THESIS

Development and optimisation of tracking methods to facilitate movement ecology research for the conservation management of black cockatoos in Western Australia.

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This thesis is presented for the degree of

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Thesis Declaration

I Lian Yeap verify that in submitting this thesis;

the thesis is my own account of the research conducted by me, except where other sources are fully acknowledged in the appropriate format,

the extent to which the work of others has been used is documented by a percent allocation of work and signed by myself and my Principal Supervisor,

the thesis contains as its main content work which has not been previously submitted for a degree at any university,

the University supplied plagiarism software has been used to ensure the work is of the appropriate standard to send for examination,

any editing and proof-reading by professional editors comply with the standards set out on the Graduate Research School website, and

that all necessary ethics and safety approvals were obtained, including their relevant approval or permit numbers, as appropriate.

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Date: 30 June 2022

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Publications

Peer reviewed publications: first author and comprising this thesis by publication.

Chapter 2

Yeap, L., Shephard, J., Le Souef, A., Holyoake, C., Groom, C., Dawson, R., Kirkby, T. and Warren, K. (2015). Satellite tracking of rehabilitated wild Baudin's cockatoos, *Calyptorhynchus baudinii*: a feasibility trial to track forest black cockatoos, *Pacific Conservation Biology*, 21(2). doi.org/10.1071/PC14917.

Chapter 3

Yeap, L., Shephard, J., Bouten, W., Jackson, B., Vaughan-Higgins, R. and Warren, K. (2017). Development of a tag-attachment method to enable capture of fine and landscape scale movement in black cockatoos, *Australian Field Ornithology*, 34. doi.org/10.20938/afo3404905.5

Chapter 4

Yeap, L., Warren, K., Bouten, W., Vaughan-Higgins, R., Jackson, B., Riley, K., Rycken, S. and Shephard, J. (2021). Application of tri-axial accelerometer data to the interpretation of movement and behaviour of threatened black cockatoos, *Wildlife Research*, 49 (2). doi.org/10.1071/WR20073

Chapter 5

Yeap, L., Shephard, J., Warren, K.S., Vaughan-Higgins, R., Hopper, L., Riley, K., Rycken, S. and, Jackson, B. (2022). Moult cycle informs retention time in telemetry tagged black cockatoos. This manuscript has been submitted for publication in the journal *Emu*.

Peer reviewed publications: collaborations arising from this thesis

Rycken, S., Warren, K.S., **Yeap, L.,** Donaldson, R., Mawson, P., Dawson, R. and Shephard, J. (2021) Forest specialist species in the urban landscape: do different levels of urbanisation affect the movements of Forest Red-tailed Black Cockatoos (*Calyptorhynchus banksii naso*). *Avian Conservation and Ecology*, 17 (1). doi.org/10.5751/ACE-02061-170111

Rycken, S., Shephard, J. M., **Yeap, L**., Vaughan-Higgins, R., Page, M., Dawson, R., Smith, K., Mawson, P., and Warren, K. (2021). Regional variation in habitat matrix determines movement metrics in Baudin's cockatoos in southwest Western Australia. *Wildlife Research,* 48 (1). doi.org/10.1071/WR19076

Rycken, S., Warren, K., **Yeap, L**., Jackson, B., Riley, K., Page, M., Dawson, R., Smith, K., Mawson, P., and Shephard, J. M. (2018). Assessing integration of GPS-tagged black cockatoos using behavioural change point analysis. *Journal of Wildlife Management,* 83 (2) 334-342. doi.org/10.1002/jwmg.21609.

Thesis structure and overview

This thesis is presented as a thesis by publication. The chapters in this thesis, comprise four manuscripts (three published and one submitted for publication in scientific journals), and as such there is some repetition of information and content, which was unavoidable as the information was required in the individual publications. As each manuscript was prepared and formatted according to the style requirements of each journal, there are some differences in style between the chapters. This is most evident in chapter 4 where the Abstract was subdivided into sections to meet the style requirements of the journal *Wildlife Research.* Whilst the content of these chapters is the same as the published manuscripts, some changes have been made to table, figure, and page numbers to comply with thesis formatting requirements and to maintain continuity of the document. Chapters 3 and 5 use International Ornithological Congress (https://www.worldbirdnames.org/new/bow/parrots/) nomenclature for Carnaby's (*Zanda latirostris*) and Baudin's cockatoos (*Zanda baudinii*) as required by *Australian Field Ornithology* and the journal *Emu,* however this nomenclature is not typically used to refer to these species and therefore the other publications and chapters use the standard scientific names for these species. A statement of author attribution precedes each manuscript.

Chapter 1 provides a general introduction to wildlife tracking and a comprehensive literature review of the three species of black cockatoos in Western Australia - Carnaby's, Baudin's and forest red-tailed, including information on biology and ecology, morphological descriptions, distribution and habitat preferences, conservation status and threats.

Chapter 2 details the successful proof of concept trial to assess the feasibility of using tail-mounted satellite tags to track Baudin's cockatoos post-release. The Telonics tags provided reliable data that allowed one bird to be tracked for over 250km from the release site. The trial demonstrated satellite tags were a useful tool for locating and tracking forest black cockatoo species which are otherwise difficult to track and monitor. Findings from this chapter have been published in Pacific Conservation Biology (Yeap *et al.* 2015).

Chapter 3 outlines the progression of tagging and tracking studies and details the development of a double-tag mounting protocol and associated aviary trials with captive birds. Combinations of tail-mounted satellite tags and back-mounted GPS tags were attached to captive black cockatoos and the functionality and tolerance assessed. The combination of Telonics tail-mounted ARGOS satellite tags and a UvA-BiTS back-mounted GPS tag was best tolerated by the study birds and deemed the optimal system for post-release tracking of all three species. Findings from this chapter have been published in Australian Field Ornithology (Yeap *et al.* 2017)

Chapter 4 focuses on the development of an automated classifier tool used to classify tri-axial accelerometer data from UvA-BiTS tags. These tags also generate GPS location data. The classifier was developed using data and video footage from tagged captive birds and identified resting, flying and foraging behaviours with 86% accuracy. Application of the classifier tool to data from released cockatoos enabled researchers to remotely identify behaviour patterns and calculate activity budgets for all three species of cockatoo, providing insight into movement, distribution and habitat use. Findings from this chapter have been published in Wildlife Research (Yeap *et al.* 2021).

Chapter 5 describes the study undertaken to investigate lifespan and timing of moulting of the tail feathers of Carnaby's cockatoos, Baudin's cockatoos and forest red-tailed black cockatoos. This data were used to determine the optimal time to attach telemetry tags to the central tail feathers to maximise tag retention and data collection. The mean tail feather lifespan for captive birds was 410 days, suggesting the feathers do not always moult annually. Tail feathers can moult year-round but the majority are lost from October to April, peaking from December to March. The optimal time to attach tail-mounted tags is at the end of the moulting period, from May to September. The manuscript for this chapter has been submitted for publication in the journal *Emu*.

Chapter 6 is a general discussion of the results of the previous chapters, in relation to the significance and implications for black cockatoo conservation and management. Knowledge gaps and potential areas for future research have also been identified.

Abstract

The three black cockatoo species endemic to south-west Western Australia – Carnaby's cockatoo (*Calyptorhynchus latirostris*), Baudin's cockatoo (*C. baudinii*) and forest red-tailed black cockatoo (*C. banksii naso*) are threatened and have Recovery Plans guiding conservation efforts. Threats include habitat loss due to land clearing for urban, agricultural and industrial development; competition with other species for nest hollows; poaching; disease; vehicle-strike and illegal shooting.

This research built on previous black cockatoo research with an overall aim to develop and validate reliable methods to track all three species, to gain insight into their movement, distribution, habitat use, activity and behaviour.

In an initial proof of concept trial, we attached tail-mounted tags to two Baudin's cockatoos. Both birds were successfully tracked for several months after release, demonstrating satellite telemetry can be used to locate and track forest species.

We then developed a double-tag mounting protocol to attach a tail-mounted ARGOS PTT satellite tag and back-mounted solar-powered UvA-BiTS GPS tag to captive black cockatoos. The combination of UvA-BiTS back mount and ventral tail mounted Telonics tags was the best tolerated and provided excellent GPS and ARGOS satellite location data with no interference between the two types of tag.

The focus then moved to the development of an automated classifier tool that used accelerometer data from UvA-BiTS GPS tags to remotely identify behaviours and calculate activity budgets. Using accelerometer data from 15 birds post-release, we determined black cockatoos spend most of their time at rest, interspersed with foraging activity through the day and some movement between roost sites and feeding habitat.

To maximise the retention time of tail-mounted tags, the tail feather life span and time of moulting was studied using moulted tail feathers from captive cockatoos and tagged bird post-

release. Captive cockatoos had a mean feather lifespan of 410 days, suggesting tail feathers do not always moult annually. Peak tail feather moulting occurs from December to March, the non-breeding period. The optimal time to attach tail mounted tags is from May to September.

The development and optimisation of tracking methodologies for use on black cockatoos has facilitated the tracking of all three species in the wild. This research has provided data which have enabled identification of key roosting, foraging and breeding habitat and determination of flock movement patterns and habitat use at a landscape scale across the species' distribution ranges. This information is being used to guide black cockatoo conservation management in relation to habitat protection and restoration.

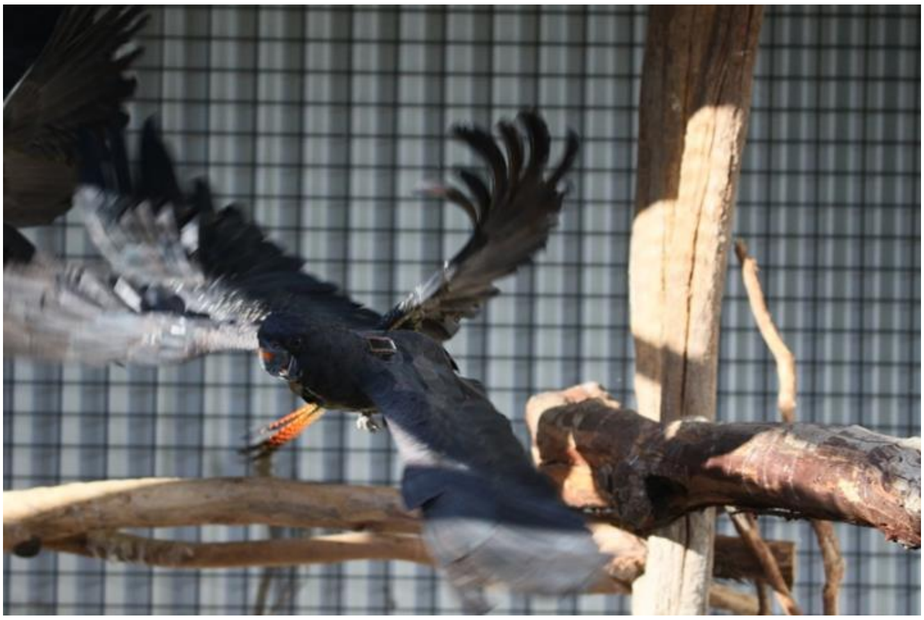

Photo: Karen Riley

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Glossary of Abbreviations

AVI	Audio Video Interleave video file format
ABBBS	Australian Bird and Bat Banding Scheme
BC	Baudin's cockatoo
CC	Carnaby's cockatoo
DBCA	Department of Biodiversity, Conservation and Attractions, Western Australia
DEC	Department of Environment and Conservation, Western Australia
EPA	Environmental Protection Authority
EPBC Act	Environment Protection and Biodiversity Conservation EPBC Act 1999
GME	Geospatial Modelling Environment
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global system for Mobile Communication
IUCN	International Union for the Conservation of Nature
KBCCC	Kaarakin Black Cockatoo Conservation Centre
PIT	Passive Integrated Transponder
PTT	Platform Transmitter Terminal
RTBC	Forest red-tailed black cockatoo
SCP	Swan Coastal Plain
SEWPaC	Australian Government Department of Sustainability, Environment, Water, Population and Communities
UvA-BiTS	University of Amsterdam Bird Tracking System
VHF	Very High Frequency 30-300MHz radio frequency
WA	Western Australia

Chapter 1. Introduction and Literature Review

Cockatoos (Order Psittaciformes, Family Cacatuidae) are large parrots, predominantly found in the Australasian region. Of the 21 recognised species, fourteen occur on the Australian mainland. There are five black cockatoo species in the genus *Calyptorhynchus* – the red-tailed black cockatoo (*C. banksii*), glossy black cockatoo (*C. lathami*), yellow-tailed black cockatoo (*C. funereus*), Carnaby's cockatoo (*C. latirostris*) and Baudin's cockatoo (*C. baudinii*). Black cockatoos are easily recognised by their predominantly black plumage, large beaks, coloured tail bands and distinctive call (Cameron 2007).

This PhD thesis focusses on the three black cockatoo species endemic to the south-west of Western Australia – the forest red-tailed black cockatoo (*C. banksii naso*), Carnaby's cockatoo and Baudin's cockatoo. Western Australia (WA) is home to many flora and fauna species unique to the region. The south-west of WA is the only Global Biodiversity Hotspot in Australia and one of only 34 around the world (The Western Australian Biodiversity Science Institute 2021). WA is also renowned for its' vast mineral resources and successful agricultural sector, both supported by an ever-growing population. In 2001, the population in WA was approximately 1.9 million people (Australian Bureau of Statistics 2019). By the end of 2020 this had grown to 2.67 million people, the majority living in the Perth metropolitan area (Australian Bureau of Statistics 2021). This rapid population growth has led to increased land clearing in the south-west for urban development, and in regional areas for mining and agriculture expansion. As a consequence, many ecosystems and species in these areas are now threatened (The Western Australian Biodiversity Science Institute 2021).

Black cockatoo populations have been declining in both number and breeding distribution for the last 50 years and all three species are the subject of species recovery plans. Recovery plans are used to guide conservation efforts – identifying threats and how to mitigate or manage them, directing research efforts and monitoring populations. The ability to locate and track black cockatoos and identify existing and potential feeding, breeding and roosting habitat is a vital part of the recovery plans (Department of Environment and Conservation 2007, 2012).

1.1 Wildlife Tracking

Tracking animals, associated with hunting for food, was a skill considered vital for the evolution of modern humans (Liebenberg 2013). Tracking generally involves visualising signs of animal activity and presence – from footprints on the ground (spoor), scrape marks and trails through vegetation to identification of scat or faeces (Stander *et al.* 1997). Tracking is considered non-invasive and can provide information, not only on the presence of animals in an environment, but also their behaviour and habits, without direct observation or handling (Elbroch *et al.* 2012). Whilst the systematic tracking of individual animals started in the early 1900s, with the establishment of the early bird banding or ringing schemes, renowned ornithologist James Audubon is credited with the first bird banding in the USA. In 1804, he attached silver thread to legs of a pair of Eastern phoebes as they were preparing to leave their nest for the season. The birds returned the following spring with the thread still attached (Rhodes 2004).

Modern banding or ringing involves the attachment of a physical tag (such as an ear or wing tag), leg band or ring to and individual animal, which requires its capture and handling. Other forms of permanent marking include tattoos, brands and ear-notching. Natural markings, such a distinctive coat pattern can also be used to identify animals (Silvy *et al.* 2012). Prior to the development and application of telemetry, most wildlife ecological and physiological studies involved trapping, observation and surveys. Locating and recapturing animals to assess and monitor them over time proved challenging (Weaver *et al.* 2021) (Wikelski *et al.* 2022). In the late 1950s LeMunyan *et al.* (1959) developed a Very High Frequency (VHF 30-300MHz radio frequency) radio transmitter to facilitate the location and recapture of previously tagged animals. The transmitter was implanted into the abdominal cavity or subcutaneous tissue of woodchucks (*Marmota monax*). Whilst the trial was successful, the transmitter was considered too expensive, transmission range too short and the size too large for use on animals smaller than a woodchuck. The first tracking device attached to a bird was reported in 1962 by Lord *et al.* (1962) who attached a radio-transmitter to the back of a Mallard duck (*Anas platyrhynchos*). Whilst the intention of the study was location of the tagged animals and radio-tracking movements, the researchers inadvertently also captured wingbeat and respiratory frequency. In

1963 Cochran *et al.* (1963) attached battery powered VHF radio transmitters to rabbits (*Sylvilagus floridanus*), skunks (*Mephitis mephitis*) and racoons (*Procyon lotor*) to study home ranges and activity. In 1972 Bray *et al.* (1972) developed a method for attaching radio transmitters to the tails of Starlings (*Sturnus vulgaris*) and red-winged blackbirds (*Agelaius phoeniceus*) using a tail clip. The transmitters were retained for up to 25 days and were shed when the birds moulted. Following on from this, Kenward (1978) developed a method for attaching VHF radio transmitters to the tail feathers of Goshawks (*Accipiter gentilis*) to further study their behaviour and hunting.

By the late 1970s, the use of VHF radiotracking and telemetry to locate animals for direct observation was commonplace. Broader applications included locating animals' roosts, nests and dens and the use of telemetry darts to assist with locating an animal after darting and immobilisation (Mech 1979). The use of satellite tracking was first reported in the early 1970's by (Craighead *et al.* 1971) who used transmitter collars to remotely locate and track black bear (*Ursus americanus*) and elk (*Cervus canadensis*). With increasing requirements for fine scale location data, Rempel *et al.* (1995) investigated the use of Global Positioning System (GPS) location data to track free-ranging moose (*Alces alces*) in forest habitat. Data is provided by 27 satellites, with each satellite orbiting the Earth twice a day (National Coordination Office for Space Based Positioning 2022).

Publication of telemetry studies has increased significantly in the last 20 years (Weaver *et al.* 2021). Whilst historically the use of the terms transmitter and tag have been used synonymously, in the scientific community there has been an evolution in the use of terminology, with a shift over time to the use of the term tag. Tags have become more accessible to researchers and tag technology continues to advance, including reductions in weight and size, reduced price and increased features (Weaver *et al.* 2021). A recent review of bird tracking studies by Geen *et al.* (2019) showed most research prior to the 1990s used radio tags and were short studies of range, habitat use and foraging. In recent years, migration has become the focus, facilitated by GPS and satellite tags. Bouten *et al.* (2013) suggested the ideal tag should be lightweight, provide three-dimensional location data, flexible measurement schemes, be able to transmit data remotely and measure both environmental and animal parameters. Tags incorporating GPS technology, accelerometers and solar charging are widely available (Bouten *et al.* 2013) and allow long distance remote tracking (Thomas *et al.* 2011). Accelerometers measure body acceleration or change in velocity, fine movements and posture. Specific behaviours, and associated movements and postures, show distinct accelerometer signatures (Brown *et al.* 2013). The use of tags containing tri-axial accelerometers can generate large amounts of behavioural data, far more than could be collected by direct observation of the animal (Cooke *et al.* 2004). Tags using the ever-expanding cellular data networks are also increasing in availability. These have the benefit of transmitting over shorter range so use less power. The downside is reliance on having cellular network coverage which may be limited in remote locations (Bridge *et al.* 2011). An overview of current telemetry technology and data transmission methods is provided in Table 1.1.

Reduction in tag size and increased battery life has made devices more useful for studying birds. The attachment of devices can impact on bird behaviour and ecology, such as increased energy expenditure due to the extra weight, decreased likelihood of nesting, stress of handling for attachment (reduced by anaesthesia), thus the benefits of using transmitters must be weighed against the potential impacts (Casper 2009; Barron *et al.* 2010). In order to reduce the impact to birds and ensure an ethical approach to tracking, ethical standards have been recommended - for example the recommended maximum weight of tags is less than three percent of bodyweight (Barron *et al.* 2010; Vandenabeele *et al.* 2012). Researchers must ensure that the tags used are appropriate for the species and the environment being studied. Tag attachment should not cause injury, restrict or affect normal movement, postures, behaviour or impact on physiologic processes. Tag shape, colour and placement should be considered as it may impact on vulnerability to predators. The method of tag attachment must also be considered. Collars and harnesses may increase the risk of snagging on vegetation or entrapment of body parts. Other animals may bite or damage the tag and the animal to which it is attached. The potential impact on animals which are growing quickly must be also be considered e.g., collars becoming too tight and causing strangulation as the animal grows. The use of safe, temporary attachment methods should be investigated and developed, particularly if recapture of the animal is unlikely (Casper 2009). Studies by Barron *et al.* (2010) and Geen *et al.* (2019) found the use of tail or leg attachment methods and attachment with glue had the least reported adverse effects on birds, but the short retention time can limit their use.

Table 1.1 Overview of telemetry technology and data transmission methods currently used for animal tracking.

Telemetry type	Signal and data transmission methods
VHF radio tracking	Tags emit very high frequency radio signal detected by antenna and receiver. Location calculated by triangulation using multiple bearings, visualising the animal or by an automated VHF tower. Accuracy varies with equipment used, local conditions and operator skill (Thomas *et al.* 2011; Wikelski *et al.* 2022).
Cellular data (mobile phone) networks	Tags send and receive data via cellular data (mobile phone) networks and infrastructure (Garg 2007). Location calculated by triangulation using data from multiple cell towers. More accurate (within 100m) in urban areas with higher density of cell towers (Trogh *et al.* 2019). - General packet radio service (GPRS) – data transmitted on the Global system for Mobile communication (GSM) network – includes second (2G) and third generation (3G) networks. Slow data transfer rate. Deployed 1998. 3G is most commonly used network globally (Ndungu *et al.* 2021). - Long-term Evolution (LTE) fourth generation (4G) – higher speed data transfer. Requires large, high power cell towers for transmission over long distances. Deployed 2009, replacing 3G in USA, Western Europe and many countries including Australia (Jones *et al.* 2021). - Fifth generation (5G) – Very high-speed data transfer. Signals transmitted short distances via numerous small cell stations. Currently being deployed around the world (Gillis *et al.* 2022).
Argos	Platform transmitter terminal (PTT) signal detected by polar-orbiting Argos satellites as they pass over the PTT (up to 14 times/day). Data transmitted to Argos receiving stations then to processing centres - location calculated from change in frequency of the signal as the satellite moves (doppler effect). Location can be accurate to within 150m (Argos System. 2022).
Global Positioning System (GPS)	Tags receive transmissions from 27 satellites orbiting Earth. High location accuracy (within metres) when 4 or more satellites in view of the tag (Wikelski *et al.* 2022). Can provide data on speed, direction, enable geofencing of the animal (Katzner *et al.* 2020). Different data download methods used to determine location. - Satellite networks (Argos, Iridium, geostationary) - Cellular data networks (GSM, GPRS, 4G LTE, 5G) - Store on board (SOB) – location data stored on tag, downloaded when base station in range, animal recaptured or tag falls off and retrieved (Thomas *et al.* 2011).
Acoustic	Tags emits sound signals - received and recorded by underwater microphones (hydrophones) at known, fixed locations. Data periodically retrieved from receivers (Heylen *et al.* 2018).
Light-level Geolocation	Archival tags – location calculated by comparing sunrise and sunset times and current light levels. Tag retrieved, data downloaded manually and locations determined(Thomas *et al.* 2011; Wikelski *et al.* 2022). Environmental factors such as weather, vegetation can affect light intensity and location accuracy (Lisovski *et al.* 2012).
Passive integrated transponders (PIT)	Tags made up of integrated circuit chip, capacitor and antenna coil in glass case (microchip). Usually implanted under skin or into body cavity of the animal. Activated by low frequency radio signal sent by nearby scanning device that generates close range electromagnetic field. Tag sends its unique alpha-numeric code back to the scanning device. Scanner can be hand-held, stationary or automated. Tags can stop functioning or migrate out of the animal (Smyth *et al.* 2013).
Autonomous drone	Unmanned flying devices used to track tagged animal. Tags transmit GPS location data via cellular data network to control device. Control device sends location data and commands to drone, which flies to location (Tansuriyavong *et al.* 2018). Proprietary tracking tags (https://www.apple.com/au/airtag) transmit location via Bluetooth (short range wireless data transfer) and cellular data networks. Receiver (Apple iPhone) attached to drone receives location data and flies to location (Mesquita *et al.* 2022). Emerging technology.

Tag selection will depend on the type of data required, constraints imposed by the animal and environment, as well as the costs associated with the tag. GPS tags are often preferred as they can provide more frequent and accurate location data, but usefulness may be limited by their greater size, weight and reduced functionality in some environments e.g., underground. The use of ARGOS or VHF tags alone or in combination with a GPS tag can overcome these issues (Thomas *et al.* 2011).

The use of telemetry has seen ecological studies progress from tracking the movement of a few animals to complex studies of migration, behaviour, ranges, human-wildlife conflict and impacts of climate change enabling researchers to develop a better understanding of behaviour of endangered species (Thomas *et al.* 2011). Conservation issues have been identified through tracking and tagging studies. In the early 1980's, populations of migratory Swainson's hawks (*Buteo swainsoni*) in North America were in significant decline, with fewer birds returning in spring. Tagged hawks were located and observed feeding on grasshoppers on farms in Argentina. Several days later, a tagged bird was found dead at a nearby roosting site, amongst a group of hundreds of dead birds. Testing confirmed organophosphate toxicity from an agricultural pesticide. The pesticide was subsequently banned by the Argentinian government and no further die-offs were recorded (Cohn 1999).

This project builds on preliminary black cockatoo tracking and telemetry research and aimed to develop and validate reliable methods of tracking all three species of black cockatoo, gaining insight into their movement, distribution, habitat use, activity and behaviour.

1.2 Black Cockatoo Biology and Ecology

1.2.1 Carnaby's cockatoo

Description

Carnaby's cockatoo, sometimes referred to as the short-billed black cockatoo, was first described in 1948 by naturalist Ivan Carnaby. At that time, it was thought to be a sub-species of Baudin's cockatoo (Johnstone 2010b). Studies documented by Saunders (1974b) and Campbell *et al.* (1976) subsequently found differences in skull and beak shape and size, distribution, seasonal movements and dietary preferences. Differences have also been noted in their calls (Johnstone *et al.* 2011).

Carnaby's cockatoos are large birds, with adults weighing from 500 to 790g and 53 to 58cm in length. Feathers on the body are dark brown to black with an off-white edge. The tail feathers are black with a broad white band, except the two central tail feathers which are solid black. Males have a dark grey/black beak, pink/red peri-orbital ring and dull off-white cheek patch. Females have a pale grey/white beak, grey peri-orbital ring and bright off-white/pale yellow cheek patch, as shown in Figure 1.1. Juveniles have a smoother, duller beak but otherwise look similar to adult females. Carnaby's cockatoos have a distinctive "weeyou-weeyou" call, a recording of this call is accessible on the Birdlife Australia website https://www.birdlife.org.au/projects/southwest-black-cockatoo-recovery/identify-your-black-cockatoo (Johnstone 2010b; Department of Environment and Conservation 2012; Department of Biodiversity Conservation and Attractions 2017).

Figure 1.1: Male (left) and female (right) Carnaby's cockatoos showing sexually dimorphic differences in appearance. (Photo: Karen Riley)

Distribution, Habitat and Diet

Carnaby's cockatoos have a wide distribution throughout the south-west of WA, extending north to the Murchison River, south-east to the Esperance area and east into inland agricultural areas such as Coorow, Lake Cronin and Ravensthorpe (Johnstone 2010b; Johnstone *et al.* 2011; Department of Environment and Conservation 2012) as shown in Figure 1.2. After breeding (January to July), the majority of birds tend to migrate, in small flocks, from the drier inland breeding areas to the higher rainfall coastal foraging areas in the west and south, including the Swan Coastal Plain (SCP), the 30km wide, biologically diverse plain bound by the Darling Scarp to the east, Indian Ocean to the west and extending from the Perth metropolitan area south to Cape Naturaliste (Mitchell *et al.* 2002). Populations residing in southern jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) forest have been thought to remain in these regions during breeding and non-breeding periods (Saunders 1980; Johnstone *et al.* 1998; Berry 2008; Johnstone *et al.* 2011).

The distribution and range of the species has changed and contracted by about 30% over the last 50 years, largely due to loss of suitable breeding and feeding habitat in what are now agricultural areas, forcing the cockatoos further west and south (Saunders 1990; Johnstone *et al.* 1998; Johnstone *et al.* 2011; Johnston 2013; Saunders *et al.* 2013).

Carnaby's cockatoos are found in areas of remnant and uncleared kwongan heath, wood and shrublands, particularly where proteaceous plant species, such as *Banksia*, *Dryandra* and *Hakea* are prolific. The diet includes the seeds, flowers and nectar from these species, as well as *Eucalyptus* species such as jarrah, *Corymbia* species such as marri and *Grevillia* species. With ongoing land clearing and habitat loss, the seeds of plantation pines (*Pinus* sp) have also become a vital food source, along with crops such as the oilseed canola (*Brassica rapa* or *B. napus*), fruit and nut trees such as apples (*Malus domestica*), macadamia (*Macadamia* sp) and persimmon (*Diospyros* sp). Insects and insect larvae may also be consumed (Cameron 2007; Johnstone *et al.* 2011). Carnaby's cockatoos feed both in the tree canopy and on the ground.

