# AN APPLICATION OF SATELLITE TRACKING TECHNOLOGIES TO CONSERVE WILDLIFE: A CASE STUDY APPROACH

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Doctor of Philosophy

in

Natural Resource Management

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MASSEY UNIVERSITY

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‘The animals of the world exist for their own reasons. They were not made for humans any more than black people were made for white, or women created for men.’

**Alice Walker (1944 - )**

# ABSTRACT

Wildlife management is an important area of conservation and has become a priority for many countries and organisations around the world. One of the fundamental components of a sound wildlife management plan is a good understanding of a species' behaviour and habitat. For animals within inaccessible environments, satellite tracking provides a powerful tool for revealing information on animal movements and their habitat requirements.

In this dissertation, the conservation benefits and technical effectiveness of satellite tracking are examined through four case studies representing a diverse range of threatened species studied for periods between six months and five years. The studies revealed important ecological insights on the *in situ* movement and behaviour of the African elephant (*Loxodonta africana*), Kruger National Park, South Africa; the New Zealand bush falcon (*Falco novaeseelandiae*), Central North Island, New Zealand; the estuarine crocodile (*Crocodylus porosus*), Darwin, Australia; and the northern royal albatross (*Diomedea sanfordi*), Taiaroa Head, New Zealand and Chile. For each of these studies, satellite telemetry provided location data enabling analyses of the animals' movements and home ranges, and these analyses inform specific management recommendations. For example, the long time series study on African elephants highlighted the importance of developing reciprocal animal management policies where cross-boundary movements of animals occurred between adjacent parks.

The strengths and weaknesses of different satellite tracking systems are compared and guidelines developed to assist wildlife managers in selecting the best technology to suit their research needs. An assessment of the trade-offs between the technical features built into transmitters and the associated cost is also presented.

The study shows how the use of satellite tracking systems provides conservation agencies with a better understanding of wildlife behaviour and strengthens their ability to improve wildlife management planning.

## DEDICATION

To my best friends, Derek, Scotty and Roger, for being by my side throughout.

## ACKNOWLEDGEMENTS

This research journey was a challenging and thrilling experience. I spent many a day in a library or by the fire at home researching an area of passionate interest to me and tracking the movements of four diverse and interesting species throughout different parts of the world. My motivation has always been a desire to contribute to conservation in some way and to obtain skills that will enable me to assist with the issues facing us today.

Thanks most of all to my two supervisors, Associate Professors Dr John Holland and Dr Edward Minot. As I waded (often blindly) my way through my never ending 'to do' lists, they were both consistently encouraging and supportive. In particular, to John for his continual supply of creative thoughts, writing guidance, humour and endless enthusiasm, and to Ed for his obvious intelligence, insight, relentless attention to detail and generous supply of home made delights and home grown fruit for meetings. They both believed in me during times when I didn't and their help and friendship was appreciated more than they'll know.

Special thanks to all those individuals involved in each of my case studies who have been personally named within the thesis. In addition, particular thanks to those who have provided funding for the satellite tracking equipment and field trips that were fundamental to the this research. This includes the Institute of Natural Resources at Massey University, Lotteries Commission, Department of Conservation in New Zealand, Kruger National Park (South Africa), Sabi Sand Game Reserve (South Africa), Parks and Wildlife Service (Northern Territory, Australia), New Zealand Postgraduate Study Abroad Awards (NZPSAA) and C. Alma Baker Postgraduate Scholarship Trust.

Thanks also to Mum and Dad for their continued support throughout my life's endeavours, and to family and friends who made valiant efforts to make sense of and show interest in my research topic. Thanks for being there during the 'out of hours' times for the love, laughs and fun.

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# CHAPTER 1: Introduction

## 1.1 Background

Wildlife management started in the United States during the 1920's and 1930's, initially developed in an attempt to use science and technology to maintain animal numbers to counteract game hunting. During the 1970's wildlife managers adopted more of a conservation focus as animal rights activists and environmentalists became more vocal.

Wildlife management has become a serious and important area of conservation and as such has become a priority for many countries and organisations around the world. There are a number of wildlife management methods, including habitat restoration, harvesting, endangered species management, captive breeding and species reintroduction. Some of these practices require more intensive management than others but all have value in the overall goal of managing and preserving wildlife.

During the last 15 years there is one area that has had a transforming effect on wildlife management and this is the ability to track animals using remote satellite methods. Whilst this is only a relatively recent field of study, its impact is enormous. Wildlife biologists are now using satellite telemetry to gather animal behaviour data that a short while ago was considered impossible to obtain (Cohn, 1999, Cargnelutti et al., 2007). The continual monitoring of animals in inaccessible environments has improved our understanding of their movements on a local and global scale (Wikelski et al., 2007). By attaching a small device to an animal, satellites can calculate location, speed, direction and altitude and send it and other useful ecological information back to the researcher. These data, combined with others such as meteorological or Geographical Information System (GIS) layers, enable bio geographic hypotheses to be tested (Gillespie, 2001) and provide important information to improve wildlife and ecosystem management decision making.

The improvements in satellite telemetry technology is increasing the ability of wildlife managers to achieve their primary goals, namely, the application of scientific information and technical skills to safeguard, protect and conserve wildlife and its habitat. This synergy between science and technology is fostering the emerging discipline of movement ecology (Cagnacci et al., 2010).

## 1.2 Problem statement

Many species in different parts of the world are becoming less abundant and many conservation agencies are struggling to reverse this trend. A key part of effective conservation is the formulation of a management plan that integrates knowledge about the behaviour and habitat requirements of species (Bradshaw et al., 2007). Understanding how and why animals move and use resources is of the utmost importance as human activities continue to affect the habitat of species (Thomas et al., 2004). At present, however, we still know little about the precise movements of many animals. The most promising solution is satellite tracking, which is capable of capturing large amounts of accurate location data. Used in conjunction with GIS analysis, these data allow for an increased understanding of home range, critical habitat, movement patterns and behaviour, that can be used to help drive policy and management plans.

