http://dx.doi.org/10.1071/WR14138

Groom, C., Warren, K., Le Souëf, A. and Dawson, R. (2014) Attachment and performance of Argos satellite tracking devices fitted to black cockatoos (Calyptorhynchus spp.). Wildlife Research, 41 (7). pp. 571-583.

Attachment and performance of Argos satellite tracking devices fitted to black cockatoos (*Calyptorhynchus* spp.)

Christine Groom [A B D], Kris Warren [C], Anna Le Souef [C D] and Rick Dawson [B]

[A] School of Animal Biology (M092), University of Western Australia, 35 Stirling Hwy, Crawley, WA 6009, Australia.

[B] Department of Parks and Wildlife, Locked Bag 104, Bentley Delivery Centre, Bentley, WA 6983, Australia.

[C] College of Veterinary Medicine, Murdoch University, 90 South St, Murdoch, WA 6150, Australia.

[D] Perth Zoo, 20 Labouchere Road, South Perth, WA 6151, Australia.

Abstract

Context: Studying interactions between a wildlife species and its spatial environment can enable a deeper understanding of its ecology. Studies of spatial ecology are generally undertaken by attaching tracking devices to selected individuals and following their movements. Highly mobile species, such as black cockatoos (*Calyptorhynchus* spp.), that occupy habitats with patchy resources are ideal candidates. The powerful beak and chewing habits of black cockatoos make it difficult to successfully attach tracking devices to them.

Aims: We developed a safe technique for attaching tracking devices to black cockatoos and assessed the impact of the tracking devices, as well as their performance in relation to battery life, retention time and accuracy of location fixes.

Methods: We describe a technique for attaching Telonics (Mesa, AZ, USA) Argos Avian Transmitter TAV 2617 tracking devices to the two central tail feathers of black cockatoos.

Key results: Of 26 tracking devices fitted (24 to Carnaby's cockatoos, *C. latirostris*; two to Baudin's cockatoos, *C. baudinii*), 20 exhibited longer retention time than the nominal battery life. One tracking device was chewed until it was non-functional before release and two were presumed chewed after release because their tracking devices failed prematurely. There was no evidence that the tracking devices inhibited the flight capability of cockatoos. The performance of the Argos tracking devices exceeded expectations with regard to retention times, battery life and overall accuracy of location fixes. The tracking devices enabled detection of instances of rapid long-distance movements, including one bird that travelled 70 km between night roosts while migrating. Most study birds (68%) remained within 50 km of their release sites while monitored.

Conclusion: The tracking devices were a suitable choice for black cockatoos and for the purpose of this study. They posed minimal snag risk, were of suitable dimensions for tail attachment and they enabled data to be collected even if birds dispersed long distances. The main limitations that must be considered when assessing their suitability for future research projects are the errors associated with location fixes, limited retention time in relation to moulting of tail feathers and limited battery life.

Implications: The development of a method for successfully attaching tracking devices to black cockatoos opens the possibility to study aspects of the ecology of black cockatoos and other highly mobile species that was not previously possible.

Additional keywords: *Calyptorhynchus baudinii*, *Calyptorhynchus latirostris*, telemetry, Western Australia.

Introduction

Research that aims to develop a deeper understanding of a species' interaction with its spatial environment over time will lead to a better understanding of its ecology. Studies of spatial ecology usually involve attaching tracking devices to selected individuals and following their movements. The tracking devices enable the location of roost or shelter sites to be determined, together with feed sites and the extent of movement animals make to locate those sites. This is particularly helpful for the study of animals that are highly mobile or occupy habitats where resources are fragmented, such as black cockatoos (*Calyptorhynchus* spp.).

To study the spatial ecology of black cockatoos, a suitable tracking device and attachment methodology needed to be developed. There are a range of choices in regard to both attachment methods and types of tracking devices available (Thomas *et al*. 2011). The ideal attachment method should cause no adverse impacts on survival or behaviour, should not cause excessive feather wear and should remain attached to the bird for the length of the study but eventually detach without further intervention (Giroux *et al*. 1990). Both species of black cockatoo (*C. latirostris* and *C. baudinii*) studied are threatened (Chapman 2008; Department of Environment and Conservation 2012); therefore, careful selection of an attachment method that minimised impact on the welfare of the birds was required. For example, Carnaby's cockatoos (*C. latirostris*) reverse into nesting hollows (Saunders 1982), which often contain wooden shards that pose a potential snag risk. Cockatoos have powerful beaks and like to chew, so tracking devices must be attached such that they do not attract attention from the study bird or its flock mates. Given the ability of birds to fly long distances, our general lack of knowledge of their movement patterns and the difficulty of recapturing individuals, we also considered it essential that birds did not need to be recaptured to remove the tracking device or to download data.

Several attempts have been made to attach tracking devices to black cockatoos (Table 1). Comprehensive aviary trials were undertaken by Le Souef *et al*. (2013), who trialled harness, backpack and tail mounts on three species of black cockatoos The aviary trials of Le Souef *et al*. (2013) used dummy tracking devices and aimed to determine the extent to which cockatoos would tolerate the different attachment methods and the potential level of risk associated with carrying them. The results of Le Souef *et al*. (2013) provided encouragement in that although 31% of tracking devices were chewed, most were tolerated; the authors concluded that tail mounts were safest. Tracking devices fitted to the proximal end of tail feathers were considered unlikely to pose a snag risk but, if snagged, the feather(s) could be pulled out, eliminating problems, and new feathers regrown. With tail feather attachments there is no need to recapture the bird or to include a break-free mechanism because the device will be eventually shed with the feathers at the next moult. Previous studies of psittacines have most often used neck collars (Lindsey *et al*. 1991, 1994; Meyers 1996), harnesses (Robinet *et al*. 2003) or devices glued to the birds' backs (Jordan 1988), and although reported problems are rare, given the threatened status of the black cockatoos being studied it was considered essential for the risk of harm to be minimised.

The aviary trials focused on the attachment method rather than the type of tracking device and the resultant quality and accuracy of the data that could be obtained, or the effort involved in acquiring the data. The type of tracking device needs to be matched to the species, the research objectives and the resources available. For the present study, birds were being released from rehabilitation, so survival and post-release dispersal were of most interest.

Black cockatoos, particularly the seasonally migratory Carnaby's cockatoo (Saunders 1980) and Baudin's cockatoo (*C. baudinii*; Johnstone and Kirkby 2008), are capable of flying long distances over short periods of time, which would make traditional very high frequency (VHF) tracking difficult. Saunders (1980) observed daily foraging movements of Carnaby's cockatoo up to 12.1 km from nests sites and one individual was recorded to travel 45 km over 2 days. The potential for long dispersal distances, our inability to recapture study birds and a general lack of knowledge of the likely pattern of movement also made global positioning system (GPS) options unsuitable because retrieval of the tracking devices to download data was unlikely and an ability to get within range of the bird for remote download was uncertain. GPS options with functionality to enable retrieval of data via phone networks or satellite (e.g. Argos; Collecte Localisation Satellites, Ramonville, Saint-Agne, France) were considered too heavy if battery powered. Solar-powered options would have required dorsal mounting close to the birds' preening gland and therefore may have attracted chewing attention. Any significant damage to the solar power system is likely to result in permanent failure of the tracking device. There was also concern that the reflective nature of the panel may attract attention from avian predators, as was the suggested cause of lower survival of Carnaby's cockatoos fitted with patagial tags (Saunders 1982, 1988).