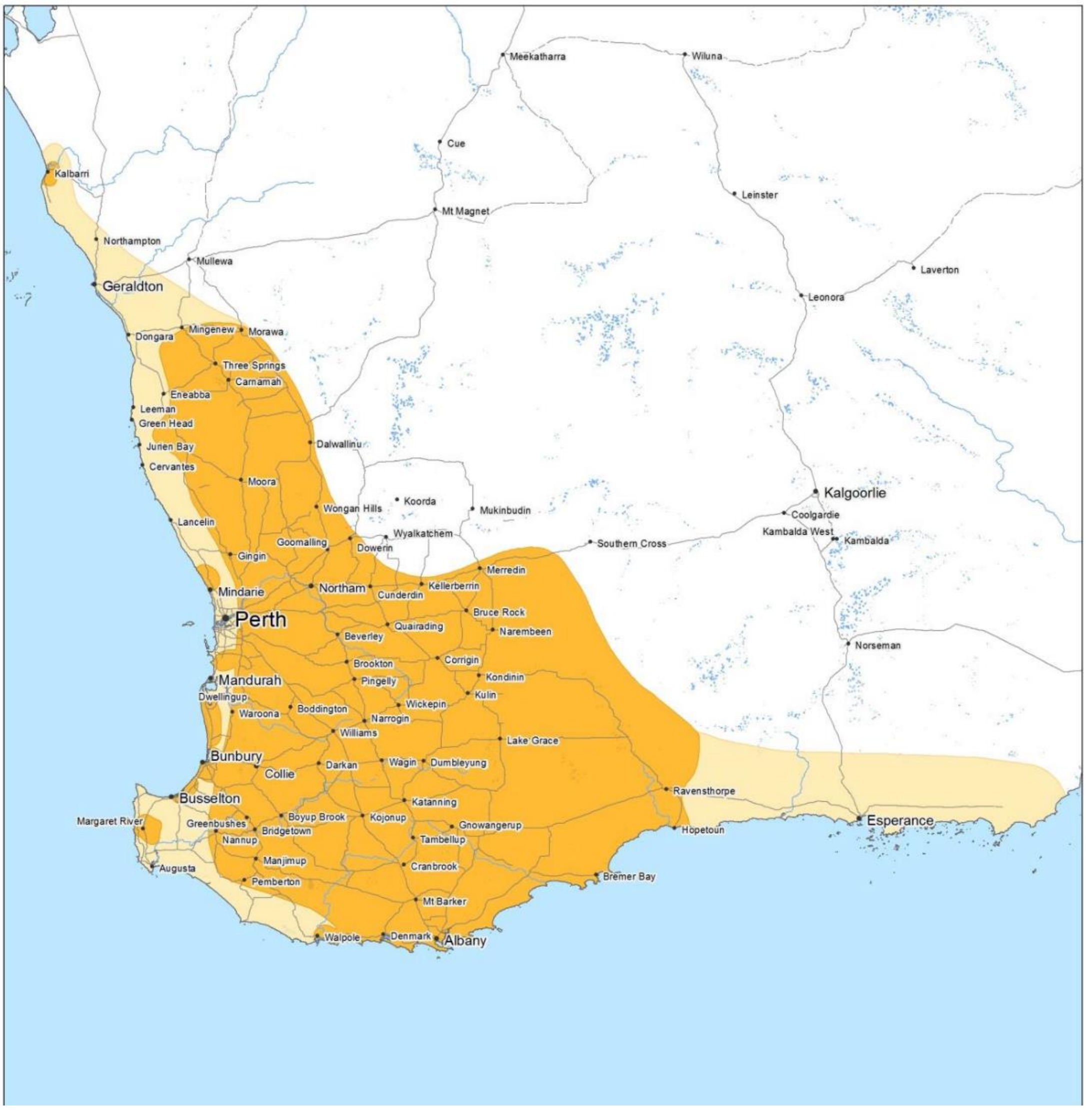

Figure 1.2: Modelled Carnaby's cockatoo distribution. Legend: orange - breeding range, yellow - non-breeding range (Department of Sustainability, Environment, Water, Population and Communities 2012).

Reproduction

The Noongar are the traditional owners and inhabitants of the south-west of Western Australia. They have long revered the Carnaby's cockatoo as a totem and refer to the cockatoos as Ngoolark (Abbott 2009) and regard them as harbingers of rain. West Australians often refer to them as 'rain birds' as the beginning of Autumn (March to May) rains historically were closely associated with the commencement of Carnaby's cockatoo breeding season (Thorburn 2020). Saunders *et al.* (2013) demonstrated the start of Autumn rains trigger both physiologic changes to begin egg and sperm production and behavioural changes to strengthen pair bonds, migrate to breeding grounds, and find and prepare nest hollows.

Carnaby's cockatoos nest in hollows formed in large eucalyptus trees, such as salmon gums (*E. salmonophloia*) and wandoo (*E. wandoo*) found in the inland breeding areas, but also marri and other tree species. They have also bred successfully in artificial nest hollows installed in known breeding areas, such as Coomallo Creek (Saunders *et al.* 2020) as shown in Figure 1.3. On the SCP, tuart trees (*E. gomphocephala*) are preferred. One or two eggs are laid at the bottom of the hollow from July to December, with usually only one chick surviving (Saunders 1982; Johnstone 2010b; Johnstone *et al.* 2011). Having suitable feeding habitat in the vicinity of breeding grounds is critical for breeding success and chick survival (Johnstone *et al.* 2011).

Conservation status

Carnaby's cockatoo populations have declined by at least 50% in the last 50 years (Saunders *et al.* 1998; Department of Environment and Conservation 2012) with the current population estimated to be somewhere between 11000 and 60000 birds. Feedback from the Recovery Team suggests the population is estimated to be approximately 40000 birds (Saunders *et al.* 1985; Birdlife International 2022). Given these declines, the Carnaby's cockatoo is afforded protection as fauna that is 'likely to become extinct' under the *WA Wildlife Conservation Act 1950* (Department of Environment and Conservation 2012)and is listed as Endangered under the *Commonwealth Environment Protection and Biodiversity Conservation Act (EPBC) 1999* (Department of Sustainability, Environment, Water, Population and Communities 2012), since it meets criteria to be listed as Endangered on the IUCN Red List (IUCN 2020).

Figure 1.3: Female Carnaby's cockatoo on an artificial nest hollow, Coomallo Creek. (Photo: Karen Riley)

1.2.2 Baudin’s cockatoo

Description

Baudin’s cockatoo was first described in the early 1800’s and named after French commander and explorer Captain Thomas Nicolas Baudin in 1832 (Department of Environment and Conservation 2007; Johnstone 2010a). Baudin’s cockatoos bear a close resemblance to Carnaby’s cockatoos and for many years were considered to be the same species.

Baudin’s cockatoos are a similar size to Carnaby’s cockatoos, weighing 560 to 770g and 50 to 60 cm in length. Their appearance is much the same as Carnaby’s cockatoo with body feathers being dark brown to black with an off-white edge. The tail feathers are black with a broad white band, except the two central tail feathers which are solid black. Males have a dark grey/black beak, pink/red peri-orbital ring and dull off-white cheek patch. Females have a pale grey/white beak, grey peri-orbital ring and bright off-white/pale yellow cheek patch. As with Carnaby’s cockatoos, juvenile Baudin’s cockatoos look much like females of the species (Figure 1.4). Baudin’s cockatoos have a much longer and slightly narrower upper beak compared to Carnaby’s cockatoos. Their call is described as a “whicha-whicha” which is slightly shorter duration than Carnaby’s cockatoos. (Department of Environment and Conservation 2007; Johnstone 2010a). A recording of their call is accessible on the Birdlife Australia website https://www.birdlife.org.au/projects/southwest-black-cockatoo-recovery/identify-your-black-cockatoo.

Distribution, Habitat and Diet

Baudin’s cockatoo is generally regarded as a forest species though this species has also been identified in more cleared agricultural areas (Department of Environment and Conservation 2007). This species occupies areas of south-west Western Australia with high annual rainfall over 600mm (Johnstone and Kirkby 2017), with a range extending north east to Gidgegannup in the Perth hills, east to the edge of the SCP and south to Albany. The distribution map for Baudin’s cockatoos is shown in Figure 1.5. Unlike Carnaby’s cockatoos, there is little data on previous and current distribution of Baudin’s cockatoos. This is largely due to the difficulties in finding and tracking the birds in thick forest canopy using traditional methods. In addition, much of the early black cockatoo research did not differentiate between these two black cockatoo species. (Department of Environment and Conservation 2007).

Figure 1.4: Male (left) and female (right) Baudin's cockatoos. Note the showing sexually dimorphic differences in appearance and distinctive long upper beak. (Photos: Sam Rycken)

The preferred habitat is the southern forest comprising mainly jarrah, marri and karri (*E. diversicolor*). Research by (Johnstone *et al.* 2008) has shown the Baudin's cockatoos move away from their nesting and breeding grounds in late summer (February, March), forming large flocks that forage and roost along the Darling Scarp and west onto the SCP. Most birds then return to the southern breeding grounds by the middle of Spring (October) (Department of Environment and Conservation 2007; Johnstone *et al.* 2008).

The diet is similar to Carnaby's cockatoos - predominantly seeds, flowers and nectar of marri but also jarrah, karri and other eucalypts, along with *Banksia* and *Hakea* species (Johnstone 2010a). Baudin's cockatoos also consume beetle larvae foraged from under tree bark. Whilst Baudin's cockatoos do not feed extensively on pine seeds, they do feed on the seeds of apple and pears (*Pyrus* sp) and can cause extensive fruit damage in commercial orchards, to the point of being considered a pest by some growers (Chapman 2007; Department of Environment and

Conservation 2007). Baudin's cockatoos have also been observed feeding on nuts such as pecan (*Carya illinoisensis)* and *Macadamia* species (Johnstone *et al.* 2008). As with Carnaby's cockatoos, Baudin's cockatoos forage at all levels from the tree canopy to on the ground. (Johnstone 2010a)

Reproduction

Baudin's cockatoos also nest in large tree hollows, mainly of marri, karri and wandoo trees (Johnstone *et al.* 2008). Nests can be difficult to locate, so less is known about the breeding cycle and reproduction. Birds are thought to reach breeding age at around 4 years, with females laying one or two eggs from late winter to spring (August to December). Only the female incubates the egg/s and usually only one chick is raised (Department of Environment and Conservation 2007).

Conservation Status

The Baudin's cockatoo population is thought to have declined in over half its known range (Garnett *et al.* 2000; Department of Environment and Conservation 2007). The current population estimate is 5000 to 8000 birds (Garnett *et al.* 2021). Like the Carnaby's cockatoo, the Baudin's cockatoo is considered fauna that is 'likely to become extinct' under the *WA Wildlife Conservation Act 1950* (Department of Environment and Conservation 2012) and is listed as Endangered under the *Commonwealth Environment Protection and Biodiversity Conservation Act (EPBC) 1999* (Department of Sustainability, Environment, Water, Population and Communities 2012). With such low numbers, Baudin's cockatoo also meet the criteria to be listed as Endangered on the IUCN Red List (IUCN 2020).

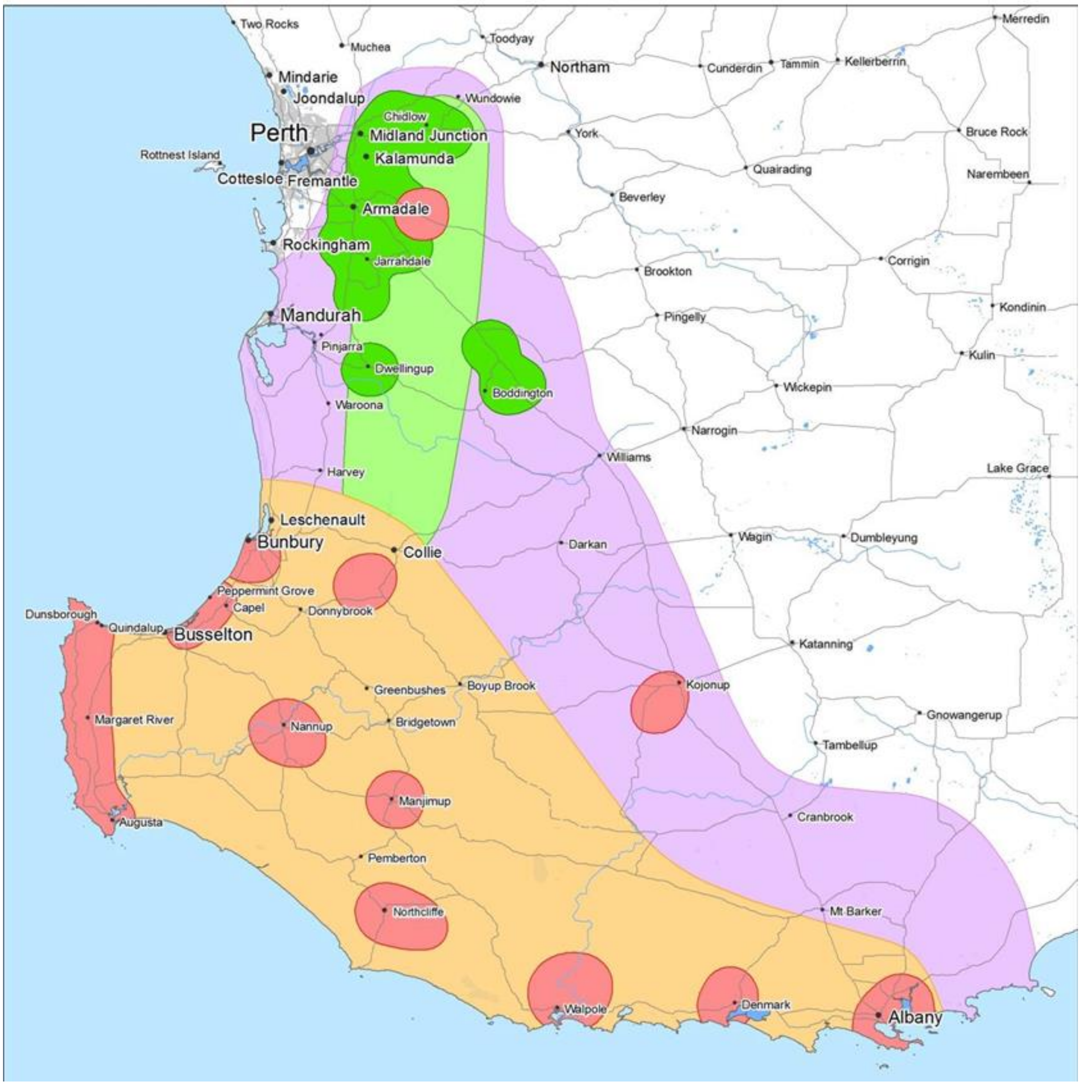

Figure 1.5: Modelled Baudin's cockatoo distribution. Legend: red - known breeding , orange - predicted breeding range, dark green - known foraging areas, light green - main wintering areas, purple - likely range (Department of Sustainability, Environment, Water, Population and Communities 2012).

1.2.3 Forest red-tailed black cockatoos

Description

The red-tailed black cockatoo genus is divided into five sub-species based on their distribution and foraging habitat: the northern red-tailed black cockatoo (*C. b. macrorhynchus*), Bank's red-tailed black cockatoo (*C. b. banksii*), south-eastern red-tailed black cockatoo (*C. b. graptogyne*), inland red-tailed black cockatoo (*C. b. samueli*) and forest red-tailed black cockatoo (*C. b. naso*) (Cameron 2007). A recent genetic study of red-tailed black cockatoos by Ewart *et al.* (2020) has recommended combining *C. b. macrorhynchus* and *C. b. banksii* into a single sub-species *C. b banksii*, due to their genetic similarities. The study also found the western population of *C. b. samueli* to be significantly genetically distinct from the central and eastern populations to warrant classification as its own sub-species *C. b escondidus.* The forest red-tailed black cockatoo is the focus of discussion in this thesis.

The forest red-tailed black cockatoo was named by renowned ornithologist John Gould in 1837. Forest red-tailed black cockatoos are large birds, weighing around 600g and 53 to 55 cm in length. Their appearance is quite distinct from Carnaby's cockatoos and Baudin's cockatoos – adult males are a solid glossy black with a dark grey beak. The central tail feathers are solid black, the remaining tail feathers have a bright red or orange band. Adult females have black feathers spotted with yellow on the head and wings, and barred feathers with yellow/orange over the chest and abdomen. The beak is white to pale grey. The central tail feathers are similarly solid black, the remaining tail feathers have orange and yellow bands (Figure 1.6). Juveniles have a similar appearance to females but tend to have less yellow spotting, dull barring on the body, red, orange and yellow tail feather bands and a grey to black bill. Their call is described as a harsh, loud "karee", "karrak" or "krarar-raak" sound and hence they are known as the "Kaarak' by the Noongar people (Johnstone 2020). A recording of their call is accessible on the Birdlife Australia website https://www.birdlife.org.au/projects/southwest-black-cockatoo-recovery/identify-your-black-cockatoo.

Figure 1.6: Female (left) and male (right) forest red-tailed black cockatoos showing sexually dimorphic differences in appearance. (Photo: Karen Riley)

Distribution, Habitat and Diet

As suggested by the name, this sub-species is found in the humid forest areas of south-west WA, extending from Gingin in the north, east to areas such as Mount Helena and Wooroloo and south to Kojonup, Rocky Gully and the Porongurup range near Albany (Johnstone *et al.* 2011). In the last 20 years, increasing numbers of birds have been observed foraging, feeding and roosting on the SCP, extending from the south-eastern suburbs of Perth (Gosnells, Armadale) to the coastal western (City Beach) and far northern suburbs (Joondalup) (Johnstone, Kirkby, *et al.* 2017). The modelled distribution is shown in Figure 1.7.

As with Baudin's cockatoos, the preferred habitat is marri, jarrah and karri forests which provide the suitable feeding and breeding habitat. The forest red-tailed black cockatoo is mostly an arboreal feeder, eating seeds of marri and jarrah, along with sheoak (*Allocasuarina fraseriana*), snottygobble (*Persoonia longifolia*), blackbutt (*E. patens*) and spotted gum (*E. maculata*). Birds on the SCP are changing their foraging behaviour, with birds often observed feeding on the ground. Movement onto the SCP has been associated with foraging and feeding on the fruits of the ornamental introduced cape lilac or white cedar tree (*Melia azedarach*), with this black cockatoo species first observed eating the fruit in 1995. They have also been observed feeding on the fruit of kaffir plum (*Harpephyllum caffrum*), another introduced ornamental garden tree and illyarie (*E. erthrocorys*) an ornamental gum tree (Birdlife Western Australia 2015), highlighting the importance of introduced and ornamental garden plants as alternative food sources (Department of Environment and Conservation 2007; Johnstone, Kirkby, *et al.* 2017; Johnstone 2020).

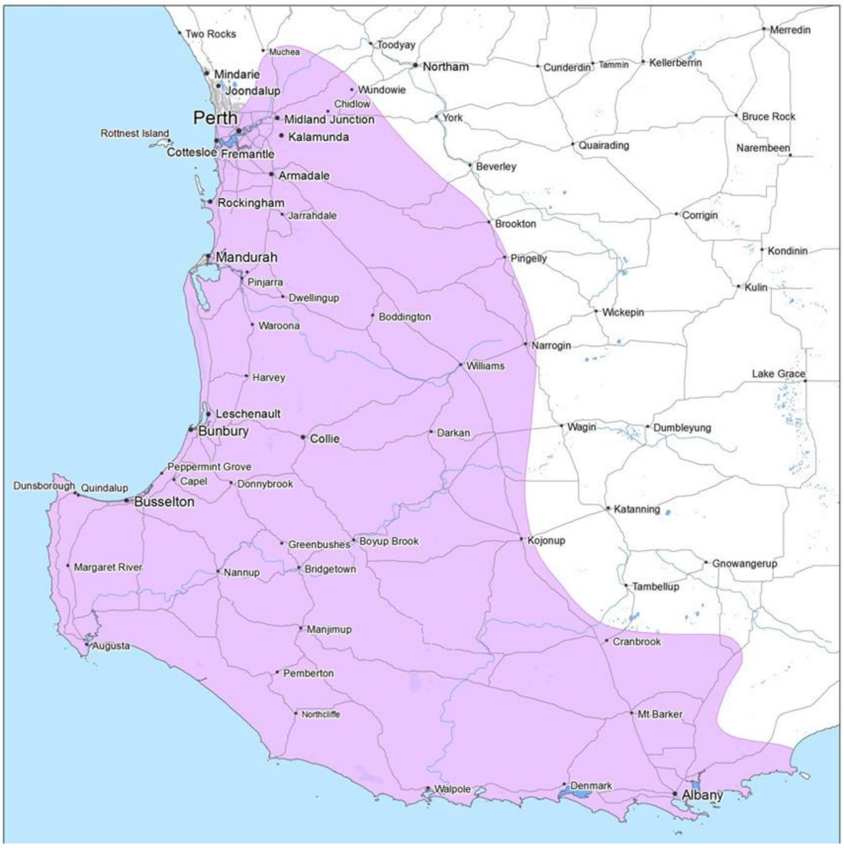

Figure 1.7: Modelled distribution of the forest red-tailed black cockatoo (Department of Sustainability, Environment, Water, Population and Communities 2012).

Reproduction

Forest red-tailed black cockatoos prefer to nest in large hollows found in marri, jarrah and karri trees. Birds reach sexual maturity at approximately four years of age. Whilst breeding has been recorded throughout the year, it peaks from April to June (autumn-winter) and August to October (spring) (Johnstone *et al.* 2013). The female lay one or two eggs, but usually only raises one chick (Department of Environment and Conservation 2007; Johnstone *et al.* 2011; Johnstone *et al.* 2013; Johnstone 2020). A number of pairs have successfully bred in artificial hollows installed on the Murdoch University campus (Johnstone, Kirkby, *et al.* 2017).

Conservation Status

Forest red-tailed black cockatoos are no longer found in about 30% of their previous known range with an overall decrease in number throughout the south-west since the early 1900s (Mawson *et al.* 1997; Johnstone *et al.* 2013). The estimated total population in 2011 was 10000 to 15000 birds (Johnstone *et al.* 2011). The most recent estimate is 16800 mature birds (Garnett *et al.* 2021). As such the forest red-tailed black cockatoo is listed under the Western Australian *Wildlife Conservation Act 1950* (Department of Environment and Conservation 2007) as Schedule 1 – Fauna that is rare or likely to become extinct. It is listed as Vulnerable under the *Commonwealth Environment Protection and Biodiversity Conservation (EPBC) Act 1999* (Department of Sustainability, Environment, Water, Population and Communities 2012) and IUCN Red List due to a likely population decline of 30% or more within the next ten years or three generations (Department of Environment and Conservation 2007; IUCN 2020).

1.3 Threats to black cockatoos in Western Australia

There are a wide range of factors implicated in the decline of the three species of black cockatoos and associated changes in their range and distribution.

Habitat loss

The removal of black cockatoo feeding, breeding and roosting habitat for development is considered to be the greatest cause of habitat loss in south-west Western Australia (Department of Environment and Conservation 2007). Land is increasingly being cleared for residential and industrial development in the Perth metropolitan area, further encroaching on the cockatoos' remnant habitat. In rural areas, land continues to be cleared for agriculture, forestry and mining (Mawson *et al.* 1997). For Carnaby's cockatoo, the degradation and loss of feeding habitat close to breeding sites (within 12 kilometres) is considered to be the greatest risk (Department of Environment and Conservation 2012). Whilst mining operations usually result in the loss of large areas, well managed site rehabilitation can provide food sources for black cockatoos within ten years (Lee *et al.* 2013). In some shires, clearing for agriculture has left less than five percent of the original vegetation. Adding to this, many areas have experienced significant reductions in annual rainfall in the last 60 years, impacting on tree and plant health (The Western Australian Biodiversity Science Institute 2021). The threat of dieback, caused by the plant pathogen *Phytophthora cinnamomi*, must also be considered as many of the plant species favoured by black cockatoos, such as jarrah and *Banksia* spp. can be infected (Department of Environment and Conservation 2012).

Fire also plays a significant role in the loss of suitable nest hollows and trees as well as foraging and roosting habitat. Severe bushfires and prescribed burns may destroy all layers of the forest habitat, forcing flocks to move away from their home range to survive (Johnstone and Kirkby 2017).

Introduced plantation pine trees (*Pinus pinaster*) are an important food source for Carnaby's cockatoos on the SCP. In an attempt to protect groundwater reserves, the complete removal of the Gnangara-Pinjar-Yanchep (GPY) pine plantation (6000 ha), north of Perth, is planned over the next few years. Associated with this continued harvesting of the GPY pine plantations, the cockatoos will not only lose a valuable food source, but also important roosting habitat, which is close to water (Stock *et al.* 2013; Shephard *et al.* 2018).

On a positive note, in 2021, the Government of Western Australia (2021) announced a new forest management plan which will limit logging and management activities in karri, jarrah and wandoo forest in south-west Western Australia, protecting black cockatoo foraging, roosting and nesting habitat.

Illegal Shooting

Illegal shooting continues to be a threat to cockatoos. Despite recently being declared an endangered species, Baudin's cockatoo was still classed as a Declared Pest of Agriculture until several years ago. Birds are still illegally shot by orchardists in an attempt to prevent damage to fruit crops such as apples and pears, even though non-lethal techniques for scarring birds out of trees are available (Chapman 2007; Department of Environment and Conservation 2007). Carnaby's cockatoos are also perceived to damage fruit and nut crops and the tops of growing pine trees and have also been illegally targeted. Of 565 Carnaby's cockatoos presented to Perth Zoo for veterinary assessment from 2000-2009, 49 birds had evidence of being shot. The true number of birds shot is likely higher as not all injured or dead birds may be found (Department of Environment and Conservation 2012). Forest red-tailed black cockatoos were targeted for food and sport in the late 1800s and early 1900s. Tail feathers were also collected for decorative purposes. There was also evidence of birds being shot for damaging plantation blue gums (*Eucalyptus globulus*) in 2000 (Department of Environment and Conservation 2007).

Nest hollows –inadequate trees, competition and poaching

A lack of suitable natural tree hollows is problematic for all three species. It generally takes over 100 years for hollows to develop in large trees (Saunders *et al.* 1982). Poor regeneration of suitable tree species such as salmon gums has been attributed to decreasing rainfall, soil degradation due to compaction by livestock and increasing salinity, in addition to weed invasion and grazing of seedlings by livestock and rabbits (Yates *et al.* 1994; Department of Environment and Conservation 2012; The Western Australian Biodiversity Science Institute 2021).

Where nest hollows are available, there is often strong competition from other parrot species including galahs (*Cacatua roseicapilla)*; corellas; both native and introduced (*Cacatua* species); rainbow lorikeets, a declared feral pest species (*Trichoglossus haemaodus moluccanus*) (Chapman 2005), as well as ducks (Australia shelducks *Tadorna tadornoides* and Australian wood ducks *Chenonetta jubata*) (Johnstone *et al.* 2011; Department of Environment and Conservation 2012). Feral European honeybees (*Apis mellifera*) occupying nest hollows make them unusable to black cockatoos and other birds. A study by Johnston *et al.* (2007) found bees in 20% of nests at some study sites, with 50% of nests taken over at other study sites. There has been one report of a female Baudin's cockatoo killed by bees whilst nesting in a hollow (Johnstone *et al.* 2011).

Whilst artificial nest hollows installed into known breeding areas have been successfully used by both Carnaby's cockatoos (Saunders *et al.* 2020) and forest red-tailed black cockatoos (Johnstone, Kirkby, *et al.* 2017), they should not be used as a substitute for breeding habitat protection and restoration, rather they should be considered a short-term supplemental measure (Saunders 1990; Saunders *et al.* 2020).

Black cockatoos are highly sought after as pet birds and illegal removal of both eggs and chicks from nest hollows has been reported. Not only does poaching put the survival of the egg or nestling at risk, often the nest hollow or entire nest tree is damaged or destroyed in the process of removing the chick (Mawson *et al.* 1997; Department of Environment and Conservation 2012). Poaching has become less of an issue with the establishment of a genetic database by DBCA to record and monitor black cockatoos kept and bred in captivity (White 2011).

Predators

Black cockatoos have a number of recognised predators, both native and introduced. Wedge-tailed eagles (*Aquilla audax*) may attack and kill Carnaby's cockatoos (Saunders 1990; Le Roux 2017). Australian raven numbers in urban areas are increasing with ample food available in rubbish bins, tips and around food service areas. With more red-tailed black cockatoos moving onto the SCP and Perth metropolitan area, contact between them and ravens is increasing, along with reports of ravens harassing, injuring and killing juveniles (Johnstone, Kirkby, *et al.* 2017). Introduced predators such as the fox (*Vulpes vulpes*) and feral cat (*Felis catus*) both pose a threat to cockatoos (Saunders *et al.* 2009), with numerous reports of cats climbing nesting trees, and killing both adult and nestling Carnaby's cockatoos and red-tailed black cockatoos (Saunders 1991, 2006).

