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Research Paper

Forest specialist species in the urban landscape: Do different levels of urbanization affect the movements of Forest Red-tailed Black Cockatoos (*Calyptorhynchus banksii naso*)?

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ABSTRACT. Anthropogenic landscape modification which leads to the displacement of species, is arguably one of the most profound impacts on animal movement globally. In urban landscapes, animal movement is generally impacted by varying levels of increased urbanization. However, this is species dependent and is mostly guided by the surrounding habitat. Fragmentation and habitat patch isolation must be considered at scales appropriate to the study species. Using telemetry, we test these assumptions investigating movement patterns of flocks of Forest Red-tailed Black Cockatoos (*Calyptorhynchus banksii naso*; RTBC) between three regions: urban, peri-urban, and forest using GPS and satellite PTT. This species occurs at varying levels of urbanization, however, how this might affect its movements is largely unknown. We did not find evidence that RTBC movement was impaired in the urban region compared with peri-urban or forest regions. It found, however, a significant within-region variation in movement extent among flocks and across regions depending on foraging resource availability and location. Differences in daily movement distance (Av. 4.96 - 16.41 km) and home range size (6.02 - 52.57 km²) between urban flocks appeared to be associated with the proximity of green spaces as roosts and foraging sites, with roadside vegetation providing important foraging resources and movement corridors. Key urban habitats were predominantly located in public nature reserves and private properties, with roadside vegetation connecting these sites for RTBC. The findings of this study highlight that conservation management for this and many other threatened species should regard the urban landscape as a critical habitat for urban adapted species. This would include management of its green spaces with connectivity and offsets from roads in mind. Furthermore, future research should focus on identifying additional key habitat sites (resource selection) and species distribution modeling, which will facilitate an active and adaptive approach towards this species' conservation management.

Espèces spécialistes de la forêt en paysage urbain : les divers degrés d'urbanisation affectent-ils les déplacements du Cacatoès banksien (*Calyptorhynchus banksii naso*)?

RÉSUMÉ. Les modifications anthropiques du paysage, qui entraînent le déplacement des espèces, représentent sans doute l'un des impacts les plus néfastes sur les déplacements des animaux dans le monde. En paysage urbain, les déplacements des animaux sont généralement affectés par des degrés variables d'urbanisation galopante. Cependant, ce phénomène dépend des espèces et est principalement guidé par l'habitat environnant. La fragmentation et l'isolement des parcelles d'habitat doivent être pris en compte à des échelles appropriées à l'espèce étudiée. Au moyen de la télémétrie, nous avons testé ces hypothèses en examinant les schémas de déplacement de groupes de Cacatoès banksiens (*Calyptorhynchus banksii naso*) entre trois régions : urbaine, périurbaine et forestière, en utilisant le GPS et des émetteurs satellitaires. Cette espèce est présente à divers degrés d'urbanisation, mais la manière dont cela peut affecter ses déplacements est largement inconnue. D'après nos données, les déplacements du cacatoès n'étaient pas restreints en région urbaine par rapport aux régions périurbaines ou forestières. Nous avons cependant constaté, au sein d'une même région, une variation significative de l'étendue des déplacements entre les groupes et pour toutes les régions, selon la disponibilité et la localisation des ressources alimentaires. Les différences de la distance de déplacement quotidien (moyenne = 4,96 - 16,41 km) et de la taille du domaine vital (6,02 - 52,57 km²) entre les groupes urbains semblent être associées à la proximité d'espaces verts comme dortoirs et sites de recherche de nourriture, la végétation en bordure de route fournissant d'importants lieux de quête de nourriture et des corridors de déplacement. Les habitats urbains clés étaient principalement situés dans des réserves naturelles publiques et sur des propriétés privées, la végétation en bordure de route permettant de relier ces sites pour le cacatoès. Les résultats de la présente étude soulignent que la gestion de la conservation de cette espèce et de nombreuses autres espèces menacées devrait considérer le paysage urbain comme un habitat essentiel pour les espèces adaptées à la ville. Ainsi, la gestion des espaces verts devrait tenir compte de la connectivité

et de compensations pour les routes. De plus, de futures recherches devraient se pencher sur l'identification de sites d'habitats clés supplémentaires (sélection de ressources) et la modélisation de la répartition de l'espèce, ce qui facilitera une approche active et adaptative de la gestion de la conservation de cette espèce.

Key Words: ARGOS; *Calyptorhynchus banksii naso*; forest red-tailed black cockatoos; GPS; movement ecology; roadside vegetation; telemetry; urban ecology

INTRODUCTION

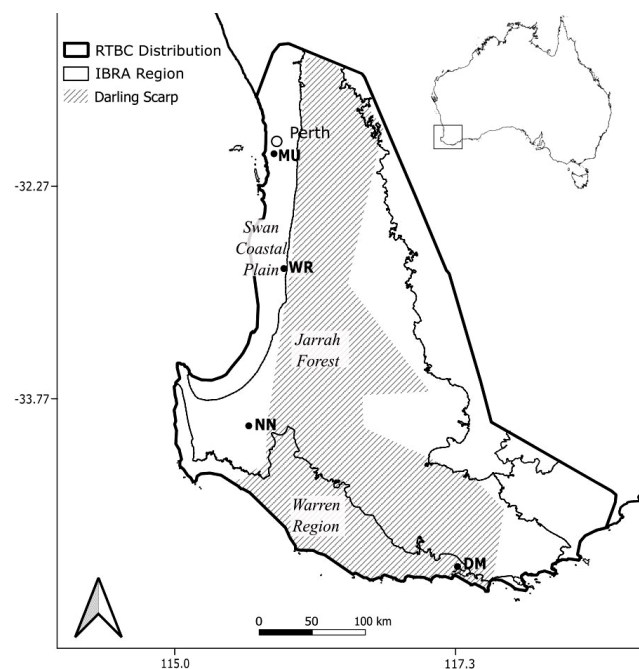
Urbanization is arguably one of the most profound factors impacting the behavior of a vast variety of species (Stenhouse 2004, McKinney 2008, Davis et al. 2013). In fact, high biodiversity hotspots across the world are often situated in densely populated and rapidly urbanizing areas (Miller and Hobbs 2002, Petersen et al. 2020). The level of urban adaptation in a species is attributed to the species' biology, their behavior, and environmental factors (Olah et al. 2016). While certain species are abundant at highly urban sites, other species fare better at intermediate levels of urban modification, with these regions typically being dominated by a small number of species with very low spatial variation (Blair 2001, Marzluff 2001, Jokimäki and Kaisanlahti-Jokimäki 2003). Several studies on the effects of urbanization have shown that although the urban environment can negatively influence an animal's movements, it can prove to be beneficial to certain species, provided they show behavioral flexibility. Major urban adaptations include shifting home range sizes, changing foraging behavior and time (Lewis et al. 2015, Adducci et al. 2020), reduced mobility associated with higher site fidelity (Fuirst et al. 2018, Teitelbaum et al. 2020), and predator evasion (Rebolo-Ifrán et al. 2017). In addition, smaller, less mobile species are able to live within the urban landscape provided connectivity exists between habitat patches (Rees et al. 2009, Moule et al. 2016).

