussion

Our results show that the pet cats spent most of their time outside their house traversing ranges that were mostly large, and that they were more active in the urban habitats compared to the vegetated spaces. Still, all cats visited vegetated spaces, some more frequently than others, this perhaps being due to the ease of access to the vegetated spaces from their open yards. We observed no differences in the movement ranges of cats by day compared to night. The maximum linear displacement distance, however, was marginally smaller at night compared to that by day. Habitat preference was the same by day and night, with the exception that urban habitat was preferred in cats' night time KUD 95 range.

Table 1: The sex [male (M); female (F)], age (years), days tracked (total consecutive days), the number of fixes (total), the maximum linear displacement distance from home (meters) and the MCP 100, KUD 95 and KUD 50 ranges (ha) for all six cats tracked in the study

Identity	Sex	Age	Days	Fixes	Max. displacement	MCP 100	KUD 95	KUD 50
Cairo	M	12	4	1027	138 m	3.992 ha Area: 79% urban, 21% green Fixes: 95% urban, 5% green JI: 0.615 urban, -0.610 green	1.165 ha Area: 85% urban, 15% green Fixes: 95% urban, 5% green JI: 0.716 urban, -0.716 green	0.127 ha Area: 100% urban, 0% green Fixes: 100% urban, 0% green JI: 1 urban, -1 green
Monty	M	1.5	6	1899	286 m	12.858 ha Area: 80% urban, 20% green Fixes: 99.7% urban, 0.3% green JI: 0.661 urban, -0.662 green	0.695 ha Area: 100% urban, 0% green Fixes: 100% urban, 0% green JI: 1 urban, -1 green	0.021 ha Area: 100% urban, 0% green Fixes: 100% urban, 0% green JI: 1 urban, -1 green
CoCo	F	1.5	7	2319	319 m	11.545 ha Area: 90% urban, 10% green Fixes: 98% urban, 2% green JI: 0.519 urban, -0.512 green	1.943 ha Area: 87% urban, 13% green Fixes: 98% urban, 2% green JI: 0.392 urban, -0.393 green	0.139 ha Area: 100% urban, 0% green Fixes: 100% urban, 0% green JI: 1 urban, -1 green
Daeng	F	3	7	2665	370 m	8.015 ha Area: 80% urban, 20% green Fixes: 96% urban, 4% green JI: -0.246 urban, 0.249 green	2.486 ha Area: 86% urban, 14% green Fixes: 96% urban, 4% green JI: -0.025 urban, 0.008 green	0.192 ha Area: 100% urban, 0% green Fixes: 100% urban, 0% green JI: 1 urban, -1 green
Tess	F	19	6	1321	187 m	2.783 ha Area: 74% urban, 26% green Fixes: 92% urban, 8% green JI: -0.355 urban, 0.355 green	1.298 ha Area: 83% urban, 17% green Fixes: 93% urban, 7% green JI: -0.092 urban, 0.092 green	0.156 ha Area: 100% urban, 0% green Fixes: 100% urban, 0% green JI: 1 urban, -1 green
Tiger	F	12	6	1142	140 m	2.673 ha Area: 74% urban, 26% green Fixes: 79% urban, 21% green JI: -0.354 urban, 0.354 green	1.412 ha Area: 75% urban, 25% green Fixes: 80% urban, 20% green JI: -0.304 urban, 0.322 green	0.244 ha Area: 83% urban, 17% green Fixes: 84% urban, 16% green JI: -0.083 urban, 0.083 green
All cats (mean)	NA	NA	6 (± 0.4)	1729 (± 274)	240 m (± 40)	6.98 ha (± 1.84) Area: 80% (± 2) urban, 20% (± 2) green Fixes: 93% (± 3) urban, 7% (± 3) green JI: 0.14 (± 0.2) urban, -0.14 (± 0.2) green	1.50 ha (± 0.26) Area: 86% (± 3) urban, 14% (± 3) green Fixes: 94% (± 3) urban, 6% (± 3) green JI: 0.28 (± 0.2) urban, -0.28 (± 0.2) green	0.15 ha (± 0.03) Area: 97% (± 3) urban, 3% (± 3) green Fixes: 97% (± 3) urban, 3% (± 3) green JI: 0.82 (± 0.2) urban, -0.82 (± 0.2) green

Also shown are the percentages of the range areas (area) in urban (urban) and vegetated space (green) habitats, the percentage of fixes (fixes) taken in urban and vegetated space habitats, and the Jacobs' index (JI) for habitat preference measures for the MCP 100, KUD 95 and KUD 50 ranges. Results in bold indicate the minimums, maximums and means. Standard errors (\pm) are given for the mean results.