Vehicle strike

Motor vehicle collisions account for a significant number of injuries or death in all three species of black cockatoo presenting to Perth Zoo and Kaarakin Black Cockatoo Conservation Centre (Saunders *et al.* 2011). Cockatoos often forage in remnant vegetation along road reserves and drink water from puddles on roads and near drains (Figure 1.8), putting them at risk of collision when they take off and fly, often into the path of oncoming vehicles (Department of Environment and Conservation 2012; Groom, Mawson, *et al.* 2014). Conservation strategies should consider revegetation and planting of food plants away from roads and the installation of warning signs in areas where there is a high level of cockatoo activity. Cockatoos can be discouraged from drinking on roads by repairing potholes, improving drainage and supplying safer alternative water sources (Groom, Mawson, *et al.* 2014) such as the type shown in Figure 1.9.

Figure 1.8: Carnaby's cockatoos drinking from a roadside pothole. (Photo: Molly Spaulding)

Figure 1.9: Bird watering station installed in the Town of Victoria Park. (Photo: Georgina Wilson - https://www.victoriapark.wa.gov.au/Around-town/Environment/Bird-waterers)

Disease

The threat of disease to black cockatoo populations remains largely unknown. The potential impact of disease on conservation is noted in the Carnaby's Cockatoo Recovery Plan (Department of Environment and Conservation 2012). There is no mention of disease in the Forest Black Cockatoo Recovery Plan (Department of Environment and Conservation 2007).

In 2009 and 2012, numerous adult Carnaby's cockatoos were found dead at a key breeding site on a property at Coorow in the northern wheatbelt of WA. No infectious or toxic cause was found at the time (Saunders *et al.* 2014). Subsequent research suggests these birds may have been affected by Carnaby's cockatoo hindlimb paralysis syndrome (CHiPS), a condition thought to be a delayed-onset neuropathy due to organophosphate exposure. Researchers suspect the cockatoos are exposed to organophosphates at their inland breeding areas, with clinical signs developing by the time they have migrated back to the SCP (Le Souëf *et al.* 2020). Further ecotoxicology research on this condition is being undertaken by the Black Cockatoo Conservation Management Research group at Murdoch University.

This research group has been carrying out avian disease screening since 2010 with biological samples collected from over 400 Carnaby's cockatoo nestlings. Samples collected include blood; faeces and swabs of the conjunctiva, choana and cloaca and have been used to determine baseline health parameters, blood reference ranges, as well as screening for Psittacine Beak and Feather Disease, Avian Polyomavirus, Adenovirus, Avian Herpesvirus and *Chlamydia* spp. Other than Herpesvirus, all these infections have been detected in wild Carnaby's cockatoos, however to date there has been no apparent evidence of clinical disease in the nestlings, and the clinical significance of these infections for the birds remains unknown (Dr Anna Le Souef, personal communication, March 2022). Given the potential threat, further research is required.

Climate change - heat events, water resources

Climate change presents a threat to terrestrial and aquatic ecosystems globally and has already resulted in loss of species, increased disease and mass mortalities in both animals and plants. Extreme events, such as fire and flood are becoming more common, putting ecosystems under more pressure to regenerate and adapt in shorter timeframes (Intergovernmental Panel on Climate Change 2022). The 2020 State of the Climate report (CSIRO *et al.* 2020) showed the average temperature in Australia has increased by almost 1.5°C in the last 100 years and rainfall in the south-west has decreased by 16% in the last 50 years. These changes have resulted in more extreme heat events and longer, more severe fire seasons. February 2022 saw the greater Perth area experience the hottest summer on record and the hottest February for 26 years – temperatures were 1.5-3°C above average, with a period of seven days over 36°C. This was coupled with below average rainfall (Bureau of Meteorology 2022).

With declining rainfall and rising temperature, the range and distribution of black cockatoos is expected to change, with ranges contracting to the higher rainfall areas of the south-west

(Johnstone *et al.* 2011), areas which are already subject to habitat degradation, clearing and fragmentation (Saunders *et al.* 2011).

A recent study by Mastrantonis *et al.* (2019) suggests that in the case of forest red-tailed black cockatoos, the effects of climate change are likely to impact mostly on food source availability, such as the flowering and fruiting of marri and jarrah and associated effects on breeding, rather than directly on the birds. These birds will likely become more dependent on introduced food sources such as cape lilac. Baudin's cockatoos preferentially feed on marri and will also be impacted by any reduction in flowering and fruiting (Johnstone *et al.* 2013). The health and survival of vegetation across Carnaby's cockatoo breeding and non-breeding habitat is also significantly at risk (Department of Environment and Conservation 2012).

A number of extreme weather events have severely impacted on Carnaby's cockatoos in particular. 2010 was a particularly devastating year for the birds. In January, 145 birds were found dead at Hopetoun golf course on the far south coast of WA. A further 63 birds were found dead in a blue gum plantation about 75km to the east of Hopetoun. The maximum temperature recorded was around 48°C, with low humidity. A beekeeper working in the area at the time reported the temperature reached 53°C and found over 50 birds of other species dead. Post-mortem examination findings from the cockatoos were consistent with heat stress. A water trough on the Hopetoun golf course which had been regularly used by the birds was broken at the time (Dr Kristin Warren, personal communication, February 2022), and there is speculation that the extreme heat also limited the birds' ability to seek water (Saunders *et al.* 2011). In March, an unseasonal hailstorm hit the Perth metropolitan area and injured or killed 81 cockatoos. More may have been affected but were not found. Many of the birds were roosting in banksia woodlands which provided no protection from the large hailstones. In some areas, large trees were completely stripped of their leaves, exposing the birds further (Saunders *et al.* 2011).

1.4 Research Objectives

This study was conducted between 2012 and 2021, building on previous black cockatoo research (Le Souef, Stojanovic, *et al.* 2013; Groom, Warren, *et al.* 2014) with an overall aim to develop and validate reliable methods of tracking all three species of black cockatoo, to gain insight into flock movements, distribution, habitat use, activity and behaviour. The specific aims of each component of the study were:

- To determine the feasibility of using tail-mounted ARGOS satellite PTT tags to track forest black cockatoos;
- To develop a tag-attachment methodology to enable capture of both GPS (fine-scale) and ARGOS satellite (landscape-scale) data when tracking black cockatoos post-release;
- To develop an automated classification tool to analyse accelerometer data and identify black cockatoo behaviour and activity; and
- To investigate the black cockatoo tail feather lifespan and timing of tail feather moulting to determine the optimal time for telemetry tag attachment to maximise tag retention.

Chapter 2. Satellite tracking of rehabilitated wild Baudin's Cockatoos *Calyptorhynchus baudinii:* a feasibility trial to track forest black cockatoos.

The following chapter has been drafted in accordance with the requirements for *Pacific Conservation Biology*. This chapter has been published:

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The following authors contributed to this manuscript as outlined below.

Authorship order	**Contribution (%)**	**Concept Development**	**Data Collection**	**Data Analyses**	**Drafting of manuscript**
Lian Yeap	80	x	x	x	x
Jill Shephard	6		x	x	x
Anna Le Souef	4	x	x		x
Carly Holyoake	1	x			x
Christine Groom	1	x	x		x
Rick Dawson	1		x		x
Tony Kirkby	1		x		x
Kristin Warren	6	x	x	x	x

Contribution indicates the total involvement the author has had in this project. Placing an 'X' in the remaining boxes indicates what aspect(s) of the project each author engaged in.

By signing this document, the Candidate and Principal Supervisor acknowledge that the above information is accurate and has been agreed to by all other authors.

Candidate **Principal Supervisor**

2.1 Preface

This chapter comprises original research undertaken to assess the feasibility of attaching tail-mounted ARGOS satellite PTT tags to Baudin's cockatoos (*C. baudinii*) to facilitate tracking post-release. Whilst satellite tags had been used to track Carnaby's cockatoos (*C. latirostris*) on the SCP, prior to this study they had not been used to track cockatoos in forest areas due to concerns that forest canopy could interfere with signal transmission. Forest black cockatoo species are considered difficult to monitor and track due to their preference for heavily forested habitat. Telonics TAV-2617 tags were used to track two Baudin's cockatoos and provided enough data to track one bird for over 250km from the release site. This was a successful proof of concept trial, providing a useful tool to locate and track forest black cockatoos.

2.2 Abstract

Baudin's cockatoos, *Calyptorhynchus baudinii,* are a threatened forest black cockatoo species, endemic to the south-west of Western Australia. In this study we fitted tail-mounted satellite transmitters to two female Baudin's cockatoos that had undergone treatment and rehabilitation at Perth Zoo and Kaarakin Black Cockatoo Conservation Centre, to investigate the feasibility of satellite tracking this species. Both birds were released in Kelmscott, Perth, into an area frequently visited by a flock of wild Baudin's cockatoos. Both telemetry units provided reliable data sets, with one bird moving approximately 250km south from the release site. The success of this trial opens the way to address key objectives in the Forest Black Cockatoo Recovery Plan including: post-release survival of rehabilitated birds, flock movement, habitat use, and the identification of critical feeding and breeding habitat. Most importantly it demonstrates that satellite transmitters can be successfully used to locate and track forest black cockatoo species, which are otherwise difficult to monitor.

2.3 Introduction

Baudin's cockatoos, *Calyptorhynchus baudinii*, are a large black cockatoo species found in the south-west forests of Western Australia. Baudin's cockatoos are currently classified as Endangered at the State level, and nominated as such at the National level, using IUCN Red List criteria (Department of Environment and Conservation 2007), with the population declining in both range and density in the last 50 years (Garnett *et al.* 2000). While the main historical threat to black cockatoo species inhabiting this region was habitat loss due to clearing for agriculture and forestry, the adverse impacts of an increasing human population in Western Australia (i.e., motor vehicle accidents, illegal shootings) are key threats that are becoming more prevalent (Chapman 2007).

Carnaby's cockatoos, *C. latirostris*, have been successfully tracked with Argos satellite telemetry to monitor their movements on the Swan Coastal Plain (Groom *et al.* 2013; Groom, Warren, *et al.* 2014). This same study also confirmed the suitability of rehabilitated birds in tracking studies of this type. Successful deployment and tracking of forest black cockatoos can provide valuable data in relation to flock movement and habitat use, and facilitate the identification of feeding and breeding habitat, all key elements in the Forest Black Cockatoo Recovery Plan (Department of Environment and Conservation 2007).Tracking of this type has not been used previously in forest black cockatoos due to the perceived difficulties associated with potential interference of the forest canopy on transmission accuracies. However, recent research addressing the impact of canopy cover and topographic obstruction on observation rate and location error has demonstrated low impact, 12.4% and 3.4% respectively (Sauder *et al.* 2012)

The aim of this study was to investigate the feasibility of satellite tracking Baudin's cockatoos which, unlike the Carnaby's cockatoo, inhabit and migrate through heavily forested areas in the south-west of Western Australia. The criteria that were used to determine success for this feasibility trial were that transmitters would: 1) remain attached to the tail feathers enabling tracking of the birds and collection of dropped (moulted) tail feathers; 2) determine the likely post-release fate of the birds; and 3) enable tracking of the birds' movements, including migratory movements.

2.4 Methods

Two wild Baudin's cockatoos were fitted with transmitters following treatment and rehabilitation at Perth Zoo and Kaarakin Black Cockatoo Conservation Centre (KBCCC). Both birds had suffered traumatic injuries, most likely associated with motor vehicle accident. Baudin's cockatoos present for rehabilitation and release much less frequently than Carnaby's and forest Red-tailed cockatoos, *C. banksii naso,* (Le Souef 2012) making these two valuable study birds.

The birds made uneventful recoveries and were assessed to be free of disease (see below) and fit for release. At KBCCC they were transferred to a large (sixty-four metre long) pre-release flight aviary to ensure they had excellent flight ability and adequate flight fitness.

2.4.1 Transmitter attachment:

Two ARGOS transmitters (TAV - 2617) manufactured by Telonics were attached to the birds using ventral tail mounts on 26 September 2012, two days before the planned release date, giving staff at KBCCC adequate time to monitor the birds after attachment. Transmitters were fitted to the birds under isoflurane gaseous anaesthesia, to reduce stress from handling. During anaesthesia, blood was collected from the right jugular vein for a routine blood profile (ZA1 Avian Profile, Vetpath Laboratories, Perth) to check their overall health. No abnormalities were detected. Faecal samples were collected from the aviary to screen for parasites to determine whether pre-release anthelmintic treatment was warranted. No parasites were detected.

Transmitter dimensions were 6.43x2.03x0.84 cm with a weight of 17 gm - approximately 3% of the bird's body weight. The transmitters were a dark green/khaki colour. The transmitters were programmed by attaching each transmitter, via a cable, to a computer prior to attaching the transmitters to the birds.

The method of transmitter attachment and materials used by Groom, Warren, *et al.* (2014) was followed in this study and is a modified version of transmitter attachment developed by Le Souef *et al.* (2013). Le Souef *et al.* (2013) compared several methodologies and found tail mounting to be the safest. Groom *et al.* (2014) subsequently showed that they also provided good retention times.

Each bird was given 15ml warmed subcutaneous fluids (Hartmann's/glucose solution 50:50 mix, Baxter Healthcare, Toongabbie NSW) prior to the end of the anaesthetic, loosely wrapped in a towel and placed into a secure pet carrier to recover. The duration of the procedure was approximately 40 minutes. Supplemental heat was maintained with an infrared heat lamp. The birds were moved back to the flight aviary once fully recovered from anaesthesia.
Behaviour, preening, activity, and flying ability were monitored by KBCCC staff until release on 28 September 2012. The transmitters had no apparent impact on their flight, behaviour or activity in the aviary.

2.4.2. Release and Tracking:

The birds were released on 28 September 2012 at a site in Kelmscott approximately six kilometres from KBCCC. This site was chosen as it was regularly visited by a flock of wild Baudin's cockatoos. Birds were transferred by vehicle to the release site in covered, reinforced pet carriers and released simultaneously, in the late afternoon.

The transmitters were initially programmed to transmit data for 12 hours per day for 12 days (5am-8pm), with an off-period between 10am and 1pm when there were no satellite passes overhead. Thereafter the transmitters were reprogrammed to transmit for 5 hours per day every five days (from 4am). This change was made with the aim of capturing bird movements when they were most active and to prolong battery life and transmission time. Transmitter recovery was facilitated with a radio receiver (Argos AL-1 PTT Locator, Communications Specialists). Data from the transmitters was decoded using the Telonics Data converter (Telonics, Mesa, Arizona), the data was filtered and only '2' (< 500m) and '3' (<250m) location classes were used as they were the most accurate . Movement paths were generated in Geospatial Modelling

Environment (Beyer 2012) and projected in ArcGIS 9.0 (ESRI 1999-2010). Flight paths were visualised using Google Earth 7.1.1.1888 (Google Inc. ; Caccamise *et al.* 1985) and minimum straight-line distance between points was calculated using the elevation profile tool.

2.5 Results/Discussion

Baudin's Cockatoo 119055

Based on the satellite tracks, this bird travelled a minimum estimated distance of 19 km from the release site up until 2 October 2012 (Fig. 1). The bird then flew south an estimated minimum of 20 km to the Cardup region that day. The following day the bird was located in the Mundijong region (approximately 30 km south of the release site) and stayed in this area until the 10 October 2012. This is a peri-urban area and ground-truthing found the bird at the Watkins Road Nature Reserve, a local nature reserve consisting of predominantly marri, *Corymbia calophylla*, woodland, a preferred food source for Baudin's cockatoos (Department of Environment and Conservation 2007). Within 10 km of this area there are four marri woodland nature reserves totalling over 150 hectares (Urban Bushland Council WA Inc 2014). Langford Park, a rehabilitated former bauxite mine is located approximately 10 km away. This area completed rehabilitation in 2001 and is now a large expanse of eucalypt (jarrah, *Eucalyptus marginata*; blue gum, *E. globulus*) and pine, *Pinus* sp., forest (Alcoa Inc. 2014). While Baudin's predominantly feed on marri, they do also feed to a lesser extent on jarrah seeds (Department of Environment and Conservation 2007). During this 8 day period, bird 119055 travelled a minimum of 82 km (Fig.2). Given the pattern of movement and ground-truthing that indicated significant cockatoo activity (chewed marri nuts) at a night roost where the bird roosted, and the fact that this species roosts communally, it appeared the bird joined a local flock, possibly its flock of origin given it was originally found injured in the nearby Serpentine region.

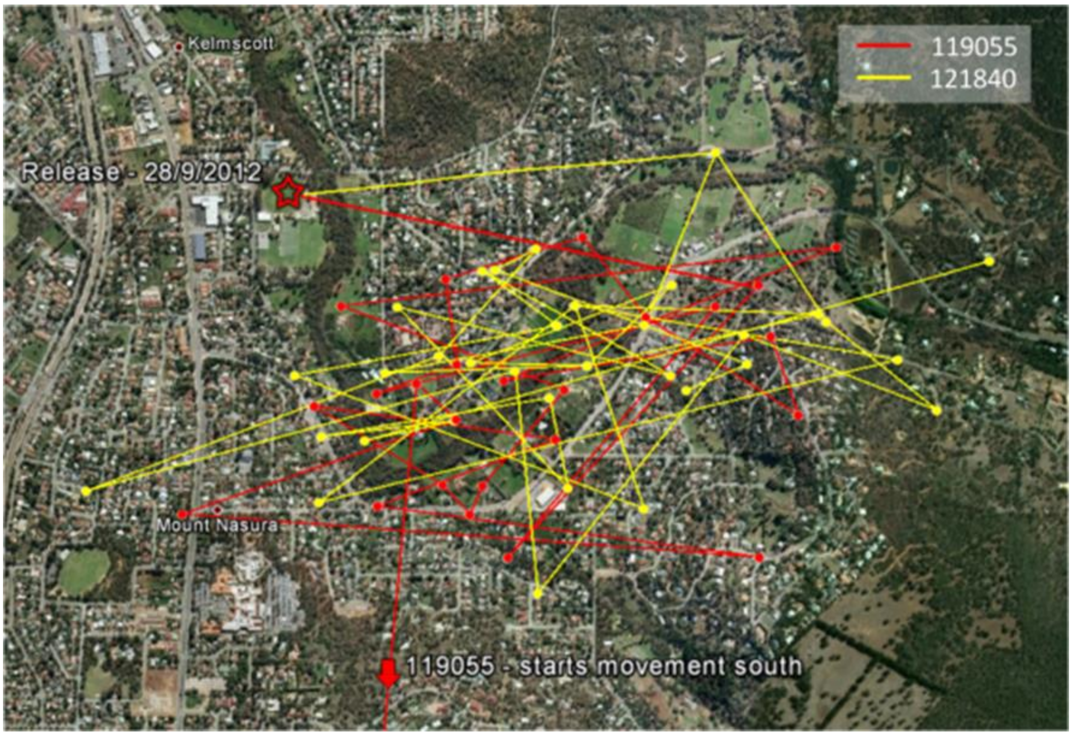

Figure 2.1: Satellite tracks showing movement of Baudin's cockatoos 119055 (Red) and 121480 (Yellow) from the point of release in Kelmscott on the 28/9/2012 until the 2/10/2012, at which point bird 119055 commenced dispersal flight south. 121480 remained in the area.

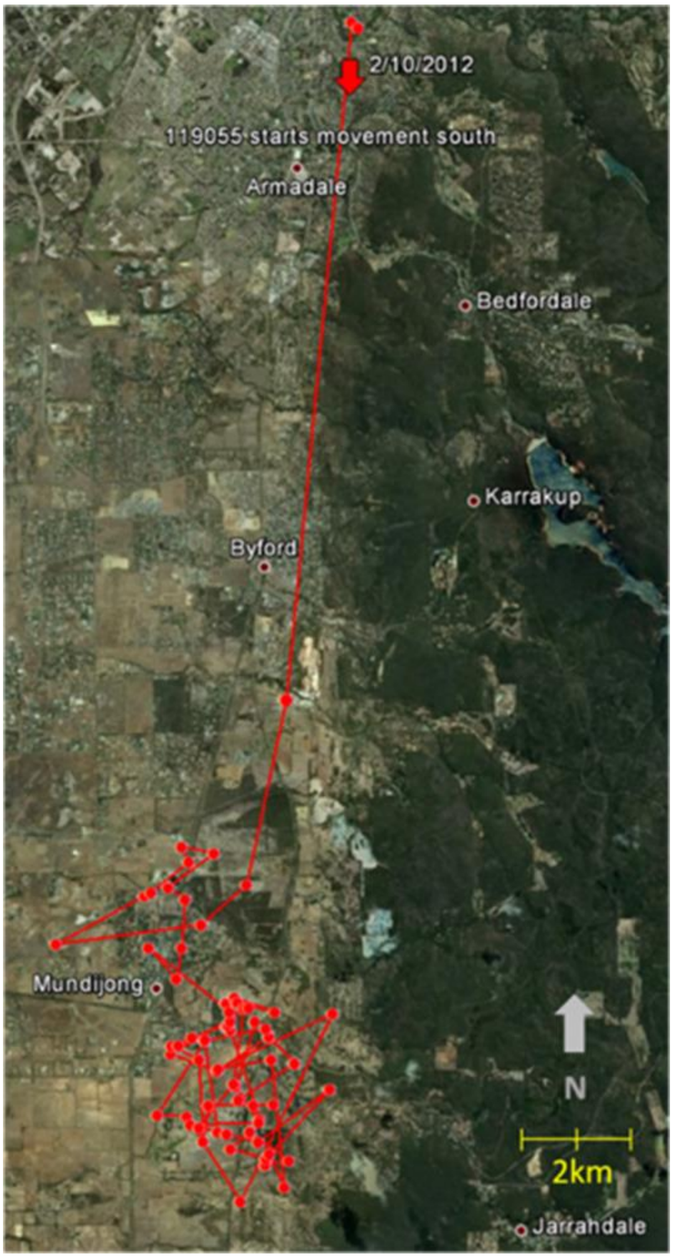

Figure 2.2: Satellite tracks showing the movement of Baudin's cockatoo 119055 on the morning of the 2/10/2012 to the Mundijong region about 20 km south of Kelmscott.

The bird flew a further 68 km to the Beela region by 29 January 2013 and this is where it was last located (Fig. 3). In total, 119055 travelled approximately 250 km south of the release site in the 123 days that its tracking device was active. Based on the assumption that 119055 was travelling with a flock, this sustained southern movement indicated possible migration to breeding habitat. Studies by Johnstone *et al.* (2008) showed large flocks of Baudin's cockatoos flying to known breeding areas in the lower south-west of Western Australia from the middle of August onwards.

Ground-truthing located 119055 at this site in the Beela region in agricultural land with marri paddock trees, which adjoined a large expanse of State forest and a pine plantation. In addition to Baudin's cockatoos inhabiting this area, Carnaby's cockatoos and forest red-tailed black cockatoos were also sighted and heard in the area. Based on observations there appeared to be several hundred black cockatoos in the area. The marri trees were flowering and there was substantial evidence of feeding on marri nuts by all three types of black cockatoos. Water was available in nearby farm dams. A local land holder owning property at this site confirmed that Baudin's cockatoos had bred in marri trees at this site in previous years (Hardy, personal communication, 2014).

Figure 2.3: Satellite tracks showing the southern movement of Baudin's119055 from the release site (yellow star) to the last known location in the Beela region of Western Australia (yellow arrow).

Baudin's Cockatoo 121840

Based on the satellite tracks recorded up until 2 October, this bird travelled an estimated minimum distance of 27 km after release, staying primarily in the Kelmscott area.

On 10 October 2012 the transmitter switched to the five-day cycle as programmed. The next transmission on 15 October 2012 was from the Cardup region, approximately 13 km south of the previous location. It appears that there was no overlap between this bird and 119055 during the time that they passed through the Cardup area. Between October and December 2012 there continued to be transmissions from the Cardup region. The location was modified agricultural land, not a known Baudin's night roost, and concerns were held for the health of the bird. In early December a ground area search was conducted with a radio receiver and the transmitter was located, attached to dropped tail feathers. Wing feathers were located nearby and DNA analysis of the wing feathers, performed by Australian Wildlife Forensic Services, confirmed the feathers were from bird 121840 which had been previously genotyped. While it is possible the central tail feathers carrying the transmitter were lost during the normal feather moult, in this case the location of the additional wing feathers indicated that it was most likely that the bird had been predated. Discussion with property owners in the area indicated there was history of raven attacks on black cockatoos in the weeks preceding the arrival of 121840 in the area.

Apparently healthy black cockatoos regularly present to Perth Zoo Veterinary Department with severe injuries associated with raven attacks during the raven breeding season (Dr Anna Le Souef, personal communication, 2012. Given the position of the transmitter at the ventral tail base and its neutral colour, the transmitter was not considered to have acted as a visual cue contributing to the fate of this bird.

The satellite transmitter on bird 119055 remained active for five months (123 days) following attachment and release. Based on the programmed schedule, the units transmitted for approximately 144 hours in the first 12 days of tracking (12 hours per day). The units then transmitted for approximately 135 hours until tracking ended in February 2013 (five hours every five days for four and a half months, that is, approximately 27 five-hour transmissions), a total of approximately 279 hours. The estimated battery life expectancy of the transmitters operating continuously is 233 hours (Telonics 2014). The time frame of transmitter attachment on this bird was anticipated due to the expected post-breeding season moult of tail feathers. However, our data suggest the possibility of birds carrying tracking units successfully over much longer timeframes. We are currently trialling this in captive, not-for-release birds at KBCCC and studies to date indicate that the transmitter retention time, associated with tail feather moulting, is likely to exceed battery life depending on transmitter programming.

The Forest Black Cockatoo (Baudin's cockatoo and forest red-tailed Black Cockatoo) Recovery Plan emphasises the importance of understanding post-release survival of rehabilitated birds, flock movement, habitat use, and identifying critical feeding and breeding habitat, particularly for forest species (Department of Environment and Conservation 2007). This trial has shown that satellite transmitters can be successfully used to locate and track forest black cockatoo species, which are otherwise difficult to monitor using conventional observational approaches (e.g., vehicle based flock follows) in forested regions (Dr Hugh Finn, personal communication, 2014).

Baudin's cockatoos prefer dense eucalypt forest, and locating birds in a forest environment is challenging due to limitations associated with road and track access in such regions. Despite research undertaken to date on Baudin's cockatoos (Johnstone *et al.* 2008; Weerheim 2008) there is still limited knowledge about migratory flock movements and habitat use and selection; and key feeding and breeding sites in the forest regions of the south-west of Western Australia remain unknown. Satellite telemetry could provide a wealth of data in these areas and allow us to develop a better understanding of these birds.

These data have shown that the transmitter battery life can be extended by using a conservative programming schedule. We are currently running additional trials, including investigating temporal feather moult patterns to maximise data capture over longer time periods.

This feasibility study is the first-time forest black cockatoos have been satellite tracked in the wild and the outcomes provide encouragement for implementing a more comprehensive movement ecology study of forest black cockatoos. Based on the success of the current work, we plan to undertake large scale tracking of all three WA black cockatoo species to investigate habitat use and movement patterns, and to identify feeding, watering, roosting and breeding sites.

Acknowledgements:
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Chapter 3. Development of a tag attachment method to enable capture of fine and landscape scale movement in black cockatoos.

The following chapter has been drafted in accordance with the requirements for *Australian Field Ornithology*. This chapter has been published:

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The following authors contributed to this manuscript as outlined below.

Authorship order	Contribution (%)	Concept Development	Data Collection	Data Analyses	Drafting of manuscript
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Jill Shephard	6	x	x	x	x
Willem Bouten	4	x			x
Bethany Jackson	2		x		x
Rebecca Vaughan-Higgins	2		x		x
Kristin Warren	6	x	x	x	x

Contribution indicates the total involvement the author has had in this project. Placing an 'X' in the remaining boxes indicates what aspect(s) of the project each author engaged in.

By signing this document, the Candidate and Principal Supervisor acknowledge that the above information is accurate and has been agreed to by all other authors.

Candidate **Principal Supervisor**

3.1 Preface

Following the successful trial of tail-mounted tags on forest black cockatoos, this study outlines the development of a successful double-tag mounting protocol. The tolerance and functionality of different combinations of tail-mounted ARGOS satellite PTT tags and back-mounted GPS tags were assessed in captive black cockatoos. The Telonics TAV 2617 tail-mounted satellite tag combined with the UvA-BiTs back-mounted, solar powered GPS tag was best tolerated and retained by the cockatoos and was determined to be the optimal combination for post-release tracking. The combination of two tags enables capture of both GPS (fine-scale) and ARGOS satellite (landscape-scale) data. This chapter uses Birdlife International nomenclature for Baudin's black cockatoo and Carnaby's black cockatoo - *Zanda baudinii* and *Zanda latirostris* respectively, as required by the publishing journal *Australian Field Ornithology*.