There is an increasing number of satellite tracking options relating to cost, size, weight, type of transmitter, duty cycle, data accuracy and download method. As this technology is only one tool among many used by conservation agencies, it can be difficult to select the technology most appropriate to the research objectives and species being tracked. To date there have been few studies that report on the *in situ* effectiveness of different satellite tracking methods on a diverse range of endangered species, but such studies are required to inform conservation managers on the best choice of available systems.

As well, the apparent high initial capital and ongoing operational costs associated with this technology can be discouraging (Hebblewhite and Haydon, 2010). This is especially true for conservation agencies, many of which must operate on restricted budgets. Compared with other wildlife tracking methods, however, the real cost effectiveness of satellite tracking can often be misunderstood. Where several techniques are available, assessing the cost effectiveness of each and comparing them is important (Franco et al., 2007).

## 1.3 Aim

The aim of this research is to assess the technology and conservation benefits derived from satellite tracking diverse endangered species.

## 1.4 Objectives

The research objectives are to:

1. Develop case studies to satellite track diverse endangered species.

2. Evaluate the technical, ecological and financial effectiveness of alternative tracking options.

3. Develop guidelines to assist researchers choose the optimum wildlife tracking method to achieve their goals.

4. Consider the implications of research and make recommendations.

## 1.5 Limitations

The focus of this research is on the application of wildlife satellite tracking location acquisition methods and their associated data download methods. This refers to the use of both the Argos® and the GPS satellite systems as location acquisition methods. There are other wildlife tracking methods not associated with the use of satellites, such as Very High Frequency (VHF) tracking, but these are not included in this assessment other than for comparison purposes.

No marine tracking studies were undertaken in this study. As transmissions are unable to penetrate water, marine tracking requires different transmitter attributes and capability. It should be considered a specialised field in its own right and thus was beyond the scope of this research.

## 1.6 Contribution of research

The results from this study will provide conservation agencies with a better understanding of wildlife satellite tracking methods and the benefits that come from using these methods. Each case study involves the first use of this technology on the species, species age class, or species within a specific environment and, therefore, will provide unique information that will contribute towards the conservation of each species. This research presents a practical tool to aid wildlife managers in selecting the most appropriate satellite tracking equipment to suite their research requirements. This information will improve wildlife and conservation management decisions.

## 1.7 Research design

Four satellite tracking case studies were undertaken involving 12 individuals of avian, terrestrial and aquatic species living in diverse environments of the world. Each case study involved the use of a different combination of satellite location acquisition and data download method. The case studies were undertaken to understand more about the *in situ* technical effectiveness of wildlife satellite tracking technology and the kinds of ecological data that may be provided. Conducting a satellite tracking study involves many variables that would not be fully understood by studying theoretical examples. It was also not practical to use existing studies for this purpose because there are very few published works that provide in-depth descriptions of the specific technology used, how well it worked and the associated costs.

## 1.8 Case Studies

The case studies undertaken to assess the technology and conservation benefits derived from satellite tracking animals comprised:

- A three-year and a five-year study of three African elephants (*Loxodonta africana*) in Kruger National Park and Sabi Sands Reserve, South Africa.
- A three-year study of five New Zealand falcon (*Falco novaeseelandiae*) within Kaingaroa plantation forest, New Zealand.
- A northern royal albatross (*Diomedea sanfordi*) study that tracked three juveniles for one year from their natal area at the Taiaroa Head albatross colony, Otago Peninsula, New Zealand to the west coast of Chile, South America.
- A study of an estuarine crocodile (*Crocodylus porosus*) in the Adelaide River, Northern Territory, Australia.

## 1.9 Thesis outline

The dissertation comprises eight chapters of which six (Chapters 2-7) are currently published, accepted or submitted to peer-reviewed journals. The journals cover disciplines that include conservation, ecology and technology. Although these stand-alone chapters are published in different journals, they combine to achieve the stated aim and objectives of the thesis. Bindi Thomas was the lead researcher and principal author of these papers and John Holland and Edward Minot were co-authors. The final chapter places the research into a wider context and offers conclusions based on the study and recommendations for future wildlife management and research. The chapters are presented in the following format:

**Chapter 1** Introduction

**Chapter 2** Thomas B, Holland JD, Minot EO (2008) Elephant (*Loxodonta africana*) Home Ranges in Sabi Sand Reserve and Kruger National Park: A Five-Year Satellite Tracking Study. *PLoS ONE* 3(12): e3902. **Published**

**Chapter 3** Thomas B, Holland JD, Minot EO (2010) A long-term satellite tracking study of elephant (*Loxodonta africana*) movements between Sabi Sand Reserve and Kruger National Park. *African Journal of Ecology*. **Submitted**

**Chapter 4** Thomas B, Minot EO, Holland JD (2010) Home range and habitat use of the New Zealand falcon (*Falco novaeseelandiae* ) within a plantation forest: A satellite tracking study. *International Journal of Ecology* **2010**(829702). **Published**

**Chapter 5** Thomas B, Minot EO, Holland JD (2010) Fledging behaviour of juvenile northern royal albatrosses (*Diomedea sanfordi*): A GPS tracking study *Notornis* **57**, 135-147. **Published**

**Chapter 6** Thomas B, Holland J. Minot E. M. 2010. Home range and movement patterns of an Estuarine Crocodile *Crocodylus porosus*: a satellite tracking pilot study. *Northern Territory Naturalist* 22. **Published**

**Chapter 7** Thomas B, Minot EO, Holland JD (2010) Wildlife satellite tracking: technology choices and cost considerations. *Wildlife Research*. **Submitted**

**Chapter 8** Conclusions and Recommendations

# CHAPTER 2: Case study one – Elephant (*Loxodonta africana*) home ranges in Sabi Sand Reserve and Kruger National Park: a five-year satellite tracking study

This chapter has been published in PLoS ONE.