For bird species, generalist foragers are better able to cope with urban pressures than specialists, resulting in globally homogenic urban populations of mostly synanthropic species (McKinney 2006, Bonier et al. 2007, Sorace and Gustin 2009). Successful urban-adapted birds are generally species that can disperse between fragmented habitat, adapt to novel food sources, are gregarious, feed on plants and seeds, nest above the ground, and have a larger brain size (Carrete and Tella 2011, Evans et al. 2011). Although birds can easily "cross the gap" between habitat patches, habitat generalists tend to move less within urban landscapes due to availability of reliable and diverse food sources (Teitelbaum et al. 2020). This reduced mobility alongside loss of connectivity within the urban landscape results in a negative correlation between animal movement and increasing levels of urbanization (Bélisle et al. 2001, Tucker et al. 2018, O'Donnell and delBarco-Trillo 2020). Although habitat patch composition in the urban matrix influences the movement of birds, habitat configuration is equally important as isolation is more likely to occur with increased distance between patches (Fahrig 2003, Ricketts 2001, Dale 2018). It is therefore important to study human modified landscapes at different scales to gain an understanding of how different degrees of urbanization influence avian movement and their persistence within the urban setting (Ricketts 2001, Melles et al. 2003, Petersen et al. 2020). (Garden et al. 2006, McIntyre et al. 2008, Evans et al. 2010).

In Australia, urban development is increasing, spreading inland from coastal regions (Garden et al. 2006). As a result, Australian cities are known to support more threatened animal and plant

species than any area in the country. In Western Australia, the landscape has been intensively modified and cleared since the first settlements in 1829 (How and Dell 2000). Given that the southwestern Australian ecoregion is recognized as a biodiversity hotspot, this has led to high numbers of endemic flora and fauna being formally recognized as endangered (McKenzie et al. 2003, Gole 2006, Davis et al. 2013). Previous studies in this part of Australia have predominantly looked at the effects of the expansion of Western Australia's wheat belt, however, the impacts of urbanization on birds are relatively understudied (Davis et al. 2013). The Forest Red-tailed Black Cockatoo (*Calyptorhynchus banksii naso*; RTBC), a threatened species endemic to Western Australia, has only recently expanded its range to include the Swan Coastal Plain (SCP; Fig. 1) and now occurs in the urban landscape throughout the year (Cooper et al. 2003, Department of Environment and Conservation 2008, Johnstone et al. 2013). As recently as the 1980s RTBC's were considered a rare and seasonal (May to November) visitor to the eastern SCP (Johnstone et al. 2018), however, in 2019 the annual Birdlife Australia Great Cocky Count recorded 3499 birds on the highly urbanized coastal plain, a six-fold increase from 601 birds counted

Fig. 1. Distribution of Forest Red-tailed Black Cockatoos (*Calyptorhynchus banksii naso*) in Western Australia relative to the Swan Coastal Plain, the Darling Scarp, and the release sites: Murdoch (MU), Waroona (WR), Nannup (NN) and Denmark (DM) (IBRA regions, Department of Environment and Energy 2019).



in 2014 (Peck et al. 2019). Forest clearing is suggested as contributing to increased numbers on the plain, as the species' distribution is predominantly associated with jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) forests, as is the presence of native and non-native food species such as cape lilac (*Melia azedarah*) (Johnstone et al. 2013, Lee et al. 2013, Johnstone et al. 2018). On the SCP, RTBC move in small family groups or large flocks, depending on the time of year, and are not confined to single communal roost sites but shift between roosts in which they spend variable lengths of time as they move through the landscape following food resources (Johnstone et al. 2013). Although this forest specialist species has adapted to forage on different food sources and move within the urban landscape, the population has experienced a steady decline over the last 60 years, with the current population estimated at 15,000 individuals (Weerheim 2008).

Although the urban landscape has become an integral part of the habitat for RTBC and many other threatened species in Australia, conservation management at the government level advocates for the protection of the existing natural environment which does not include areas that are highly modified and fragmented (Ives et al. 2016). While urban environments comprise both negative and positive elements influencing a species' ecology, it is worthwhile considering these sites in the overall biodiversity conservation scheme and not to hastily disregard habitat deemed compromised due to its location within the urban matrix (Ricketts 2001, Ives et al. 2016, Rebolo-Ifrán et al. 2017). Miller and Hobbs (2002) suggested that in order to effectively plan for conservation outcomes it is important to take areas with varying degrees of human modification into account. In addition, research at multiple spatial scales is regarded as more beneficial in developing conservation guidelines as it creates a more complete picture of how species are affected by different modified landscapes (Fischer and Lindenmayer 2006). Here we investigate movement patterns of flocks of RTBC over three regions of varying human development: Urban, Peri-urban, and Forest using satellite PTT and GPS transmitters. We expect that RTBC movements will be restricted in urban regions evidenced by shorter distances between night roosts, shorter daily flight distances, and smaller home range sizes compared to Peri-urban or Forest regions. In addition, as connectivity within the urban landscape determines the viability of suitable habitat for birds (Aouissi et al. 2021) and can be dependent on a single green space to maintain its integrity (Dearborn and Kark 2010), this research aimed to identify key habitat within the urban matrix and the use of green corridors to travel between these. Furthermore, this research focused on the use of roadside vegetation as habitat for RTBC and whether this differed between Urban and Peri-urban regions since roads containing vegetation are known to provide corridors between habitat (Fernández-Juricic 2000, Beaugeard et al. 2021, Radford et al. 2021). Roadside vegetation is commonly used by RTBC within urban areas, but is associated with vehicle strikes which constitutes a major threat to the species (Le Souëf et al. 2015).

STUDY AREA

This study was conducted over three bioregions: Swan Coastal Plain, Jarrah Forest, and Warren in Western Australia between 2015 and 2017 (Department of Environment and Energy 2019), the latter regions being predominantly forested (Fig. 1). Tracked

birds were released into wild flocks at four different sites, Murdoch (-32.06° S, 115.83° E), Waroona (-32.79° S, 116.01° E), Nannup (-33.98° S, 115.73° E), and Denmark (-34.96° S, 117.21° E) (Fig. 1). The SCP had been extensively cleared for urban and agricultural development of which the Perth metropolitan area (-31.928S, 115.878E; 6418 km²) comprises approximately 20% (Mitchell et al. 2002). Based on data from the Australian Bureau of Statistics (2020), Perth's population is approximately 2.65 million with a recorded growth rate of 0.9% to 9.58% over the last eight years.

The Swan Coastal Plain comprises highly fragmented but diverse remnant vegetation, including wetlands, heathlands, and banksia woodlands (*Banksia* spp.), with the majority close to sea level and most woodland comprising tall *Eucalyptus* spp. in the east as part of the Darling Range (elevation 582 m) (Mitchell et al. 2002). Most of the larger remnant vegetation patches occur at the Peri-urban fringe of the metropolitan area with smaller areas with low connectivity occurring within the urban landscape (Stenhouse 2004, Davis et al. 2013).