3.2 Abstract.

This study reports on a successful trial of a double-tag mounting protocol using both satellite and GPS tags on captive black cockatoos (forest red-tailed black cockatoo *Calyptorhynchus banksii naso*, Baudin's black cockatoo *Zanda baudinii* and Carnaby's black cockatoo *Z. latirostris*). The aim of the study was to assess the feasibility and tolerance of a novel back-mount and a double-mount protocol combining a back- and tail-mount in black cockatoos. We trialled solar 3D Global Positioning Systems (GPS) tags, standard solar and battery-operated GPS and Platform Terminal Transmitter (PTT) tags and developed an attachment method to fit back-mounted solar-powered UvA-BiTS GPS tags, incorporating a 20Hz tri-axial accelerometer, to captive black cockatoos. We investigated the effect of a variety of different types of tail-mounted satellite tags on the operational ability of the primary UvA-BiTS units and the feasibility of the double-mounted tag system with regard to tolerance by the birds. Our study determined that the combination of a 7.5-g UvA-BiTS GPS tag and 17-g Telonics TAV 2617 satellite tag was best tolerated by the birds and was the optimal tag system for use on birds to be released. This system enables capture of movement data to better understand the ecology of black cockatoos, and identify critical feeding, roosting and breeding habitats, thereby informing conservation management initiatives to conserve these threatened species.

3.3 Introduction

The movement ecology of birds has been heavily researched but often focuses simply on describing and measuring movement itself. Studies rarely investigate the reasons for and factors affecting movement patterns, such as food availability, habitat, breeding and predation (Holyoak *et al.* 2008; Sekercioglu 2010). Tracking birds also poses many difficulties to research and management efforts including the vast distances that they can cover, as well as difficult terrain and habitat in which they reside.

Parrots and cockatoos present particular challenges to tracking studies given their strong beaks and natural desire to chew tracking devices. As suggested by Kennedy *et al.* (2015) and Groom, Warren, *et al.* (2014), the risk of damage to, and destruction of, expensive tracking devices has often prevented their use in these species. Recent technological improvements, together with reductions in the size and cost of tracking devices, have made telemetry a much more viable option, with successful use of radio-transmitters on the Scarlet Macaw *Ara macao* (Myers *et al.* 2004) and Rosy-faced Lovebird *Agapornis roseicollis* (Ndithia *et al.* 2006), Global Positioning System (GPS) transmitters on the Kea *Nestor notabilis (Kennedy et al. 2015)*, and satellite PTT tags on Carnaby's black cockatoo *Zanda latirostris* (Groom *et al.* 2013) and Baudin's black cockatoo *Z. baudinii* (Yeap *et al.* 2015).

Previous research has shown that black cockatoos are well-suited for tail-mounted ARGOS satellite tags (Le Souef, Stojanovic, *et al.* 2013), with retention times often exceeding battery life (Le Souef, Stojanovic, *et al.* 2013; Groom, Warren, *et al.* 2014; Yeap *et al.* 2015). However, although these studies were well suited to landscape-scale characterisation of species movement, they were limited by both battery life and data resolution. Depending on its programming schedule, a typical satellite tag can provide several usable position fixes a day (Thomas *et al.* 2011). In contrast, GPS units allow collection of much larger volumes of data with resultant higher accuracy and precision, and can provide information regarding individual position and behaviour. Typically, GPS tags now combine acquisition of location observations with tri-axial accelerometer measurements (3D GPS), facilitating a multi-scale approach to studying bird movements and behaviour. In addition, solar recharge capabilities can greatly prolong the working life of tags; this facility is available in both satellite and GPS tags. Ultimately the choice of tag is dependent on the questions asked and the limitations of the attachment method that are imposed by the species.

Carnaby's black cockatoo, Baudin's black cockatoo and the forest red-tailed black cockatoo *Calyptorhynchus banksii naso* are species endemic to south-western Western Australia. All three taxa are listed as Threatened, under the Federal *Environment Protection and Biodiversity Conservation (EPBC) Act 1999* (Department of Sustainability, Environment, Water, Population and Communities 2012). In Western Australia, all three are listed under Schedule 1 (species that are rare or likely to become extinct) of the Western Australian *Wildlife Conservation Act 1950* (Department of Environment and Conservation 2007, 2012). Black-cockatoos are threatened by multiple factors including: habitat loss and fragmentation; competition with other bird species and feral bees for nest-hollows; poaching; disease; and anthropogenic factors such as vehicle-strike and illegal shooting (Saunders *et al.* 2011). Significant declines in black cockatoo numbers have been observed from the 1980s (Saunders *et al.* 1998), and thus all are the subject of species Recovery Plans (Department of Environment and Conservation 2007, 2012). Flock movements, habitat use and critical feeding and breeding sites across these species' distribution ranges remain largely unknown (Department of Environment and Conservation 2007, 2012). Previous tracking research has been limited to the urban and peri-urban areas of the Swan Coastal Plain, and generally has not coincided with long-distance migratory movements to breeding areas, and has involved only two of the three target species (Groom, Warren, *et al.* 2014; Yeap *et al.* 2015). Tracking across the complete annual migratory cycle of these species is required to address the aims of the Recovery Plan and facilitate long-term conservation planning (Department of Environment and Conservation 2007, 2012). Our previous work (Yeap *et al.* 2015) has shown that individually tagged birds integrate with wild flocks and function effectively as indicators of flock movement.

Black cockatoos are some of the most destructive bird species, both in the wild and in captivity (Johnston 2013). All three Western Australian species are specialist foragers that routinely manipulate large hard eucalypt capsules to extract the seeds. Thus they are likely to pose some of the greatest challenges to the long-term persistence and functionality of tracking devices.

We trialled several different combinations of trackers and attachment types on captive individuals of all three species to inform and optimise tag deployment strategies for wild birds. Given the destructive capability of our study species, our results should be broadly applicable to most other cockatoo species (some of which are Critically Endangered) and other large parrot species.

3.4 Methods

Feasibility of the double-tag method was tested via a multi-stage process. In this paper, the term 'double-tag' refers to the attachment of two separate tags to an individual bird. Previous tag deployments have used battery-powered tags and placement ventrally on the tail (Groom, Warren, *et al.* 2014; Yeap *et al.* 2015). We tested the use of solar tags that require dorsal placement for battery recharge. Both dummy (non-functional) and live transmitters were used during the trials to assess: (1) optimal tag placement, (2) bird tolerance to back-mounts, (3) bird tolerance to two tags (double-tag), (4) the feasibility of using a dorsal satellite/GPS combination tail-mounted tag, and (5) possible message interference between the GPS and (PTT) tags used.

The birds used in this study were either not-for-release education birds, or wild birds in the final stages of rehabilitation, which were all housed at Kaarakin Black Cockatoo Conservation Centre (KBCCC), Martin, Western Australia.

3.4.1 Cadaver trial

Before deployment of the double-tag system on live birds, we trialled the attachment procedure on black-cockatoo cadavers. We were then able to establish landmarks for attachment to ensure consistent positioning on each bird. Tail-mounts followed the protocols of Le Souef, Stojanovic, *et al.* (2013) and Groom, Warren, *et al.* (2014). To deploy back-mounted solar GPS transmitters, we first attached a flexible plastic backing plate (~1 mm thick) to the feathers using adhesive cloth tape (Bear Black Gaffer Tape, Saint Gobain Abrasives Pty Ltd, Thomastown, Victoria, Australia). Two strips of tape were used, one at the top of the back-plate and one at the bottom.

The tape made several turns over the feathers and base-plate, so that tape adhered to tape. Three to four feathers were used to secure the back-plate. If possible, two separate rows of feathers were used to improve stability of the plate. The back-plate approximated the shape of the tag and was a dark colour to reduce visual cues to the bird and conspecifics. It had attachment holes matching the positioning of the eyelets on the tag to facilitate attachment of the tag to it. It was centred over the bird's vertebral column, 10 mm posterior to the pectoral girdle and 20 mm anterior to the pelvic girdle. The GPS tag was then glued (Selleys Ultra Repair Glue; Selleys, Padstow, New South Wales, Australia) and tied to the back-plate using braided nylon fishing-line (Fireline®, Berkley®, Spirit Lake, Iowa, USA) using the eyelets on the tag. Any feathers on the bird's neck that might obscure the solar panel were trimmed. This attachment method allowed the tag to be shed with the feathers, or to be removed easily by the bird if not tolerated.

3.4.2 Tolerance of double-tag mounting protocol and solar-only GPS/satellite tail-mount—Preliminary aviary trial

To test tolerance of the back-mounted GPS tag on live birds, we attached the tag using the protocol above to one forest red-tailed black cockatoo, one Baudin's black cockatoo and one Carnaby's black cockatoo. These birds were all in the final stages of rehabilitation before release back to the wild and were housed in a pre-release flight aviary (6 m × 64 m).

To minimise stress to the birds during attachment, tags were fitted under isoflurane gaseous anaesthesia (induced at 5% isoflurane, 1.5L/min. oxygen, maintained on 2% isoflurane). The birds were weighed and given a subcutaneous injection of Hartmann's solution (Compound Sodium Lactate, Baxter Healthcare Pty Ltd, Old Toongabbie, NSW) under anaesthesia. Supplementary heat during anaesthesia was provided by positioning the birds on a Mistral-Air® Warming Blanket (The 37°Company, Amersfoort, The Netherlands). Each bird was placed prone (Figure 3.1), which allowed for dorsal attachment of the 7.5-g GPS tag, incorporating a 20Hz tri-axial accelerometer (University of Amsterdam, The Netherlands—UvA-BiTS 2CDSe). Once extubated, the bird was loosely wrapped in a towel and placed into a secure pet-carrier to recover. All birds were standing and mobile within 30 minutes of extubation. Supplemental heat during recovery was maintained with an infrared heat lamp. The tagging procedure took a maximum of 15 minutes. Once recovered from anaesthesia, birds were returned to the flight aviary and their behaviour was observed. Correct operation of each tag was tested by downloading data using the UvA-BiTS antenna and base station. After 2 hours of observation and data collection, the bird was captured, and the GPS tag was removed, under manual restraint, by cutting the quills of the feathers used for attaching the base-plate. The underlying skin and feathers were checked for abnormalities before release of the bird.

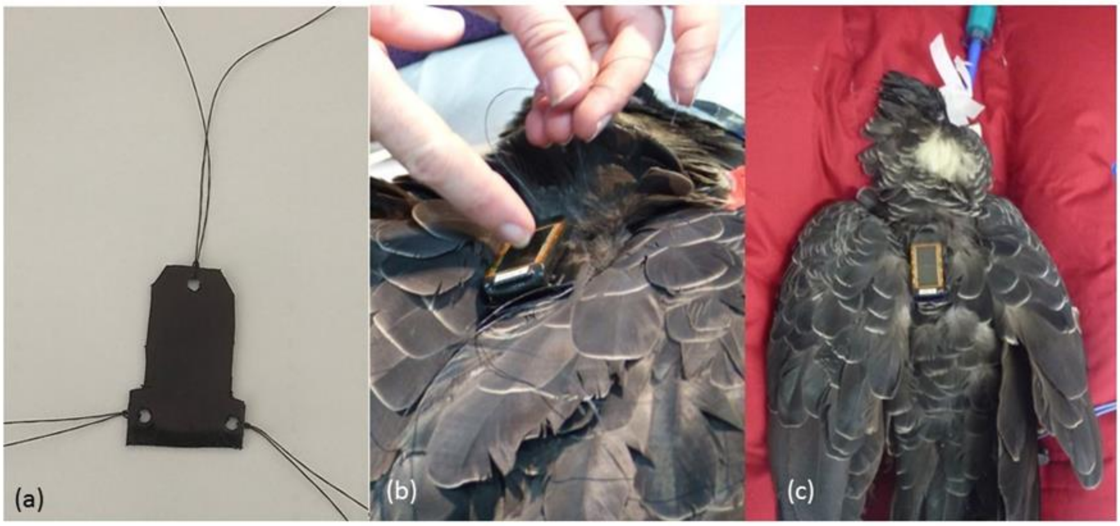

Figure 3.1: Back-mount of solar-powered UvA-BiTS tag on a black cockatoo: (a) backing plate with braid attachment ties, (b) backing plate and UvA-BiTS tag attached to feathers between the shoulders of a Carnaby's black cockatoo, and (c) final attachment on a Carnaby's black cockatoo. (Photos: Lian Yeap & Jill M. Shephard)

3.4.3 Tolerance of double-tag mounting protocol and solar-only GPS/satellite tail-mount—extended aviary trial

Six 'not-for-release' birds (four Carnaby's black cockatoos and two forest red-tailed black cockatoos) were each tagged with two tags, a back-mounted GPS tag and a tail-mount. Two of the Carnaby's black cockatoo had tail-mounts that were solar-powered tags, which required mounting on the dorsal aspect of the tail. In addition, a fifth Carnaby's black cockatoo was tagged with a single dorsal tail-mounted solar transmitter that combined both GPS and satellite capability, so a back-mounted GPS tag was not fitted to this bird. A total of seven birds were used in the trial (Table 3.1). All live satellite tags were programmed to transmit for 5 hours, every fifth day. The expected battery life using this schedule was 233 hours (Telonics 2014). GPS back-mounts were attached using the protocol described above, and tail-mounts followed the protocols of Le Souef, Stojanovic, *et al.* (2013) and Groom, Warren, *et al.* (2014). Dorsal tail-mounts followed the ventral tail-mounting protocol except that the tag was positioned on the dorsal aspect of the tail (Figure 3.2). The tags used in this study were Microwave Telemetry PTT-100, Telonics TAV 2617 and UvA-BiTS GPS (2CDSe, 5CDLe). Each Microwave Telemetry solar tag (PTT-100) had its antenna at an angle of 45° to the surface of the tag, which prevented the antenna being tied to the feather shafts as described for the ventral tail-mounts. All procedures were performed under isoflurane general anaesthesia as described previously. Birds were weighed and blood was collected for a routine blood profile (ZA1 Avian Profile, Vetpath Laboratories, Perth, Western Australia). Where birds were handled to remove trackers at the end of the study, weights and blood were repeated under anaesthesia. Birds were not reweighed or bled if they removed their tracking devices or lost their tracking devices through feather moult. In this trial we were interested in how long the tags would be retained and we did not remove tags unless they were damaged by the bird and/or posed a welfare risk. The double-tagging procedure took an average of 45 minutes. The combined weight of the tags (including mounting materials) was <5% of total body weight, which is within suggested recommendations (Cochran 1980).

Figure 3.2: Double-mount of satellite and GPS tags dorsally on a black-cockatoo: Microwave Telemetry PTT-100 (at right) attached to dorsal aspect of central rectrices, and UvA-BiTS (5CDLe, at left) attached to the feathers on the back of a Carnaby’s black cockatoo. (Photo: Lian Yeap & Jill M. Shephard)

The cockatoos were housed in their normal aviaries before, during and after the attachment trials. The not-for-release education Carnaby’s black cockatoos were housed together in an aviary adjacent to the food-preparation kitchen, where they were easily observed by KBCCC staff. Staff were asked to observe feeding and preening behaviour, flight activity and interaction between birds and to report any abnormalities. Birds were observed during normal husbandry procedures (i.e. aviary cleaning, food delivery).

The remaining birds were housed in a large flight aviary. All birds were given behavioural-enrichment items, such as marri *Corymbia calophylla* capsules and branches and radiata pine *Pinus radiata* cones several times per week.

3.5 Results

Tag placement and tolerance

The positioning of the back-mounted GPS tag was very successful, and none of the birds in the GPS back-mount trial showed interest in the tag, which stayed in position on the back between the shoulders. The tag moved with the feather shafts, so birds were able to preen around and under the tag at will, and in all trials the birds were routinely observed roosting with the head tucked next to the tag. Perching and flying behaviour was observed to be normal, and all data downloads were successful.

With the exception of one UvA-BiTS GPS tag in the extended double-tag aviary trial, tags remained in place for 5–29 days (Table 3.1). Tags were removed by the cockatoos, or manually removed because of partial detachment of the tag from the backing plate, most likely as a result of the birds preening and nibbling at the attachment points or through allopreening. GPS back-mount tags were less well tolerated by the forest red-tailed black cockatoos. One bird began to chew the tag whilst recovering from anaesthesia in the pet-pack, emphasising the need to observe birds closely before release back into the aviary and into the wild. This tag subsequently was removed by the bird several hours after deployment.

Table 3.1: Tag combinations and duration of their attachment to black cockatoos. Species: CBC = Carnaby's black cockatoo, FRTBC = forest red-tailed black cockatoo; sex: F = female, M = male; mount: DT = dorsal tail-mount; VT = ventral tail- mount: DB = (dorsal) back-mount; tag status: D = dummy, L = live; dates for attachment and detachment are given as day, month, year; and the durations of attachment (far right column) are given in days.

Black-cockatoo			*Tag*						
Identity (& microchip no.)	*Species*	*Sex (& weight, g)*	*Combination (& weight)*	*Mount*	*Status*	*Dimensions (mm)*	*Attachment*	*Detachment*	*Days*
Katanning (0006397AF1)	CBC	M (571)	Microwave Telemetry GPS/ Satellite Solar PTT-100 (22 g)	DT	L	64 x 23 x 16.5	21.5.15	11.11.15	175
Denmark (0006FO5157)	CBC	M (613)	Microwave Telemetry Solar PTT-100 (9.5 g)	DT	D	38 x 17 x 12	22.5.15	2.6.15	12
			UvA-BiTS GPS (2CDSe) (7.5 g)	DB	L	52 x 22 x 9	22.5.15	19.6.15	29
Harmony (000638A9AF)	CBC	F (632)	Microwave Telemetry Solar PTT-100 (9.5 g)	DT	L	38 x 17 x 12	21.5.15	9.6.15	20
			UvA-BiTS GPS (5CDLe) (13 g)	DB	L	61 x 25 x 10	21.5.15	26.5.15	6
Chasey (0006E6A1E3)	CBC	M (551)	Telonics TAV 2617 (17 g)	VT	L	64.3 x 20.3 x 8.4	21.5.15	5.1.16	230
			UvA-BiTS GPS (2CDSe) (7.5 g)	DB	L	52 x 22 x 9	21.5.15	1.6.15	12
Carnie (0007259858)	CBC	M (631)	Telonics TAV 2617 (17 g)	VT	D	64.3 x 20.3 x 8.4	19.6.15	3.3.16	259
			UvA-BiTS GPS (2CDSe) (7.5 g)	DB	L	52 x 22 x 9	19.6.15	30.6.15	12
Squeak (000725960E)	FRTBC	M (630)	Telonics TAV 2617 (17 g)	VT	D	64.3 x 20.3 x 8.4	19.6.15	1.8.15	44
			UvA-BiTS GPS (2CDSe) (7.5 g)	DB	L	52 x 22 x 9	19.6.15	19.6.15	0
Wubba (0006E6CD44)	FRTBC	M (498)	Telonics TAV 2617 (17 g)	VT	D	64.3 x 20.3 x 8.4	19.6.15	21.7.15	33
			UvA-BiTS GPS (2CDSe) (7.5 g)	DB	L	52 x 22 x 9	19.6.15	23–24.6.15	5–6

Retention of the ventral tail-mounts was high. Both Carnaby's black cockatoos retained the tag for >230 days (Table 3.1), which was beyond the calculated battery life of the units based on the programming schedule. Retention was longer in the Carnaby's black cockatoos than in the forest red-tailed black cockatoos, but it is unclear if this reflects a difference in species' tolerance. For at least one of the forest red-tailed black cockatoos, tag loss after 33 days appears to have been because of poor attachment rather than removal by the bird as the intact tag was observed to have moved down the tail and eventually slid off.

Tolerance of double-tag mounting

The optimal double-mounted tag combination was the 7.5-g UvA-BiTS GPS and 17-g Telonics TAV 2617 satellite tag, as trialled on Carnaby's cockatoos "Chasey" and "Carnie". This combination was well tolerated by the birds, and facilitated the collection of both GPS and satellite data at the required temporal resolution to support tracking releases in the wild.

There did not appear to be any effect of using a double-tag back- and tail-mount on the birds. In the six birds with the double-mount, no differences in behaviour, flight or feeding were reported by KBCCC staff. Where birds were recaptured for removal of the back-mounted GPS tag, there were no abnormalities of the feathers or skin underlying the back-mount. Blood screening results were compared with the reference ranges established by Le Souef, Holyoake, *et al.* (2013), and no abnormalities were noted. The blood profile assessed complete blood cell count (indicators of inflammation or infection), muscle enzymes (indicators of injury), kidney and liver function, blood glucose and electrolytes.

Feasibility of dorsal tail-mounting

All solar dorsal-mounted tail-tags were well tolerated by the birds. However, the Microwave Telemetry satellite/GPS tag (PTT-100) failed to recharge as, at rest, the bird's primary wing-feathers covered the solar panel. Interestingly, despite the angled (45°) antenna pointing outwards away from the tail, the bird did not chew it. The tag was naturally moulted with the two central rectrices after 175 days. The Microwave Telemetry 9.5g solar tag was mounted on a bird with only one fully erupted rectrix. The normal protocol requires two central rectrices. The tag had a tendency to hang slightly off to the side of the feather to which it was attached.

This transmitter stayed in place for 12 days before being recovered from the floor of the aviary in multiple pieces, having been chewed off by the bird (Figure 3.3).

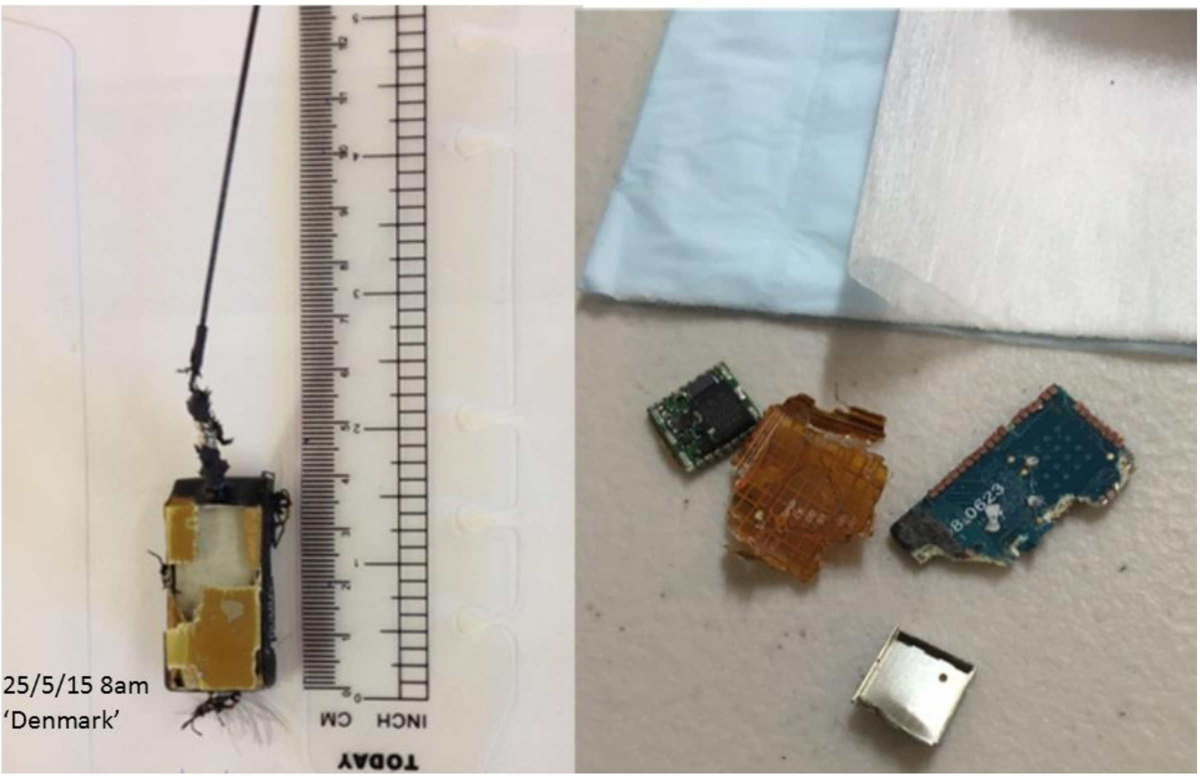

Figure 3.3: Satellite and GPS tags removed by black cockatoos. Microwave Telemetry tail-mount PTT (left) and UvA-BiTS tag (right) chewed off by the birds to which they were attached (left, Carnaby's black cockatoo; right, forest red-tailed black cockatoo). (Photos: Lian Yeap & Jill M. Shephard)

Signal interference

There was no interference during signal transmission between the satellite and GPS tags with the double-mounted tag system. Data transmissions and downloads from both tags in the double-mounted tag system were of the same quality and frequency as from single-mounted tags.

3.6 Discussion

In this study we trialled the use of solar 3D (tri-axial accelerometer) GPS tags as well as standard solar and battery-operated GPS and PTT tags. We were particularly interested in the feasibility and tolerance of a novel back-mount and a double-mount protocol combining a back- and tail-mount.

The success of the back-mounts in particular was surprising and very encouraging as we had expected that the birds would quickly remove them. UvA-BiTS tags have been used successfully to track marine species such as gulls (Camphuysen *et al.* 2015; Thaxter *et al.* 2015), and raptors (Schlaich *et al.* 2015) and vultures (Donázar *et al.* 2015). Our study was the first to trial UvA-BiTS tags on a cockatoo. As Carnaby's black cockatoos are renowned for their strong beaks and destructive feeding behaviour (Johnston 2013), we developed a means of attachment that maximised tolerance of the tag through careful positioning on the bird. This attachment method would not prevent the tag being chewed by another bird in the aviary; however, such behaviour was not observed during the project. Using tags and attachments that were dull-coloured (khaki-green or black) probably reduced any visual stimulation to investigate the tag. GPS tags attached with harnesses have been successfully used to track the New Zealand kea *Nestor notabilis*, a parrot also known for being both inquisitive and destructive (Department of Conservation New Zealand 2014). The kea nests on the ground (Kea Conservation Trust 2016) so the risk of a harness snagging on the nest is low. Radio-transmitters attached with harnesses have similarly been used to track the kakapo *Strigops habroptila*, another ground-dwelling New Zealand parrot (Powlesland *et al.* 1995). Carnaby's black cockatoos nest in tree-hollows, with the female entering the hollow tail first (Saunders 1982), so the risk of a harness or collar snagging and endangering the bird is significant. Given the Threatened status of Carnaby's black cockatoo and the intention to use these tags on birds for release, the attachment method has to minimise the risk of harm to the bird. Results of our study showed no evidence of the tag interfering with the birds' ability to fly, feed or perch, and there was no effect on the skin or feathers underlying the tag. We concluded that the back-mounting technique (which, unlike a harness design, has no straps) would pose the least risk of snagging or entanglement whilst also allowing the tag to be moulted naturally with the attached feathers. No birds engaging in nesting behaviour were used in this study, so we cannot be sure that the UvA-BiTS tags will not snag on protrusions in nest-hollows. However, this is unlikely given that the tag is dorsally mounted, and the attachment is designed to enable the tag to be lost with the feathers, therefore in the event of snagging, the tag attachment would likely detach with the small feathers on the back, allowing the bird to break free. In these trials, a bird quickly removed a UvA-BiTs tag if this was irritating it. Therefore, we consider it unlikely that these tags would pose a long-term snagging risk.

Our study determined that solar-powered PTTs can be successfully attached to the dorsal aspect of the central rectrices and retained for long enough to provide useful data. Unfortunately, because of the positioning of the wings at rest, the tips of the primary feathers sat directly over the PTT solar panel, effectively blocking exposure to sunlight. As a result, the tag battery failed to recharge and stopped transmitting data. We investigated means of elevating the tag with neoprene pads to position the solar panel above the feathers, but this made the unit too bulky, unstable and potentially uncomfortable for the bird and hence was not trialled further. Thaxter *et al.* (2014) encountered similar recharging issues when trialling UvA-BiTS tags secured with leg-loop harnesses in lesser black-backed gulls *Larus fuscus*. They attempted to elevate the device with neoprene pads to reduce feather overlap and improve solar exposure but, after release, no transmissions were received from the tag and when the bird was sighted again, the tag was missing, probably lost soon after release of the bird (Thaxter *et al.* 2014). This is further evidence to support the use of back-mounted solar-powered tags.

Battery-powered PTTs attached ventrally to the central rectrices proved to be well tolerated by black-cockatoos, with one tag staying in place for 259 days before being moulted out, still securely attached to the central rectrices (Figure 3.4). This period exceeded the expected battery life for the tag. Aviary trials in 2013 (Yeap unpubl. data) using dummy Telonics TAV2617 tags on Carnaby's black cockatoos had retention times of up to 274 days, and when tags were retrieved intact, they appeared to have been moulted out still attached to both central rectrices. This previous study showed that the central rectrices tend to moult out simultaneously, and we did not observe partially attached tags because of birds moulting out only one central rectrix. It should be noted that when a tag was attached to only one rectrix (only one central rectrix erupted at the time of this study), the tag sat unevenly and was removed by the bird after 3 days. The extra movement was clearly an irritant to the bird, and it is recommended that tail-tags are always attached to two central rectrices. It is interesting to note that, in the present study, both Carnaby's black cockatoos retained the tail-mounted Telonics tags for >200 days, compared with a maximum of 44 days for the forest red-tailed black cockatoos. Whether this apparent difference in tolerance reflects a difference between species or between individual birds is still to be determined. The not-for-release education birds used in the trials were habituated to regular interaction with humans, hence their behaviour towards the tags may not be indicative of behaviour in wild birds. Wild birds spend more time flying and foraging to meet their basic requirements, therefore would likely have less time available to investigate the tags attached to them.