## 2.1 Abstract

During a five-year GPS satellite tracking study in Sabi Sand Reserve (SSR) and Kruger National Park (KNP) we monitored the daily movements of an elephant cow (*Loxodonta africana*) from September 2003 to August 2008. The study animal was confirmed to be part of a group of seven elephants, therefore her position is representative of the matriarchal group. We found that the study animal did not use the habitat randomly and confirmed strong seasonal fidelity to its summer and winter five-year home ranges. The cow's summer home range was in KNP in an area more than four times that of her SSR winter home range. She exhibited clear park habitation with up to three visits per year travelling via a well-defined northern or southern corridor. There was a positive correlation between the daily distance the elephant walked and minimum daily temperature and the elephant was significantly closer to rivers and artificial waterholes than would be expected if it were moving randomly in KNP and SSR. Transect lines established through the home ranges were surveyed to further understand the fine scale of the landscape and vegetation representative of the home ranges.

## 2.2 Introduction

The 650 km$^2$ Sabi Sand Reserve (SSR) is an association of 17 freehold game lodges and private game reserves sharing a common 50-km unfenced eastern boundary with Kruger National Park (KNP). Together, they form 20,650 km$^2$ of undisturbed savanna, woodland, mountain terrain and riverine forest, and are home to 490 bird species, 147 mammals, 94 reptiles, 33 amphibians and 200 tree species (Braack, 2000). The reserves are in the north east of South Africa where KNP is bordered by Mozambique to the east and Zimbabwe to the north.

At one time, the study area was a popular hunting region where elephants were heavily targeted. However, after its establishment as a South African Government Reserve in 1898, and KNP in 1923, elephants began to recolonise the area. Both KNP and SSR are managed as autonomous units with the former answerable to a conservation minister and the latter to private shareholders.

The fence between KNP and SSR was dropped in 1993 after which elephant numbers in SSR increased rapidly from 60 to 1,398 (2.15/km$^2$) by 2007, an average annual increase of 13.8%. This compares with 3.9% per annum in KNP where elephant numbers during the same period rose from 7,834 to 13,050 (0.65/km$^2$) (Whyte, 2007). The increase in elephant numbers has led some scientists to fear that continued growth will result in tree canopy destruction that may exacerbate reductions in species richness of birds and other taxa (Whyte, 2001, Owen-Smith et al., 2006).

In 1989, Whyte (2001) concluded that effective elephant management policies in KNP should be supported by a better understanding of elephant movement patterns. Consequently, Whyte (2001) used radio transmitters to study the movements of 29 adult KNP elephants during a seven-year period to 1996. He tracked each elephant for an average period of four years and, using an average of 10 location points each year, identified home ranges varying from 45 km$^2$ to 1800 km$^2$ and observed that movements were not always confined within individual parks. In 2006, the paucity of elephant movement data was highlighted by a panel of scientists who reported that a more precise understanding of elephant movements is required if successful management programmes are to be developed (Owen-Smith et al., 2006).

In our study we tracked the daily movements of the study animal for five years to further understand the location, size and inter-annual variability of home ranges; identify travel corridors between parks; and consider how the resources within the reserves influence movement.

## 2.3 Materials and Methods

In conjunction with the Sabi Sand ecologist and staff from KNP's Scientific Services and Veterinary Wildlife Services, a breeding herd cow was identified and darted from a helicopter on the 26 September 2003 and a satellite collar attached. Before the batteries of the tracking collar expired, the animal was retagged on 15 August 2006. Observations of daily movements since the retagging showed no obvious signs of stress as there were no changes in the daily movement patterns. In previous studies, the matriarchs of the family group were selected (Whyte, 2001), however, because these are the oldest animals and susceptible to a higher mortality (Whyte, 2001), we selected a younger, lactating cow, estimated to be 24 years old with a small calf at foot (see Figure 2.1). The study animal is a member of a matriarchal group of three adult and four juvenile elephants.

**Figure 2.1.** Study elephant with satellite tracking collar (Photo J Holland)

We tagged the elephant on a cool day to avoid overheating and death of the animal. The tranquiliser dart was fired from a modified shotgun at the rump using a 24 cm x 7 ml aluminium syringe dart with a 3 mm ‘collared’ needle. The drug combination used to tranquilize the lactating cow was short-acting Azaperone (Janssen Pharmaceutica) and the analgesic etorphine hydrochloride or M99 (Norvartis) with Diprenorphine or M-5050 as an anaesthetic and antidote respectively (Whyte, 2001, Bothma, 2002). Upon the elephant becoming recumbent, the rest of the matriarchal group was herded off to a safe distance by the helicopter.

The helicopter team was accompanied by a ground crew to roll the immobilized elephant on its side in the event it collapsed on its haunches after tranquilising. The pressure from the weight of the elephant upon the diaphragm and sternum may have injured or killed the animal (Bothma, 2002). The elephant's exposed eye was covered with its ear to protect it from direct sunlight and dust and the trunk was extended to ensure the animal breathed comfortably.

### 2.3.1 Equipment

A combination of satellite receivers and a GPS transmitter were used to monitor the elephant's movements. The Inmarsat 3 F1 is a third generation satellite (1996) covering the whole of Africa, Australia and Middle East (Africa Wildlife Tracking, 2010).

The tracking unit attached to the elephant had a GPS receiver and a VHF radio transmitter incorporated into the collar. The unit on the elephant was set to obtain and transmit a single location signal at noon (local time) each day. We monitored the period 26 September 2003 to 30 July 2008, equating to approximately 1,750 tracking-days.

The location data were mapped and analysed using ArcGIS® ArcMap® 9.2 (Environmental Systems Research Institute, Redlands, California, USA), with Spatial Analyst® and Tracking Analyst® extensions. Home range area was determined by calculating the Minimum Convex Polygon (MCP) using Animal Movement Analyst Extension (AMAE) (Hooge and Eichenlaub, 1997). A MCP is known to inflate the actual area occupied by the animal because it includes outliers. According to Kenward (2001), however, a MCP including all locations is the most widely used home range estimator allowing for meaningful comparisons between home ranges of different studies. This being the case, we calculated home range using a MCP with all the locations for our study animal and, to allow for a more conservative estimate, recalculated it with 95 and 50% of the locations. Outliers were removed with AMAE utilising the harmonic mean method (Dixon and Chapman, 1980).