The Jarrah Forest bioregion borders the SCP to the east and consists primarily of reserves for recreational use, forestry water catchment management, and mineral production with tall jarrah forest as its main ecosystem (Mitchell et al. 2001). The Warren bioregion lies south of the Jarrah Forest bioregion along the south coast and includes karri (*E. diversicolor*) and other large eucalypt species with coastal areas consisting of jarrah, marri, and banksia coastal heath (World Wildlife Fund 2007). These regions have a Mediterranean climate with a summer period in December-February and a winter period in June-August, a mean annual rainfall of 959.7 mm and mean annual temperatures ranging from 11.6°-21.8°C (Australian Bureau of Meteorology 2020).

METHODS

Tag attachment and scheduling

We released 14 RTBC into wild flocks of conspecifics, 12 of which were tagged with both ARGOS Satellite PTT and GPS units and two with ARGOS PTT only (Appendix 1, Table A1). The tagged birds were wild birds that had been admitted to the Perth Zoo Veterinary Department having sustained injuries on the SCP. Increasing numbers of birds are injured on the SCP each year (Le Souëf et al. 2015) associated with anthropogenic factors, particularly collisions with vehicles and trains. After receiving treatment, they were rehabilitated at the Kaarakin Black Cockatoo Conservation Center and passed as fit for release by the Western Australian Department of Biodiversity, Conservation, and Attractions. As the point of capture is the SCP we have no knowledge of whether birds were resident on the plain or seasonal visitors, however, previous studies on satellite-tagged black cockatoos in Western Australia using rehabilitated wild birds have shown that birds successfully reintegrate into wild flocks on release (Le Souëf et al. 2013, Yeap et al. 2015, Groom et al. 2017) and follow the movement of the flock they have joined (Rycken et al. 2019). Birds were therefore released at three different release sites within their distribution (Gingin, Albany, and Esperance). All birds in this study were confirmed to have integrated into a wild flock of Carnaby's cockatoos and followed the movement patterns of that flock.

Telonics ARGOS Satellite PTT tags (TAV-2617) were attached ventrally to the two central tail feathers using nylon fishing line (Fireline®, Berkley®, Spirit Lake, IA, USA) and the GPS tags (Bouten et al. 2013; UvA-BiTS, Amsterdam, The Netherlands; 2CDSe) were glued and tied to a backing plate which was taped with cloth tape to several feathers between the shoulder joints (Yeap et al. 2017, Rycken 2019). Attachment of the tags was considered to be within the ethical threshold of less than 5% of the body mass (Cochran 1980, Kenward 2001), as the combined mass of both tags averaged between 3.4% to 4.4% of the total body mass for all research birds, and birds either molted or removed tags after a period of time (5 - 406 days in this study). Procedures were undertaken in accordance with the Department of Biodiversity, Conservation, and Attractions, Regulation 17 License number SF010448, the Murdoch University Animal Ethics Permit (RW2768/15), and Australian Bird and Bat Banding Scheme banding authority number 1862.

We programmed the ARGOS PTT tags to enable location of night roosts of wild flocks of RTBC and to allow manual data downloads from the GPS tags at the roost site using a base station antenna. The ARGOS PTT tag's schedule was programmed to communicate at night (2000 hours - 2400 hours) to facilitate data downloads for the GPS tags, with morning communication periods (0600 hours - 1000 hours) at regular intervals to enable flock follows to be conducted using an ARGOS AL-1 PTT Locator. The initial two weeks post-release consisted of daily communication to maximize the ability of downloading GPS data, as trials had shown that birds were more likely to remove their GPS tags during the first two weeks. The solar powered GPS tags were programmed to communicate every ten minutes and collect data at a frequency of every 15 minutes (accuracy $\pm$ 20m) between 0530 hours - 1830 hours and 30 minutes (max. time interval) between 1830 hours - 0530 hours. In case of an energy surplus the tag was set to collect locations every 2.5 minutes.

In addition to telemetry, flock follows were conducted to confirm flock integration, record flock size estimates through direct observation, and to record foraging or roosting activity as well as food species being eaten, and the presence of water sources.

Data analysis

Data collected from ARGOS PTT and GPS (error approx. $\leq$ 4 m) were examined for accuracy, and only PTT location fixes with an error less than 500 m were used. Any erroneous locations for both GPS and satellite PTT were removed from analysis. In addition, we only used data from birds that had integrated into a flock, which was confirmed through either visual confirmation or Behavioral Change Point Analysis (Gurarie et al. 2009) using the method of Rycken et al. (2019). Behavioral Change Point Analysis uses a combination of mean, standard deviation, and autocorrelation of the calculated velocity and turning angles of a movement trajectory to identify change points in an animal's movement (Gurarie et al. 2009, 2016, Nilsson 2014). This analysis has proved to be able to assess between different movement behavioral modes in black cockatoos and to determine whether an individual is showing flock movement and is therefore integrated into a wild flock (Rycken et al. 2019).

To determine whether a flock showed daily movement behavior between roosts and foraging sites within one area or whether it

showed ranging movement toward a different area we identified three movement types using the telemetry data: resident movement, ranging movement, and landscape-scale ranging movement. These movement types and their characteristics were defined through exploration of mean distances traveled to any direction within and between resident home ranges. We defined *resident movement* as all daily activities such as foraging and roosting within a home range. *Ranging movements* were defined as unidirectional movements exceeding 10 km from the center of a home range. *Landscape-scale ranging movements* usually identified from the long-term ARGOS PTT data were defined as accumulated ranging movements, including stopover sites, with a total distance exceeding 50 km. We distinguished between these movements occurring in different regions classified as Urban, Peri-urban, and Forest regions. Regions were categorized as Urban if they possessed continuous settlements within a distance of fewer than 200 m between buildings as per Hedblom and Söderström (2010). Peri-urban regions were defined as regions that displayed a mixture of fragmented urban and rural landscapes (Jaquinta and Drescher 2000). Forest regions comprised mainly forest habitat, which was generally classified as state forest, national parks, or nature reserves. Roost sites for RTBC were defined as sites consisting of one or more roost trees within a 500 m radius in Urban or Peri-urban regions, or a 1 km radius in a Forest region where, depending on flock size, core roosts could be surrounded by a number of satellite roosts in close proximity (Glossop et al. 2011).

Using GPS data further movement analysis for the three regions looked at the average distances between roosts in a resident area using the satellite PTT data (Table 1); and the daily movement distances of flocks measured as the sum of all Euclidian steps of a movement track between sunrise and sunset to and from the roost (Table 2). Both the daily movements of flocks in a region and the distances between different roosts within a resident area in a region were calculated for their pairwise averages in the "sp" package (Pebesma and Bivand 2005) in R (version 3.5.3; R Core Team 2019). Distances between roosts and daily distances traveled were then tested for differences between regions, and between tagged birds within a region using a linear mixed-effects model (LME) model in R. LME models were selected for analysis to account for irregularity and non-independence of both of these data sets (Galecki and Burzykowski 2013); and region was used as the fixed effect and bird ID as the random effect to determine differences in flock movement (distance traveled) between regions. Additionally, we analyzed for differences in flock movement within the same region using bird ID as the fixed effect.