Tracking devices with Argos functionality were chosen for the present study. They are light, enable location fixes to be downloaded via satellite and do not require birds to be recaptured or researchers to get close to the bird to obtain data. Although the accuracy of fixes is of lower quality than from GPS tracking devices (Thomas *et al*. 2011), given the scale at which the cockatoos were thought to move, we expected Argos would provide usable information on the survival and movements of the study birds after release. As knowledge grows of the movement patterns of the birds, other options may be applicable.

The Argos tail mounts used were larger than those trialled by Le Souef *et al*. (2013), so a modified attachment method was developed. Herein we describe a method for attaching tracking devices to the two central tail feathers of black cockatoos. The performance of the tracking devices was assessed and we describe the type of research questions suited to the strengths and limitations of the technology.

Methods

This research was approved by the University of Western Australia Animal Ethics Committee (RA/3/100/1100), Murdoch University Animal Ethics Committee (R2485/12) and Department of Parks and Wildlife Animal Ethics Committee (DEC AEC 2011/30) and the work was carried under licence SF008648 from Department of Parks and Wildlife, Western Australia.

Study area and study birds

Two species of black cockatoo were used in this study, namely Carnaby's cockatoo and Baudin's cockatoo. Both species are threatened and endemic to south-western Western Australia. The study focused on the city of Perth on the Swan Coastal Plain and the adjacent Darling Plateau separated by the Darling Scarp. Carnaby's cockatoo occupies the entire area, but Baudin's cockatoo prefers the scarp and plateau habitats. Land use in areas used by the cockatoos varied from high-density housing to semirural, forestry and farmland.

The study birds were injured wild individuals that had been taken into care. They received primary veterinary care at Perth Zoo and then longer-term rehabilitation at either Kaarakin Black Cockatoo Conservation Centre or the Native Animal Rescue facility.

Before release, cockatoos were flight tested in a 64-m long flight aviary. Their ability to fly true, avoid obstacles, land and walk was observed by an experienced observer (RD) both before and after fitting of the tracking devices. Cockatoos were not selected for fitting tracking devices or for release if there were any concerns regarding their ability to survive in the wild.

Selection of tracking device

The tracking device used was the Telonics (Mesa, AZ, USA) Argos Avian Transmitter TAV 2617, weighing 17 g and altered to have the aerial at 0° and attachment rails. Encapsulating material was not strengthened because it was considered impossible to cockatoo-proof the devices and we preferred to maximise battery life and reduce overall weight by minimising encapsulating material.

Attachment of tracking devices

Tracking devices were attached while the birds were anaesthetised with isoflurane inhalation anaesthesia. This also provided the opportunity to take blood samples, administer subcutaneous fluids, collect breast feathers for DNA, attach leg bands and mark their tail feathers for visual identification after release. Tail feather marking was undertaken on Carnaby's cockatoos only and involved stencilling a letter with a black felt-tipped permanent marker pen and applying coloured ink to the white panels (Groom *et al*. 2013). The resulting colour and letter combination became the identification for that individual (e.g. 'Pink B'). None of these procedures was particularly painful or invasive; however, anaesthesia was required in order to minimise stress to the bird. A heat pad was used to maintain body temperature during anaesthesia.

Anaesthetised birds were weighed using scales (Model 323; Salter, Melbourne) before fitting to ensure the tracking device did not exceed 5% of their bodyweight.

Tracking devices were attached to the proximal ventral surface of the two central tail feathers of the bird. The device was secured using black thermally fused braided fishing line (Fireline; Berkeley, Spirit Lake, IA, USA) threaded through the rails of the tracking device and around the shaft of each feather (Fig. 1). During attachment, the fishing line was threaded through both rails and the device was manually held in place while the fishing line was pulled with forceps up between the two feather shafts, cut and then each half tied around the feather shaft and attachment rail. Surgical haemostats were used to temporarily hold pairs of fishing line until they could be tied using surgical knots. The aerial was laid along the length of one central tail feather and tied at approximately 30 mm intervals. The fishing line was not threaded through the shaft as in Kenward (1978) to avoid weakening the feather, as was found by Soderquist and Gibbons (2007). All knots were further secured by applying a moisture cure adhesive glue (Selleys Ultra Repair Glue; Selleys, Padstow, NSW, Australia). A hairdryer was used to speed up the drying of the glue before the bird was left to recover from the anaesthetic procedure in a darkened pet pack with a heat lamp provided during recovery. Once the birds had recovered fully they were released back into the flight aviary for 2–21 days and closely observed to determine their reaction to the fitting of the tracking devices.

Releases and programming schedule

Study birds became available for fitting tracking devices and release as they recovered from injuries in rehabilitation and were considered fit for release. Several releases occurred during this study, ranging in size from one to seven individuals. Release sites were known communal night roost locations within the greater Perth region (Burnham *et al*. 2010; Kabat *et al*. 2011, 2013). Study birds were released in the late afternoon and early evening (0–77 min before sunset) to enable them to join wild flocks arriving at established night roosts. One release occurred in the middle of the day to a site where the cockatoos are reliably present throughout the day.

The tracking devices were fully user programmable before deployment and could be switched on and off as often as desired, which influenced the overall battery life of the tracking devices. Different research objectives were being investigated during the study and so different programming schedules, and therefore battery life, were achieved at different phases of the study.

Releases in 2012 aimed to closely follow the birds' movements for the first 2 weeks to determine short-term survival and obtain as much early dispersal data as possible before expected high rate of loss or damage to tracking devices. After the first 2 weeks the tracking devices only switched on for 5 h in the morning every 5 or 10 days to obtain survival and dispersal data over a longer period of time. The predicted battery life under this schedule was 4–5 months.

Releases in 2013 were aimed at determining communal night roost site fidelity and foraging area around roosts, and so the tracking devices were programmed to switch on for 4 h every night to determine roost locations and for 8 h on two mornings and two afternoons each week to identify foraging areas. The predicted battery life under this schedule was 1–2 months.

Assessing the impact of the tracking devices

To assess the suitability of these tracking devices we considered both the impact of the tracking device on the bird and of the bird on the tracking device. If a bird was bothered by the device, behavioural evidence would be expected in the form of impacted flight ability or excessive preening attention to tail feathers and/or physical evidence in the form of visible wear on the feathers or chewing marks on the tracking device. Like Meyers (1996), we assumed that if a tracking device failed well before its predicted battery life then it had been damaged by the birds rather than due to other plausible explanations, including electronic or battery failure.