Weather data were obtained from the South African Weather Bureau station at Skukuza. The station is located within the study area and recorded average annual rainfall and temperature of 541 mm and 23.8°C respectively during the five-year period. Summer is the rainy season and winter is the dry period when the animals become increasingly dependant upon waterholes and manmade dams. This is true for most African national parks (Lindeque and Lindeque, 1991, Shannon et al., 2006, Dolmia et al., 2007).

### 2.3.2 Habitat study

We mapped daily location points to identify core winter and summer home ranges through which transect lines were surveyed to further understand the fine scale of the predominant landscape and vegetation representative of the home ranges. The SSR and KNP transect lines (Figure 2.2) were 28 km and 20 km long respectively and sampling was conducted at one kilometre intervals. Vegetation and landscape attributes within a 30-meter radius of each study site were recorded. The SSR home range area was shown to be more biologically diverse. Dominant tree species in both areas include knob thorn (*Acacia nigrescens*), sickle bush (*Dichrostachys cinerea*) and russet bushwillow (*Combretum apiculatum*). Guinea grass (*Panicum maximum*) is ubiquitous to both home range areas.

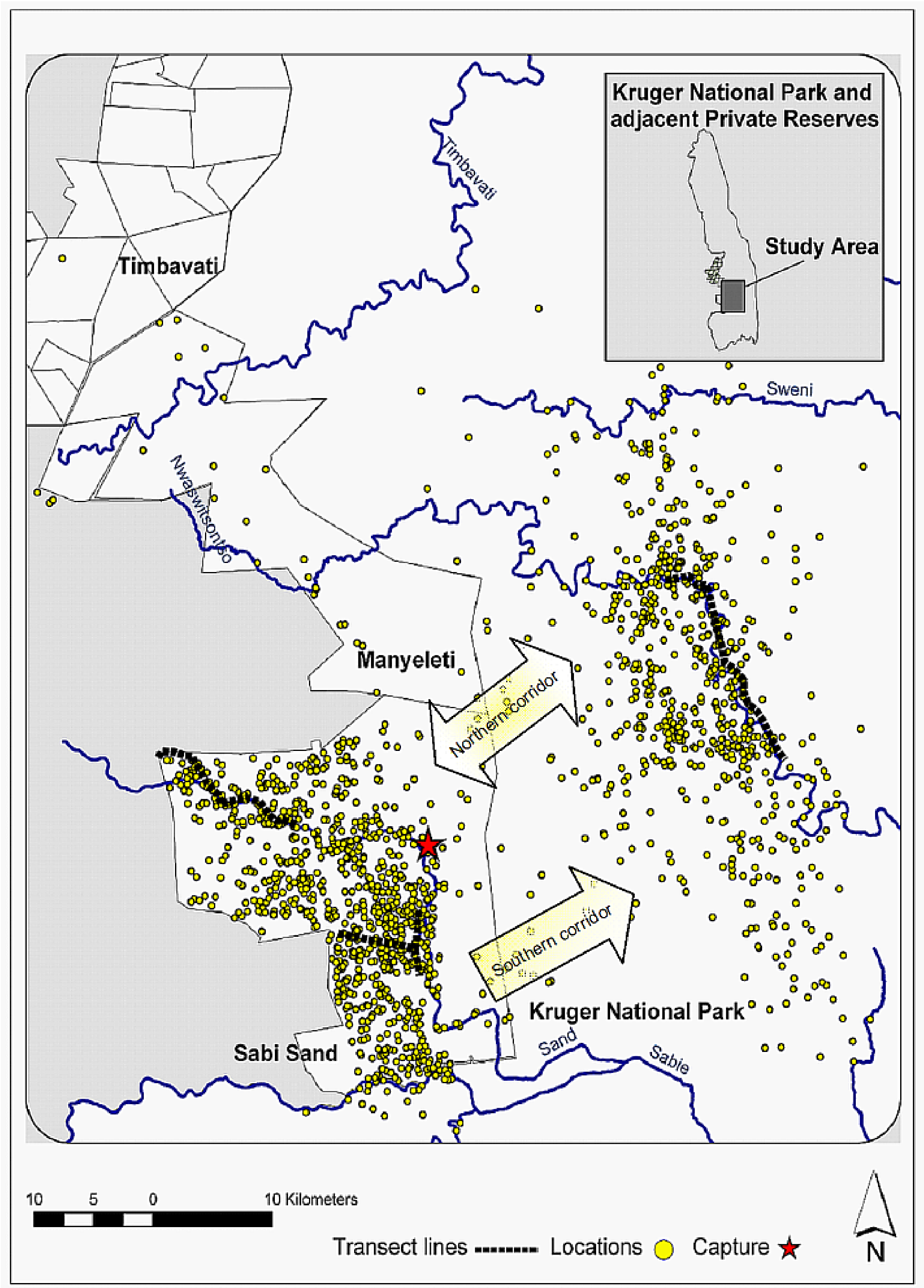


**Figure 2.2.** Study area and daily locations of study elephant. Map of KNP, South Africa showing the locations of daily GPS fixes from the study animal obtained from September 2003 to July 2008.

## 2.4 Results and Discussion

### 2.4.1 Habitat use

The elephant's daily location points are mapped in Figure 2.2, showing the concentrations of location points within each park.

We found that the elephant in this study did not use the available habitat randomly, instead developing a strong preference for a specific habitat while others were seldom, if ever, used. These findings are similar to those of Ntumi, van Aarde, Fairall, and de Boer (2005).

Seventy two percent of all positions recorded during the summer months (December, January and February) were located within KNP and 77% of winter positions (June, July and August) were located within SSR. Average monthly visitation rates to KNP over the five-year period peaked at 20 days during December and January before the herd moved to the well-watered SSR in June when visitation rates are highest (23 days) and coincide with lowest average rainfall and temperature (Figure 2.3).