GPS data was used to determine key foraging habitat and key roosting sites using the "recurse" package (Bracis et al. 2018) which analyzes revisitation rates to sites using a preset radius. The choice of radii for foraging habitat in each region was made through exploration of the median values in step length (Bracis et al. 2018). To accurately capture revisitation, a threshold of one hour was set to account for the species' foraging behavior and the GPS tag's intensive recording schedule. This allowed the bird to leave the circle and return within a 60-minute period without the revisit being counted and also catered for small excursions due to disturbance or flushing. Foraging behavior was confirmed through the revisitation analysis, flock follows, and the species' daily movement ecology (RTBC are known to have a midday

Table 1. Movement metrics using ARGOS PTT data for Forest Red-tailed Black Cockatoos (*Calyptorhynchus banksii naso*) in Urban, Peri-urban, and Forest regions in Western Australia. Areas of resident movement (R) are numbered sequentially as flocked tagged birds made ranging movements (> 10 km) between them. Collectively a series of ranging movements exceeding 50 km was considered landscape-scale ranging movement. All flocks were single species RTBC flocks. Areas of resident movement generally contained multiple night roosts (Roosts in Area [N]).

ARGOS PTT data										
RTBC ID	Resident movement Area	No. reloc	Date. begin	Date. end	Area type	Flock Size	Distance to next resident movement area (km).	Days in area	Roosts in area (N)	Av. Dist between roosts (km)
96	R1	47	26/08/2015	11/09/2015	Urban	<50	10.02 to R2	16	5	1.37
	R2	71	22/09/2015	7/04/2016	Peri-urban	>70	-	199	12	1.18
97	R1	55	26/08/2015	9/10/2015	Urban	<50	-	44	7	2.95
98	R1	33	26/08/2015	22/10/2015	Urban	<30	40.24 to R2	58	7	2.84
	R2	11	6/11/2015	7/04/2016	Peri-urban	>70	-	153	6	4.13
99	R1	69	26/08/2015	3/11/2015	Urban	50	33.67 to R2	69	5	2.07
	R2	18	8/12/2015	8/04/2016	Peri-urban	>50	-	122	3	1.01
66	-	8	5/11/2016	7/11/2016	Forest	<100	-	4	2	9.28
67	R1	48	4/11/2016	18/01/2017	Forest	100	11.00 to R1	75	7	1.48
68	-	14	5/11/2016	7/11/2016	Forest	>100	-	5	1	-
69	R1	177	4/11/2016	16/08/2017	Forest	50	9.75 to R2	91	21	10.54
	R2	20	13/09/2017	14/12/2017	Peri-urban	50	13.24 to R1 31.19 to R2	32	5	5.98
56	-	2	8/06/2017	9/06/2017	Forest	<50	26.60 to R1	1	1	-
	R1	49	11/06/2017	5/08/2017	Forest	20	47.99 to R2	55	4	2.83
	R2	24	17/08/2017	21/12/2017	Forest	30	50.10 to R3	126	3	2.27
	R3	9	19/01/2018	19/02/2018	Forest	50	63.83 to R4	31	3	3.06
	R4	8	20/03/2018	21/05/2018	Forest	50	-	62	2	2.29
6166	R1	11	5/08/2017	19/08/2017	Peri-urban	<50	3.11 to R2	14	1	-
	R2	16	19/08/2017	22/10/2017	Forest	100	-	64	1	-
75	R1	119	21/09/2017	4/02/2018	Peri-urban	50	-	146	13	5.23
82	R1	50	23/09/2017	8/10/2017	Peri-urban	>100	55.95 to R2	15	9	6.53

roosting period which would on average last from 10 AM to 12 PM depending on temperature). Roost sites were determined by grouping all first occurrences after sunset when flight speed dropped to 1 m/s and within a radius of 500 m or 1 km if within forest. Key foraging sites had ≥ 5 visitations and key roost sites ≥ 10 visits. Both rates were in the 3rd quartile for all revisitation data. In addition, we used the GPS data to calculate home ranges for three flocks in the Urban region and one in the Peri-urban region using a continuous time movement approach applying the Ornstein-Uhlenbeck F (OUF) model (ctmm - Calabrese et al. 2016). This method can only be applied to resident movement data and calculates home range (HR) using a kernel density estimation that considers autocorrelation for both position and velocity and provides a bandwidth by correcting for area estimate bias (Fleming and Calabrese 2017). Home range was not calculated in forest areas using this method as we did not have GPS data.

To investigate the proportion of roadside vegetation used between the urban areas, we calculated the occurrence of foraging data proximal to the nearest road by using the GPS data in combination with a shapefile of the Western Australian road network (Western Australian Government 2020) and analyzing it using “rgeos” (Bivand et al. 2018). Percentages of foraging data within 10 m, 20 m, 50 m, and 100 m of any road for the Urban and Peri-urban region were then compared for individual flocks and for region using a Pearson’s Chi-squared test in R.

RESULTS

Data collected over the four release events between 2015 and 2017 comprised more than 1248 km of satellite track data (N = 952;

retention time up to 407 days) and 1644 km of GPS track data (n = 18,350; retention time up to 73 days; Appendix 1, Table A1). A total of 93 hours of flock follow observations were conducted across all three regions.

Comparative movement analysis for the three regions

Urban region

Analysis of the ARGOS PTT data showed that RTBC96, RTBC98, and RTBC99 released at Murdoch University in August 2015 joined three different flocks all of which made ranging movements toward the Peri-urban region at the base of the Darling Scarp in mid-September to early November (Fig. 2a and b). Daily movement data within the Urban region, through GPS data analysis, demonstrated that RTBC98’s flock (N $\approx$ 30) traveled significantly further than the other flocks (LME, $n = 117$, $P < 0.001$), averaging 16.41 km/day, and traveling over 20 km/day on several occasions, and up to 38 km/day at least once during the tracking period (Table 2). RTBC99’s Urban flock (N $\approx$ 50) traveled less on average (8.53 km/day) but also showed several 20 km daily movements (Table 2).

Peri-urban region

We recorded GPS data for one flock (N $\approx$ 70) in the Peri-urban region which traveled on average 7.5 km daily and did not exceed a maximum daily movement of 12.43 km during the 50 days the bird (RTBC96) was tracked in the area (Table 2). All the flocks for the Murdoch release recorded in this region moved between the Peri-urban area and the forested areas of the Darling Scarp during the months of December 2015 and April 2016 (Fig. 2a-c).

Table 2. Daily movement (GPS) and flock sizes for the Forest Red-tailed Black Cockatoos (*Calyptorhynchus banksii naso*) in their resident movement areas (Area [R]) in Western Australia in 2015. “Nb. reloc” represents the number of relocations between beginning and end of the dataset for the area; “Distance travelled in area (km)” represents the minimum distance traveled in the area during the time period of the dataset for the area; “Av. Daily Dist.(km)” represents the average distance flown on a daily basis for the time period of the dataset.