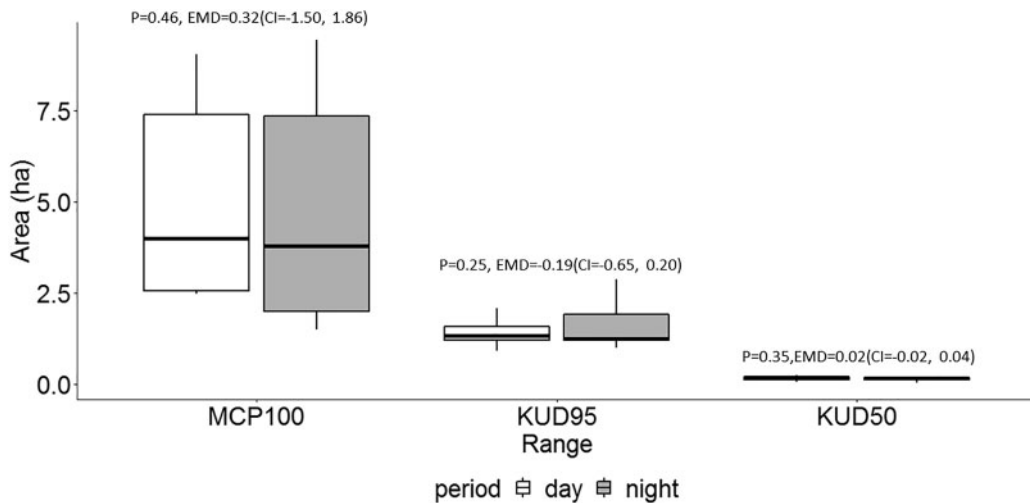


Figure 2: Areas of the MCP 100, KUD 95 and KUD 50 ranges for pet cats, compared across day and night periods. Paired Wilcoxon signed ranks test results comparing the day range area size to the night are given above the boxplots for each range (P-value, the estimated mean difference ‘EMD’ and 95% confidence intervals ‘CI’).