To observe the behaviour of the study birds after release, flocks containing study birds were followed using Argos AL-1 PTT Locators (Communications Specialists, Orange, CA, USA) with aerials attached to the roof of a Nissan X-Trail. The AL-1 units received signals from tracking devices approximately once a minute during on-periods and converted it into an audible voice read-out of signal strength. With excellent road access available in the urban areas and the noisy flocking habits of the birds, it was possible to locate and follow flocks containing study birds to obtain behavioural observations and the tail markings enabled study birds to be distinguished from their flock mates.

Assessing the performance of the tracking devices

The performance of the tracking devices was assessed by comparing the retention time to battery life achieved and by comparing the predicted battery life to the actual battery life achieved. Predicted battery life was obtained from software used to program the duty cycle of the tracking devices (Telonics Product Programr; Telonics). The value used was the predicted battery life at an ambient temperature of 20°C.

Performance was also assessed by comparing the proportion of accurate versus inaccurate location fixes. Argos assigns a categorical accuracy level to each estimated location. The highest accuracy is Class 3, which is within 250 m, through to Class A or B, for which an estimation error cannot be calculated and may be several kilometres (Table 2).

The data obtained from the tracking devices were assessed for their potential to provide useful information on the spatial scale of daily and seasonal movements, roosts site fidelity and foraging area around roosts by plotting location fixes of Class 2 and 3.

Results

Fitting tracking devices

Tracking devices were fitted to 24 rehabilitated Carnaby's cockatoos and two rehabilitated Baudin's cockatoos. Time taken for all procedures (including tracking device attachment, blood sampling and tail marking) reduced with experience from approximately 1 h to <40 min per bird over nine fitting sessions.

Following flocks

Over 540 h was spent following flocks and regularly sighting study birds. Location fixes from Argos were used to drive to the last known location of a study bird and the AL-1 locator was then used to locate and follow the flock containing the study bird. Black cockatoos are capable of flying more than a kilometre in the minute between received signals, so it was difficult to follow fast-moving flocks unless they remained within sight or a departure trajectory was observed. The cockatoos would often spend extended periods feeding or resting, and these provided opportunities to re-locate flocks. Location fixes from Argos also assisted in relocating flocks.

Signal interference regularly occurred between 0715 and 0930 hours, and between 1915 and 2130 hours local time, corresponding to the times that meteorological balloons are launched from Perth Airport that transmit on a similar frequency (usually 401.5 MHz; A. Bryde, pers. comm., 2014). In Australia, the frequency range 400.15–406.1 MHz is allocated to meteorological aids and meteorological satellite (Earth to space) communications (Australian Communications and Media Authority 2013), which overlaps with Argos tracking devices, which transmit in the range 401.65 MHz (± 30 kHz; Collecte Localisation Satellites 2013*a*). The interference covered the entire study area. The interference did not prevent the tracking devices communicating with satellites, but it did significantly reduce the overall accuracy of location fixes compared with periods when balloons were not present ($\chi^2 = 241.391$, d.f. = 5, $P < 0.0001$; Fig. 2) and it prevented the signal strength being read out among background noise by the AL-1 and therefore inhibited following study birds. When physically close to a study bird (within ~1 km), the signal could be attenuated and this was unaffected by interference, which allowed the flock to continue to be followed.

Similarities in the frequencies transmitted by tracking devices meant that it was sometimes difficult to distinguish which birds were within range. Argos tracking devices transmit over a narrower bandwidth than VHF tracking devices, which limits the number of tracking devices that can be tracked individually in a study area; however, the range over which signals can be picked up is much greater.

Assessing the impact of the tracking devices

When fitted, the tracking devices represented 2.4%–3.2% (mean (± s.d.) 2.7 ± 0.2%) of the body mass of the study birds. This is below the generally accepted guidance of less than 5% of bodyweight (Kenward 2001). Study birds fitted with tracking devices showed no indication of tail drooping or any abnormality of flight in the aviary before release. It was very difficult to detect that the birds had been fitted with tracking devices with only the tip of the aerial protruding beyond the end of the tail feathers. The bulk of the tracking device is hidden by the under-tail coverts. Given the covering of feathers, we expected that the tracking device would have minimal impact on the aerodynamics of the bird's flight.

We aimed to observe each study bird released in 2013 at least once a week. Sightings showed that the preening behaviours and frequency of those behaviours were similar to their flock mates (i.e. occasional) and study birds were never observed paying any particular extra attention to the tracking device or the aerial.

To assess whether the tracking devices were inhibiting the ability of study birds to keep up with the flock, we recorded the number of times study birds were found to roost or forage alone. On most occasions (91.9%) study birds were found roosting or foraging with a flock. However, of the 12 study birds followed intensively in 2013, six were found alone on at least one occasion. It is not clear whether the tracking devices were actually inhibiting movements, whether the rehabilitated birds were having some difficulty reintegrating back into wild flocks or whether it is normal behaviour for birds to occasionally be alone. There was no indication of deterioration of health over time and all birds were subsequently found foraging or roosting with a flock. For example, Pink D was a study bird that was found alone on two of seven occasions she was observed. When her body was necropsied after being illegally shot, Pink D was found to be in very good condition with strong flight muscles, suggesting it was not her physical abilities that were limiting her capacity to be with a flock. Pink L was found alone the most often (four of 10 occasions she was observed); however, she was sighted 72 days after her tracking device had failed and 141 days after release, alive and well, interacting in a large flock.

Only one of the 26 tracking devices inspected before release showed signs of chewing (Table 3; Fig. 3*a*). Of the four tracking devices recovered after release, three were recovered after the birds had died but showed no indication that the tracking device contributed to the deaths (i.e. no feather wear or chewing). In the case of the Baudin's cockatoo (#121840), the tracking device had shifted position on the feather, which was consistent with being pulled. Other evidence gathered at the site of the mortality suggested that Australian raven (*Corvus coronoides*) attack may have been the cause of death, because this involves feathers being pulled out, and this may have been the reason for the shifted position of the tracking device. It should be noted that it is not uncommon for wild black cockatoos to be attacked by ravens during raven breeding season, and the tracking device is not considered to have predisposed the cockatoo to raven attack. Pink D was illegally shot and the pellets caused damage to the attachment rail and side of the device, but it was still functioning (Fig. 3*b*). Blue J's tracking device was recovered from below powerlines after her flock had been followed and was assumed to have moulted out. There was no evidence of feather wear or chewing, as shown in Fig. 1.

Of those tracking devices that were not recovered, two had stopped working prematurely and although the cause will remain unknown, they are presumed to have been chewed (as described above).

The birds impacted on three tracking devices by chewing, but we found no evidence of the tracking devices causing discomfort or injury to the birds. The three deaths observed during the study could not be attributed to the tracking devices worn by those birds.

Retention and performance of tracking devices

In general, retention time exceeded battery life for tracking devices fitted to the black cockatoos. The maximum retention time observed was at least 289 days (Table 4). All but one tracking device ceased transmitting before detachment, so the true retention time is unknown.