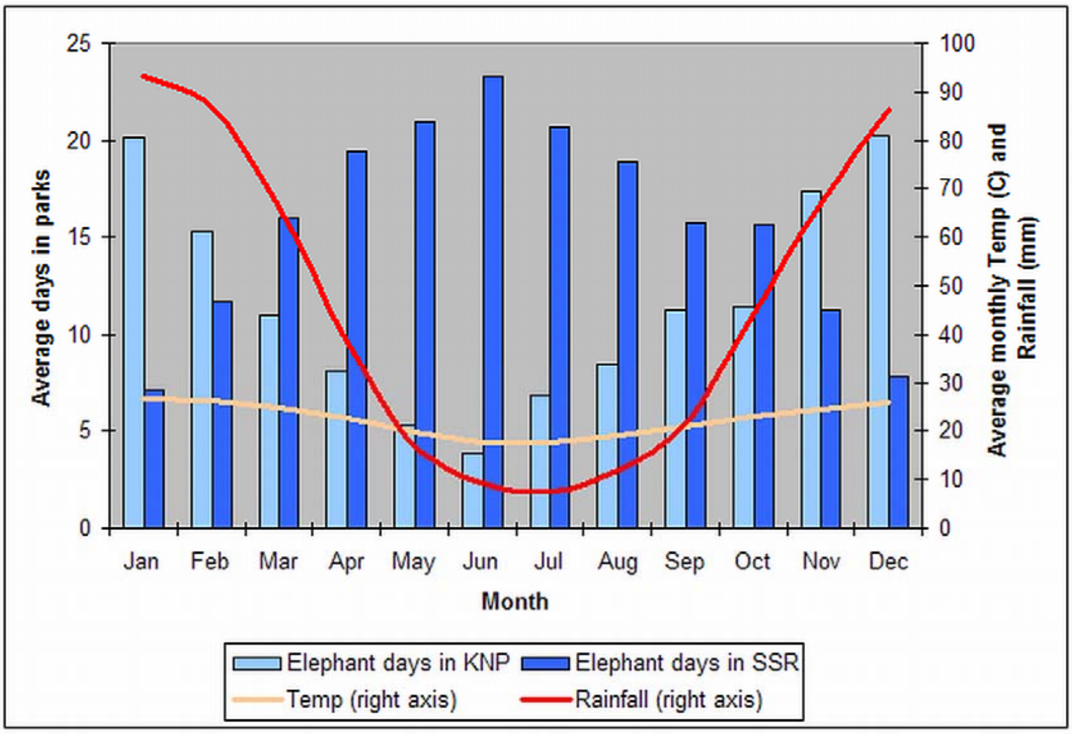


**Figure 2.3.** Average monthly occupancy rates. The average monthly occupancy of the study elephant within Kruger National and Sabi Sand Parks compared to average monthly temperature (° C) and rainfall (mm) from September 2003 to July 2008.

Using the distance between consecutive mid-day locations as a proxy for daily distance travelled by the elephant, we found that it walked an average of 127 km per month during summer compared with 101 km per month during winter (paired-sample $t = 2.25$, df = 3, $P < 0.05$). Whilst it is difficult to attribute changes in behaviour to specific variables, or combinations of variables, we found that the study elephant's movement increased as temperature increased ($r = 0.71$; $P < 0.001$; Figure 2.4). This is most likely because the coldest months are also the driest and, given that elephants need to drink every day or two (Owen-Smith et al., 2006) they move to their winter home range where there is a high density of waterholes, so less movement is necessary.

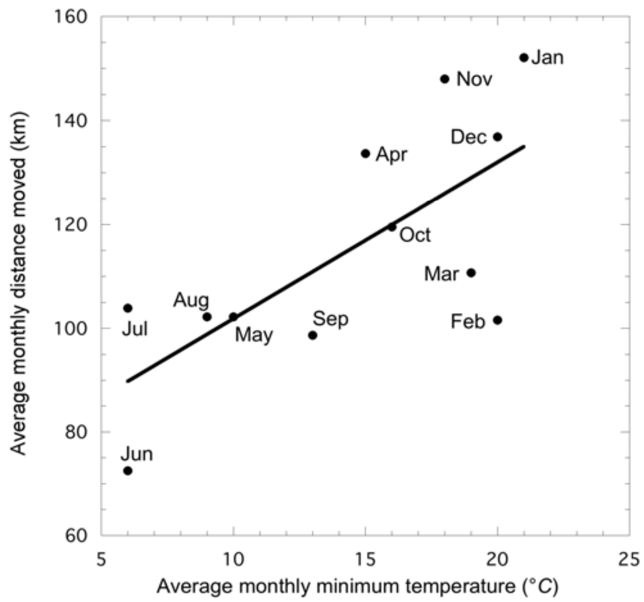


**Figure 2.4.** Average monthly distance and minimum temperature. Distance is based on a single GPS location taken at noon each day and average minimum temperature for the period 1960 – 1990 from the Skukuza weather station.

Within SSR, the study elephant barely utilised the eastern boundary with KNP and a small pocket in the south west of SSR (Figure 2.2). This may be attributable to the limited number of eastern border waterholes (South African National Parks, 2009) and the large human presence near the unutilised south west pocket of the SSR.

In June 2007, landscape and vegetation transects were conducted in the core home ranges and 33 tree and 21 grass species were identified in the SSR and KNP home ranges respectively. The SSR home range was more biologically diverse with 30% of the trees and 57% of the grasses found in SSR not represented in the KNP transect samples (Table 2.1).