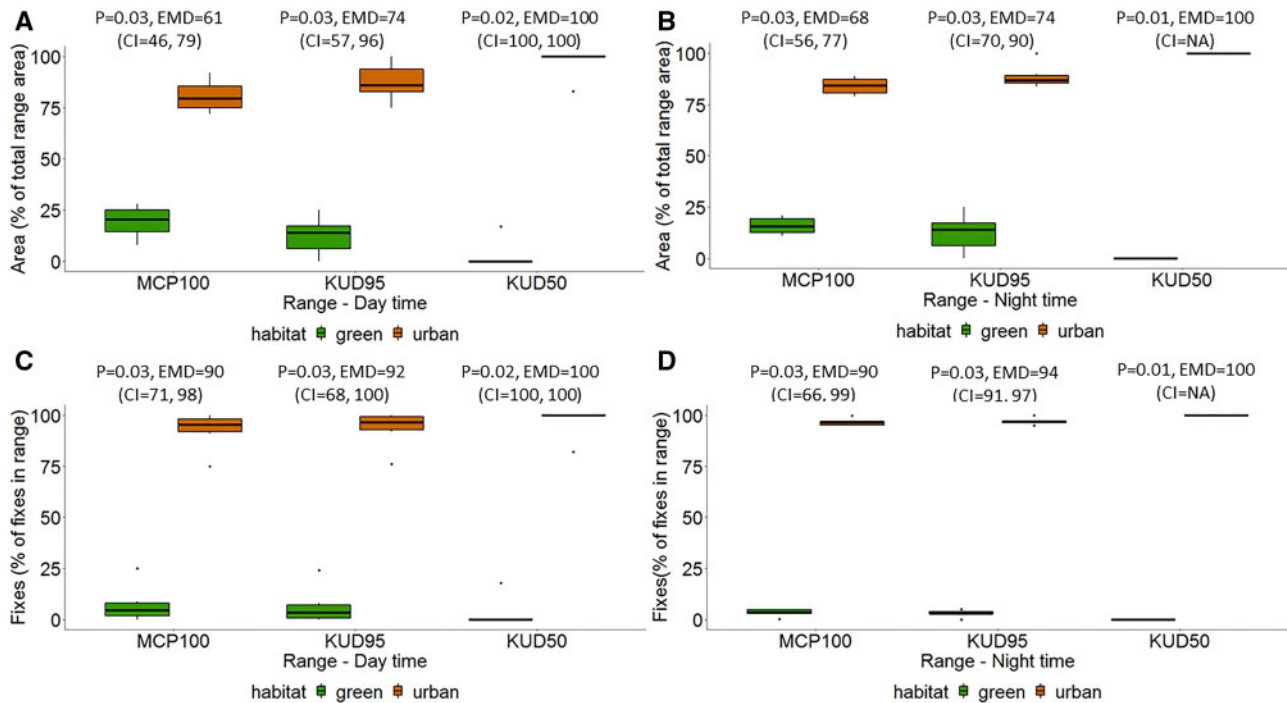


Figure 3: The percentage range area in each habitat type, ‘urban’—including yards and roads and ‘green’—as any green space or nature reserve vegetated area [(A) day time and (B) night time], and the percentage number of fixes taken in each habitat type [(C) day time and (D) night time] for pet cats across their MCP 100, KUD 95 and KUD 50 ranges. Paired Wilcoxon signed ranks test results comparing the ‘green’ to the ‘urban’ measurements are given above the boxplots for each range [P-value, the estimated mean difference ‘EMD’ and 95% (or 60% or NA at the KUD 50 range) confidence intervals ‘CI’].

Movement and range sizes in comparison to other studies

The differences we observed between the MCP 100 and KUD 95 range areas are probably indicative of the sporadic roaming behaviour of cats (Bradshaw, Casey, and Brown 2012) that occurs less frequently than does activity within their home range areas. When considering the definition of cats being ‘wanderers’ if they routinely traverse a range area >1 ha outside of their home, as opposed to being ‘sedentary’ and remaining close to home (Das 1993; Meek 2003; Roetman et al. 2017), then all cats in our study, except Monty, met the wanderer criterion. Monty,

a 1.5-year-old male cat, had the smallest KUD 95 and KUD 50 range areas, and hence would not fit the definition of a wanderer, but as Monty had the largest MCP 100 range area this may be indicative of a different behaviour pattern that includes fewer infrequent roaming events across long distances. In considering age as a possible driver for range differences, the youngest three cats roamed the furthest across their MCP 100 ranges, whilst the older three cats retained similar area sizes at this range. However, it is worth noting that the older cats in our study still kept MCP 100 ranges larger than what may be

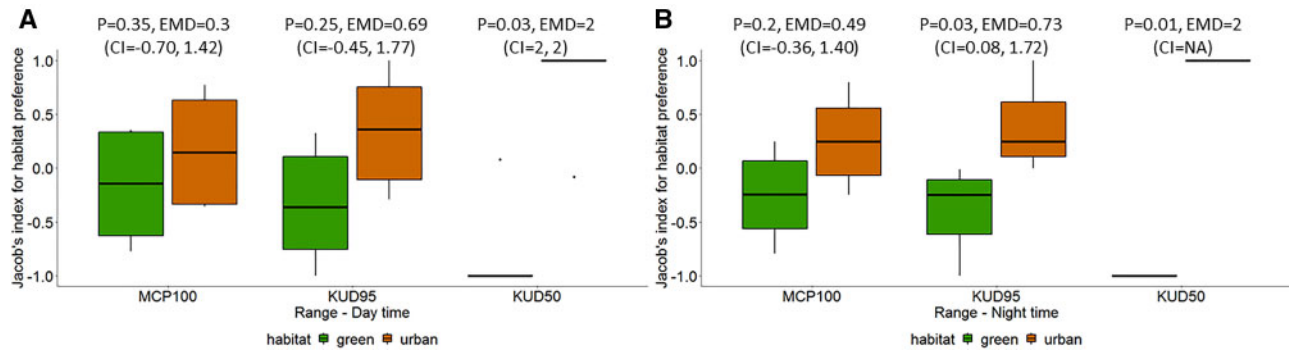


Figure 4: Jacobs' index showing preferences for each habitat type, 'urban'—including yards and roads and 'green'—as any green space or nature reserve vegetated area [(A) day time and (B) night time], across the MCP 100, KUD 95 and KUD 50 ranges for pet cats. Paired Wilcoxon signed ranks test results comparing 'green' with 'urban' habitat index values are given above the boxplots for each range [P-value, the estimated mean difference 'EMD' and 95% (or 60% or NA at the KUD 50 range) confidence intervals 'CI'].

expected for their age (12–19 years: 2.7–4.0 ha). At the KUD 95 range level, one of the youngest cats retained the largest area whilst the other young cat retained the smallest area. There was no discernible pattern at the KUD 50 range, with one of the older cats traversing the largest observed area and one of the youngest traversing the smallest. These variable results may be due in part to personality differences, as suggested by Barratt (1997a), which may also be influenced by age and experience (Zablocki-Thomas et al. 2018).