Most (21 of 26) tracking devices exceeded the predicted battery life (Table 4). Five tracking devices failed before their expected battery life. Three of 26 (11.5%) were attributed to chewing, with one failing before release and the others failing 2 and 13 days after release. These tracking devices showed no reduction in the number and accuracy of location fixes in the days immediately before stopping when compared with others that stopped beyond their expected battery life. The remaining two premature failures were very close to the expected battery life so, given the variability in battery performance, we assumed that they could be attributed to battery failure. One of these individuals was found injured following a suspected collision with a vehicle 5 months after its tracking device had failed. The tracking device was no longer attached and its central tail feathers had regrown, indicating that the retention time was between 5 months (the length of time the tracking device was active) and 10 months.

Overall, 57.6% of fixes were of location quality ‘2’ or ‘3’, meaning they were accurate to within approximately 500 m (Table 4). Green R’s tracking device performed poorly throughout the study and was excluded from the dataset. Green R’s tracking device provided only 24.3% of fixes being location quality ‘2’ or ‘3’ (Table 4).

A significant drop in the accuracy of their fixes was observed following the deaths of two study birds (Fig. 4). Pink N’s tracking device was found on the ground, under the canopy of a mature pine plantation (*Pinus pinaster*), whereas the tracking device for Baudin #121840 was on the ground among trees but not under dense canopy cover. The change in performance of the tracking devices was presumed to be caused by them being at ground level under cover, rather than in an elevated location. The shift in accuracy was used to infer the time at which the birds were likely to have died.

The tracking devices provided data potentially useful for understanding both large-scale movements (Fig. 5) and daily roosting and foraging patterns (Fig. 6). The tracking devices picked up instances of rapid long-distance movements that would have made relocation of individuals extremely difficult without the aid of location fixes from satellites. For example, Purple F travelled 70 km between night roosts while migrating, and Pink S was the most mobile of study birds, travelling a total of over 450 km between broad regional areas during the 6 months of monitoring (Fig. 5). However, most study birds did not exhibit such long-distance movements, with 68% remaining within 50 km of their release sites while monitored.

Night roost locations can be identified by clusters of points obtained at night with tracking devices switching on for at least 4 h to help ensure that at least one or two of the approximately hourly satellite passes results in an accurate location fix (i.e. within 500 m; Fig. 6). In the example provided in Fig. 6 it is possible to distinguish the location of night roosts used by Green E, their relative use and an indication of the foraging area around the most often used night roost at Bentley.

Discussion

Impact of tracking devices

Attaching a tracking device involves adding a burden for a bird to carry and so it is likely to have some impact on the energy budget of the bird. However, the impact can be minimised by reducing weight and carefully considering the position and shape of the tracking device. The method of fitting tracking devices described in the present study involves attaching the device close to the body, and therefore the centre of gravity of the bird, to minimise the impact on balance. The device was also covered by feathers to minimise impact on the aerodynamics of the bird and to make individuals within a flock not noticeable to avian predators (see Saunders 1980).

We aimed to make the tracking device not noticeable to the bird; however, 11.5% (3/26) of tracking devices were chewed by the birds, indicating that at least some birds noticed the devices. This percentage is less than half the proportion (31%) of study birds that Le Souef *et al*. (2013) observed with chewed tracking devices. The different positioning of tracking devices and attachment methods used by Le Souef *et al*. (2013) may have resulted in additional chewing attention. The aerials of some of the attachment methods used by Le Souef *et al*. (2013) protruded away from the bird's body and were chewed by aviary mates when they were effectively placed in front of other birds while the 'owner' of the aerial was manoeuvring on perches (A. T. Le Souef, pers. comm.) Birds held in aviaries may be more likely to chew both their own tracking devices and those of aviary mates through boredom. However, in the present study only one bird chewed its tracking device to the point of damage before release. Most study birds were held for 2–3 days between fitting and release, but two were held 21 days and the tracking devices showed no signs of chewing. This suggests that the birds are not bothered by the tracking devices or the method of attaching them.

Many studies recommend tracking devices that weigh less than 5% of the body mass of the study animal. The exact origin of this ‘rule’ is unclear; however, Naef-Daenzer (1993) calculated that the body mass variability of birds repeatedly trapped at Swiss ringing stations was on average 7.7% and therefore assumed that birds were capable of carrying a tracking device that was 5%–7% of their body mass. Caccamise and Hedin (1985) argue that using 5% as a guide for tracking device weight is inappropriate because it ignores aerodynamic relationships that indicate small birds can carry loads equal to a larger proportion of their body mass than larger birds, and nor does it provide an estimate of the energetic costs of transporting the tracking device. Energetic costs of locomotion increase with additional weight. In flight, the increase can be substantial and this increase in energy demand is likely to affect behaviour. Tracking device weights based on a fixed percentage of body mass (e.g. 5%) will affect the flight characteristics of large birds more than small birds (Caccamise and Hedin 1985). Black cockatoos are large birds, with Carnaby’s cockatoo ranging in weight from 520 to 790 g and Baudin’s cockatoo from 560 to 770 g (Johnstone and Storr 1998). Our study birds ranged in weight between 537 and 698 g, with an average of 628 g. Only one tracking device fitted in this study exceeded 3%, but was still less than 5%, of the bird’s bodyweight and we found no conclusive evidence to indicate this represented an observable burden to the bird.

Retention time

The tracking devices attached using the methods described here will only be carried by the bird, at most, until the two central tail feathers are moulted. Little is known of the timing and sequence of moult in black cockatoos. The tail feathers of one nestling male yellow-tailed black cockatoo (*C. funereus*) had all moulted in just over a year (Courtney 1986*a*), in contrast with four glossy black cockatoo (*C. lathami*) nestlings that moulted only half their tail feathers each year and were over 2 years old when they completed their first tail moult (Courtney 1986*b*). Moulted wing and tail feathers of Carnaby’s cockatoo are most noticeable around communal night roosts in February and March, which coincides with the end of the breeding season. Detailed study of moult in a smaller psittacid

(*Purpureicephalus spurius*) indicates that its tail feathers are moulted in late summer–early autumn in adult birds (Mawson and Massam 1996). Birds in the present study were fitted with tracking devices between late February and June with the hope that they would most likely not be lost until early the following year and therefore maximise potential tracking period for tail mounted devices. Only one tracking device was moulted before battery life ended. Battery life, rather than retention time, was the main limiting factor in the present study. The longest battery life achieved during this study was 289 days (Table 4). In comparison the retention time reported by Le Souef *et al*. (2013) was between 1 and 287 days, with an average of 71 days.

Two tracking devices that failed prematurely were fitted to mature females (Pink K and Blue B). It is possible that females may be more inclined to chew tracking devices given that they chew the hollow entrance and nest chamber in preparation for laying and while incubating. Overall, females have a much more aggressive demeanour and tend to vocalise and be more aggressive during capture and while being handled (CJG, RD, pers. obs.). Of the tracking devices chewed in the study of Le Souef *et al*. (2013), three were chewed by males and six were chewed by females (with equal numbers of males and females in the study), which supports a female bias in an inclination to chew tracking devices.