Figure 3.4: Moulted central rectrices with Telonics TAV 2617 satellite tag still attached to both feathers of a Carnaby's black cockatoo. (Photo: Lian Yeap & Jill M. Shephard)

Overall, the tags that we investigated in this study were well tolerated by the birds and retention times exceeded expectations. Six of the seven birds were fitted with both UvA-BiTS GPS and tail-mounted PTT tags. Two birds retained both tags for 12 days, the remaining birds retained them for shorter periods. In the case of 'Harmony' and 'Chasey', the UvA-BiTS tags were removed manually when the tag partially detached, to preserve the units for future trials. In most other cases, there were underlying reasons for detachment of one or both tags. In the case of 'Denmark', the Microwave Telemetry tail-mounted tag could not be attached to two central rectrices, as one was missing at the time of the study; accordingly, the tag appeared to sit in a lopsided manner. As previously noted, the antennae of the Microwave Telemetry tags sat at an angle of 45º; we suspect that this combination of factors probably played a role in the relatively short retention time for this unit. Irrespective of this, it is unlikely that the solar dorsal tail-mount would have been effective, as again there was significant overlap of the wings across the solar panel. In the case of forest red-tailed black cockatoo 'Squeak', the UvA-BiTS tag was chewed off in the post-anaesthetic recovery period, which highlights the need to closely monitor birds during recovery (distracting them if necessary) to ensure that the tags are not removed prematurely.

When black cockatoos were fitted with two live tags, there was no evidence of interference with the transmissions from these. In all cases, the Telonics tags functioned normally and transmitted data according to their programming whilst UvA-BiTS tags were in place. Similarly, data were downloaded normally from the UvA-BiTS tags whilst the Telonics tags were active. In the case where the UvA-BiTS was combined with a Microwave Telemetry solar PTT, the latter tag failed to function because of inadequate solar recharging, so we cannot comment conclusively on interference between the devices.

Although all measures were taken to ensure that tags were securely attached to the birds, the attachments were designed (and tested) to ensure that the tags could be moulted out naturally with the feathers on the body or tail, or removed physically by breaking the mounts (braid ties). Black cockatoos are thought to have a 1–2-year moult cycle (Cameron 2007), so it is unlikely that a tag would remain on a bird for longer than this.

By successfully developing an effective attachment method for the back-mounted UvA-BiTS tags and trialling the concurrent use of GPS and satellite tags on captive birds, we have validated this tracking system for future use in wild birds. Tracking data will provide information at both an individual and population level, and will mark a major advance in our ability to understand the spatial and movement ecology of these black-cockatoo species, and significantly enhance our capacity to address the aims of the species' Recovery Plans. Although this study focused on black cockatoos, this attachment method could readily be applied to other parrot and cockatoo species around the world, providing a means of increasing spatial data collection to better understand their ecology and conservation.

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Chapter 4. Application of tri-axial accelerometer data to the interpretation of movement and behaviour of threatened black cockatoos.

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The following authors contributed to this manuscript as outlined below.

Authorship order	**Contribution (%)**	**Concept Development**	**Data Collection**	**Data Analyses**	**Drafting of manuscript**
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Kristin Warren	6	x	x		x
Willem Bouten	4	x		x	x
Rebecca Vaughan-Higgins	1				x
Bethany Jackson	1				x
Karen Riley	1		x		x
Sam Rycken	1		x		x
Jill Shephard	6	x	x	x	x

Contribution indicates the total involvement the author has had in this project. Placing an 'X' in the remaining boxes indicates what aspect(s) of the project each author engaged in.

By signing this document, the Candidate and Principal Supervisor acknowledge that the above information is accurate and has been agreed to by all other authors.

Candidate **Principal Supervisor**

4.1 Preface

As described in the previous chapter, UvA-BiTs tags provide both GPS and tri-axial accelerometer data. This chapter comprises original research undertaken to develop an automated classifier tool to analyse accelerometer data from UvA-BiTs tags and identify behaviours. Accelerometer data and video footage of captive black cockatoos was used to create a tool capable of identifying resting, flying and foraging behaviours. We then applied the tool to data from released black cockatoos to remotely determine behaviour patterns and activity budgets. Combined with location data, this provides vital insight into cockatoo movement, distribution, feeding and breeding habitat and resource use.

4.2 Abstract

Context. Carnaby's (*Calyptorhychus latirostris*), Baudin's (*Calyptorhynchus baudinii*) and forest red-tailed black cockatoos (*Calyptorhynchus banksii naso*) are threatened parrot species endemic to south-western Australia. Behavioural monitoring has previously involved direct observation, which has proven challenging due to their cryptic nature, the type of habitat they move through and their speed of movement. The development of a model to accurately classify behaviour from tri-axial accelerometer data will provide greater insight into black cockatoo behaviour and ecology.

Aims. To develop an automated classifier model to classify accelerometer data from released black cockatoos to determine behaviour and activity budgets for three species of black cockatoo.

Methods. In this study, we attached tri-axial accelerometers, housed in GPS tags, to four Carnaby's cockatoos, three forest red-tailed black cockatoos and two Baudin's cockatoos in captive care, undergoing rehabilitation for release back to the wild. Accelerometer data from these birds was coupled with 19 video files of the birds' behaviour when flying, feeding and resting, to develop an automated behaviour classifier. The classifier was then used to annotate accelerometer data from 15 birds released after successful rehabilitation and to calculate activity budgets for these birds post-release.

Key results. We developed a classifier able to identify resting, flying and foraging behaviours from accelerometer data with 86% accuracy, as determined by the percentage of observed behaviours correctly identified by the classifier. The application of the classifier to accelerometer data from 15 released cockatoos enabled us to determine behaviours and activity budgets for all three species of black cockatoo. Black cockatoos spent most of their time at rest, followed by foraging with a short period of time flying.

Conclusions. Application of the classifier to data from released birds, gives researchers the ability to remotely identify patterns of behaviour and calculate activity budgets.

Implications. Combining behaviour and activity budgets with location data, provides useful insight into cockatoo movement, distribution, and habitat use. Such information is important for informing conservation efforts and addressing outstanding research objectives. Further studies including larger sample sizes of Baudin's and forest red-tailed black cockatoos and comparing behaviour and activity between birds in breeding and non-breeding areas are warranted.

4.3 Introduction

Accelerometers have been used in animal behavioural studies since the late 1990's (Brown *et al.* 2013). Accelerometers measure acceleration in three planes – dorso-ventral (up-down, Z axis), anterior-posterior (forward-back, X axis) and lateral (side-side, Y axis), typically referred to as heave, surge and sway respectively (Shepard *et al.* 2008). When analysing behaviour, the accelerometer data measured must be translated into specific behaviours (Shamoun-Baranes *et al.* 2012). This is achieved through expert interpretation of sensor and video behavioural data collected in the field, automated clustering of sensor data without field observations, or automatic classification of sensor data in conjunction with behavioural observation (Shamoun-Baranes *et al.* 2012). Whilst the first two methods rely on inferences of animal behaviour, the third involves careful observation of animal behaviours which are then matched to distinctive accelerometer signatures. This validated data can then be used to train machine learning algorithms to recognise specific accelerometer signatures. These algorithms then automatically classify new accelerometer data into specific behaviour categories (Brown *et al.* 2013; Tatler *et al.* 2018).

The attachment of an accelerometer directly to an animal allows measurement of the body's acceleration or change in velocity, fine movements and posture. Specific behaviours, and associated movements and postures, show distinct accelerometer signatures (Brown *et al.* 2013). Advances in technology, such as miniaturisation of components and solar recharging of batteries (Bouten *et al.* 2013) have resulted in a significant reduction in the size of tracking devices in recent years, enabling their use to study the movement and behaviours of a wider range of avian species, including small birds. Tracking devices can impact on bird behaviour, such as flying ability, foraging and energy expenditure, thus researchers try to adhere to the 'rule of thumb' that the weight of a device should not exceed three to five percent of the animal's body weight (Cochran 1980; Kenward 2001). This is easier to achieve with the smaller devices available today. For example, Bäckman (2017) used accelerometer data from a 1.2g device to create annual actograms for the red-backed shrike (*Lanius collurio*), a small (25-35g) migratory songbird. The study provided new insights into migratory behaviour and flight patterns. Arai *et al.* (2000), in a study of foraging behaviour of free-ranging Adélie penguins

(*Pygoscelis adeliae*), attached two-direction accelerometers to determine swimming and diving activity. Shamoun-Baranes *et al.* (2016) described the use of tri-axial accelerometer data to determine body movement of lesser black-backed gulls (*Larus fuscus*), providing useful information on flying behaviour in different conditions and habitats, as well as the impact on foraging patterns and associated energy budgets. Accelerometers have even been placed into artificial eggs to study the egg turning behaviour, incubation temperature and the impact on hatching success of nesting Cassin's auklets (*Ptychoramphus aleuticus*), western gulls (*Larus occidentalis*), and Laysan albatrosses (*Phoebastria immutabilis*) in California (Shaffer 2014).

Whilst animal movement can be determined by telemetry trackers, direct visual observation is often used to study activity and behaviour. Direct observation is not always possible, however, due to difficulties posed by the terrain (e.g. dense forest), lack of access (e.g. private land), or the distance to, and time taken to locate animals. Furthermore, whilst direct observation has its advantages, an observer cannot easily watch a target animal continuously from morning to night and behaviours may be missed whilst the observer is not present (Altmann *et al.* 2003). The presence of an observer may also impact on the animal's behaviour (Lendvai *et al.* 2015). The amount of data that biologging devices, such as accelerometers, could provide, may offer useful insights into habitat use and movement patterns which are otherwise difficult to acquire (Tatler *et al.* 2018).

Carnaby's cockatoo (*Calyptorhychus latirostris)*, Baudin's cockatoo (*Calyptorhynchus baudinii*) and the forest red-tailed black cockatoo (*Calyptorhynchus banksii naso)* are iconic parrot species endemic to south-western Western Australia. All three species of black cockatoo are increasingly threatened by: urban, agricultural and industrial development; habitat loss and fragmentation; competition with other bird species and feral bees for nest hollows; poaching; disease; and anthropogenic factors such as vehicle strike and illegal shooting (Saunders *et al.* 2011). Significant declines in black cockatoo numbers have been observed since the 1980s (Saunders *et al.* 1998; Williams *et al.* 2017) and all three species are classified as threatened under state and federal legislation and according to IUCN criteria (Department of Environment and Conservation 2007, 2012; IUCN 2020). Whilst there has been previous research on the ecology and breeding biology of black cockatoos, particularly of Carnaby's cockatoos, these studies have been restricted to a relatively small number of known breeding, foraging and roosting sites (Johnstone *et al.* 2008; Johnstone *et al.* 2011; Johnstone and Kirkby 2017; Saunders *et al.* 2018). Little is known about flock behaviour and movement patterns more broadly across these species' distribution ranges (Johnstone *et al.* 2008; Saunders *et al.* 2018).

Animal tags containing tri-axial accelerometers can facilitate the collection of a large amount of behavioural data (Cooke *et al.* 2004). These data can be used to determine physiological measurements such as time-energy budgets, as well as an assessment of biotic and abiotic factors impacting on activity budgets. For example, Carnaby's cockatoos tend to migrate to feed in the higher rainfall coastal areas within their range in the non-breeding season (January-July), as food is more abundant (Department of Environment and Conservation 2012; Stock *et al.* 2013; Saunders *et al.* 2018). Accelerometer data can be used to quantify the extent to which energy budgets differ in different landscapes enabling researchers to address ecological questions such as: how do activity demands differ for birds in urban environments (such as the Swan Coastal Plain) compared to those in the Wheatbelt or southern forest regions?; are the activity budgets similar across the three black cockatoo species, given the variation in preferred habitats? This information can be used to guide conservation management decisions, such as protection of foraging, roosting and breeding habitat from development, determine the potential impact of proposed developments and identify suitable conservation offsets for developed land. (Department of Environment and Conservation 2012)

Behavioural monitoring has previously been achieved through direct observation, which has proven difficult due to the cryptic nature of black cockatoos, the type of habitat that they move through and the speed with which they move. In this study, we collected accelerometer data from wild black cockatoos undergoing rehabilitation for release back to the wild. These data were coupled with video footage of the birds' behaviour in a flight aviary, prior to release. The aim of this project was to develop an automated classification model able to identify resting, flying and foraging behaviour from accelerometer data. This model was applied to data from released black cockatoos, allowing us to calculate activity budgets for three black cockatoo species, providing insight into their post-release behaviour and activity budgets.

4.4 Materials and methods

This study was carried out in two stages. Stage One – aviary-based filming of bird behaviour to train an automated classifier. Stage Two – application of the classifier to data retrieved from accelerometer tagged birds in wild flocks.

4.4.1 Stage One

Tag attachment

Nine black cockatoos, four Carnaby's cockatoos, three forest red-tailed black cockatoos and two Baudin's cockatoos, were used to develop the classifier in this study. These were all injured wild birds that had been treated at Perth Zoo and undergone rehabilitation. The birds had no discernible differences in flight or activity compared to wild birds and were assessed as ready for release back into the wild by the Western Australian Department of Biodiversity, Conservation and Attractions. All birds were housed in a pre-release flight aviary (6m x 64m) to undergo flight conditioning at Kaarakin Black Cockatoo Conservation Centre (https://www.blackcockatoorecovery.com).

As the birds were destined for release, they had two tags attached. A Telonics TAV 2617 Platform Terminal Transmitter (PTT) ARGOS satellite tag was attached to the ventral base of the central tail feathers and a 7.5 gram solar University of Amsterdam Bird Tracking System (UvA-BiTS) GPS tag incorporating a 20Hz tri-axial accelerometer was attached to the feathers between the wings, on the upper back as described in Yeap *et al.* (2017). Tags were attached under isoflurane anaesthesia to minimise stress.

To affix back-mounted accelerometer tags, we first fixed a flexible plastic backing plate (~1 mm thick) to the feathers using adhesive cloth tape (Bear Black Gaffer Tape, Saint Gobain Abrasives Pty Ltd, Thomastown, Victoria, Australia; (Yeap *et al.* 2017). Two strips of tape were used, one at the top of the back-plate and one at the bottom. The tape made several turns over the feathers and base-plate, so that tape adhered to tape. Three to four feathers were used to secure the back-plate. If possible, two separate rows of feathers were used to improve stability of the plate. The back-plate mirrored the shape of the tag and was a dark colour to reduce visual cues to the bird and conspecifics to reduce the likelihood of removal. Attachment holes were made to match the positioning of the eyelets on the tag to facilitate attachment of the tag to it. The tag was centred over the bird's spine, 10 mm below the shoulders and 20 mm above the pelvis. The tag was then glued (Selleys Ultra Repair Glue; Selleys, Padstow, New South Wales, Australia) and tied through the tag eyelets to the back-plate with braided nylon fishing-line (Fireline®, Berkley®, Spirit Lake, Iowa, USA). Any feathers on the bird's neck that might obscure the solar panel were trimmed. This attachment method allowed the tag to be shed with the feathers, or to be removed easily by the bird.

The satellite tags were attached to the ventral aspect of the base of the two central tail feathers following the protocols of Le Souef, Stojanovic, *et al.* (2013) and Groom, Warren, *et al.* (2014). The tag was secured using black braided fishing line (Fireline®, Berkley®, Spirit Lake, Iowa, USA) threaded through mounting holes along the sides of the tag and around the shaft of each central tail feather, tied with a surgeon's knot. The tag antenna was laid along the shaft of one of the central tail feathers and secured with braid ties approximately 30mm apart. A flexible, rapid setting glue (Selleys Ultra Repair Glue; Selleys, Padstow, New South Wales, Australia) was applied to each knot for additional security. The combined weight of the tags was less than five percent of the bird's body mass, and meets ethical requirements (Cochran 1980; Kenward 2001). Birds were under anaesthesia for an average of 35 minutes. Once recovered from anaesthesia, birds were returned to the flight aviary.

Satellite PTT tags provide an ARGOS satellite location (ARGOS CLS System, 2018) to within 250m - 500m accuracy. These locations were used to locate the study bird in the field during Stage two of the project to facilitate accelerometer and GPS data downloads to a mobile base station.

Collection of Accelerometer Data and Behavioural Observations

For Carnaby's cockatoos and forest red-tailed black cockatoos, each bird was banded with an Australian Bird and Bat Banding Scheme (ABBBS) metal numbered leg band on the right leg, just above the intertarsal joint. Two coloured metal leg bands were placed on the left leg; each colour combination corresponding to a specific bird. Placement was reversed for Baudin's cockatoos with the ABBBS band placed on the left leg and colour bands on the right, to allow rapid differentiation from Carnaby's cockatoo. The leg bands allowed identification of the bird from a distance in the field with binoculars or telephoto lens, or if recaptured. A spot of low-toxic (10-Free™ https://www.kesterblack.com/blog/edu/whats-the-deal-with-non-toxic-nail-polish) nail polish (Kester Black, Collingwood, Victoria, Australia) was applied to the upper beak to allow quick identification of the study bird in the aviary as birds were housed in groups among non-study birds to facilitate normal activity.

Kaarakin staff observed the black cockatoos in the pre-release flight aviary were most active in the morning, between 09:00 to 10:00hrs (Western Standard Time), after the aviary had been serviced and fresh food, water and native browse supplied. Feeding, flying and resting behaviour was frequently observed, hence filming was scheduled during this period.

The tags were programmed to collect 200 accelerometer samples every 2 seconds for 30 minutes. High frequency was required to capture fine scale movement but depleted the tag battery. The program was limited to 30 minutes to ensure the tag had sufficient power to function on release of the bird the following day. On the day following tag attachment, the study bird was observed in the pre-release flight aviary and its behaviour filmed with a Sony HDR-PJ30VE Handycam (Sony Corporation, Tokyo, Japan) video camera. Filming commenced at the start of the accelerometer tag program and continued for 30 minutes, corresponding to the tag program. Footage was filmed in 720p high definition resolution at 50 frames per second. The start time of filming was noted by recording UTC (Coordinated Universal Time) from an internet time server on a mobile phone. This allowed the synchronisation of accelerometer data and video footage during the annotation phase. Once saved, video footage was converted to AVI format for use with the annotation software, using Any Video Converter software (Anvsoft Inc., Shenzhen, Guangdong, China; www.anvsoft.com). Each study bird was filmed once.

At the completion of filming, the GPS and accelerometer data were remotely downloaded to the base station netbook computer. Data were then transferred for processing to the UvA-BiTS e-infrastructure platform and permanently stored in a PostgreSQL spatial database and accessed through the Virtual Lab portal www.UvABiTS.nl/virtual-lab (Bouten *et al.* 2013). Within the Virtual Lab, the data from individual tags were selected (filtered by the tag identification number, date and time of filming) and downloaded for use within the annotation software.

Annotation of data and video footage

To annotate the accelerometer data, eight activities or behaviours of interest were determined and used to create a classification scheme (Table 4.1). The behaviours selected were resting, walking, feeding, drinking, flying – take-off, flying – flapping, landing and other behaviours (preening or aggressive interactions) that did not fit into those categories. Some behaviours could not be classified with sufficient reliability and were grouped within the classification of foraging. Foraging included walking, climbing, feeding behaviour and other unspecified behaviours such as preening or aggressive interactions; on the ground or on a perch. From viewing the video footage and personal observation of the cockatoos in the aviary and in the wild, walking behaviour mainly occurred whilst birds were eating or going to and from food sources, thus grouping walking and feeding in the foraging category was considered appropriate. Similarly, aggressive interactions and preening behaviour often involved walking and feeding, hence they were also grouped into the forage category. Flying included take-off, landing and flapping flying so these behaviours were all grouped in the same class. There was insufficient video footage to reliably classify drinking, so it was excluded from the behaviour scheme. This resulted in three behaviour classes: resting, foraging and flying that were used for the final classification.

Table 4.1: Behaviour scheme used for data classification.

Behaviour	Behaviour Definition	Grouped behaviour	Duration of Observation (secs)
Resting	Sitting inactive on ground or perch*	Resting	4373
Walking	Walking on ground or perch, including climbing.	Foraging	533
Feeding	Feeding on ground or perch	Foraging	1104
Drinking	Drinking from a water source	Deleted	0
Flying – take-off	Take-off flight from ground or perch	Flying	31
Flying - flapping	Sustained flight	Flying	107
Landing	End of flight	Flying	31
Other	Behaviours not specified – preening, aggressive interactions	Foraging	249

As outlined by de Bakker (2011), a software tool developed in the Matlab software package, version 2013a (The Mathworks Inc., Natick, Massachusetts, USA) provides a visual interface to view the accelerometer data, synchronised with associated video footage (hereafter this will be referred to as the Annotation Tool) as shown in Figure 4.1. Access to this tool was provided by UvA-BiTS. The relevant movie file (.avi), corresponding accelerometer data file (.csv) and behavioural scheme were opened in the Annotation Tool and the timestamp at the start of the video was synchronised to the accelerometer data to facilitate annotation. The annotated data was saved as a .mat file for use in developing the classifier.

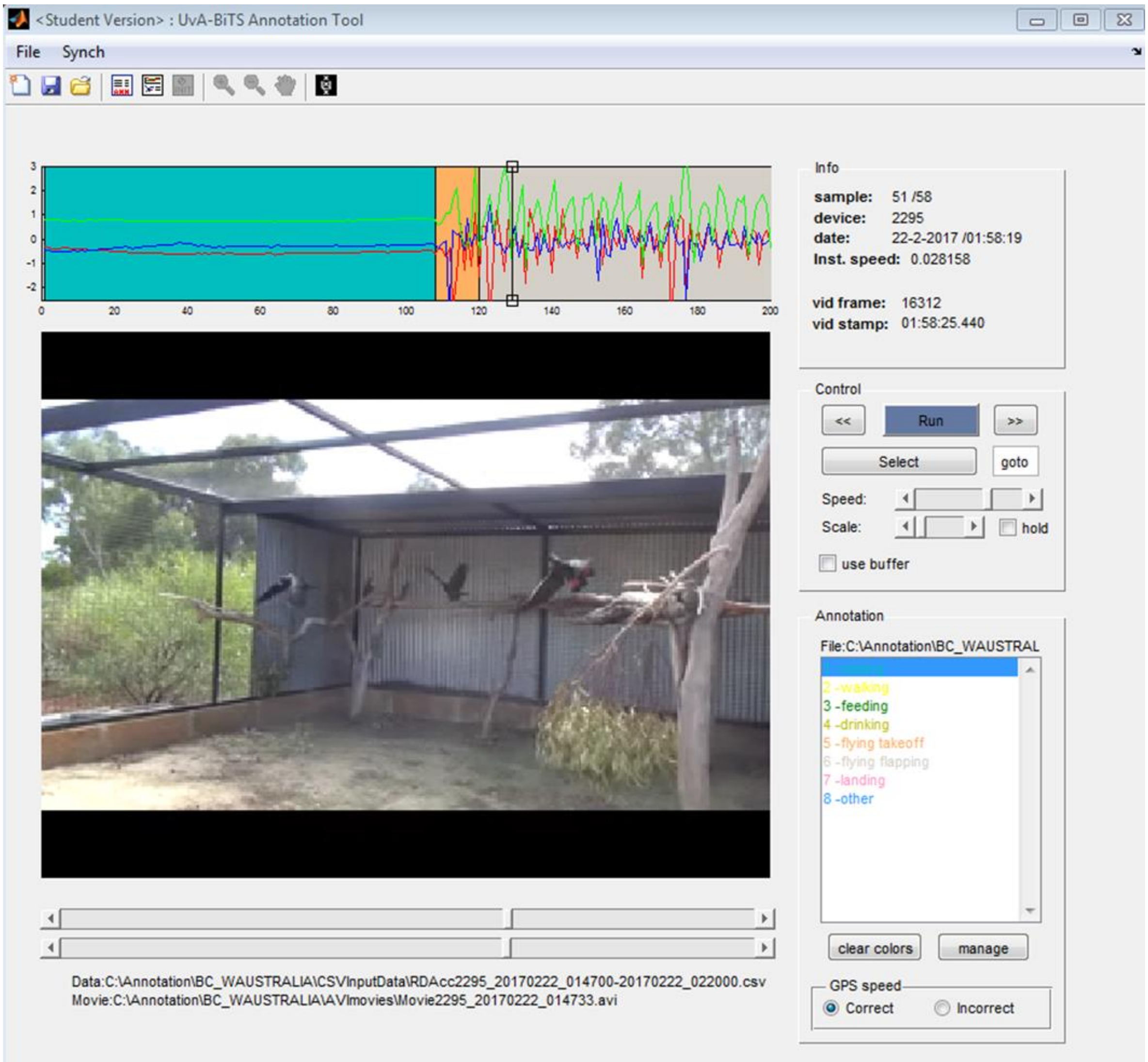

Figure 4.1: Annotation tool demonstrating accelerometer graph corresponding to flying behaviour. Legend: aqua = resting; orange = flying takeoff; grey = flying flapping. On the accelerometer signature, y-axis shows acceleration (in units of g-force) with green = heave (up-down), red = surge (forward-back), blue = sway (side-side).

Additional accelerometer data from released birds, without accompanying video footage, was analysed and annotated based on knowledge of the distinct accelerometer signatures generated by each behaviour (Meijer *et al.* 2016; Shamoun-Baranes *et al.* 2016). Examples of accelerometer signatures are included in **Appendices 1 to 4**. As there was significantly less video footage of flying, this behaviour was targeted to increase the amount of flying accelerometer data used in the classifier to improve accuracy. Twelve data files consisting of 750 seconds of additional flying data were used. The addition of more flying data beyond this did not improve the classifier accuracy.

Classifier development

The classifier tool uses a decision tree machine learning algorithm. There are 37 features or predictor variables (Shamoun-Baranes *et al.* 2012) that can be calculated for each one second segment (x-surge, y-sway, z-heave) to classify behaviours. We selected one feature then added additional features in a forward-stepwise approach to differentiate behaviour.

The data set of 1881 data points was randomly split, with 40% used to train, 30% used to test and the remaining 30% used to validate the classification model (Vansteelant *et al.* 2016). Behaviours were visualised using scatterplots based on the features used in the classification software. Features were useful if behaviours were well differentiated (datapoints scattered), and not useful if behaviours were poorly differentiated (data points tightly clumped).

The features 'mean pitch', which measures forward-backward movement over all accelerometer points in the segment, and 'mean of the absolute value of the derivative of z', which measures up-down movement in the z-axis, produced the most accurate and consistent model for differentiating and classifying behaviours. Using more features did not improve accuracy of classification, so a simple model with two features was chosen. The model development process used was similar to that described by Camphuysen *et al.* (2012); (Shamoun-Baranes *et al.* 2012).

The modelling process resulted in a random forest classifier with 500 decision trees and two features. A confusion matrix was calculated to determine the number of correctly and incorrectly classified data points (Table 4.2). Accuracy was determined by the percentage of observed behaviours correctly identified by the classifier (Ladds *et al.* 2017).

Table 4.2: Confusion matrix showing the number of correctly (bold) and incorrectly classified data points in the final classifier.

Observed behaviour	Predicted behaviour			
	Resting	Foraging	Flying	Total observed
Resting	**1172**	195	0	1367
Foraging	57	**403**	9	469
Flying	0	2	**43**	45
Total predicted	1229	600	52	1881

4.4.2 Stage Two

Application to tracked birds in the wild

The nine birds that were used to develop the classifier in the aviary (Stage one) were subsequently released to the wild with an additional nine Carnaby's, two Baudin's and two forest red-tailed black cockatoos (N=22) as part of a large and ongoing movement ecology study (Black Cockatoo Ecology Project, Murdoch University). The nine birds also had the same two tags attached as the birds in Stage one. Tag attachment procedures were as described above, however, the GPS and accelerometer release programme were adjusted to maximise battery life. Birds were released during non-breeding periods (Saunders 1980; Johnstone *et al.* 2011; Johnstone *et al.* 2013) into areas where wild flocks were known to be active or roosting. Carnaby's cockatoos were released in May and June 2016 and March 2018; forest-red tailed black cockatoos in July 2016 and February 2017 and Baudin's cockatoos in August 2015 and May 2017. During daylight hours (from 05:30hrs), tags were scheduled to collect accelerometer readings and GPS location every 2.5 minutes when battery voltage was high, or every 15 minutes otherwise. During the night (from 18:30hrs) GPS locations were collected at 30-minute intervals. For both day and night programs, accelerometer readings and GPS locations were measured at a frequency of 20Hz for one second.