The pet cats in our study generally occupied larger ranges at the KUD 95 level than in most previous work undertaken on pet cats in other low–medium-density housing areas in Australia (Barratt 1997a; Meek 2003; Liliith, Calver, and Garkaklis 2008; Heenan and Low 2017; Roetman et al. 2017). However, there were some exceptions where individual cats, but not the mean/median, occupied even larger ranges than in our study [three 'suburban cats' by Barratt (1997a); two 'urban-forest-fringe cats' by Meek (2003); and two 'rural cats' by Liliith, Calver, and Garkaklis (2008)]. In comparison to global studies, the KUD 95 ranges we observed were similar to those of other urban dwelling pet cats (Hanmer, Thomas, and Fellowes 2017; Kikillus et al. 2017), but smaller than others ['rural/urban-forest fringe cats' by Metsers, Seddon, and van Heezik (2010) and 'urban cats' by Thomas, Baker, and Fellowes (2014)], and larger than other forest-adjacent-urban dwelling cats (Kays and DeWan 2004). A similar pattern was evident in comparisons of the MCP 100 ranges. Our whole range areas were larger than most previous work undertaken on pet cats in Australia, but again showed individual differences with only several cats having larger ranges [two 'suburban cats' by Barratt (1997a); three 'urban-forest-fringe cats' by Meek (2003); and Liliith, Calver, and Garkaklis (2008)]. They were, however, almost half the size of the mean MCP 100 range in the Northern Territory (Heenan and Low 2017). The relatively large ranges covered by our cats may reflect the small sample size. More likely, however, it probably represents fewer boundaries for our cats to traverse from their homes, a conclusion supported by natural barriers (Dickman 1992; Burbidge and Manly 2002) and cat exclusion fences (Moseby and Read 2006; Robley et al. 2007) restricting feral cat movements. This explanation may also hold in the Northern Territory study, where cats likely had few boundaries and larger distances to traverse in the lightly populated arid area where they were studied. Furthermore, as personality and experience influence behaviour (Barratt 1997a), it is also likely to be the reason for variances observed in the maximum displacement distances across comparable studies.

Our maximum displacement distance results add to a diverse dataset obtained on Australian pet cats. Our results were similar to observations made on the south coast of New South Wales (Meek 2003), but were 23% larger than observations from Western Australia (Liliith, Calver, and Garkaklis 2008) and 6% larger than data from the Australian Capital Territory (Barratt 1997a) for 'farm' dwelling cats. However, our results are 61% smaller than Barratt's (1997a) findings for 'urban' dwelling cats, and 26% smaller than those from the arid Northern Territory (Heenan and Low 2017). When compared to a similar UK-based study, the maximum displacement distance that we observed was twice the size (Hanmer, Thomas, and Fellowes 2017). The maximum displacement distances from home that we observed were significantly, but marginally, larger by day than by night, but the range sizes did not differ at night compared to day for each of the cats individually or as a group. This finding contrasts with some previous research that has observed larger ranges at night compared to the day (Barratt 1997a; Metsers, Seddon, and van Heezik 2010; Thomas, Baker, and Fellowes 2014; Roetman et al. 2017), but supports other research that has reported no day vs night differences (van Heezik et al. 2010; Hanmer, Thomas, and Fellowes 2017; Heenan and Low 2017; Kikillus et al. 2017). Such temporal differences may be attributed to prey, competitor and/or predator species active periods relevant to each area, as well as human activity levels (Brook, Johnson, and Ritchie 2012; Bogdan, Jünek, and Vymyslická 2016; Cunningham, Johnson, and Jones 2020).