Performance of tracking devices

We were satisfied with the performance of 21 of the 25 tracking devices that were deployed on released birds with regard to retention time, field battery life and overall accuracy of location fixes. Three tracking devices failed earlier than expected, and were known or assumed to have been chewed; therefore, there was little that could have been done to prevent this occurring. The fourth unsatisfactory tracking device performed comparatively poorly throughout the duration of its deployment in terms of both the number and accuracy of location fixes. This may have been caused by a technical issue, such as electronic or battery failure, a damaged aerial or some other unknown cause.

The accuracy of the location fixes provided by the tracking devices exceeded expectations based on previously published studies using Argos systems (Britten *et al*. 1999; Soutullo *et al*. 2007; Dubinin *et al*. 2010), where it is common for the lower accuracy classes to dominate results and for the accuracy of location classes to not be as great as that reported by Argos (Meyburg and Fuller 2007; Douglas *et al*. 2012; Boyd and Brightsmith 2013). There are several factors that may explain the better performance of the Argos tracking devices during the present study. These factors are related to characteristics and behaviour of the study species, the geographic location of the study and improvements to technology and data processing over time.

Carnaby's cockatoos like to perch and forage on top of the canopy of trees and, at night, they roost among the leaves of the outer branches of the tallest trees, which aids good communication with the passing Argos satellites. The benefit of elevation was demonstrated when a reduction in accuracy of location fixes was observed following the deaths of two study birds resulting in their tracking devices being at ground level. The cockatoos generally spend little time foraging on the ground, so when alive they are most often in a position for obtaining good location fixes. Although Sauder *et al*. (2012) concluded canopy cover and topographical obstruction would not have a practical effect on Argos telemetry performance, all their devices were suspended 1 m above the ground under different canopy covers and topographical positions, and the 1 m above ground may be sufficient to improve communication with the satellites. Other studies have shown that the physical location of the animal in the landscape can greatly affect location fixes. Stewart *et al*. (1989) reported that location efficiency for harbour seals almost doubled while ashore compared with at-sea, and almost no locations were observed when the seals were engaged in diving behaviour.

Previous studies have shown that the geographical location of the study can affect Argos performance and Dubinin *et al*. (2010) recommend testing of tracking devices before deployment to trial whether the performance of the tracking devices will be suitable for study aims in a particular area. Compared with Europe, where other studies have reported poor performance of Argos tracking devices, there is less electronic interference in Perth, enabling satellites to receive more signals per pass to calculate more accurate location fixes (Gros *et al*. 2006; Anonymous 2005, 2007; Meyburg and Fuller 2007).

With regard to improvements in technology over time, new satellites have been launched, which has increased the number available to receive signals, and older satellites have been replaced with ones carrying newer instruments with improved performance. The new instruments have greater sensitivity, increased bandwidth and an increased number of data receivers, all of which mean they have the ability to detect more signals simultaneously, on a wider range of frequencies that are weaker in strength, compared with the satellites used previously (Sarthou 2007). During the present study, one satellite was decommissioned and two new satellites equipped with ARGOS-3 were launched (CLS 2013*b*). There are now seven orbiting Argos satellites compared with the time of earlier studies assessing the performance of Argos tracking devices undertaken by Britten *et al*. (1999) and Hays *et al*. (2001) when there were fewer than five Argos satellites.

Improvements have also been made to data-processing algorithms. In 2005, digital elevation models were incorporated in the calculation of locations for terrestrial and bird species (CLS 2013*a*) that address a major source of error observed by Keating *et al*. (1991). In 2011, just before the commencement of the present study, a Kalman filtering algorithm was implemented that uses measurements from the current satellite pass, as well as information from previous satellite passes, to provide improved estimates of location errors and, compared with the previous least-squares algorithm, provides more positions of better accuracy (Malarde *et al*. 2010).

Changes in performance of tracking devices can be used to identify when a tracking device has been damaged (Hays *et al*. 2007) or the animal may have died. For Carnaby’s and Baudin’s cockatoos, detachment of the tracking device and death were both associated with a reduction in the proportion of high-quality location fixes. Whether or not the tracking device has been damaged or the study animal has died, these are both reasons to trigger a response from the researcher to attempt to locate the tracking device. With the aid of an Argos PTT Locator AL-1 (as used in the present study) or Argos Goniometer (CLS 2013*c*) it is possible to find downed transmitters. This is useful for recovering expensive equipment and confirming the fate of study animals.

Research objectives and suitability of tracking devices

The Telonics TAV 2617 tracking devices were a suitable choice for black cockatoos and for the purpose of the present study. We used the tracking devices to monitor the survival and movements of study birds after release from rehabilitation and to obtain data to determine roost site fidelity and foraging area around roosts. The essential requirements that led to the decision to use the tracking devices chosen were minimal snag risk, suitable size and dimensions for tail attachment and the ability to obtain data even if birds dispersed long distances. The novel use of the AL-1 tracking gear made it possible to follow flocks containing study birds to observe flock size and behaviours. The main limitations of the tracking devices that must be considered when assessing their suitability for future research projects are the errors associated with location fixes, limited retention time in relation to moulting of tail feathers and limited battery life.

The technology involved has improved over time such that over a decade ago Britten *et al*. (1999) recommended Argos tracking devices only if a position accuracy of <35 km was needed. More recently, Boyd and Brightsmith (2013)recommended that Argos was suitable for users who require position accuracies of up to 2 km. The present study has shown that for species that spend most of their time in elevated positions and in suitable global geographic locations, then daily position accuracies of within 250 m are possible.

The methodology described herein was developed for attaching tracking devices to birds while in captivity. The length of time taken to fit the tracking devices necessitates anaesthesia to minimise stress on the birds. However, field anaesthesia is possible and the birds recover quickly. The development of a method for successfully attaching tracking devices to black cockatoos opens the possibility to study aspects of the ecology of black cockatoos and other species that was not previously possible. The ability to fit tracking devices to wild birds in the field would provide valuable knowledge, particularly with regard to the migratory habits of the species and the location of breeding areas and non-breeding areas used. Highly mobile species without fixed home ranges are very difficult to study. Argos tracking devices and the methodology described herein provide a helpful insight into the spatial ecology of such species and open opportunities for further study.

Acknowledgements

The efforts of staff and volunteers at Perth Zoo, Kaarakin Black Cockatoo Conservation Centre and Native Animal Rescue to rescue, treat and rehabilitate black cockatoos are gratefully acknowledged. Particular thanks to Louise Hopper, Dr Lian Yeap, Dr Carly Holyoake and assistants for their support catching, anaesthetising and helping attach tracking devices to study birds. Thank you to the volunteers who assisted following flocks in the field. This project was supported with funds received as part of an offset package approved by the Australian Government Department of the Environment. Newmont Boddington Gold provided financial assistance that supported aspects of this study.