Accelerometer data were successfully downloaded from fifteen birds to the mobile base station (laptop and base antenna plus relay antenna) at night roosts and uploaded to the UvA-BiTS Virtual Lab for processing (classification) and activity budgets determined.

Each bird was assigned an identifier based on species - BC for Baudin's cockatoo, CC for Carnaby's cockatoo, FRTBC for forest red-tailed black cockatoo; and UvA-BiTS four-digit tag number.

4.5 Results

4.5.1 Stage One

Video footage and corresponding accelerometer data were successfully retrieved from four Carnaby's cockatoos, three forest red tailed black cockatoos and two Baudin's cockatoos in the flight aviary. A total of 19 annotated data files were created from the video and accelerometer data.
The resulting classifier was able to differentiate behaviours that were grouped as flying, foraging, or resting with 86% accuracy. Misclassifications occurred most frequently with resting behaviour, as 195 out of 1367 (14%) resting behaviours were incorrectly classified as foraging. Similarly, in regard to foraging behaviours, 57 out of 460 (12%) were incorrectly classified as resting and 9 out of 460 (2%) were incorrectly classified as flying. Two out of 45 (4%) flying behaviours were incorrectly classified as foraging.

4.5.2 Stage Two

Activity budgets by species
Despite the limited number of misclassifications that occurred, the classifier's accuracy of 86% ensured that the activity budgets generated were a good indication of true activity. The activity budget for each of the released birds is shown in Table 4.3. CC 2330 only retained the accelerometer tag for one day and little data was retrieved. As such, results from this bird were excluded. During the tracking period, Baudin's cockatoo behaviour was classified as 50%

foraging, 3% flying, and the remainder at rest. Carnaby's cockatoo behaviour was 60% resting, 33% foraging and approximately 6% flying. Forest red tailed black cockatoo behaviour was 75% resting, 20% foraging, and the remaining 4% flying.

Table 4.3: Activity budgets of 15 released black cockatoos
BC = Baudin's cockatoo, CC = Carnaby's cockatoo, FRTBC = forest red-tailed black cockatoo.

	Behaviour %			
BIRD ID	Rest	Forage	Fly	Days tracked
BC 2167	36	62	3	104
BC 2172	43	54	2	38
BC 2305	64	33	3	17
Average	47.7	49.7	2.6	
CC 2216	43	47	10	98
CC 2222	40	52	8	75
CC 2258	76	21	3	13
CC 2260	66	30	4	21
CC 2261	60	37	3	34
CC 2263	70	26	4	10
CC 2327	72	24	4	9
CC 2328	57	35	7	3
CC 2331	70	24	6	10
Average	61.5	33	5.5	
FRTBC 2264	76	18	6	14
FRTBC 2295	74	23	3	35
FRTBC 2296	78	18	4	5
Average	76	19.6	4.4	

4.6 Discussion

Understanding the movement of species through the landscape is a fundamental aspect of conservation management. Southwest Western Australia is a biodiversity hotspot (Mittermeier *et al.* 2004) but is subject to widespread habitat modification through urban, industrial and agricultural development which has resulted in a complex and continually evolving habitat matrix. Habitat modification, loss of transit corridors and anthropogenic threats, including vehicle strike, increase energy demands highlighting the importance of understanding activity budgets relative to the activity cost of individual habitat types on black cockatoo species. As with other species where visual observation was both difficult or inaccurate (e.g. lesser black backed gulls (*Larus fuscus*) (Shamoun-Baranes *et al.* 2016); griffon vultures (*Gyps fulvus*) (Nathan *et al.* 2012); and, red-backed shrike (*Lanius collurio)* (Bäckman 2017), our indirect behaviour classification model was successful in capturing key rest, forage and flight behaviour classes that can be used to directly quantify the impact and activity cost of habitat type and structure on black cockatoo species. Our classification was 86% accurate for the three behavioural classes analysed and is comparable to the accuracy reported in Shamoun-Baranes *et al.* (2012), Sur *et al.* (2017) and Tatler *et al.* (2018).

Classifier development and performance

The original classification scheme had eight distinct behaviours we were interested in detecting in the wild release birds, however, the classifier was unable to reliably differentiate some behaviours with the amount of data and video footage available. Whilst all types of flying behaviour were observed and filmed, there was both insufficient accelerometer data and video footage of take-off and landing behaviour to accurately train the classifier to differentiate between them and flapping flying. This was primarily due to the infrequent occurrence and very short duration (0.5 to two seconds) of each behaviour. As we were interested in overall movement associated with flying behaviour, not including take-off and landing flight in the classifier was not a major concern. We will be able to apply the model to quantify and compare the proportion of flight time between habitats that may be a result of flushing rates or other disturbance pressures that exert an energetic cost.

Activity budgets and behaviour

The three species of black cockatoo had quite similar activity budgets (Table 3) with birds spending most of their time at rest, interspersed with foraging activity throughout the day and some movement between roost sites or feeding habitat. Flying and foraging occurred most frequently around sunrise and sunset.

The Carnaby's cockatoos in this study were released on the Swan Coastal Plain, which is recognised as important feeding grounds for Carnaby's cockatoos in the non-breeding season of February to June (Johnstone *et al.* 2011), thus a high level of foraging was not unexpected. Adults and young birds feed in *Banksia spp* woodlands (Saunders 1980, 1990), as well as pine plantations *(Pinus spp*) which is recognised as an important food source (Stock *et al.* 2013).

The Baudin's cockatoos in this study appeared to spend almost equal amounts of time resting and foraging, with only a small amount of time spent flying. These birds were released in the Perth hills area in August, the start of the breeding season. Flocks have been observed gathering in traditional roosting areas on the Darling Scarp, -32°S, 115°E (Johnstone and Kirkby 2017) and southern Swan Coastal Plain prior to flying south to their breeding grounds (Johnstone *et al.* 2008). The limited flying activity captured at this time may be related to reduced activity in these pre-migration flocks. Tracking more Baudin's cockatoos would undoubtedly reveal more detail about their activity and movement. Since this project began in 2015, only 16 Baudin's cockatoos have been available for release post-rehabilitation. Given they primarily occupy the southern forest, fewer injured Baudin's cockatoos are presented for treatment and subsequent rehabilitation (Black Cockatoo Conservation Project, Murdoch University, unpubl. data).

Forest red-tailed black cockatoos spent more time resting than Carnaby's and Baudin's cockatoos. Whilst one bird was released on the Swan Coastal Plain and two birds were released into a south-west forest area, all three birds exhibited similar behaviours during the period they were tracked. Forest red-tailed black cockatoos have a distinctive way of feeding. Birds have often been observed feeding in one part of a tree, eating all the nuts or fruit around them, and only moving to another part of the tree when all the food in their vicinity is exhausted. Birds will return to the same tree day after day until all the nuts or fruit are consumed (Johnstone *et al.* 1999; Department of Environment and Conservation 2007; Johnstone, Kirkby, *et al.* 2017).

Observations of black cockatoos foraging and feeding show they are often quite stationary with only slight body movement (Black Cockatoo Ecology Project, Murdoch University, unpubl. data), for example lifting food items to the beak with a foot. In this position, there is little movement of the accelerometer tag in any axis. This may go some way to explaining the higher level of rest and lower levels of foraging in the black cockatoo activity budgets compared with other black cockatoos of similar size.

Western Australian black cockatoos seem to spend less time foraging than Glossy black cockatoos (*Calyptorhynchus lathami*) found in eastern Australia. Pepper (1996) calculated activity budgets showing the birds spent almost 60% of their time foraging, 34% of their time at rest and less than 1% of their time flying. Feeding behaviour was similar to forest red-tailed black cockatoos, with birds tending to feed in one tree, eating everything within reach before moving to another feeding tree. Glossy black cockatoos feed predominantly on *Allocasuarina* seeds and have been observed to be highly selective when deciding where to feed. They tend to choose trees with abundant cones then select cones of high seed weight (Cameron 2007). Studies by Cooper *et al.* (2003) suggest marri seeds (*Corymbia calophylla*), which are the principle food source of forest red-tailed black cockatoos and Baudin's cockatoos (Johnstone *et al.* 2008) have higher energy content than *Allocasuarina* seeds thus birds feeding on marri would not need to forage for as long to meet their daily energy demands. Similarly studies by Stock *et al.* (2013) revealed many seeds eaten by Carnaby's cockatoos were also much higher in energy. It is anticipated that planned removal of pine plantations on the Swan Coastal Plain will reduce food availability for Carnaby's cockatoos (Williams *et al.* 2017). Pine seeds provide a readily available, high energy food source in summer and autumn, when breeding birds are feeding fledgling chicks. Removal of pine plantations and loss of this food source may impact fledgling survival (Stock *et al.* 2013; Williams *et al.* 2017).

The daily pattern of activity of cockatoos is generally considered to be dictated by a bird's energy requirements and the availability of food. If a bird cannot meet its daily energy requirements in one location, inevitably it will need to move to find another food source or risk starvation. Increased energy demands, such as during the breeding season, will also increase the length of foraging time required to meet those demands. The length of time a bird spends foraging is affected by their foraging strategy, supply of food and feeding technique. Time of year and weather will also impact on foraging ability. Cockatoos only forage in daylight hours, thus time available for foraging is less in winter when daylength is reduced. Cockatoos need suitable foraging habitat and water close to (six to seven kilometres) breeding and roosting sites (Saunders 1990; Groom 2015; Le Roux 2017). With land clearing and development resulting in habitat loss and fragmentation, loss of roosting trees and food resources, one would anticipate cockatoos will need to spend more time flying greater distances between diminishing resources. They will need to forage more to meet increasing energy demands. Numerous studies by Saunders (1982; 1985; 1990) have shown an association between longer foraging distances with poor chick health and reduced breeding success. In some locations, inadequate food resources has resulted in breeding areas being abandoned.

Whilst black cockatoos are capable of flying further afield to find food, water and roost sites, increased use of habitat in urbanised areas exposes them to numerous risks. Birds feeding and drinking on or by roadsides are at risk of being hit by motor vehicles. 21.2% of Carnaby's cockatoo's which presented to Perth Zoo Veterinary department in 2017-2018 suffered from motor vehicle trauma (Environmental Protection Authority 2019). Apples, pears and nut crops in south west Western Australia have become a food source for Baudin's cockatoos, particularly in years when marri (*Corymbia calophylla*) flowering is poor (Johnstone *et al.* 2011). Due to the damage caused to the crops, the birds are often considered a threat by growers and may be illegally shot and killed (Chapman 2007). Forest red-tailed black cockatoos are spending more time on the Swan Coastal Plain, utilising ornamental trees such as Cape Lilac (*Melia azedarach*) as a food source. Birds on the plain have also been observed foraging on the ground - this behaviour is uncommon in forest habitat (Johnstone, Kirkby, *et al.* 2017). Movement into urban areas has also seen immature forest red-tailed black cockatoos being attacked and injured by Australian Ravens (*Corvus coronoides*), a species that has become abundant in suburbia (Johnstone, Kirkby, *et al.* 2017).

Whilst daily activity is primarily governed by individual energy requirements and food availability, environmental conditions also have a significant impact. Many cockatoo species have a recognised pattern of feeding in the early morning and late afternoon with a rest period in the middle of the day to avoid higher temperatures (Cameron 2007; Shephard *et al.* 2019). Recent studies by Shephard *et al.* (2019) show that black cockatoos rest, roost and forage in home range areas that shift spatio-temporally in response to food availability and time of year.

Anthropogenic changes can have a significant impact on activity budgets. A recent study by Tucker *et al.* (2019) revealed that birds living in homogenous environments, for example crop lands and desert areas, can fly up to seven times further in search of resources (nesting sites, shelter, food) compared to birds in heterogenous environments which provide a more diverse range of habitats and resources. Human driven landscape disturbance and homogenisation result in resources being spread further apart, therefore birds must fly further to access them and expend more energy doing so.

Cockatoos tend to forage in flocks, rather than individually as it reduces the risk of predation (Westcott *et al.* 1988), the collective knowledge of the flock is used to locate food sources and more than one bird can exploit a food source when in abundance (Cameron 2007). Carnaby's cockatoos are recognised as a social species that forage in flocks by day and gather in groups to roost communally at night (Saunders 1977, 1980; Groom *et al.* 2017). Baudin's cockatoos behave in a similar manner to Carnaby's cockatoos, usually moving in family groups or small foraging flocks which then form larger roosting flocks in the evening (Cameron 2007; Johnstone *et al.* 2008). Studies by Johnstone and Kirkby (2017) indicated that forest red-tailed black cockatoos moved in smaller areas, tending to stay close to their home range territory to feed and breed.

Knowledge of black cockatoo behaviour, such as daily routines and seasonal movements, provide insight into overall flock behaviour during specific time periods. Whilst not all birds will be engaged in the activity during a short period of data capture, it is likely that all birds will be engaged in the primary behavioural activity over time whilst at that site. For example, if a bird is classified as foraging at a location, it is highly likely other birds in the flock will also be foraging around that time, at that particular location. Johnstone *et al.* (2008) study of Baudin's cockatoos, and our direct observations of study birds post-release (Black Cockatoo Ecology Project, Murdoch University, unpubl. data), showed that during the day, whilst many birds in a flock were engaged in a specific activity such as foraging, others would be resting, cleaning, preening and socialising during the same observation period. The primary purpose, however, of the birds at this site was foraging. Accordingly, there is strong support for the application of the model data from a tagged flocked bird to the activity of the flock.

The difficulties faced by researchers using traditional methods of observation in the field further highlight the advantages of remote tracking devices. These data can provide specific insight into activity and behaviour for the duration of the transmitter recording period. Across the complete tracking period this is much longer than is possible through direct observations. Researchers involved in this study occasionally had difficulty accurately identifying individual birds in large flocks of birds, particularly in flight. Birds were often partially obscured by foliage, or high up in trees and difficult to observe clearly. On some occasions, birds were not accessible to researchers on foot or in vehicles due to fences, locked gates and poor track conditions. The use of remote tracking devices allowed researchers to track/follow birds over much greater distances and habitats without the physical limitations often faced by direct observation and tracking.

Application of the classifier tool to management issues and future research

From a management perspective, knowledge regarding the manner and speed at which black cockatoos move within urban or forest landscapes is valuable in planning the size, species composition and spacing of habitat resources. This tool is also valuable in assessing suboptimal habitats to guide revegetation and restoration activities to support species retention. Specifically, given the species activity bias toward foraging and resting, it is important that appropriate roost and forage trees are considered in restoration design. As the tool concentrates on key activities, the methodology will likely have strong transferability to other species, particularly birds.

In our future research we will combine our classifier tool with behavioural change point analysis (Rycken *et al.* 2018) and species distribution modelling, to model the impacts and energetic cost of different habitat types on black cockatoos on the Swan Coastal Plain and more broadly across the southwest. As different habitats will incur different costs, the application of the tool to newly acquired accelerometer and location data will increase our ability to guide current and future conservation action, environmental offset priorities, and restoration activities as we determine which habitats or corridor configurations retain functional landscape connectivity for these species.

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Chapter 5. Moult cycle informs retention time in telemetry tagged black cockatoos.

The following chapter has been drafted in accordance with the requirements for *Emu*. This chapter has been submitted for publication.

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Authorship order	**Contribution (%)**	**Concept Development**	**Data Collection**	**Data Analyses**	**Drafting of manuscript**
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Kristin Warren	5	x	x	x	x
Rebecca Vaughan-Higgins	1		x		x
Louise Hopper	1		x		
Karen Riley	2		x		x
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Contribution indicates the total involvement the author has had in this project. Placing an 'X' in the remaining boxes indicates what aspect(s) of the project each author engaged in.

By signing this document, the Candidate and Principal Supervisor acknowledge that the above information is accurate and has been agreed to by all other authors.

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5.1 Preface

This chapter comprises original research to determine the nature of the tail feather (rectrices) moulting cycle of Carnaby's (*C. latirostris*), Baudin's (*C. baudinii*) and forest red-tailed (*C. banksii naso*) black cockatoos. The study began in 2013 with monitoring and collecting moulted tail feathers from captive (not for release) black cockatoos. With the commencement of tracking research on black cockatoos which were released back to the wild following successful treatment and rehabilitation, the opportunity arose to collect moulted central tail feathers when retrieving the attached telemetry tag. This provided further information on the timing of tail feather moulting in wild birds. Determining the lifespan of the tail feathers and knowing when they will likely moult gives researchers the opportunity to attach telemetry tags at a time to maximise retention, and the associated period of tracking and data collection. As noted in the thesis overview, this manuscript uses International Ornithological Congress (https://www.worldbirdnames.org/new/bow/parrots/) nomenclature for Carnaby's (*Zanda latirostris*) and Baudin's cockatoos (*Zanda baudinii*) as required by the journal Emu.

5.2 Abstract

The moulting cycle of the tail feathers of Carnaby's (*Zanda latirostris*), Baudin's (*Z. baudinii*) and forest red-tailed (*Calyptorhynchus banksii naso*) black cockatoos was studied to determine the lifespan of the tail feathers and time of year the feathers were moulted. Moulted feathers were collected from captive black cockatoos and rehabilitated birds that were released with tail-mounted telemetry tags. The mean lifespan of captive black cockatoo tail feathers was 295 days (5-732 days, n=38). Lifespan data from the sequential cohort (birds from which tail feathers were collected in consecutive years) was most representative with a mean lifespan was 410 days (range 86-716 days, n=24) suggesting tail feathers are not always moulted annually. Tail feather moulting can occur throughout the year, but typically peaks from December to March. This corresponds to the non-breeding season. Attaching tail-mounted telemetry tags from May to September gives researchers the opportunity to maximise tag retention time, tracking duration and data collection. Data generated by tail-mounted telemetry tags is now

being used to guide black cockatoo conservation management. Further research into feather moult patterns and lifespans may facilitate the application of similar telemetry methods and movement ecology studies to the conservation of other threatened bird species.

5.3 Introduction

Globally, 28% of parrots species are threatened (Birdlife International 2017), due to fragmentation and loss of habitat associated with agriculture, development and logging; poaching for the pet trade, competition from invasive species and climate change (Olah *et al.* 2016; Berkunsky *et al.* 2017). Given the variety of threats facing parrots, bespoke research is necessary to understand and manage the unique risks faced by species on local and regional scales. Foundational to such work, are empirical studies that focus on movement ecology, which can provide critical data on habitat selection for feeding and roosting. In the urban matrix such data can inform urban planning and policy, in more remote sites it provides an evidence-base for habitat protection and environmental impact assessments for planning and development (Department of Sustainability 2012). Traditional approaches to deriving such data can be fieldwork intensive, using flock following and sightings. More recently, telemetry tags (VHF radio, satellite and GPS) have shown promise in contextualising threats to endangered parrot species, including kakapo (*Strigops habroptilus*) (Whitehead *et al.* 2012), kea (*Nestor notabilis*) (Kennedy *et al.* 2015), blue-throated macaw (*Ara glaucogularis*) (Davenport *et al.* 2021), scarlet macaw (*Ara macao*) (Myers *et al.* 2004), Malherbe's parakeet (*Cyanoramphus malherbi*) (Ortiz-Catedral *et al.* 2010), Ouvéa parakeet (*Eunymphicus cornutus uvaeensis*) (Robinet *et al.* 2003), as well as black cockatoos in Western Australia (Groom, Warren, *et al.* 2014; Yeap *et al.* 2015; Rycken *et al.* 2021). However, as Davenport *et al.* (2021) discovered with blue-throated macaws, the manner in which these tags are deployed is likely to be species specific, dictated to a large degree, by species behaviour and environmental factors and requires validation.

Western Australia hosts three species of black cockatoo, Carnaby's cockatoo (*Z. latirostris),* Baudin's cockatoo (*Z. baudinii*) and the forest red-tailed black cockatoo (*Calyptorhynchus banksii naso).* Carnaby's cockatoo and Baudin's cockatoo are considered endangered by the

IUCN (IUCN 2020) and under the Commonwealth Environment Protection and Biodiversity Conservation (EPBC) Act 1999 (Department of Sustainability 2012). The forest red-tailed black cockatoo is listed as Vulnerable by the IUCN and under the EPBC Act (Department of Sustainability 2012; IUCN 2020). Further, black cockatoo numbers have been in significant decline since the 1980s (Saunders *et al.* 1998), therefore all are the subject of species Recovery Plans (Department of Environment and Conservation 2007). A number of studies have demonstrated the successful use of tail-mounted ARGOS PTT satellite tags to locate and track Baudin's cockatoos, Carnaby's cockatoos and forest red-tailed black cockatoos post release (Groom, Warren, *et al.* 2014; Yeap *et al.* 2015; Rycken *et al.* 2018), however they rely on knowing tail feather moult patterns to maximise their longevity, and therefore utility. Unfortunately, moult patterns in parrots, as with many bird species are largely understudied (Pyle 2013; Jenni *et al.* 2020)

The moult is recognised as one of the three major stages in the annual cycle of birds – the other two being breeding and migration (in migratory species). As all three stages have a high energy demand, they tend to occur with little overlap. Environmental conditions influence the order in which these stages occur (Jenni *et al.* 2020), with breeding usually occurring when food and conditions are optimal. Moult or migration then follow (Newton 2011). In most birds, moult occurs annually, although this can vary to be more (willow warbler *Phylloscopus trochilus*) or less frequent (albatrosses) (Newton 2011). Most studies of moulting use a moult scoring system described by Newton (1966) and Ginn *et al.* (1983) where individual feathers are scored based on the degree of eruption and the scores totalled to give a moult score. Whilst this system is useful for determining the stage of moult at that point in time, it provides little information on individual feather lifespan or timing of moult. This method also requires the regular catch-up and examination of individual birds, which can have logistical, financial, and welfare implications.

As discussed by Jenni *et al.* (2020), despite the impact and importance of the moult in the annual cycle, it is an area of study that remains neglected. Most reviews of moult are descriptive and do not take into account the impact on behaviour, physiology or ecology. There have been a limited number of studies on moult patterns in Australian parrots (Table 5.1). Cameron (2007) noted that to conserve energy for breeding efforts, most cockatoos appear to begin moulting after breeding. The processes of moulting, breeding and migration all demand higher energy inputs (Meier *et al.* 2017). Whilst the three processes generally occur at different times, moult cannot be viewed as an isolated event and the relationship with breeding and migration must be taken into account. Saunders (1974b) observed adult Carnaby's and Baudin's cockatoos moulted for several months after the breeding season and Carnaby's cockatoos have been observed undergoing a partial or full moult whilst on the Swan Coastal Plain following migration from breeding sites (Groom, Warren, *et al.* 2014), which further increases their need to find suitable food sources to regain feather and body condition before the next breeding season (Berry *et al.* 2010).

Table 5.1: Studies in Australian parrots describing body and tail feather moult pattern and timing.

Species	Moult Pattern	Timing	Tail feather moult
Eastern rosella ***Platycercus eximius***	Annual moult	Post-breeding, Dec-Apr	Peaks mid Dec- Apr (Wyndham *et al.* 1982)
Budgerigar ***Melopsittacus undulates***	Continuous, often overlapping	New moult may start before previous moult is complete	Moult from central feathers outwards, takes up to 6mths, any time of year (Wyndham 1981)
Red-capped parrot ***Purpureicephalus spurius***	Annual moult of flight feathers Continuous moult of body feathers	Nov-May, 1-2 mths later in wild birds	Moult Nov-Apr, variable sequence (Mawson *et al.* 1996)
Galah ***Eolophus roseicapilla***	Annual moult	Post-breeding Nov-Apr	Nov-Apr, variable sequence (Rowley 1988)
Glossy black cockatoo ***C. lathami***	Annual	Sept-Nov	Sept-Nov, half of tail feathers shed annually, feathers last 2 years (Courtney 1986b)
Yellow-tailed black cockatoo ***Z. funerea***	Annual (Cameron 2007)	Dec-Apr	All tail feathers moulted by 12 months of age (n=1), moulted Dec-Apr (Courtney 1986a)
Mulga parrot ***Psephotus varius,*** **Red-rumped parrot** ***P. haematonotus,*** **Mallee ringneck** ***Barnardius barnardii***	Variable	Oct-Feb	No information provided (Keast 1968)

The use of telemetry devices to track and monitor birds was first reported in 1962 by Lord *et al.* (1962) who used radiotelemetry to monitor ducks in flight. Since then, tags have been employed for a wide range of purposes in birds, and have included attachment methods such as body and leg loop harnesses (Thaxter *et al.* 2014; Kennedy *et al.* 2015; García-Macía *et al.* 2022; Smetzer *et al.* 2022), feather attachments (Bianchini *et al.* 2020), collars ((Davenport *et al.* 2021) and less frequently implants (Beuth *et al.* 2017). Although generating valuable spatial ecological data, limitations of such attachment methods include collar and harness entanglement in vegetation (Barron *et al.* 2010), wing injuries, ranging from mild soft tissue wounds to bone remodelling and fractures (Michael *et al.* 2013), tag migration and loss following implantation (Malachowski *et al.* 2020). Tail-mount attachment was first described in the literature over four decades ago (Bray *et al.* 1972; Kenward 1978) and offers the benefit of the tag being shed with the next moult, however it is reliant on knowledge of moulting patterns to maximise longevity of data acquisition. A search of the Web of Science Core Collection (Web of Science Core Collection 2021) and BioOne Complete (BioOne Complete 2021) databases using the search terms 'bird telemetry' then refined by 'tail feather' and 'transmitter', found less than one percent of articles referred to tail-mounted devices (Web of Science – 13 out of 1570 results, 1992-2022; BioOne Complete 6 out of 2080 results, 1965-2022). These were mostly in birds of prey, waterfowl, seabirds with limited references to psittacines. In a 2017 meta-analysis of the effects of tags on birds, Bodey *et al.* (2018) only identified four studies of tail-mounted tags out of 214 studies reviewed. Similarly, in another meta-analysis of avian transmitter effects, Barron *et al.* (2010) only identified three studies using tail-mounted transmitters out of 84 studies reviewed. The benefits of tail-mounted tags include less interference with flight and breeding behaviours (Bray *et al.* 1972), less wear on the feathers (Giroux *et al.* 1990) and detachment without intervention (Hiraldo *et al.* 1994). Limitations, such as shorter retention time due to tail feather moulting (Woolnough *et al.* 2004) and not being able to attach tags when tail feathers are missing or moulting (Stanton Jr. *et al.* 2018; Geen *et al.* 2019) demonstrate the considerations needed for this approach. Studies by Ortiz-Catedral *et al.* (2010); Le Souef, Stojanovic, *et al.* (2013); Groom, Warren, *et al.* (2014) and Irwin *et al.* (2021) found tail-mount attachment to be a useful and safe method in psittacines. Ultimately, the limited published research on tail-mounts suggest they satisfy the core criteria for a tracking device proposed by Giroux *et al.* (1990) and have the least potential side-effects (Geen *et al.* 2019) as they do not cause excessive wear of the feathers or interfere with behaviour or survival, and remain on the bird for the duration of the study and should eventually detach without intervention.

Given the importance of spatial data for black cockatoo research, to inform threatened parrot conservation locally and globally, and the recognised value of tail-mounts with satellite and GPS capability, a study of moult patterns in these species is useful. In this study, we aimed to determine, for all three species of black cockatoo (i) the time of year tail feathers are moulted, (ii) the estimated lifespan of the tail feathers, and (iii) the optimal time to attach telemetry tags to the tail feathers for maximum retention and data retrieval. Based on observations of black cockatoos and studies of moulting in other cockatoo species, we expect that black cockatoos will moult the tail feathers after the breeding season - July to December for Carnaby's cockatoos, August to December for Baudin's cockatoos and April to October for forest red-tailed black cockatoos (Saunders 1974a; Cameron 2007; Berry *et al.* 2010; Groom, Warren, *et al.* 2014).

5.4 Methods

This study was conducted between April 2013 and May 2021, using captive, rehabilitated/released and wild Carnaby's cockatoos, Baudin's cockatoos and Forest red-tailed black cockatoos in the Perth metropolitan and regional areas of Western Australia, as shown in Figure 5.1 (map).

This project was completed under Murdoch University Animal Ethics Permits RW 2576/13, RW2768/15, RW2826/16 and RW3232/20 and Department of Parks and Wildlife (Western Australia) Regulation 17 Licence to Take Fauna for Scientific Purposes SF009332, SF009887, SF010393, SF010872, Section 40 Fauna taking (scientific or other purposes) licence - Standard 17, TFA 2020-0043.

The study comprised two parts; (i) the timing of tail feather moult and lifespan of tail feathers in captive black cockatoos, and (ii) the timing of tail feather moult and estimated lifespan of tail feathers in tagged black cockatoos with ARGOS satellite tags attached to the central tail feathers. See Figure 5.2 for details of study design, study groups and cohorts, and reasons for exclusion.