GPS data												
RTBC ID	Area	Nb. reloc	Date begin	Date end	Region	Flock Size	Distance traveled in area (km)	Days in area	Min. Daily Dist.(m)	Av. Daily Dist.(km)	Max. Daily Dist.(km)	Home range size (km ²)
96	R1	695	2/09/2015	18/09/2015	Urban	<20	74.44	17	0.67	4.96	16.72	6.02
	R2	5050	18/09/2015	7/11/2015	Peri-urban	80	376.7	50	3.05	7.53	12.43	8.03
98	R1	9149	26/08/2015	30/09/2015	Urban	30	591	36	1.78	16.41	38.34	52.57
99	R1	5885	26/08/2015	4/11/2015	Urban	50	597.43	70	2.55	8.53	25.86	9.7

In Denmark’s Peri-urban region in June 2017, RTBC6166 (Fig. 2c) was observed during flock follows to have bonded with an adult female and a juvenile of the flock at the release site on the 5th of August and shortly after moved with the flock to a forested region inland and northwards. In Waroona in September 2017, RTBC75 (Fig. 2d) joined a flock of approximately 50 conspecifics, comprising small family groups with juveniles, which foraged on remnant vegetation on agricultural land at the edges of the Waroona township until the start of February 2018. RTBC82 joined a flock of approximately 100 birds north of the release site and shortly after this flock moved to an agricultural area 56 km east over a period of 11 days (Table 1).

Forest region

Birds (RTBC66, RTBC67, RTBC68, and RTBC69) that were released in November 2016 into jarrah/marri forest at Nannup in the southwest of Western Australia, all joined different flocks. Generally, these flocks numbered 100 or more individuals consisting of pairs with that year’s fledglings (Table 1). The flocks of RTBC66, RTBC67, and RTBC68 showed mainly resident movement (movements not exceeding 10 km from roosts.) while RTBC69’s flock (Fig. 2e, Table 1) showed a gradual spatial shift in the flock’s foraging activity to the northwest, including one ranging movement, through the forest onto the southern SCP (Peri-urban region). RTBC56 (Fig. 2f) initially flew west to a Forest region, where it joined a flock ($n \approx 20$). After two months its flock moved east to another Forest region, where it joined another flock ($n \approx 50$) and subsequently traveled across a national park (Mt. Lindesay) north to a Peri-urban region, where its PTT tag ceased transmission (Table 1). These data show that RTBC56 traveled a distance of at least 188 km to this area over a period of nine months making use of predominantly forested areas.

Movement variation between regional landscape types

Results for the comparative analysis of average distances between night roosts (Table A1) did not show a significant difference between Urban, Peri-urban, or Forest regions ($n = 518$, $P > 0.05$). Within regions, however, average distances between roosts varied significantly between flocks. For example, in the Peri-urban region for the flock of RTBC96 (Av. 1.18 km) and the flock of RTBC75 (Av. 5.23 km; $n = 518$, $P < 0.001$), RTBC96’s flock and RTBC82’s flock (Av. 6.53 km; $n = 205$, $P < 0.001$), and RTBC96’s flock and RTBC98’s flock (Av. 4.13 km; $n = 205$, $P < 0.05$). In the Forest

region a significant difference was found between RTBC56 (Av. 2.27-3.06 km) and RTBC69 (10.54 km; $n = 251$, $P < 0.05$), and between RTBC67 (Av. 1.48 km) and RTBC69 (Av. 10.54; $n = 251$, $P < 0.001$) (Table 1). Across releases ranging movements were between 10.02 - 63.83 km (mean = 30.51 km, SD = 18.56 km) (Table 1). GPS data were collected from three birds over two urban regions, including three resident areas in the Urban region and one in the Peri-urban region (Table 2). Daily movement distances within resident areas were not different between Urban and Peri-urban regions (LME, $n = 117$, $P > 0.05$) (Appendix 1, Table A3).

Key habitat and resident movement within the urban regions

Urban region

Based on the results of the movement and revisitation analysis, we determined foraging in the Urban region to take place mostly on private properties, inner-city reserves, and public green spaces (Appendix 1, Table A2). Additional evidence of foraging behavior at these sites was provided through flock follow observations. For at least one flock (RTBC98, $n \approx 30$) roadside vegetation was used to travel between key foraging sites from south to north through the Perth metropolitan urban areas (Fig. 3a, Sites 4, 5, 6, and 7; Fig 3.1) and foraging occurred within 10 m of a road for 11.7% of foraging data within the region (Table 3). Conversely, RTBC99’s flock foraged mainly in retained or remnant native vegetation on Murdoch University campus, only using roadside vegetation occasionally (3.7% of foraging data within 10 m of a road), while transiting to and from large blocks of native vegetation. This difference in movement between the two flocks was reflected in a much larger resident home range size for RTBC98 in comparison to RTBC99 (Table 2).

Peri-urban region

In the Peri-urban region key roosts were situated in remnant tall eucalypt trees on private property and near nature reserves. All key foraging sites in the Peri-urban region occurred in close proximity to the South Western Highway. Foraging in this semi-agricultural landscape was focused on roadside vegetation (Fig. 3b, Sites 1, 2, and 3) and occurred within 10 m of a road for 10.8% of the data demonstrating roadside vegetation as a connective feature throughout the landscape (Fig. 3b and d).

Fig. 2. Landscape-scale movement (ARGOS PTT data) of flocked Forest Red-tailed Black Cockatoos (*Calyptorhynchus banksii naso*) in the Urban region (RTBC96, RTBC98), Peri-urban region (RTBC6166, RTBC75) and the Forest region (RTBC69, RTBC56). Resident movement is shown in red, ranging movement in white. Urban region: a) and b) Ranging movement of RTBC96 and RTBC98 between the Urban and Peri-urban region to the Darling Scarp in late September-November. Peri-urban region: c) RTBC6166 joined a flock near the original release site (R1) and moved to State Forest north of this area (R2), d) Resident movement of RTBC75 around Coolup and Waroona. Forest region: e) Resident and ranging movement of RTBC69 which moved between Nannup and Busselton over a one-year period, f) RTBC56 released in Denmark moved 140 km from Frankland State Forest to Redmond State Forest and across the range off Mt. Lindesay to Tonebridge.