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Table 1. Summary of tracking devices fitted to black cockatoos (*Calyptorhynchus* spp.)

Species	No. birds	Mount method	Aim	Source or origin	Reference
Glossy black cockatoo	1	Collar (VHF)	Trial	Captive	Murdoch (2008)
Glossy black cockatoo	1	Collar (VHF)	Movements, activity patterns	Wild caught and released	Murdoch (2008)
Yellow-tailed black cockatoo	4	Tail (VHF)	Survival and movements after soft release	Captive reared	J. van Weenen, pers. comm.
Red-tailed black cockatoo	8	Tail (VHF)	Not stated	Not stated	Commonwealth of Australia (2006)
Baudin's cockatoo	2	Collar	Trial	Rehabilitating wild birds in captivity	Le Souef *et al.* (2013)
Baudin's cockatoo	2	Tail	Trial	Rehabilitating wild birds in captivity	Le Souef *et al.* (2013)
Baudin's cockatoo	2	Harness	Trial	Rehabilitating wild birds in captivity	Le Souef *et al.* (2013)
Carnaby's cockatoo	3	Collar	Trial	Rehabilitating wild birds in captivity	Le Souef *et al.* (2013)
Carnaby's cockatoo	5	Tail	Trial	Rehabilitating wild birds in captivity	Le Souef *et al.* (2013)
Carnaby's cockatoo	9	Harness	Trial	Rehabilitating wild birds in captivity	Le Souef *et al.* (2013)
Forest red-tailed black cockatoo	1	Collar	Trial	Rehabilitating wild birds in captivity	Le Souef *et al.* (2013)
Forest red-tailed black cockatoo	2	Tail	Trial	Rehabilitating wild birds in captivity	Le Souef *et al.* (2013)
Forest red-tailed black cockatoo	2	Harness	Trial	Rehabilitating wild birds in captivity	Le Souef *et al.* (2013)

Table 2. Argos Doppler location class accuracy as estimated and documented by Collecte Localisation Satellites (2013*a*) using Kalman filtering

Class	Estimated error (m)	No. messages received per satellite pass
3	<250	Four or more
2	250–<500	Four or more
1	500–<1500	Four or more
0	>1500	Four or more
A	Unbounded accuracy	Three
B	Unbounded accuracy	One or two

Table 3. Summary of tracking devices retrieved after being worn by birds in the present study

Study bird	No. days worn	Reason retrieved	Chewed	Feather wear	Moved position on feather
Blue B	5	Chewed in aviary before release	Yes	No	No
Blue J	55	Moulted	No	No	No
Pink D	53	Mortality (shot)	No	No	No
Pink N	34	Mortality (unknown cause)	No	No	No
Baudin #121840	25	Mortality (unknown cause)	No	No	Yes

Table 4. Retention time and performance of Argos tracking devices while fitted to released cockatoos

Note that the number of location fixes is provided only for the period when the birds were in the wild and still living. In the 'Observed (days)' column, '+' is used to denote when the tracking device was manually switched off after retrieval and so actual battery life would have been longer. Similarly, '+' in the 'No. days fitted to living bird after release' indicates that the battery failed before the device detached and so actual retention time would have been longer. Schedule refers to programming of on-periods for the tracking devices

Study bird	Battery life			Retention time		Location quality while fitted to living bird after release[A]						
	Expected	Observed (days)	Reason for failure	No. days fitted before release	No. days fitted to living bird after release	3	2	1	0	A	B	Total
Released 18 May 2012. Schedule: all day first 14 days, then morning every 5 days												
Blue A	125	220	Battery failure	3	220+	88	84	70	32	34	72	380
Blue E	125	170	Battery failure	2	170+	153	78	69	17	17	37	371
Blue H	125	12	Chewed?	3	9+	27	33	26	14	5	11	116
Blue L	125	115	Battery failure	3	115+	98	95	62	23	11	25	314
Blue P	125	125	Battery failure	2	125+	100	55	52	27	21	31	286
Blue X	125	160	Battery failure	3	160+	115	56	59	25	29	47	331
Released 24 May 2012. Schedule: all day first 14 days, then morning every 5 days for 2 months, then morning every 10 days												
Pink B	139	169	Battery failure	2	169+	151	92	60	23	27	49	402
Pink C	139	289	Battery failure	2	289+	155	107	78	28	33	58	459
Pink N	139	179+	Mortality	2	32	101	51	33	12	17	46	260
Pink S	139	199	Battery failure	2	199+	128	95	91	38	26	44	422
Pink U	139	259	Battery failure	2	259+	165	75	61	29	25	63	418
Released 28 September 2012. Schedule: all day first 12 days, then morning every 5 days												
119055	124	164	Battery failure	3	164+	119	62	46	21	12	27	287
121840	124	103	Battery failure after mortality	3	22	117	39	19	5	24	50	254
Released 25 February 2013. Schedule: each night for up to 4 h plus 2 mornings and 2 afternoons each week												
Pink D	40	50+	Shot	3	50	203	101	47	20	31	38	440
Pink K	40	1	Chewed?	3	1+	8	1	0	1	2	2	14
Pink L	40	69	Battery failure	3	141+[B]	266	109	67	33	41	75	591
Pink T	40	60	Battery failure	3	60+	223	90	56	23	32	80	504
Pink Z	40	60	Battery failure	3	60+	239	108	78	21	24	60	530
Released 5 April 2013. Schedule: each night for up to 4 h plus 2 mornings and 2 afternoons each week												
Green T	40	87	Battery failure	2	87+	275	137	115	48	70	143	788
Released 24 April 2013. Schedule: each night for up to 4 h plus 2 mornings and 2 afternoons each week												
Green E	40	78	Battery failure	21	114+[B]	273	123	72	50	59	162	739
Green P	40	122	Battery failure	21	122+	296	128	106	55	105	274	964
Green R	40	121	Battery failure	2	121+	71	55	30	17	95	250	518
Released 5 June 2013. Schedule: each night for up to 4 h plus 2 mornings and 2 afternoons each week												
Blue B	40	0	Chewed	5	0	0	0	0	0	0	0	0
Blue G	40	67	Battery failure	8	67+	272	146	82	41	61	99	701
Blue J	40	47+	Moulted	8	47+	245	105	42	20	27	57	496
Released 5 June 2013. Schedule: delayed start by 1 month then each night for up to 4 h plus 2 mornings and 2 afternoons each week												
Purple F	59	97	Battery failure	2	97+	292	158	100	35	47	130	762
Total						4180	2183	1521	658	875	1930	11 347

[A]See Table 2 and/or Collecte Localisation Satellites (2013*a*).
[B]Sighted after tracking device stopped working but with device still attached.

Fig. 1. Telonics (Mesa, AZ, USA) model TAV 2617 attached to the two shed central tail feathers of a Carnaby's cockatoo. The photograph is of the moulted tail feathers of study bird Blue J.