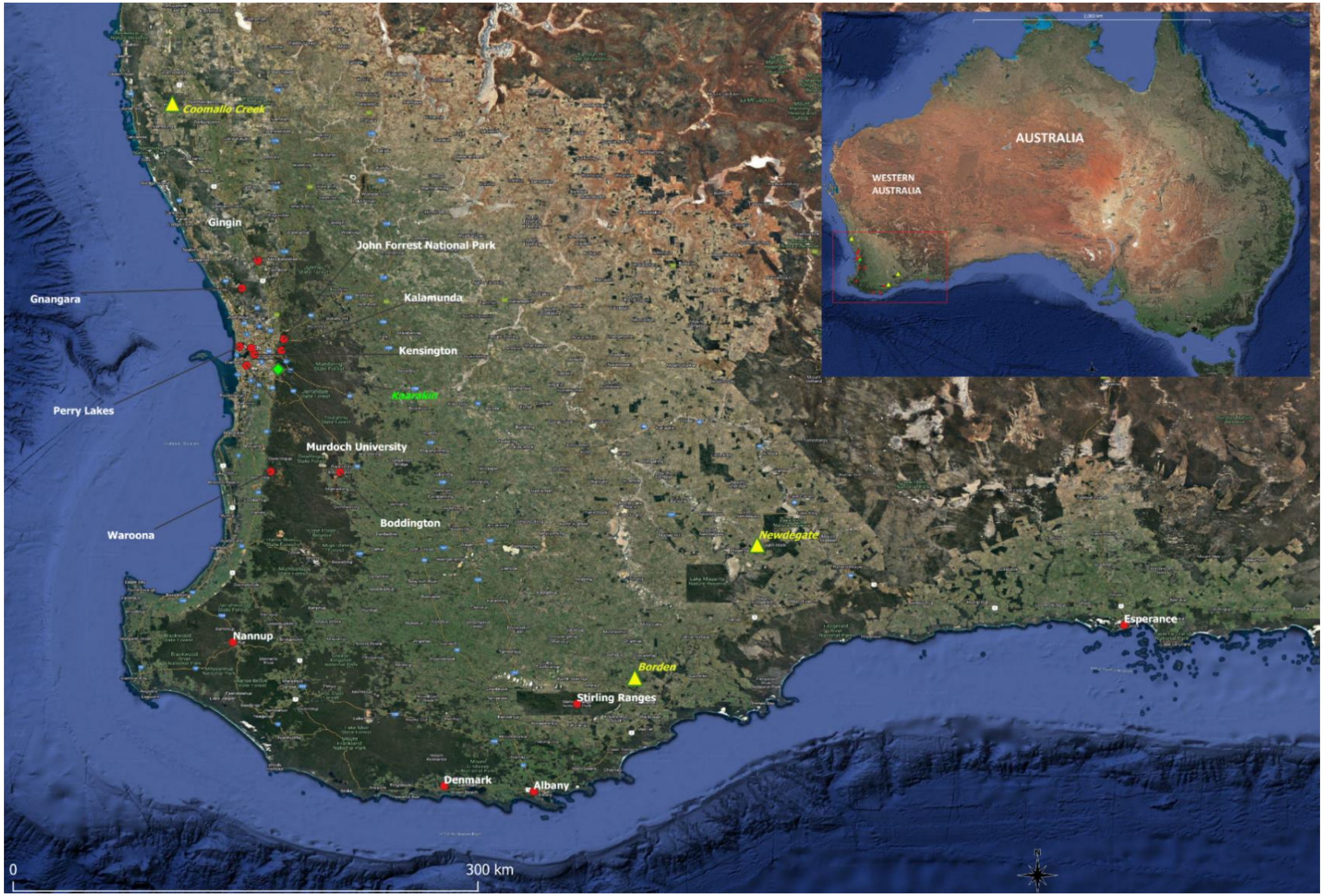


Figure 5.1: Map of all study sites in Western Australia. Inset image showing study area (red rectangle) in south-west Western Australia. Legend: green– captive (Kaarakin Black Cockatoo Conservation Centre); red – non-breeding sites; yellow – breeding sites (Made with QGIS).

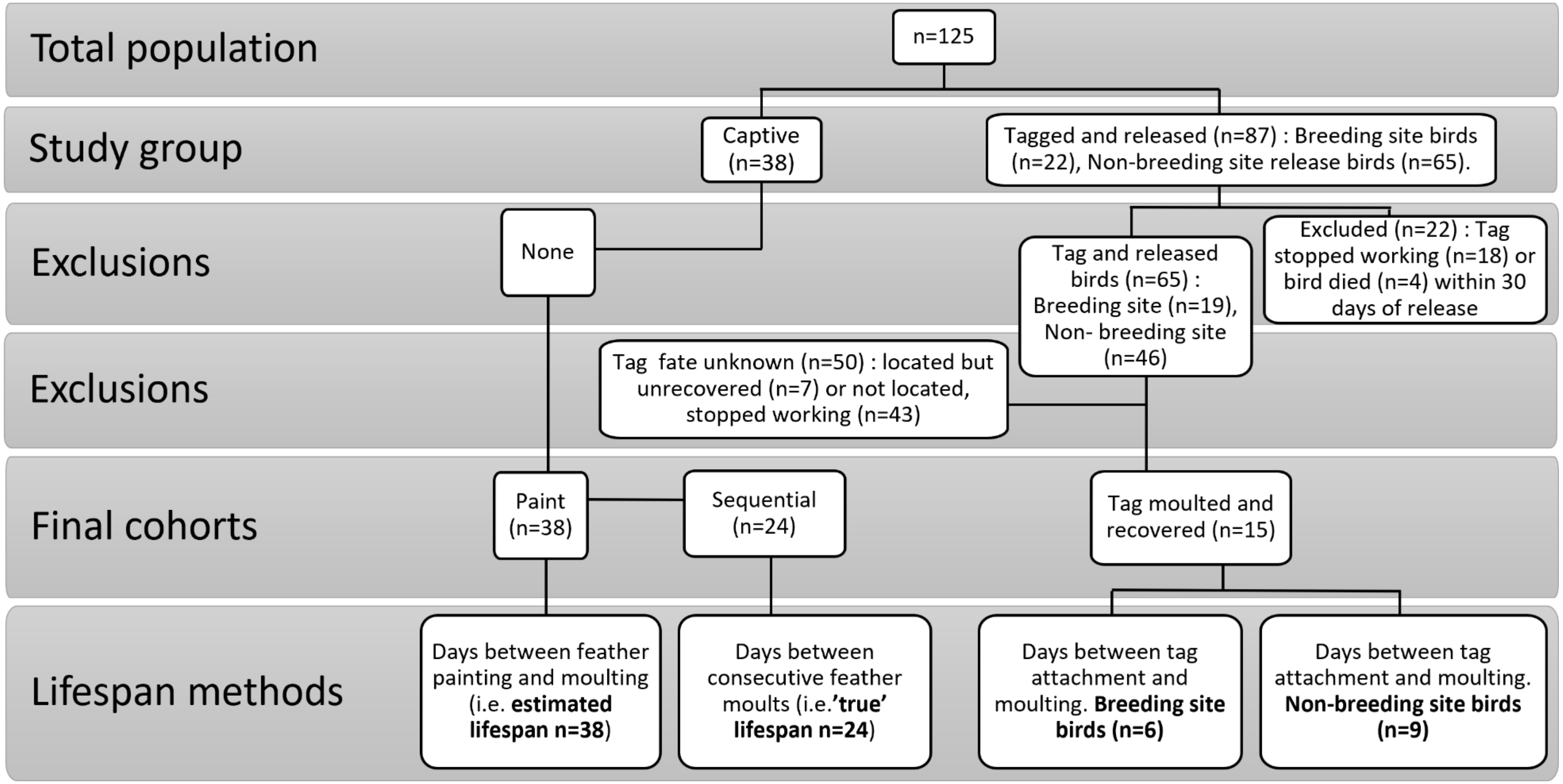


Figure 5.2: Study design including study groups ("captive" or "tagged and released"), exclusions, final cohorts for lifespan of feather calculation ("paint", "sequential", "tag moulted and recovered"), and methods for estimating lifespan of feathers.

5.4.1 Captive cockatoo tail feather moult study

The cockatoos (n=38) used in the captive study were not-for-release education or resident birds, housed at Kaarakin Black Cockatoo Conservation Centre (KBCCC), Martin, Western Australia (32° 05’ S, 116°.02’E). The study population comprised 22 Carnaby’s cockatoos (CC, F:11, M:11), 12 forest red-tailed black cockatoos (FRTBC, F:5, M:7) and four Baudin’s cockatoos (BC, M:4). All birds were adults (> four years of age). Marking of tail feathers for the moult and lifespan study began in April 2013 and was completed in April 2016. Collection of moulted tail feathers was completed by the end of 2016.

To minimise stress to the birds during marking of the tail feathers, each bird was placed under isoflurane gaseous anaesthesia (induced at 5% isoflurane, 1.5 L/min. oxygen, maintained on 2% isoflurane). Each bird was weighed and given a subcutaneous injection of Hartmann’s solution (Compound Sodium Lactate, Baxter Healthcare Pty Ltd, Old Toongabbie, NSW) whilst under anaesthesia. Supplementary heat during anaesthesia was provided by positioning the birds on a Mistral-Air® Warming Blanket (The 37°Company, Amersfoort, The Netherlands). Each bird was placed in dorsal recumbency, and the tail examined. Any erupting, missing or damaged tail feathers were recorded. The 12 tail feathers were individually marked with a letter and number (1-12), from left to right, using a white or black permanent marker (Artline 93 Clix Permanent marker, Shachihata Inc, Nagoya, Japan) to identify the individual bird (letter) and each tail feather (number). A band of coloured ink (Art Spectrum® Artists’ pigmented ink, Art Spectrum, Epping, VIC) was then applied to the white bands on the tail feathers of the Carnaby’s and Baudin’s cockatoos, such that the marking would stand out on a moulted feather. Due to the bright colour bands on the tail feathers of the forest red-tailed black cockatoos, they were marked with either black or white ink on the coloured area. Examples of marked tail feathers are shown in Figure 5.3. Once extubated, the bird was loosely wrapped in a towel and placed into a secure pet-carrier to recover. All birds were standing and mobile within 30 minutes. Supplementary heat during recovery was maintained with an infrared heat lamp. The marking procedure took a maximum of 30 minutes. Once recovered from anaesthesia, birds were returned to the flight aviary and their behaviour was observed.

Figure 5.3: Carnaby's cockatoo tail feathers marked with colour bands, numbered from one to twelve to identify the individual feather and letter to identify the bird it moulted from.

A spreadsheet (Excel, Microsoft Corporation, Washington, USA) was used to record the following variables for each bird; species, sex, microchip number, tail feathers present, tail feather condition (full or partial eruption, or damaged), date of tail marking, and the identifying letter used. KBCCC volunteers and staff checked aviaries daily and moulted tail feathers were collected. The date of collection was recorded on an adhesive label which was then attached to the shaft of the feather. Moult dates were subsequently entered into the data spreadsheet.

Birds used in the study were observed in their aviaries at KBCCC every six months, or opportunistically (e.g., if undergoing health checks), and their tails visually checked for feather loss and fading of the feather markings. The tail feathers were marked again (following the procedure described above) once the majority of the marked feathers had moulted out or the markings had faded or become unclear.

Lifespan determination

As the aviaries were checked daily, the date of feather collection was deemed to closely approximate the date of moulting. When a feather was not found and collected during a moulting period, the number of days between the feather painting date of the newly grown feather and subsequent moulting date was used to approximate the lifespan of the feather (paint cohort). For a subset of this cohort, when a feather was moulted and collected in consecutive years the number of days between moulting dates was calculated and used to approximate the lifespan of the feather (sequential cohort). The lifespan determination methods are shown in Figure 5.2.

5.4.2 Tagged and released cockatoo tail feather moult study

i. Non-breeding site birds (rehabilitated birds for release)

Between 2016 and 2020, 65 cockatoos (33 adult, 32 juvenile), comprising 30 forest red-tailed black cockatoos (15 male, 15 female), 27 Carnaby's cockatoos (10 male, 17 female), and eight Baudin's cockatoos (four male, four female) scheduled for release underwent general anaesthesia (using the method described above) to attach ARGOS satellite tags to the ventral aspect of the base of the two central tail feathers, following the protocols of Le Souef et al. (2013), Groom et al. (2014) and Yeap *et al.* (2017). Birds were under anaesthesia for an average of 45 minutes. Once recovered from anaesthesia, birds were returned to the flight aviary. The birds were released 48 hours later into wild flocks at key roosting sites throughout the south-west of Western Australia during the non-breeding season (Figure 5.1).

ii. Breeding site birds

Between 2017 and 2020, 22 adult Carnaby's cockatoo (ten male, 12 female), trapped on the hollow whilst provisioning young at known breeding sites (Coomallo Creek, Borden, Newdegate – see Figure 5.1) for movement ecology research (under Scientific Licenses SC001289 and SC001405), had satellite tags attached to the central tail feathers, using the same anaesthetic and tag attachment protocols as described earlier.

Lifespan determination

After the release of a tagged bird, if the tag continued to transmit, but remained stationary at a location for longer than two months, it was deemed to have either detached from the bird either by moulting with the tail feathers or the bird was deceased. Tags were located and recovered, where possible, using a CLS Goniometer (RXG-134 Receiver and AXG-134 Antenna, Woods

Hole Group; Lanham, Maryland, USA) or ARGOS AL-1 PTT locator (with multidirectional Yagi antenna, Communications Specialists; Orange, California, USA), in combination with data from the last known location. When the tags and tail feathers were able to be retrieved, it was possible to determine whether the feathers had been moulted, and the lifespan of the feather was calculated from the date of tag attachment and the date of last tag movement. The number of days was an estimate as the date of eruption of the central tail feathers was not known. Due to the small sample size in this study group, univariate analyses (influence of sex or species on lifespan of feathers) were not conducted. Of the 87 birds in the cohort, 22 birds (19 non-breeding site, three breeding site) were excluded from the lifespan determination as either the bird died (n=4) or the transmitter stopped working (n=18) within 30 days of release (Figure 5.2), leaving 65 birds (46 non-breeding site, 19 breeding site birds) in the tagged and released study group.

5.4.3 Timing of moult

The timing of tail feather moulting was recorded as the month the feather moulted in the *captive* study group or the month the tag stopped moving or ceased functioning in the *tagged and released* study group.

A summary of the demographics and structure of the captive and tagged study groups and their component cohorts used for the lifespan determination is shown in Table 5.2.

5.5 Results

Between 2013 and 2016, a total of 347 tail feathers were collected from 38 captive birds (M=22, F=16), representing 22 Carnaby's cockatoos, 12 forest red-tailed black cockatoos and four Baudin's cockatoos, all housed at KBCCC (Table 5.2). Although collected feathers represented all tail feathers (1-12), the central tail feathers (6,7) were largely under-represented in this cohort (Figure 5.4).

Table 5.2: Demographics and structure of study groups – captive painted cohort, captive sequential cohort, tagged non-breeding site cohort, tagged breeding site cohort, including number of feathers retrieved for calculating lifespan of feathers.

	Captive group: painted cohort	**Captive group: sequential cohort**	**Tagged group: non-breeding site cohort**	**Tagged group: breeding site cohort**
N	38	24	46	19
Sex (M:F)	22:16	12:12	25:21	9:10
Species	22 Carnaby's 12 Red-tailed 4 Baudin's	20 Carnaby's 3 Red-tailed 1 Baudin's	21 Carnaby's 19 Red-tailed 6 Baudin's	22 Carnaby's
Feathers retrieved (n individuals)	263 (38 birds)	84 (24 birds)	18 (9 birds)	12 (6 birds)

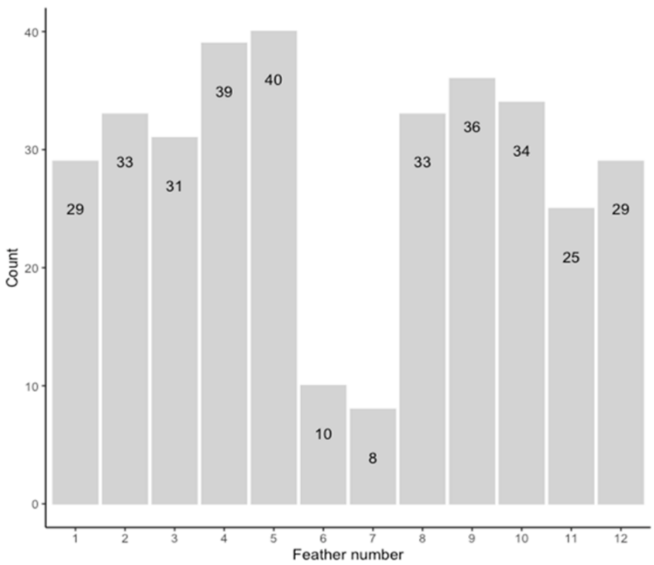


Figure 5.4: Total counts of tail feathers collected from 38 individual captive black cockatoos (Carnaby's, Baudin's, forest red-tailed), according to feather number (1-12), between 2013-2016 at Kaarakin Black Cockatoo Conservation Centre, Western Australia.

Between 2016-2020, central tail feathers were retrieved from 9/46 tagged cockatoos at non-breeding sites, and 6/19 tagged cockatoos at breeding sites (Table 5.2). This is further categorised by species in Table 5.3.

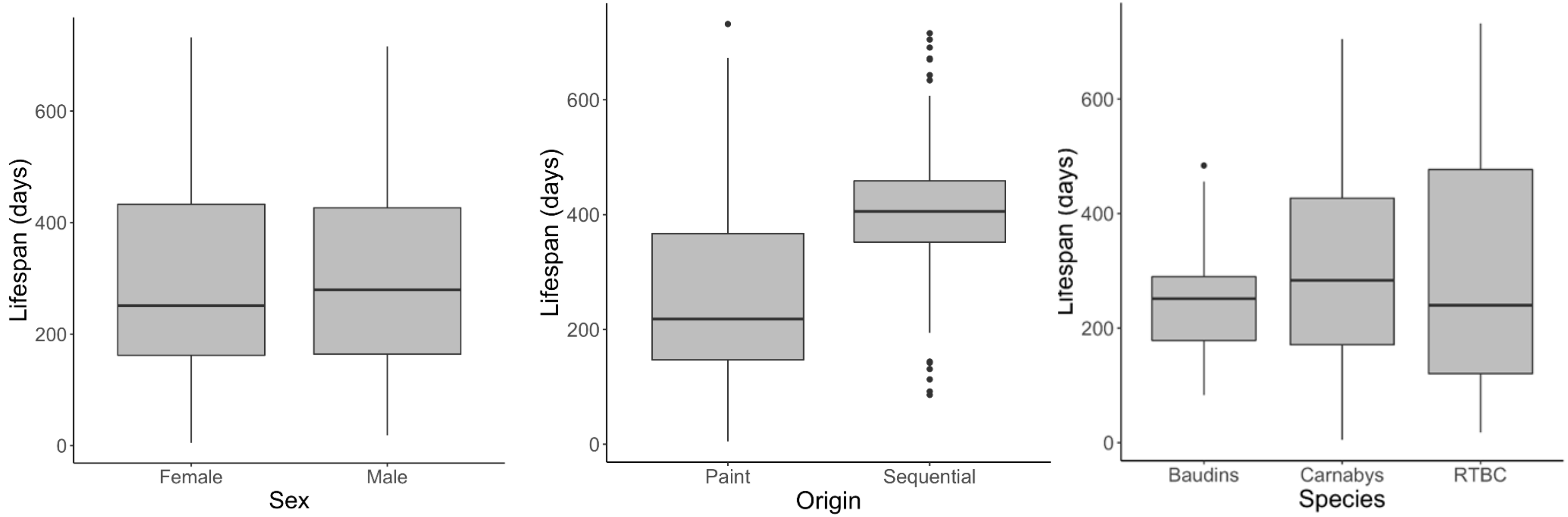
Table 5.3: Number of tagged individuals with central tail feathers retrieved at breeding and non-breeding sites, by species.

	Non-breeding (n=46)	**Breeding (n=19)**
Carnaby's	5/21 (M=2, F=3)	6/19 (M=1, F=5)
Baudin's	0/6	NA
Forest red-tailed	4/19 (M=1, F=3)	NA

5.5.1 Lifespan of feathers

Lifespan data for tail feathers of the captive study population are presented in Figure 5.5 (a-c). For this population, including the 'sequential' and 'paint' cohorts, the feather lifespan for all three species ranged from 5-732 days (mean = 295 days, median = 275 days, standard deviation = 162 days). The mean lifespan of tail feathers for the *paint* cohort (259 days) was significantly lower than the mean for the *sequential* cohort (410 days, range 86–716 days), using the Welch two sample t-test ($t = 8.66$, $df=158$, $p<0.0001$). However, with data aggregated for the captive group, mean lifespan was not significantly affected by species, or sex nor for the *sequential* cohort alone.

Within the *tagged and released* study population, the estimated lifespan of tail feathers for the non-breeding site birds (all species) ranged from four days to 409 days (mean = 178, median = 169, standard deviation =106), whereas the breeding site birds lifespan ranged from 35 days to 241 days (mean =107, median = 85, standard deviation = 57).

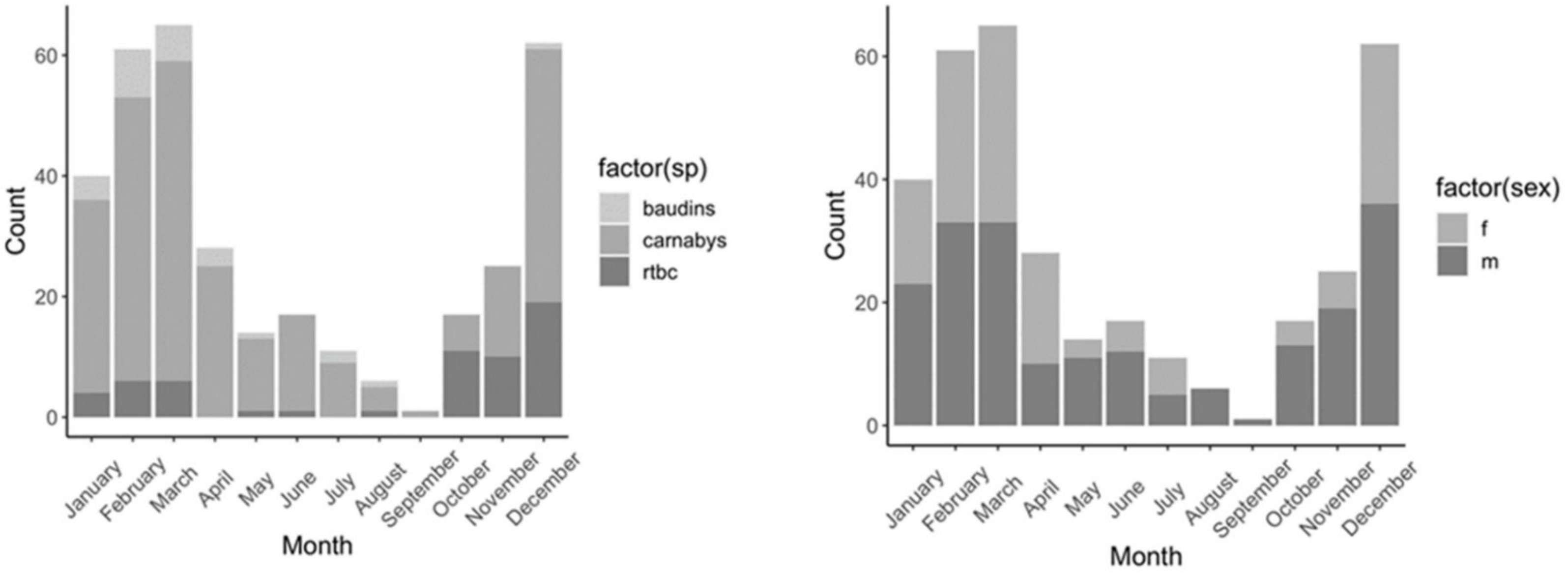


a **b** **c**

Figure 5.5 (a,b,c): Captive study population tail feather lifespan by sex, origin (paint vs sequential) and species. Horizontal line = mean, vertical line = range, black dots = outliers.

5.5.2 Timing of moult

In the captive study population, tail feathers were lost throughout the year, with the majority of feathers (298/347, 86%) moulted from October to April, peaking from December to March (Figure 5.6a&b).



a b

Figure 5.6 (a,b): Timing of tail feather moult in captive cockatoos, by species and sex.

For the non-breeding group, nine tags attached to central tail feathers were moulted and recovered between October to April. For the breeding group, six tags attached to central tail feathers were moulted and recovered, in January and February.

5.6 Discussion

This study provides the first documented evidence that all three species of West Australian black cockatoos, both in captivity and in the wild, moult their tail feathers primarily between October and April, peaking from December to March, the non-breeding period (Saunders 1974a; Cameron 2007; Berry *et al.* 2010). Further, we describe feather lifespans that range from five to 732 days, with a mean across all species in the captive study population of 295 days. Taken together, these findings support attachment of telemetry tags to tail feathers at the end of the moulting period (May onwards) to optimise tag retention and maximise the time available for data collection. Importantly, when considering the data from the sequential cohort, it appears that tail feathers may not moult on an annual basis in black cockatoos, which may facilitate tracking of these species for over a year, providing valuable data on annual migratory flock movements and habitat use.

The data from the sequential cohort of captive cockatoos provided the most informative data with regard to tail feather lifespan. As this data estimated the time between a tail feather moulting and the subsequent feather moulting, it was a more accurate estimate of the true feather lifespan. The data from the paint cohort was less useful as it underestimated the lifespan, given it was calculated from the date the feather was marked, not the date of feather eruption. Whilst there were no significant differences in feather lifespan between sexes and species, larger datasets from forest red-tailed black cockatoos and Baudin's cockatoos would help refine our understanding in these species. The mean feather lifespan in the sequential cohort was 410 days, however for a number of these birds, tail feathers lasted for over 700 days – this suggests not all tail feathers are moulted annually (Stock *et al.* 2013). This is similar to findings by Courtney (1986b) in a small study of glossy black cockatoos. As previously noted, detailed information on feathers and moulting, in Australian parrots specifically and birds in general, is lacking (Bridge 2011; Jenni *et al.* 2020). The longevity of tail feathers in these captive cockatoos may be an effect of their care and husbandry i.e. regular, high quality food and readily available water, and reduced daily flight and energetic demands. This warrants further research, given waning food and water resources for wild black cockatoos (Stock *et al.* 2013). The longevity of the marked tail feathers also suggests that painting did not affect feather integrity.

Across all the study cohorts, peak tail feather moulting occurred from December to March, the end of the breeding season for Carnaby's cockatoos and Baudin's cockatoos. Forest red-tailed black cockatoos can breed throughout the year, with peaks noted from April to June and August to October, hence moulting appears to occur most frequently after the second peak. This fits with the timing noted for other cockatoo species (Cameron 2007) and from direct observations of wild black cockatoos (Saunders 1974a; Berry *et al.* 2010; Groom, Warren, *et al.* 2014). The timing of moult and its duration is influenced by environmental factors such as day length and ambient temperature, along with complex hormone interactions. One trigger for moult may be decreasing plasma prolactin secretion is stimulated by increasing daylength and breeding activity, such as nesting and egg laying (Dawson *et al.* 2000; Dawson *et al.* 2009). Confirming this timing has given the research group further confidence to attach tail tags in the non-breeding season to maximise the tag retention. Attachment of tail tags at other times of the year can still be useful but we expect the duration of attachment to be shorter.

The primary limitation of this study was that not all marked tail feathers were collected once moulted, so the lifespan could not be determined for all twelve tail feathers. This also meant we could not determine if the tail feathers moulted in a particular pattern. Few central tail feathers (feathers six, seven) were collected overall. As the central tail feathers had less colour markings, it's possible that the moulted feathers were more difficult to distinguish from the substrate on the aviary floor (other moulted feathers, leaves, bark, gumnuts) and were not seen by the volunteers. A shortage of volunteers, with less time to clean and check aviaries at various times during study period, may have also affected the collection of feathers. Moult scoring using the British Trust for Ornithology system described by Ginn *et al.* (1983) may have yielded a more complete data set but is a more intensive process requiring regular catching and examination of the birds. We deemed the stress of catch-up and risk of injury outweighed the benefits of this method. Timing constraints and staff shortages also made this unviable. Whilst moult scoring gives an indication of the stage of moult at a point in time (Newton 2009) and duration of moult (Jenni *et al.* 2020) it does not readily provide data on the lifespan of the feathers.