**Table 2.1.** Dominant tree and grass species identified in vegetation transect through elephant home ranges in Kruger National Park and Sabi Sand Reserve (June 2007) [1, 2]

| ***Dominant species*** | ***Soils and topography*** | ***SSR (n=28)*** | | ***KNP*** **(n=20)** | |
|---|---|---|---|---|---|
| **Trees** | | **No.[3]** | **%** | **No.** | **%** |
| *Euclea divinorum* Magic guarri | Mostly found in the brackish flats in granite & alluvial soils along river courses. Generally growing in pockets among other tree species, in thorn scrub, hillsides & woodland. | 19 | 68 | 5 | 25 |
| *Acacia nigrescens* Knob thorn | Usually occurs in groups. The largest trees are found in the flood-plains & shrub form is common in the gabbro & basalt areas. | 16 | 57 | 1 | 5 |
| *Dichrostachys cinerea* Sickle bush | Prefers clay-like soils but also found on all soils & close to rivers & brackish flats. Also along roads due to increased run-off. | 16 | 57 | 11 | 55 |
| *Combretum hereroense* Russet bushwillow | Most often seen around pans, rocky areas & sometimes on stream banks. Usually occurs in closely associated groups. | 14 | 50 | 13 | 65 |
| *Ziziphus mucronata* Buffalo thorn | Found everywhere but prefers brackish flat & koppie, open woodland, often in alluvial soils & on termite mounds. | 12 | 43 | 0 | 0 |
| *Sclerocarya birrea* Marula | Common throughout the Lowveld, growing on all soil types. | 12 | 43 | 7 | 35 |
| *Combretum apiculatum* Red bushwillow | Often found on granite crests. As with the mopane, the red bushwillow is one of the most abundant trees in area. | 8 | 29 | 1 | 5 |
| *Lonchocarpus capassa* Apple-leaf | Common in most parts, grows on all soil types, tallest & most plentiful on alluvial plains & on river & stream banks. | 7 | 25 | 13 | 65 |
| *Acacia nilotica* Scented thorn | Prefers brackish soils near rivers & drainage lines. Also found on clay soils. | 7 | 25 | 4 | 20 |
| *Terminalia sericea* Silver cluster-leaf | Found in granite area, prefers deep, well-drained, sandy soils. Prolific on mid-slope seep-lines where it grows in dense groups. Common in higher rainfall areas. | 6 | 21 | 0 | 0 |
| *Grewia monticola* Silver raisin bush | Small to medium size deciduous tree 2–10 m. Occurs over wide range of altitudes in riverine fringes & open woodland - often on termite mounds. | 5 | 18 | 5 | 25 |
| *Spirostachys africana* Tamboti | Occurs on all soil types, common in the Lowveld. Often in groups of a few big trees along rivers or streams in the brackish flats. | 5 | 18 | 5 | 25 |
| *Peltophorum africanum* African weeping wattle | Grows best in lower altitudes in wooded grassland & on well-drained sandy soils, but occurs on all soil types in area. | 5 | 18 | 4 | 20 |
| *Diospyros mespiliformis* Jackal berry | Grows along most river courses & bigger streams at lower altitude woodlands. Often found growing away from drainage lines & on termite mounds. | 5 | 18 | 4 | 20 |
| **Grasses** | | | | | |
| *Panicum maximum* Guinea grass | Tufted perennial, grows on all soils; damp places along fertile soil; shade of trees & along rivers. | 17 | 61 | 16 | 80 |
| Heteroptogon contortus Spear grass | Fast-growing grass that likes well-drained stony soils; open areas; twisted seed-heads are often seen along roadsides. | 9 | 32 | 11 | 55 |
| *Digitaria eriantha* Finger grass | Tufted perennial that grows in open areas & on moist soils - especially in sandy areas. | 8 | 29 | 6 | 30 |
| *Pogonarthria squarrosa* Sickle grass | Perennial that grows in well-drained sandy soils. Common in disturbed places - an indicator of poor, sandy soils, old lands. | 8 | 29 | 0 | 0 |
| *Perotis patens* Cat's tail grass | Tufted perennial that grows on disturbed soils, often in poor sandy soils and dry exposed sites. | 5 | 18 | 7 | 35 |
| *Setaria Sphacelata Torta* Creeping bristle grass | Creeping perennial grass that likes granitic, well-drained soils. Good soil conservation grass that forms runners that bind soil. | 5 | 18 | 11 | 55 |

| ***Dominant species*** | ***Soils and topography*** | ***SSR (n=28)*** | | ***KNP* (n=20)** | |
|---|---|---|---|---|---|
| *Dactyloctenium australe* L.M. grass | Creeping perennial that thrives in shade in sandy soil. Popular lawn grass in Lowveld. | 4 | 14 | 0 | 0 |
| *Themeda triandra* Red grass | Tufted perennial that grows on basalt, gabbro and dolerite and undisturbed grassland areas. | 4 | 14 | 0 | 0 |
| *Chloris virgata* Feather top chloris | Variable annual grows in shade but prefers open country. Not drought tolerant. | 3 | 11 | 0 | 0 |

[1] (Fyvie, 2008)
[2] A total of 33 tree and 21 grass species were identified in SSR and KNP.
[3] Refers to the number of times species were identified in the 28 SSR transect location sites.

This may explain the elephant's preference for the undulating granite/gneiss and gabbro plains of SSR during winter while the summer, rain-charged rivers of the Karoo Sediment home range plains in KNP may be one of the reasons that the elephant targets this landscape and vegetation type. During the rainy season the elephant selects from a narrower choice of habitats. At this time of the year, the plants in KNP elephants' diet decrease (Ntumi et al., 2005). Codron et al. (2006) have shown that elephants in the study area tend to become dependant upon grass during summer, with tree-felling and debarking of larger trees starting in winter when the grass dries and the elephants begin eating woody plants. This response is intensified during drought periods (De Beer et al., 2006, Owen-Smith et al., 2006). We agree with Ntumi et al. (2005) who stress that most elephants favour closed canopy habitat types like riparian thickets and vegetation types associated with water.

Our findings concur with those of Smit, Grant and Whyte (2007), namely, that the herd occurred closer to water sources more frequently than would be expected if they were randomly distributed. The observed locations were significantly closer to waterholes and rivers in both KNP and SSR than random locations (Figure 2.5).