Fig. 2. Influence of meteorological balloons on the quality of Argos location fixes

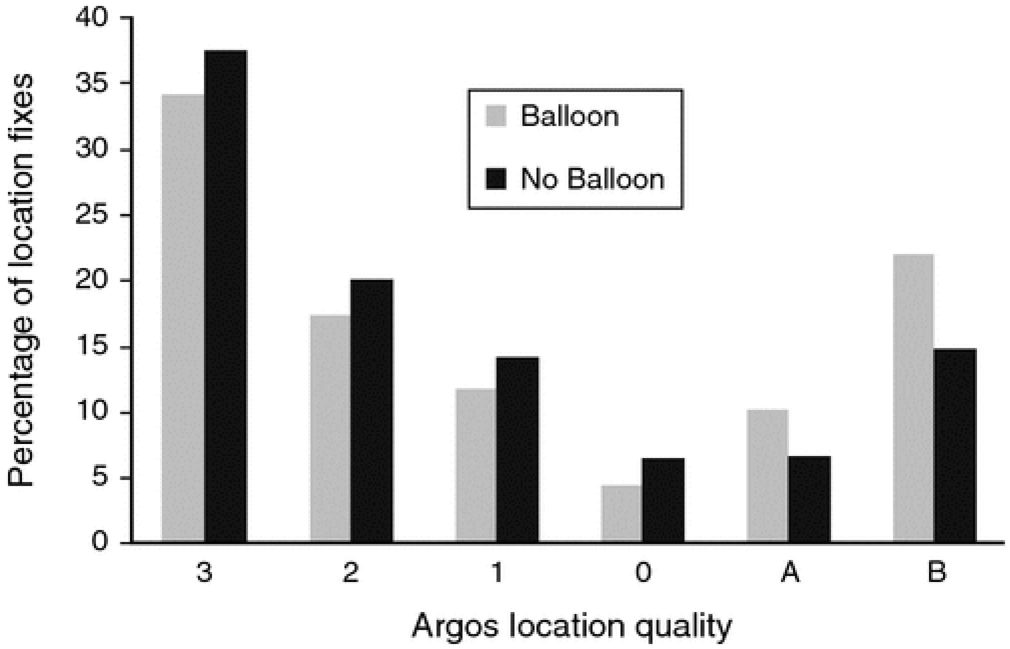

Fig. 3. (*a*) Blue B's chewed tracking device and (*b*) Pink D's shot tracking device.

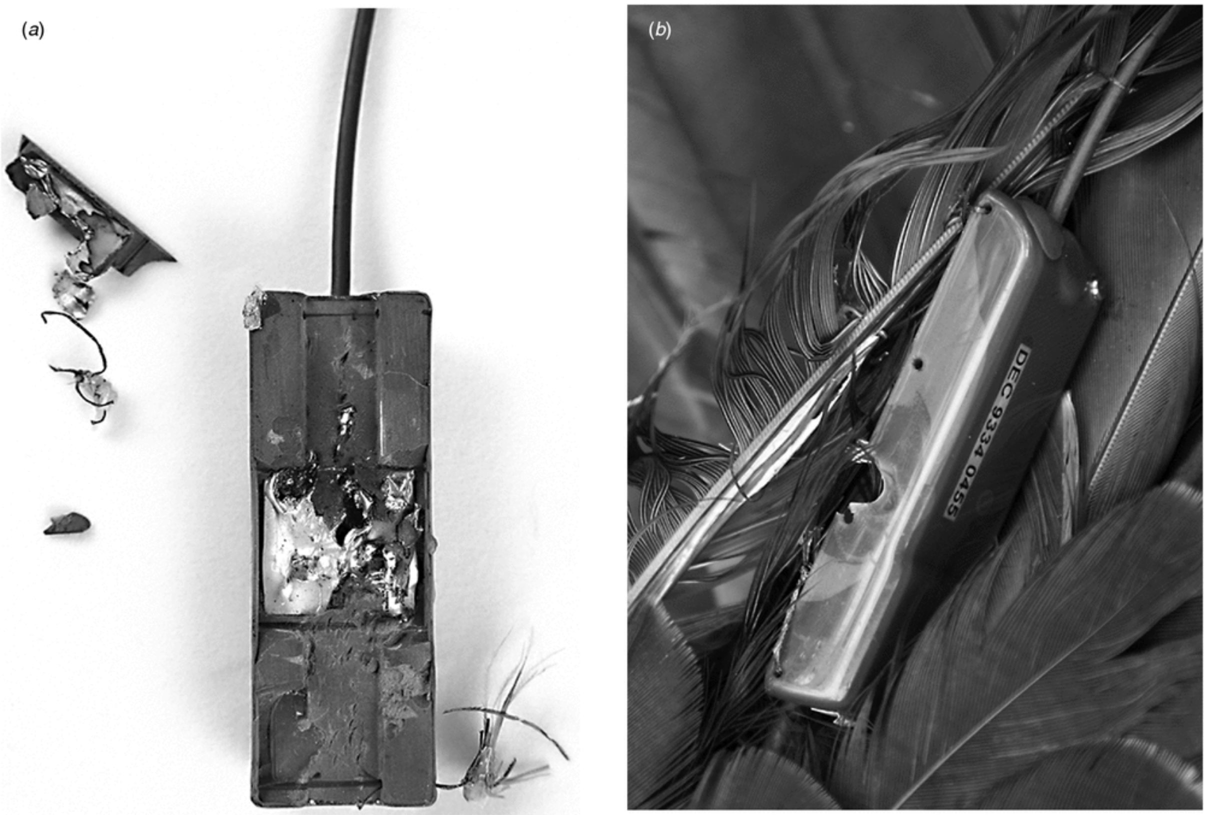

Fig. 4. Influence of mortality on the quality of Argos location fixes for Pink N (*a*) and Baudin #121840 (*b*).