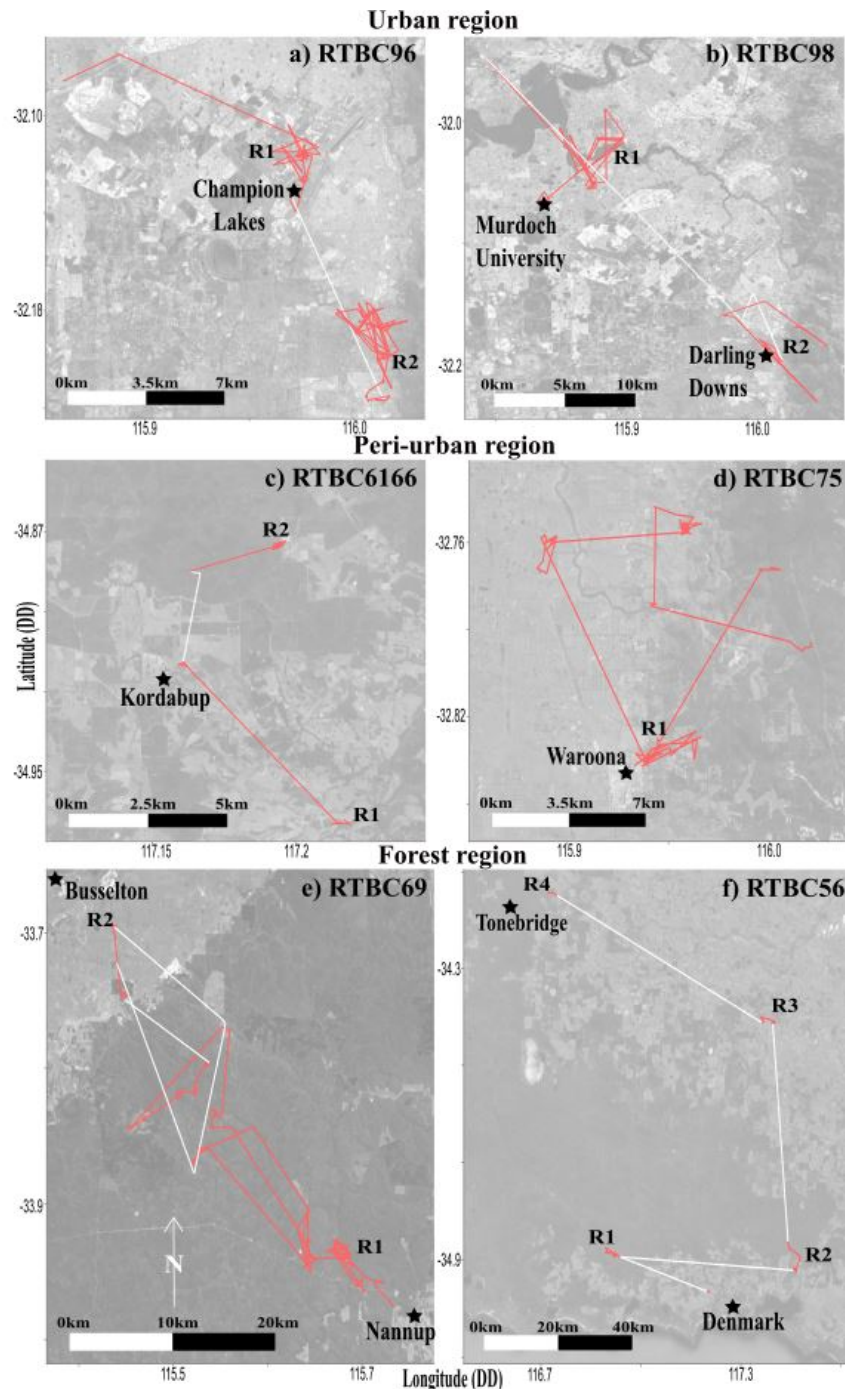


Fig. 3. a) Revisitation rates (R) for RTBC96, RTBC98, RTBC99 in Urban and b) Peri-urban regions using GPS relocation data. Black numbers and dots indicate key roosts, white numbers and dots indicate the upper 20% of key foraging habitat sites (Appendix 1, Table A2). Urban roosting occurred mostly in public urban green space (e.g., golf clubs, schools) and foraging in small reserves or in roadside vegetation. In the Peri-urban region, roosting occurred on private property and foraging occurred in roadside vegetation. Home range estimates for a1) RTBC98 (52.57 km², 95% C.I. 41.01 km² - 65.53 km²), a2) RTBC99 (9.7 km², 95% C.I. 8.71 km² - 10.75 km²), a3) RTBC96 (6.02 km², 95% C.I. 4.51 km² - 7.76 km²) in the Urban region; and b4) RTBC96 (8.03 km², 95% C.I. 6.71 km² - 9.47 km²) in the Peri-urban region.