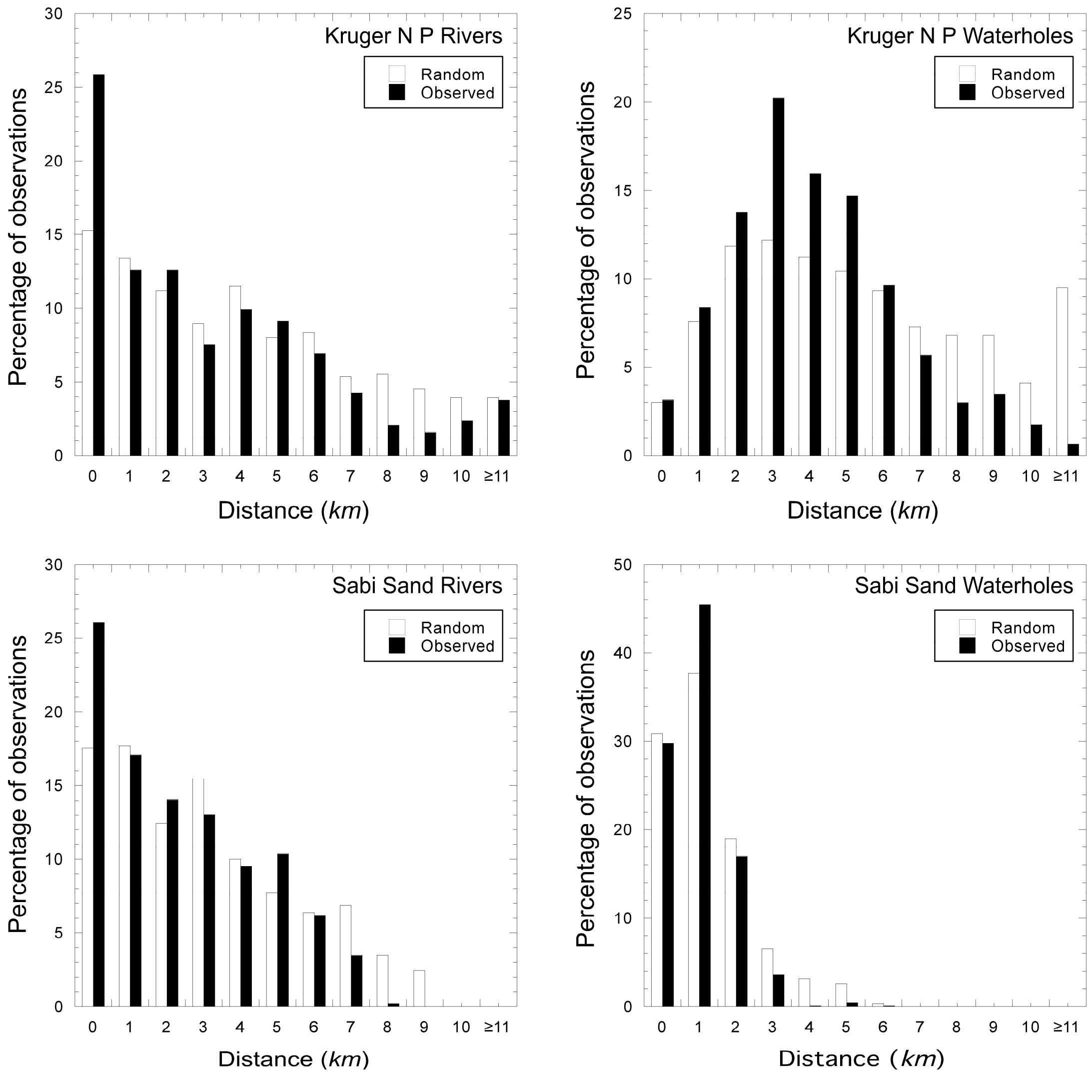


**Figure 2.5.** Observed and random location distances from water sources. Random points were generated within the 95% MCP for the KNP and SSR home ranges. For both observed elephant locations and random points, the distance to the nearest water, either waterhole or river, was calculated.

By 2007, SSR had 376 waterholes or 0.58 waterholes per km² and 2.15 elephants per km² compared with a KNP density of 0.65 elephants per km². This, in conjunction with improved winter browsing and a well-distributed, reliable water supply make the SSR an attractive winter destination. Elephants in KNP consume varying proportions of browse to grass in different seasons (Codron et al., 2006) and it may be that the wider diversity of woody plants in the study animal's winter home range allows elephants to utilise this resource more efficiently after grass production drops off following the dry summer. During the wet summer, elephants increase their grass consumption to around 50% and then change over to the less varied summer diet (Owen-Smith, 1998, Codron et al., 2006).

### 2.4.2 Home range

The distance between the core summer and winter home ranges was 32 km. The 95 and 50% MCP combined home ranges for KNP and SSR were 2,244 km² and 783 km² respectively. Comparable results from KNP from Whyte's study of 29 radio-tracked elephants give 90% MCPs ranging from 45 to 1,800 km². While our results align with his upper estimates his overall results will tend to be low because he used only 10 locations per year.

The elephant's five-year SSR winter home range was 308 $km^2$ and its annual average home range during the same period was 131 $km^2$. This shows that, whilst the elephants move back to the same broad geographic area each year, only 40% is utilised during any one year. The five-year KNP summer home range was 1,139$km^2$ and its annual average home range for the same period is 424 $km^2$. The annual average home range within SSR is in line with the findings of Fairall (1979) for the same reserve (<200 $km^2$). Also our estimates for the KNP home range is similar to reports by Whyte (523 $km^2$) and Hall-Martin (436 $km^2$) in 2001 and 1984 respectively (Ntumi et al., 2005).

In Table 2.2 the details of the study animal's movements between SSR and KNP over the five-year period are presented, revealing that only eight of the 26 habitation periods were less than a month in duration. The cow moved between the two home ranges up to three times a year. The average annual winter home range size in SSR is 195 $km^2$ compared with 331 $km^2$ for its summer counterpart in KNP and, as can be expected, the home range increases with the time the elephant spends in each reserve ($r = .78$, $p < 0.002$ for SSR; $r = .61$, $p < .03$ for KNP). From tracking the elephant's movement between the two reserves, a northern and southern corridor were identified (Figure 2.2). Between November 2003 and April 2008, the corridors were traversed on 25 occasions with the busier northern corridor used for 78% of the crossings. Notably, all the movements from KNP to SSR were through the northern corridor.