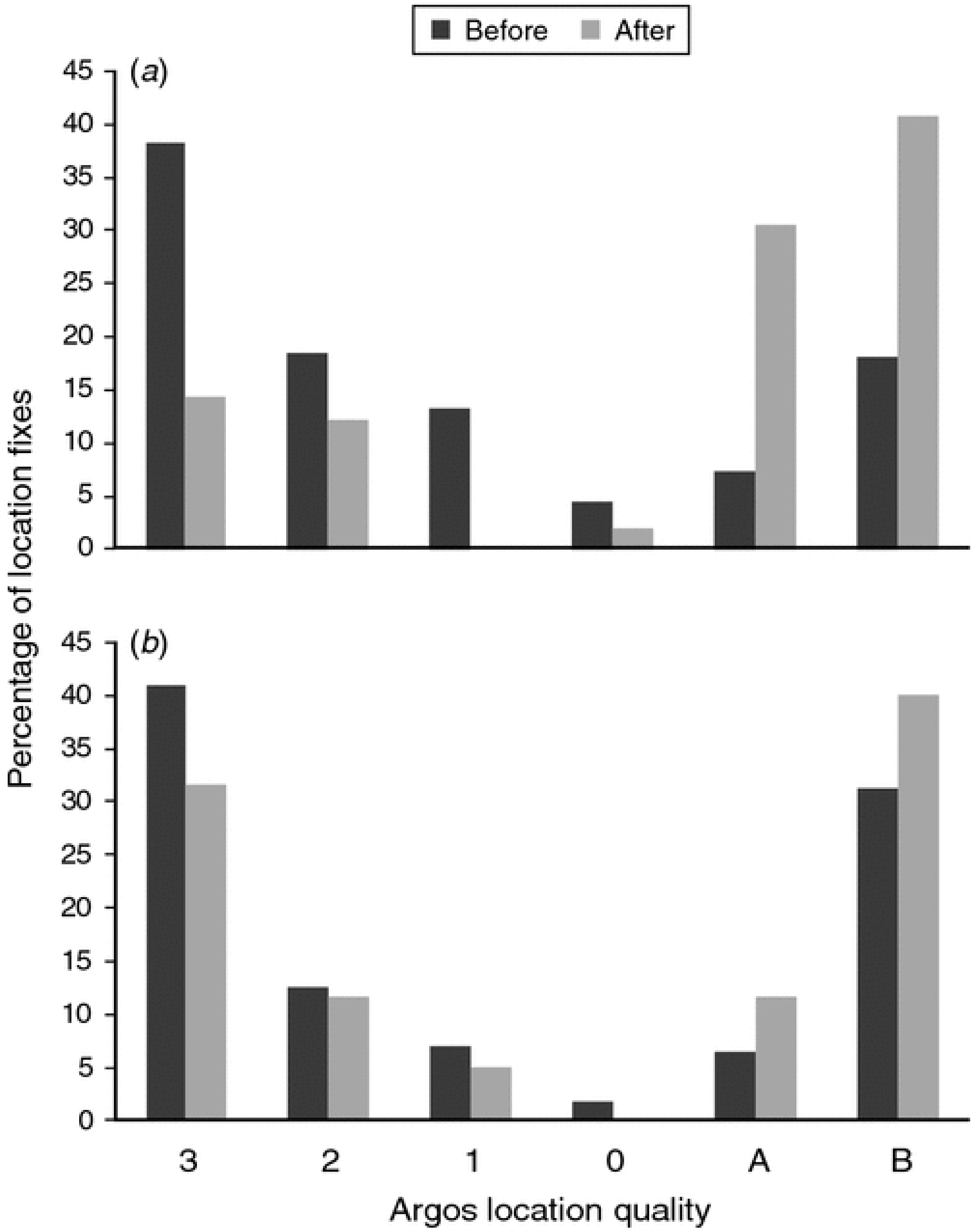

Fig. 5. Movements of black cockatoos (*Calyptorhynchus* spp.) fitted with tracking devices that travelled the greatest distance from release to the north, south and east.

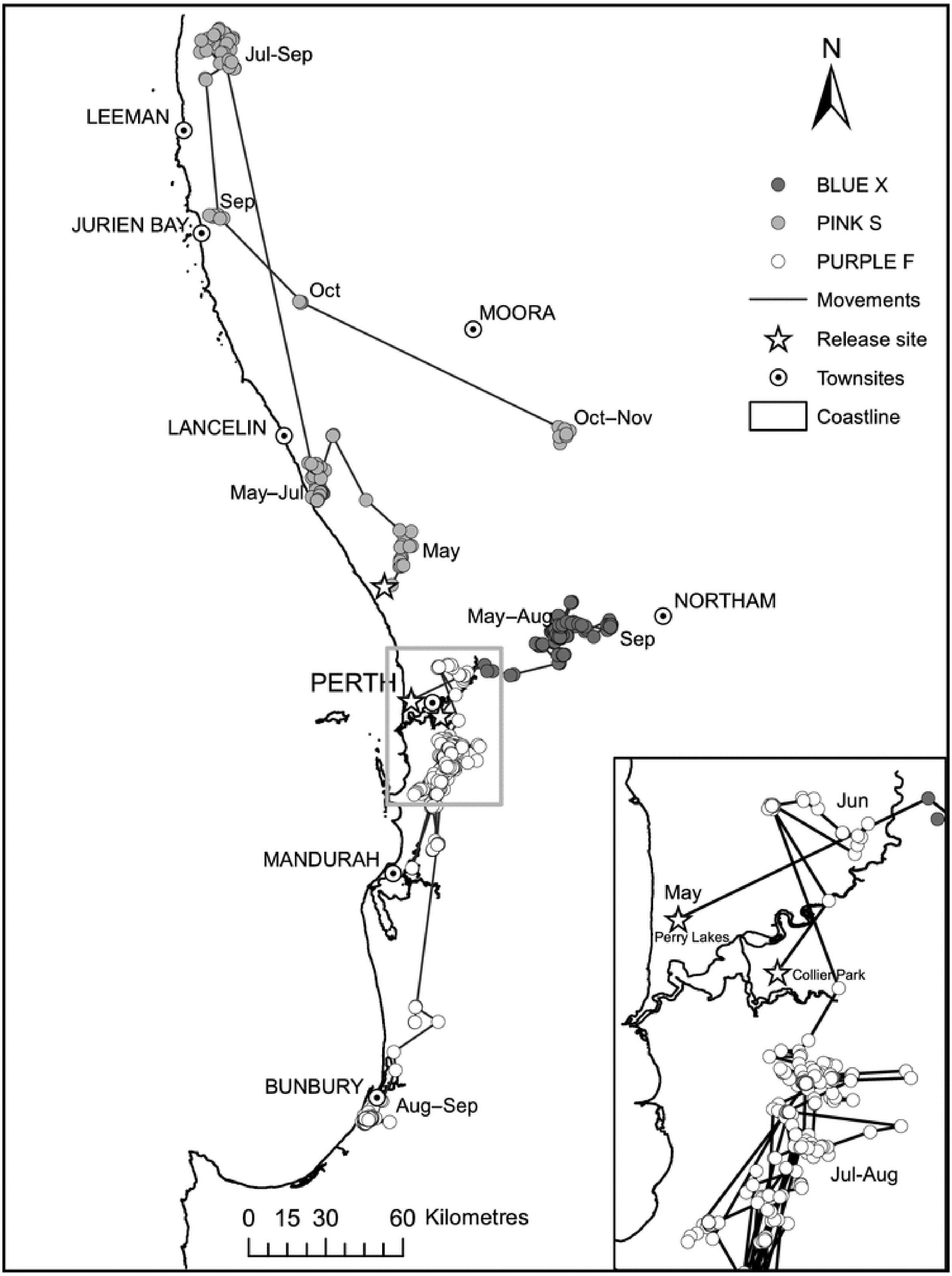

Fig. 6. Foraging movements and roost sites of Green E within the urban landscape of Perth.