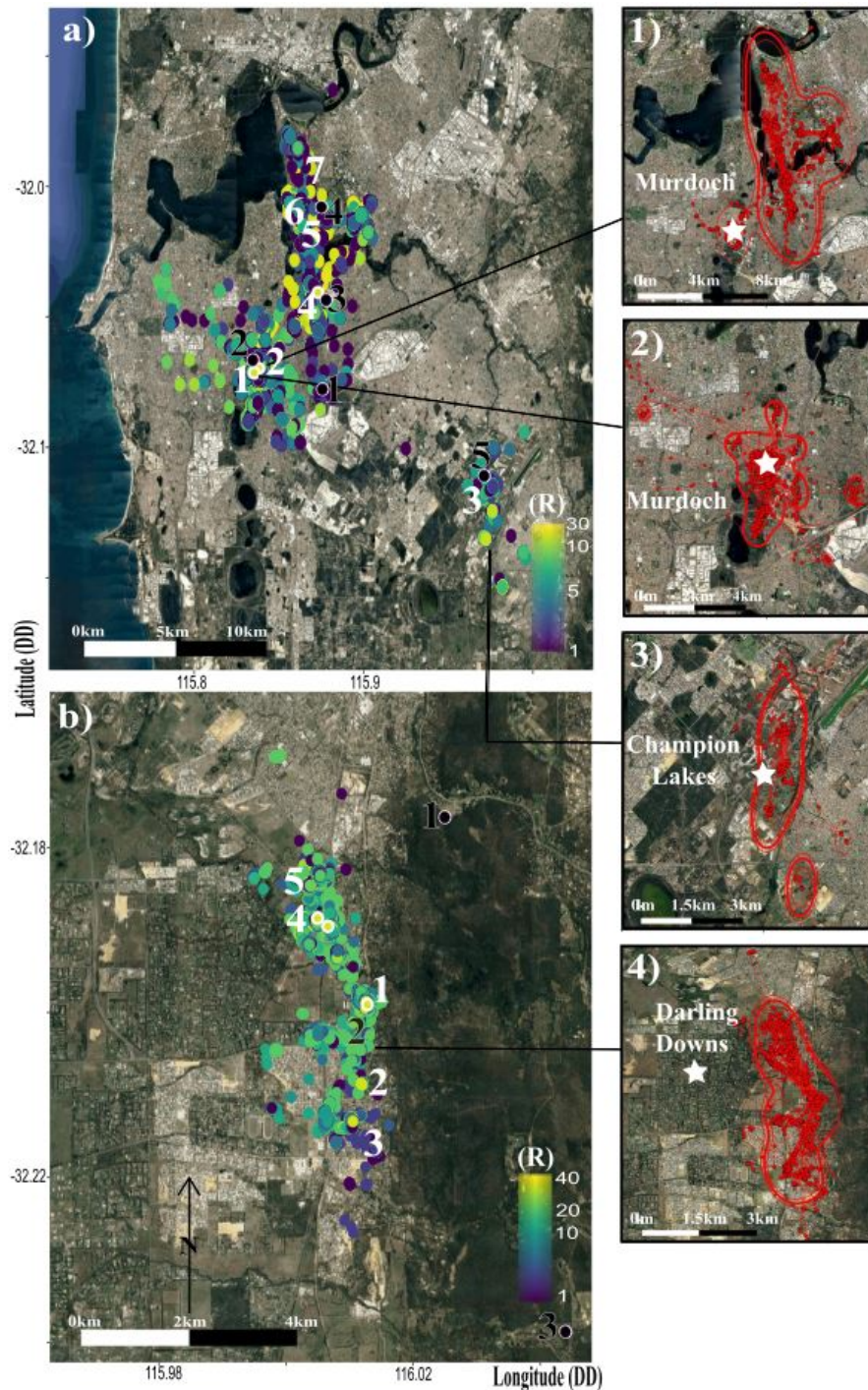


Table 3. Foraging data in relation to the distance to nearest roads for the flocks of Forest Red-tailed Black Cockatoos (*Calyptorhynchus banksii* naso) in an Urban and Peri-urban region of the Perth Metropolitan area in Western Australia in 2015. The amount of foraging data for the Urban and Peri-urban region is shown together with its percentage occurring within 10, 20, 50, and 100 meters of any road.

Region	Data (n)	Dist. to road (<10m)	Dist. to road (<20m)	Dist. to road (<50m)	Dist. to road (<100m)
Urban	10644	11.72	28.74	49.76	59.99
Peri-urban	3919	10.79	17.91	48.86	75.50

Overall, the percentage of foraging in proximity to roads was similar between Urban and Peri-urban regions ($\chi^2 = 4.3$, $df = 3$, $P > 0.05$; Table 3). Where flocks were range resident, home range sizes were similar in Urban and Peri-urban areas (average < 10 km²; Table 2) with the exception of one urban flock (RTBC98) whose home range was 52.57 km² (95% C.I. 41.01 km² - 65.53 km²).

DISCUSSION

Variation in movement between regions

Our research demonstrated that the urban environment provides key roost and foraging sites for RTBC. In accordance with other research suggesting that urban adapters demonstrate high site fidelity and travel shorter distances (Furst et al. 2018, Teitelbaum et al. 2020), we also found flocks of RTBC occurred at the same habitat sites each year. For instance, Murdoch University is a consistent key roost site every year and, given that RTBC97 (flock of RTBC98) was found dead the year after release (May 2016) in key urban foraging habitat back on the SCP, this indicates that RTBC98's flock revisited that same site the following year. In addition, the shift of the flocks of RTBC99, RTBC98, and RTBC96 toward the Peri-urban region bordering the Darling Scarp between September and November 2015 coincided with extensive marri fruiting recorded in this region (Johnstone and Kirkby 2018), suggesting that shifts between the Urban and Peri-urban regions are seasonal. In regard to traveling shorter distances, however, this research indicates that this is dependent on the occurrence of suitable habitat in the urban landscape. This was demonstrated by the daily movements and home range size of the flock of RTBC99 ($n \approx 50$) which foraged in remnant native vegetation on the Murdoch University site or nearby in the reserves of Beeliar Regional Park. However, the flock of RTBC98 ($n \approx 30$) foraged over numerous smaller urban green spaces, making use of roadside vegetation to travel between these areas, resulting in larger overall daily movements (av. 16.41 km) and a larger home range (HR 52.57 km², 95% C.I. 41.01 km² - 65.53 km²).

Compared to the Peri-urban and Forest region, RTBC daily movement does not appear to change with regard to foraging and roosting, which was demonstrated by the comparative analysis of the Urban and Peri-urban data. Even for a forested region with large uninterrupted habitat, movement patterns do not take on

significantly larger forms as the distances between roosts indicated. For the Forest region we did record, however, mostly data of flocks with juveniles which might explain inhibited movement due to extended periods of time feeding on jarrah, marri, and blackbutt (*Eucalyptus patens*) (S. Rycken, personal observation). Flocks such as these (RTBC66, RTBC67, RTBC68, RTBC69, RTBC75, RTBC6166) could show longer periods of resident movement, due to juvenile RTBC being dependent on their parents for at least 18 months during which adults teach the necessary skills to forage on jarrah and marri seeds (Johnstone et al. 2013). Forest regions, although relatively homogeneous in terms of habitat complexity and richness, consist of different areas with regard to the quality and productivity of foraging trees such as marri (Abbot 1998, Cooper 2003), which for some flocks (RTBC69, RTBC56) resulted in long-range movements.

We did not find strong evidence to support the hypothesis that movement in Forest Red-tailed Black Cockatoos was different in urban environments compared with Peri-urban or Forest regions, but rather that there was significant within-region variation in movement extent by individual flocks across regions. This is predominantly due to RTBC flocks having readily adapted to the urban landscape and adjusting their movements to target highly diverse habitat dependent on seasonality and habitat connectivity. In addition, their movements are partly attributed to density dependence, in accordance with the foraging resources of the region, as evidenced by the differences between RTBC99 and RTBC98's flock, as well as different priorities for the individual since RTBC do not breed every year (Ashmole 1963, Johnstone et al. 2013).

Key habitat and the use of roadside vegetation

The key habitat sites in both the Urban and Peri-urban regions were closely linked to nearby reserves, supporting the maintenance of key roosts in the urban landscape. In both regions, key habitat occurred on private property and remnant vegetation indicating the importance of preserving native habitat on private properties or small patches that can serve as "stepping stones" or temporary roost sites. The revisitation analysis showed that small patches of remnant vegetation throughout the urban region are invaluable in providing foraging resources and connecting key habitat. Our research demonstrates that although major reserves provide large patches of key habitat that can sustain flocks for a certain period of time, it is important to regard the matrix in which these lie. Without the surrounding connective habitat and small patches of highly diverse habitat which provide quality foraging resources, the capacity of these reserves for sustaining flocks of RTBC is greatly diminished.

Furthermore, our research showed connectivity to be critical for flocks of RTBC to be able to demonstrate their daily foraging behavior. This was perfectly exemplified by the movements of RTBC98's flock within the urban landscape, which made use of small habitat patches, usually closely associated with roads, to travel between key foraging sites. In addition, we demonstrated that the use of roadside vegetation did not differ between the Urban and Peri-urban regions, which indicates its value for preservation at high and intermediate levels of human modified environments. The importance of roadside vegetation to facilitate movement through the landscape has previously been

documented for a variety of woodland bird communities (Leach and Recher 1993, Meunier et al. 1999, Hall et al. 2016), as well as for 13 other parrot species (Davis et al. 2012). Our research adds to these findings, with clear use of roadside vegetation as foraging habitat and transit corridors in Urban and Peri-urban regions.