Habitat use: when vegetated spaces surround the urban environment

Similar to the estimates of range size, use of different habitat types did not differ between night and day. All cats that we observed frequented urban habitats over vegetated spaces, across all range areas and time periods. However, there was more vegetated space habitat in all but one cat's MCP 100 range area compared to that in their KUD 95 range area, indicating that forays in vegetated space habitats occurred regularly but not routinely enough to feature in their weekly KUD 95 range. Cairo and Monty had the most vegetated space habitats available to them in the 370 m radius area, followed by CoCo, then by Daeng, Tess and Tiger. The latter three utilized vegetated space the most, despite having <1/3 of that potentially available to the other cats. This may reflect that Daeng, Tess and Tiger had easier access to vegetated space habitats via corridors connected to their fenceless backyards, whereas the other cats

were more restricted by physical or behavioural barriers such as fences, roads or other cats or dogs. At the KUD 50 range, five cats showed a preference for urban habitats. At the MCP 100 and KUD 95 ranges three of the cats preferred urban habitats, and the other three showed little selection or a slight preference towards vegetated space habitats.

When combined, there was no significant habitat type preference across the cats' ranges or time periods, except for the night time KUD 95 range, when cats favoured urban habitats. This may be due to the vegetated space habitats being colder at night (Gartland 2012); the attention/food that cats may get from people at these hours (Meek 2003); attraction/avoidance to other cats in the area (Bradshaw, Casey, and Brown 2012); or even aversion to the nocturnally active top predator in the neighbouring vegetated spaces—the powerful owl (*Ninox strenua*) that has been observed to include domestic cats in its diet (Chafer 1992), or avoidance of the largely nocturnal intraguild mesopredator—the red fox (Ferreira et al. 2011). Similar studies have found that pet cats in urban areas adjacent to large vegetated spaces (such as national parks or conservation areas) are generally more active at the edge of these areas than deeper within, despite their proximity and hunting possibilities for cats (Oehler and Litvaitis 1996; Crooks 2002; Meek 2003; Kays and DeWan 2004). It is unknown if this is a general pattern or depends on environmental conditions, possible boundaries to the vegetated spaces or influences from predators, competitors, prey or human activity.

Management applications

Ranges, use of habitat types and percentage of time spent in their house are accessible ways to demonstrate to pet cat owners the movement patterns of their cats. The results may be surprising to owners who believe their cat moves mostly close to home in urban areas, i.e. in the KUD 50 range only, or spends most time in their house. Showing that their cats wander much further and possibly more frequently than they think could assist in gaining support for stronger cat management (e.g. Roetman et al. 2017). Our research illuminated that the observed pet cats spent most of their time out of their house in urban areas, and in vegetated spaces to a lesser degree, which demonstrates the dire need for mitigation, given the conservation value of urban areas in patchy vegetated environments. The movements of pet cats often vary within and across studies (Hall et al. 2016b), perhaps suggesting that differences are geographically or personality/experience-dependent (Bradshaw, Casey, and Brown 2012). Personality may be difficult to test, but future site-specific studies that investigate behavioural and physical boundaries to mitigate domestic cat range expansion may be effective, where time and funding permits. Still, containment indoors with possible controlled outings on a lead or in enclosed run cages remains the most efficient way to reduce the threat to wildlife that wandering pet cats pose (Legge et al. 2020a), but it requires the support of owners who may be reluctant to do so.

Patchy urban areas with vegetated spaces are often hotspots of wildlife activity (Ives et al. 2016; Weller, Hoch, and Huang 2017), and as such encounters between pet cats and native wildlife are likely to be more frequent than currently understood. Based on our findings, effective buffer zones for cat containment could be applied to properties within a 600-m radius of any vegetated space habitat (our furthest displacement distance + 61% to account for the largest difference between our study and that in a comparative study). Such restrictions would help

to maintain wildlife and also reduce the risks to pet cats of encountering larger predators and other hazards. Informing people on pet cat movements and implications for cat safety and the persistence of local wildlife may be the best way for mitigation efforts to progress (MacDonald, Milfont, and Gavin 2015; Linklater et al. 2019; Legge et al. 2020a). A public selling point that piqued the interest of the cat owners in our study was that containment reduces the risk of pet cats encountering native predators, such as powerful owls that occur throughout vegetated spaces and hunt in urban and urban edge areas in southeastern and eastern Australian cities (Pavey, Smyth, and Mathieson 1994; McAllan and Larkins 2016; Carter et al. 2019).

Supplementary data

Supplementary data are available at JUECOL online.

Data availability

The tracking data are available online in the repository at zoa-track.org. Supplementary Materials are available at JUECOL online.

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