The data from the tagged cockatoo group was of limited use for this study. In the breeding site group, the tags were attached just before or after expected moulting period, so a short lifespan was expected. The main aim of tagging was to track dispersal of birds from breeding grounds, the collection of moulting data was a secondary consideration. The mean tail feather lifespan was shorter in tagged birds than captive birds – this is likely due to the feathers being aged or part way through their normal lifespan when tags were attached. The time of tail feather moulting in the tagged group was similar to the captive group and is indicative of the true timing of moult, i.e., at the end of the breeding season. The retrieval of moulted tail feathers with tags attached proved challenging – many of the tags classified as an 'unknown' fate were likely moulted but could not be recovered to confirm this. A number of tags were located, but recovery was prevented by restricted access to property (landowner denied access) or difficult terrain (swamp, dense bush). Whilst the attachment of a tag to the central tail feathers could affect the feather strength and integrity, black cockatoos tagged and tracked by this research group have retained tags for over 400 days, suggesting tags have little, if any impact on feather lifespan (unpublished data BCCMP)

Knowledge of feather moult timing and duration has implications beyond movement ecology, including broader applications for conservation of threatened and endangered species and habitats through stable isotope analysis (Meier *et al.* 2017); identification of stopover habitats (Yang *et al.* 2020) and genetic analysis (Dawson *et al.* 2009; Hou *et al.* 2018). Developing a better understanding of the relationship between each part of the annual cycle is also becoming increasingly important. Prolonged or delayed breeding can result in delayed moult of shorter duration (also influenced by decreasing daylength) and feathers of poor quality. Poor quality feathers may impact flight performance and provide less effective insulation (increasing energy demand), decreasing an individual's chances of survival and future breeding (Dawson *et al.* 2000). Poor body condition and elevated cortisol (associated with stress) may supress thyroid hormones, potentially slowing the rate and increasing the duration of moult (Beltran *et al.*

2018). Light pollution and poorer nutrition in urban areas may affect the speed and duration of moult (Hutton *et al.* 2021). For wild black cockatoos and other bird species, habitat loss, development and agriculture are likely to impact on food and water availability (Stock *et al.* 2013; Johnston *et al.* 2019). Whether this affects the timing of moult and potentially impacts on subsequent breeding and survival warrants further research.

A better understanding of the black cockatoo feather life span and moult cycle may assist in guiding treatment and rehabilitation decisions in birds missing flight or tail feathers e.g., keeping the bird in care and allowing missing feathers to regrow versus replacing the feathers using imping techniques. This also raises the question as to how soon feathers regrow after traumatic removal (immediately replaced or delayed until the normal growth and eruption stage of the cycle). Injured black cockatoos often have damaged or missing flight and tail feathers - forest-red-tailed black cockatoos can suffer extensive tail feather loss from Australian raven attacks (Johnstone and Kirkby 2017).

This study estimated the lifespan of the tail feathers of captive Carnaby's cockatoos, Baudin's cockatoos and forest red-tailed black cockatoos. We confirmed the findings of previous studies of Carnaby's cockatoos, showing that tail feather moulting occurs from October through to April but is most frequent from December to March, the end of the breeding season. The attachment of tail-mounted telemetry tags between May and September, will likely maximise attachment time. When attached to new, fully erupted feathers, tags have the potential to remain attached for over 12 months. This information may prove useful for telemetry studies of other black cockatoo species in Australia and other parrot and cockatoo species with similar annual cycles (breeding, moulting, migration).

Tail-mount attachment of telemetry tags has proven extremely useful in black cockatoos and could be used in other psittacine species globally- movement ecology is key to conservation policy, therefore feather moult patterns and lifespans in parrots globally warrant further research to underpin telemetry use.

Disclosure statement

The authors report there are no competing interests to declare.

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Data availability

Data available on reasonable request from the authors

Geolocation

The study area covered the following extent: 30°16’36”S 115°19’45”E (Coomallo Creek) to 33°51’29”S 121°52’02”E (Esperance).

Chapter 6. General Discussion

The primary objective of this PhD project was to develop and validate reliable methods to track Carnaby's cockatoos, Baudin's cockatoos and forest red-tailed black cockatoos, to enable subsequent movement ecology research using the tracking methodology to determine flock movement, distribution, habitat use, activity and behaviour. The collaborative efforts of wildlife veterinarians, ecologists, biologists and wildlife rehabilitators resulted in a successful outcome with all project aims achieved in this study, and the application of the methodology to enable ecological tracking of all three species of black cockatoos.

Prior to this study, ARGOS satellite PTT tags had been used to track Carnaby's cockatoos on the Swan Coastal Plain but had not been used to track cockatoos in forest habitats due to concerns the canopy would interfere with signal transmission. To determine the feasibility of using tail-mounted telemetry tags to track forest black cockatoos, we undertook a proof-of-concept trial and attached ARGOS satellite PTT tags to Baudin's cockatoos (Chapter 2). Forest black cockatoo species are difficult to locate, track and monitor using traditional methods due to their preference for heavily forested habitat such as the south-west jarrah, marri and karri forests. We attached Telonics TAV-2617 satellite PTT tags to two Baudin's cockatoos due for release after successful treatment and rehabilitation. The tags provided accurate location data that allowed one bird to be tracked for over 250 kilometres from the release site. Ground truthing at a night roost and analysis of its movement pattern suggested this bird had successfully joined a flock. Not only did this study prove that satellite tags are useful for locating and tracking black cockatoos in forest habitat, we also demonstrated that with careful, conservative programming, Telonics tags can transmit for longer than the expected battery life. The location data retrieved from these satellite tags also identified previously unknown breeding, foraging and roosting sites; all of which are key Actions listed in the Forest Black Cockatoo Recovery Plan (Department of Environment and Conservation 2007).

Whilst ARGOS PTT tags can provide several location fixes per day and are useful for characterising movement at a landscape scale, GPS tags provide more frequent and accurate location data, giving greater insight into fine-scale movement patterns (Thomas *et al.* 2011).

The use of GPS satellite tags to locate and track birds is now common, facilitated by reductions in size and cost, improved battery life and solar recharging capacity (Bouten *et al.* 2013). Tags incorporating a tri-axial accelerometer can also provide information on the individual's behaviour. To take advantage of the capabilities of both types of tags, we conducted a trial on captive black cockatoos to determine the feasibility of using a combination of tail-mounted satellite and back-mounted GPS telemetry tags, the optimal combination of tags and whether the different types of tags interfered with each other (Chapter 3). Combinations of tail-mounted ARGOS PTT satellite tags and a UvA-BiTS back-mounted GPS tag were attached to captive Carnaby's cockatoos, Baudin's cockatoos and forest red-tailed black cockatoos at KBCCC and their functionality and tolerance by the birds assessed. Both the back-mounted and tail-mounted tags were well tolerated and retained by the cockatoos, with no effects on their behaviour, flight or feeding. There were no changes noted on blood profiles which were collected when tags were detached or removed. There was no evidence of signal interference between the two types of tags. We found the combination of a ventrally tail-mounted Telonics TAV-2617 PTT tag and a UvA-BiTS back-mounted GPS tag to be the best tolerated and retained by black cockatoos. We validated the concurrent use of PTT and GPS satellite tags to track wild black cockatoos post-release. This study was the first time UvA-BiTS tags had been used on a cockatoo species. Given their strong beak and destructive chewing behaviour (Johnston 2013), the successful attachment and retention was an exciting outcome and the tag attachment methods can be applied to other parrot and cockatoo species. The tracking data generated from the use of this tag attachment methodology has improved our understanding of spatial and movement ecology of black cockatoos, both at an individual and population scale and provided significantly more information to address the aims of the species' Recovery Plans. The ability to improve spatial data collection will hopefully lead to a better understanding of their ecology and conservation.

Whilst telemetry tags can be used to study animal movement, direct observation is often required to monitor behaviour and activity. Observing black cockatoos is often challenging given their cryptic nature, habitat preferences (e.g. dense forest) and speed of movement. To take full advantage of the capabilities/features of the UvA-BiTS tags, we also developed an automated classifier tool which could analyse tri-axial accelerometer data and identify patterns of behaviour remotely (Chapter 4). The accelerometer in a UvA-BiTS tag measures body acceleration, posture and fine movement. Specific behaviours and the postures and movements associated with them, generate a distinct accelerometer signature. Observations of animal behaviour can be matched to these signatures. The data produced can then be used to train a machine learning algorithm to recognise specific accelerometer signatures, allowing the classification of new accelerometer data into specific behaviour categories. To develop the classifier tool, we attached UvA-BiTS tags to captive Carnaby's cockatoos, Baudin's cockatoos and forest red-tailed black cockatoos then filmed their behaviour in a pre-release flight aviary at a time when they were most active. We established a behaviour scheme for data classification, then combined the video footage and accelerometer data using a Matlab software tool. The annotated data files were then used to develop the classifier tool. We incorporated annotated accelerometer data from a group of released black cockatoos to improve the accuracy of the classifier tool. The end result was a classifier tool able to differentiate flying, foraging and resting behaviours with 86% accuracy, which is comparable to other published reports (Shamoun-Baranes *et al.* 2012; Sur *et al.* 2017; Tatler *et al.* 2018). We then applied the classifier tool to data from 15 released black cockatoos to remotely determine their behaviour and create activity budgets. All three species had similar activity budgets – black cockatoos spend the majority of their time at rest, interspersed with daytime foraging activity and some movement between feeding habitat and roost sites. Conservation management requires an understanding of how species move through the landscape. This is particularly important for black cockatoos, with habitat loss and modification and anthropogenic threats increasing their energy demands as they spend more time flying greater distances between dwindling resources. Combining behaviour and activity budgets with location data can also provide useful insight into species distribution and habitat use and assist in addressing outstanding research objectives in the species Recovery Plans. Further studies including larger sample sizes of Baudin's cockatoos and forest red-tailed black cockatoos and comparing behaviour and activity between birds in breeding and non-breeding areas are warranted.

Telemetry tags are expensive pieces of equipment, therefore knowing the best time of year to attach tail-mounted tags can maximise the retention time of the tag and data retrieved from it. Running concurrently with the telemetry studies, we investigated both the tail feather lifespan and time of moulting in all three species of black cockatoo to determine the best time for telemetry tag attachment (Chapter 5). We marked and then collected tail feathers that moulted from a group of Carnaby's cockatoos, Baudin's cockatoos and forest red-tailed black cockatoos at KBCCC over a three year period. We opportunistically collected moulting data from tagged black cockatoos post-release when their tail-mounted tags were located and recovered attached to the tail feathers. A mean tail feather lifespan over 400 days suggests that tail feathers do not always moult annually. Tags have the potential to remain in place for over twelve months, if attached to new, fully erupted tail feathers. This opens up the possibility of tracking black cockatoos over a full year, providing valuable data on annual migratory movements and habitat use. Moulting of tail feathers peaked from December to March, coinciding with the end of the breeding season for all three species. Confirming this timing has validated the research group's decision to attach tags during the earlier months of the non-breeding season to maximise retention when tracking black cockatoos on the Swan Coastal Plain or in regional areas. Attachment at other times of the year is still useful, for example if the objective is to study habitat use at breeding sites, but the duration of attachment is likely to be shorter. This information may prove useful for telemetry studies of other Australian black cockatoo species, as well as other parrot species with similar annual moulting cycles.

Achieving the aims of this PhD project led to the development of a successful methodology to track black cockatoos, and this has enabled the research group to track all three species of black cockatoo and gain new insights into black cockatoo behaviour and survival following release from rehabilitation; movement and habitat use around breeding grounds and during the non-breeding season. Cryptic forest black cockatoo species have been successfully located and tracked, helping to identify flock movements and vital feeding and breeding habitat that was previously unknown. We have been able to attach combinations of tail and back mounted telemetry tags to optimise tag retention and maximise data collection. A number of birds, and their associated flocks, have been tracked for over a year, providing data and information on annual migratory flock movements. The classification tool developed to utilise accelerometer data has given us the ability to remotely determine black cockatoo behaviour patterns and activity budgets. Together with accurate location data, we now have a better understanding of black cockatoo movement patterns at a landscape level, their changing distribution and how they use resources for both breeding and feeding.

The use of telemetry tags and associated technology underpins current and future black cockatoo studies by this research group. A total of 86 black cockatoos were tagged and their flocks tracked as part of the Black Cockatoo Ecology Project which ended in 2019. A second large scale research project, The Black Cockatoo Conservation Management Project, started in 2020, and has so far tagged 42 black cockatoos from all three species and tracked their flocks in urban and regional areas throughout their distribution range (Black Cockatoo Conservation Management Project 2022). Across both projects, over 87000 kilometres of tracking data has been generated, with over 271000 GPS and 5 million accelerometer data points. Studies by Rycken *et al.* (2018) have shown that tag movement data is indicative of black cockatoo flock movement data. The current study using telemetry data will help characterise the habitat use and movement of the three black cockatoo species across the Swan Coastal Plain and south-west forests. Accelerometer data is being used to determine the energetic costs for black cockatoos living in different environments and modified landscapes. Analysis of the migratory movements of black cockatoos enables identification of new and previously unknown breeding sites in the inland and southern parts of WA, facilitating habitat protection and restoration. Predictive modelling incorporating movement data, assessing threatening processes and habitat use to determine survivorship scenarios for Carnaby's cockatoos, Baudin's cockatoos and forest red-tailed black cockatoos across their distribution range is also being undertaken.

This movement ecology research is being used to guide black cockatoo conservation management and inform selection of environmental offsets, land management and habitat restoration and protection. Only time will tell if enough has been done to arrest or reverse the population declines of these iconic birds.

It is a special day when an endangered species (Carnaby's cockatoo) decides to hang out next door.

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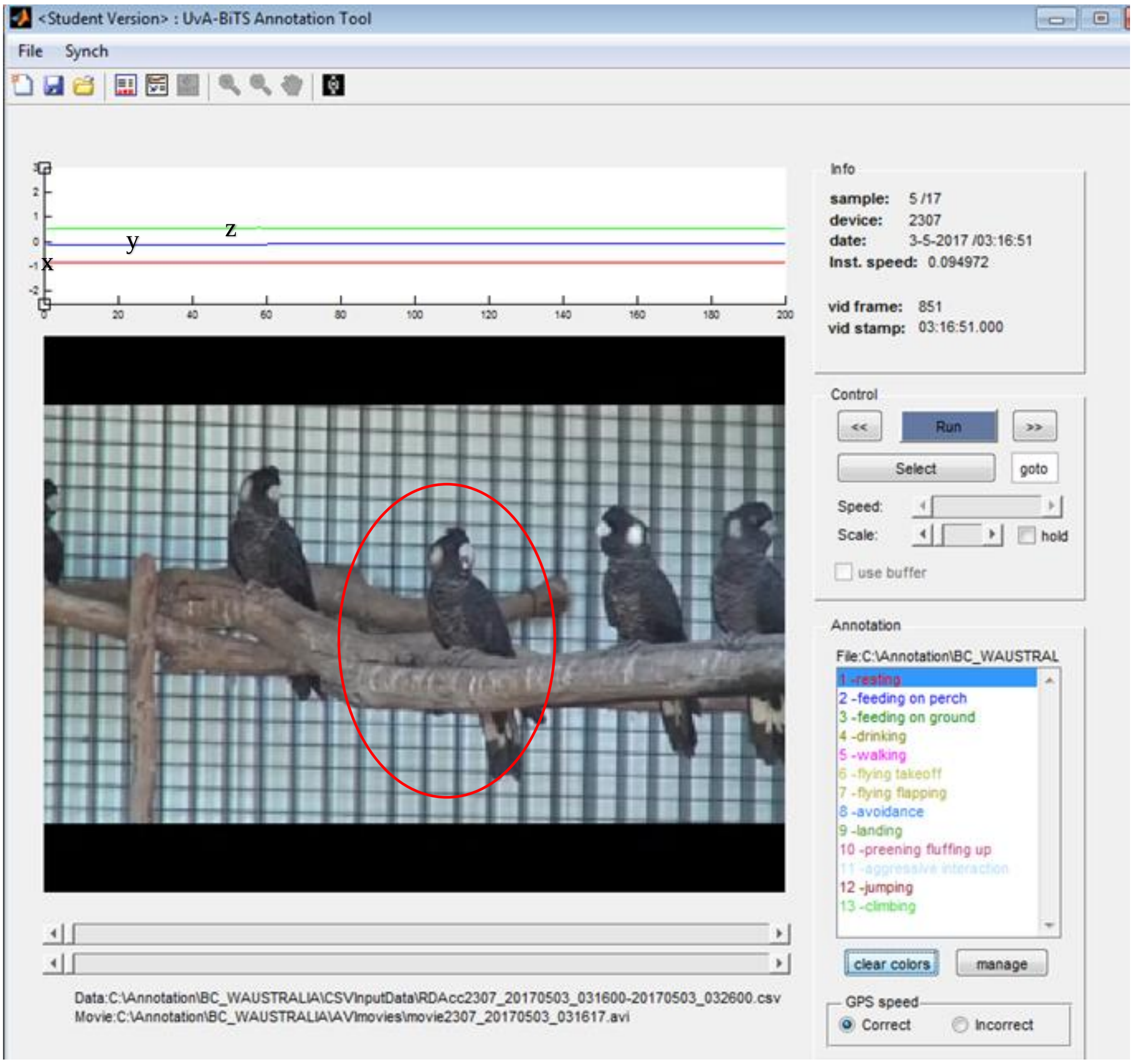
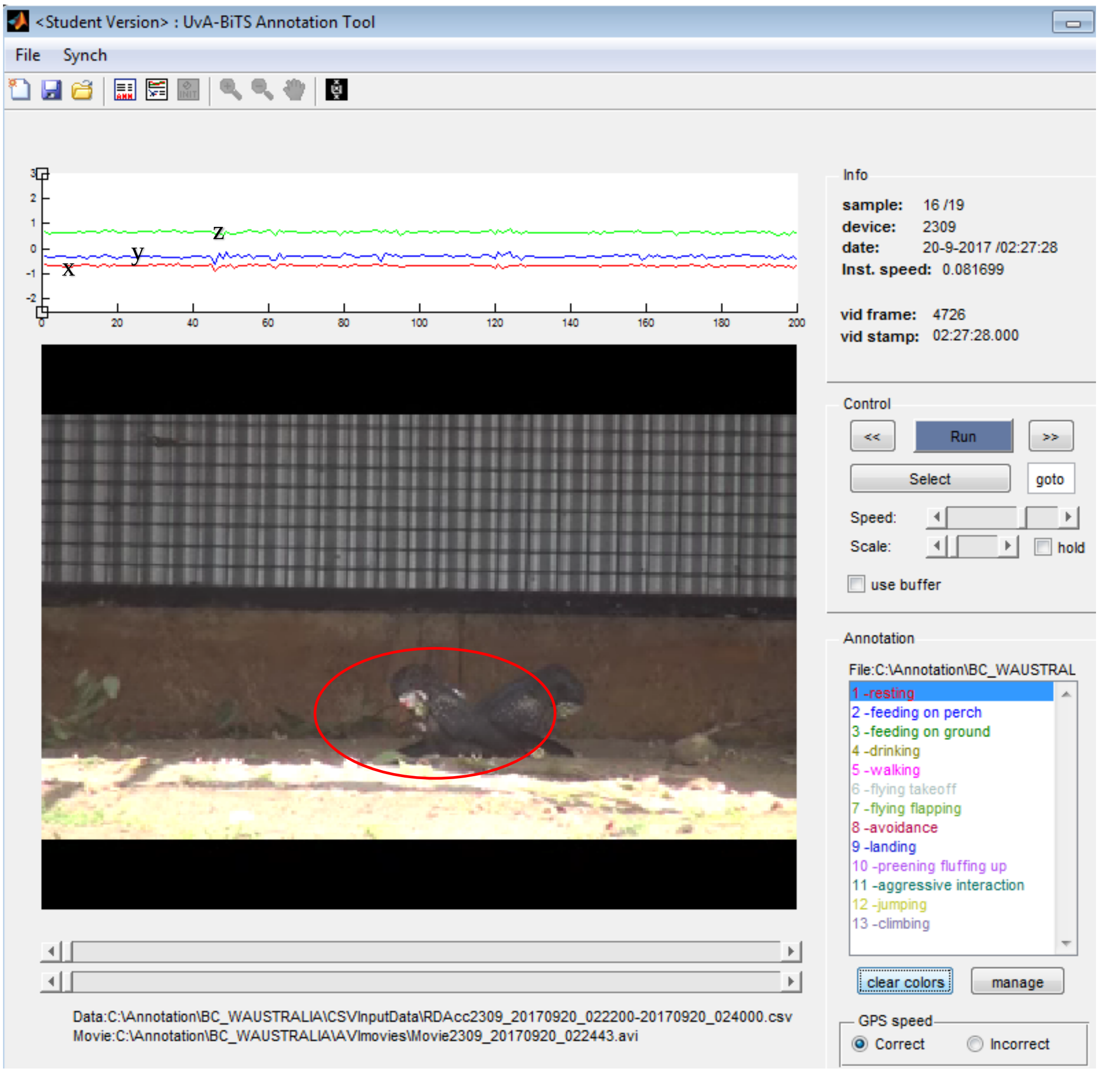
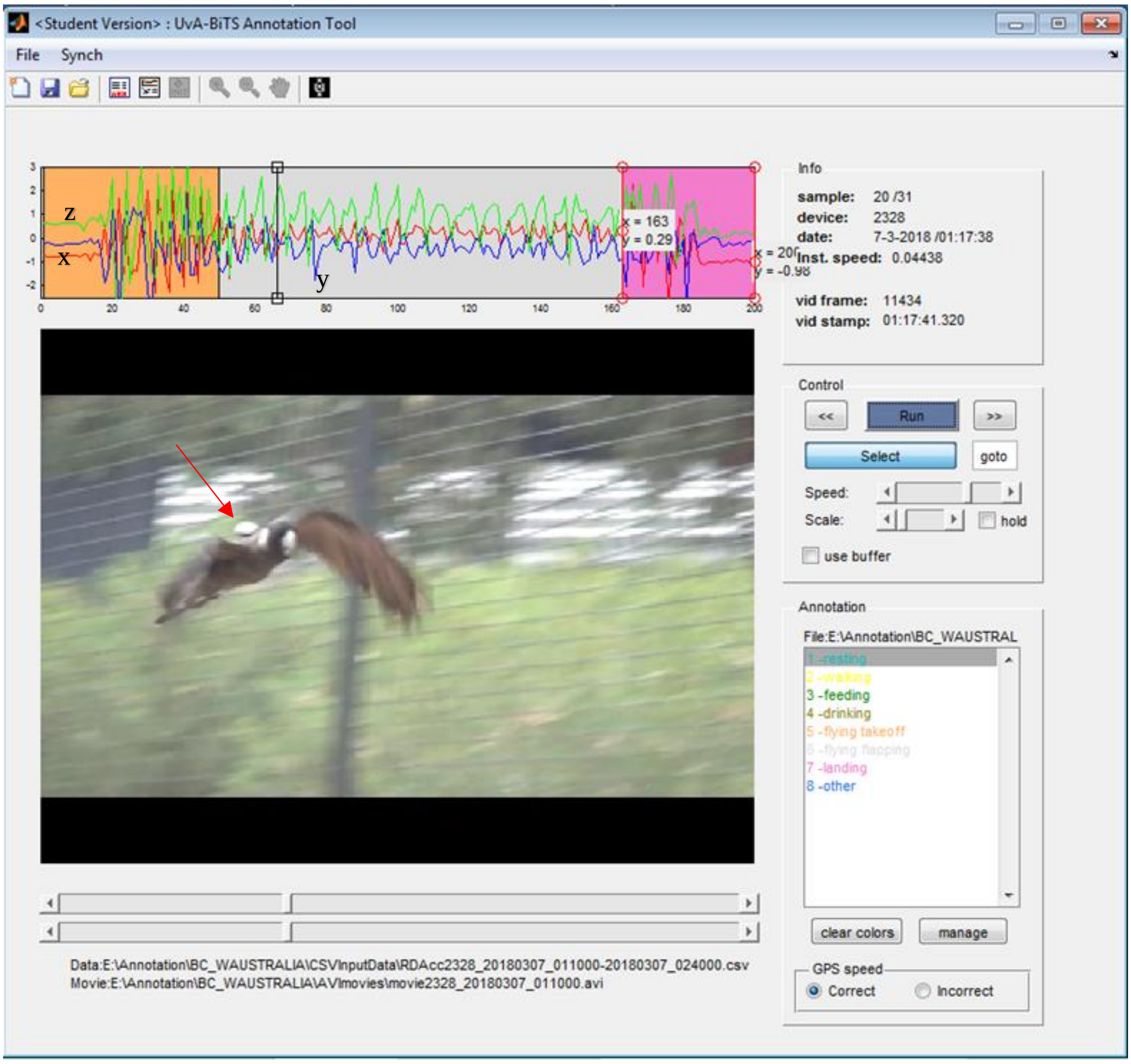
Appendices



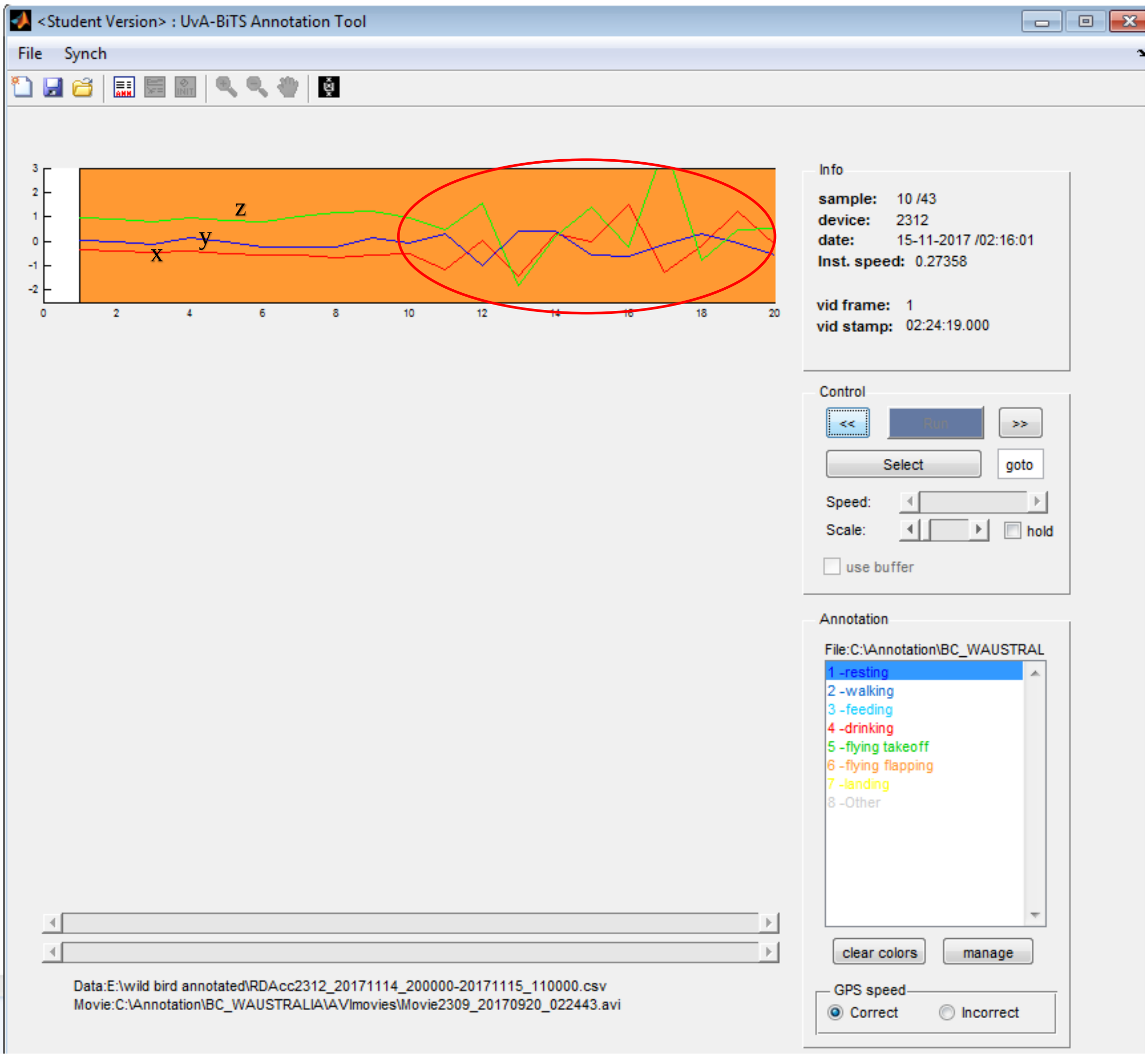
Appendix 1: Typical flat accelerometer signature for resting behaviour with accompanying video footage of black cockatoo at rest (study bird circled in red). 200 accelerometer measurements per video frame. x – surge, red line; y – sway, blue line; z – heave, green line.



Appendix 2: Typical accelerometer signature for feeding/foraging behaviour with accompanying video footage of black cockatoo feeding on the ground (study bird circled in red). 200 accelerometer measurements per video frame. x – surge, red line; y – sway, blue line; z – heave, green line.



Appendix 3: Typical accelerometer signature for flying behaviour with accompanying video footage of black cockatoo in flight. 200 accelerometer measurements per video frame. Red arrow indicates the UvA-BiTs tag attached to the back of the bird. x – surge, red line; y – sway, blue line; z – heave, green line.



Appendix 4: Typical accelerometer signature for flying behaviour (circled in red) without accompanying video footage. 20 accelerometer measurements per frame. x – surge, red line; y – sway, blue line; z – heave, green line.

For Chasey