Conservation recommendations

The increased and sustained movement of RTBC onto the SCP indicates a significant opportunity for conservation managers to create and maintain connectivity within the Urban and Peri-urban landscape matrix to support these populations. Specifically, the finding that daily travel distance and HR size differs between flocks within the urban region, depending on patch size, suggests there is no “one-size fits all” approach to the conservation management of this species. Furthermore, this research has shown that RTBC can travel large distances between resident areas, depending on time of year, habitat connectivity, and the availability of foraging resources. Therefore, it is important that conservation plans regard the urban landscape as a whole since key sites lie within a connectivity network of different size patches of remnant vegetation. As many roosts in the Perth metropolitan area and more broadly on the SCP have been recorded (Birdlife data, Great Cocky Count), we advocate that a precautionary approach is adopted with regard to conserving remnant vegetation in these areas. A connectivity threshold does exist within the urban landscape, and while this might be quite high for species such as birds, it is probably much lower for less mobile species. It is therefore of crucial importance that conservation models move away from the definition of “natural environment” as only being habitat where the species is known to occur and breed, and incorporate urban environments, as these are a valid part of the species range and influence their seasonal movements. In addition, we suggest that roadside vegetation is identified as crucial habitat within the conservation scheme. Moreover, habitat conservation plans need to adopt a scoring system that accounts for the species-specific carrying capacity of a habitat patch based on its size and vegetation diversity as well as the patch's connectivity potential based on a “nearest neighbor” factor and the occurrence of species-specific key habitat in the area.

As urbanization is irreversible, we advocate a more urban inclusive approach in urban landscape planning. Considering urban areas are home to several threatened species globally, with 30% of all threatened species in Australia known or likely to occur within cities (Ives et al. 2016). Through close cooperation between ecologists and landscape designers, we can achieve wildlife inclusive developments within the city landscape that are mutually attractive to people and wildlife (Apfelbeck et al. 2020). In addition, we propose retaining remnant vegetation on private and public lands, and revegetating community green spaces with forage plant species to create green spaces of high quality and diversity, which will support and maintain roost and forage sites in Urban and Peri-urban regions. In the case of roadside vegetation, management measures should include road signage to alert motorists to the presence of black cockatoos, reduced traffic speeds, appropriate vegetation setbacks along road verges, and trimming of lower branches from established forage species to reduce the potential for vehicle strike, while retaining this habitat resource as a forage and movement corridor.

Further research should focus on identifying key habitat within urban landscapes, determining resource selection for this species, and species distribution modeling at regional scales to both predict the value of habitat and model future habitat modification. This will provide the necessary information to enable the retention of patch matrix qualities that will conserve this species, particularly across the SCP where urbanization is projected to increase.

Responses to this article can be read online at:
<https://www.ace-eco.org/issues/responses.php/2061>

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Appendix 1, Table A1: Track and movement summaries for tagged forest red-tailed black cockatoos (RTBC) released between 2015 and 2017 on the Swan Coastal Plain and in the South-west of Western Australia. Birds are identified uniquely using the last 2 or 4 numbers of their satellite identification number (Sat ID). The GPS ID tag number is only listed for birds where GPS data was collected. Age: Sub-adult (2-4 years), Adult ($4\leq$ years).

RTBC ID	Sat ID	GPS ID	Year	Release Site	Age, Sex	Start date	End date	GPS fixes(N)	Satellite fixes(N)	Track length (km)	Days tracked
96	151396		2015	Murdoch	Sub-adult F	26/08/2015	8/04/2016		106	104	225
		2177				26/08/2015	7/11/2015	5951		517	73
97	151397	-	2015	Murdoch	Sub-adult F	26/08/2015	9/10/2015		55	45	44
98	151398		2015	Murdoch	Sub-adult M	26/08/2015	8/04/2016		80	162	225
		2178				26/08/2015	30/09/2015	6720		591	35
99	151399		2015	Murdoch	Adult M	26/08/2015	8/04/2016		93	93	226
		2176				26/08/2015	4/11/2015	5885		597	69
66	159166	-	2016	Nannup	Adult F	2/11/2016	7/11/2016	-	17	44	5
67	159167	-	2016	Nannup	Sub-adult M	2/11/2016	18/01/2017	-	54	30	76
68	159168	-	2016	Nannup	Adult F	2/11/2016	7/11/2016	-	14	18	5
69	159169	-	2016	Nannup	Adult F	2/11/2016	14/12/2017	-	205	233	406
56	159156	-	2017	Denmark (WA)	Adult F	8/06/2017	21/05/2018	-	103	240	346
65	166165	-	2017	Denmark (WA)	Adult F	12/06/2017	22/06/2017	-	13	15	11
6166	166166	-	2017	Denmark (WA)	Sub-adult M	8/06/2017	22/10/2017	-	27	19	79
6167	166167	-	2017	Denmark (WA)	Adult F	8/06/2017	13/06/2017	-	12	35	5
75	166175	-	2017	Waroona	Adult F	21/09/2017	6/03/2018	-	120	171	166
82	163582	-	2017	Waroona	Adult M	23/09/2017	19/10/2017	-	54	129	26

Appendix 1, Table A2: Key regional habitat sites for the forest red-tailed black cockatoos (RTBC), and their associated flocks, studied in this research as determined by recurse analysis (Bracis et al. 2018). ‘Regional Site Type’ represents either a roost or foraging site in the Urban or Peri-urban region; ‘Radius’: represents the radius in meters used to calculate revisitation; ‘Key habitat’: refers to the numbers shown in Figure 4 indicating the key habitat sites.

Regional Site Type	Radius (m)	Key habitat	revisitations (N)	Description of the site
Urban Roost	500	1	12	Murdoch University
		2	16	Melville Glades Golf Club
		3	7	Brolga Park
		4	7	Trinity College (sport fields)
		5	7	Champion Lakes, (cattle paddocks)
Urban Foraging	10	1	42	Chelodina Reserve, MU
		2	37	Murdoch University
		3	16	Private property, Champion Lakes
		4	19	Roadside vegetation, Karel Avenue
		5	19	Private property near Rossmoyne Park
		6	16	Private property between Olives Reserve and Neil McDougall Park
		7	12	Private property between Perth Royal Golf Club and Ernest Johnson Oval
Peri-urban Roost	500	1	11	Private property near Oscar Bruns Reserve/Darling Downs
		2	5	Private property near State Forest
Peri-urban Foraging	50	1	47	Private property near Oscar Bruns Reserve/Darling Downs
		2	32	Roadside vegetation near Darling Downs
		3	20	Roadside vegetation near John Crescent Park
		4	17	John Crescent Park
		5	15	Remnant vegetation across Fletcher Park

Appendix 1, Table A3: Linear mixed models for the average distances between roosts (ARGOS PTT data) and the average daily distances travelled (GPS data) presenting the estimated marginal means (emmeans) and their confidence limits for each region.

Average distances between roosts (ARGOS PTT)					
Region	emmeans	SE	df	Lower.CL	Upper. CL
Urban	1.09	0.0306	10	1.02	1.16
Peri-urban	1.10	0.0277	10	1.04	1.16
Forest	1.12	0.0368	10	1.04	1.20
Average daily distances (GPS)					
Region	emmeans	SE	df	Lower.CL	Upper. CL
Urban	-0.01	0.0012	2	-0.01	-0.00
Peri-urban	-0.01	0.0014	2	-0.01	-0.00