**Table 2.2.** Park and corridor usage of SSR and KNP

| Sabi Sand Reserve | | | | Kruger National Park | | | |
|---|---|---|---|---|---|---|---|
| **N**[1] | **Departure Date**[2] | **95% MCP ($km^2$)**[3] | **Departure corridor**[4] | **N** | **Date** | **95%MCP ($km^2$)** | **Departure corridor**[4] |
| 37[5] | 3 Nov 03 | 115 | Southern | 7 | 10 Nov 03 | 127 | Northern |
| 45 | 25 Dec 03 | 220 | Northern | 108 | 11 Apr 04 | 485 | Northern |
| 189 | 16 Oct 04 | 322 | Southern | 91 | 13 Jan 05 | 514 | Northern |
| 196 | 29 Jul 05 | 447 | Northern | 31 | 29 Aug 05 | 177 | Northern |
| 7 | 5 Sep 05 | 20 | Northern | 59 | 3 Nov 05 | 230 | Northern |
| 27 | 30 Nov 05 | 180 | Southern | 37 | 6 Jan 06 | 341 | Midway |
| 6 | 12 Jan 06 | 68 | Northern | 54 | 8 Mar 06 | 547 | Northern |
| 128 | 12 Jul 06 | 288 | Northern | 50 | 1 Sep 06 | 235 | Northern |
| 84 | 24 Nov 06 | 340 | Southern | 83 | 15 Feb 07 | 188 | Northern[6] |
| 46 | 1 Apr 07 | 149 | Northern | 22 | 24 Apr 07 | 242 | Midway |
| 160 | 1 Oct 07 | 137 | Northern | 19 | 20 Oct 07 | 192 | Northern |
| 14 | 3 Nov 07 | 35 | Northern | 71 | 11 Jan 08 | 624 | Northern[7] |
| 98 | 18 Apr 08 | 209 | Northern | 47 | 5 Jun 08 | 403 | |
| **Ave MCP** | | 195 | | | | 331 | |
| **5 year MCP** | | 308 | | | | 1139 | |

[1] Number of days within the park before movement.
[2] Date that elephant started journey to other home range.
[3] The MCP ($km^2$) is based on locations obtained inside the relevant park calculated after arrival date from previous home range.
[4] Refer to Figure 2.2 for corridor location.
[5] From 26 September onwards.
[6] Entered the corridor via Manyeleti.
[7] Entered the corridor via Timbavati.

### 2.4.3 Management implications

This study followed a single female, and consequently her group of three adults and four juveniles, for a period of five years. While this long duration is not a substitute for extensive replication, this is the first KNP/SSR elephant to be tagged with a satellite collar and, being the longest continuous study of its kind in the area, the results provide the first insight into within- and between-season movements. It is known that female elephants live and travel within distinct matriarchal groups each led by closely related matriarchs who may be sisters or cousins and, together, the groups form part of a wider composition known as a ‘bond group’. Therefore, movement of one adult female could be extrapolated to the movements of a matriarchal group. Two similar elephant tracking studies are currently being undertaken by Thomas, Minot and Holland in the same study area and the data from the first 18 months of this on-going research support the findings of this study. Namely, that both move between the two parks, summer MCP home ranges are larger than winter home ranges and both are utilised in the same manner as reported in this study.

This long time series has enabled us to report on the reciprocal importance of KNP and SSR to the elephant and its attendant herd and that since the fence between the two reserves was dropped, the elephants consistently rely upon KNP for summer grazing and SSR for winter grazing and water. It has also enabled us to identify possible important northern and southern corridors between the reserves. This, combined with the rising number of elephants in both reserves signals the importance of ongoing co-operation between wildlife managers from both reserves.

In 1999, SANParks approved a new policy for managing the KNP elephant population based upon the park being divided into zones and managed according to biodiversity impacts rather than on fixed elephant numbers (Whyte, 2001, Whyte, 2007). These were designed to broadly conform to home ranges that were identified using radio-collared elephants of herds in selected zones (Whyte et al., 1998, Whyte, 2007). However, the radio data were limited to less than one location point per month and, notwithstanding the valuable contribution of this early research to understanding elephant movements at a broad level, it would not have been possible to identify specific movement corridors between home ranges; isolate shorter visits made by animals to home ranges; identify movement patterns between home ranges; and map the full extent of an elephant's home range.

Future management plans could be made more comprehensive by recognizing that the two areas must be managed as a single unit. From the results of our study, we conclude that the boundary recommended for the southern high-impact region (Whyte, 2001) would only accommodate the elephant's summer home range. The proposed 'high-intensity' elephant zone does not include the elephant's SSR winter home range area. Both KNP and SSR share similar challenges associated with overpopulation, the provision of artificial waterholes, and monitoring and evaluation of flora and fauna. Therefore, a co-operative management plan taking into account seasonal elephant use of both parks, and the corridors between them, should be a priority.

This study illustrates the advantages of long-term continuous monitoring of wildlife in both better understanding their seasonal ecology and formulating management plans based on their habitat requirements throughout the year.

## 2.5 Acknowledgements

We warmly thank Jonathan Swart, Gavin Hewlett and Johnson Mahluli (Sabi Sand Reserve); Dr Ian Whyte (KNP Scientific Services), Hennie de Waal (pilot), Dr Peter Buss (KNP's Veterinary Wildlife Services); and Sarah Holland for their assistance with the field research.

# CHAPTER 3: Case study one – A long-term satellite tracking study of elephant (*Loxodonta africana*) movements between Sabi Sand Reserve and Kruger National Park

This chapter has been submitted to the African Journal of Ecology.

## 3.1 Abstract

We studied the seasonal home ranges and space use of three breeding herds of elephants (*Loxodonta africana*) for three to five years in South Africa's Sabi Sand Reserve (SSR) and Kruger National Park (KNP). GPS transmitters, set to transmit a single daily location, were placed on the matriarch within three herds and obtained successful locations 93%, 86% and 69% of the time. For two of the three herds, home range maximum was reached within two years of tracking. Thirty one percent, sixty percent and eighty-four percent of the time each herd was located in SSR. Each herd moved longer distances in the wet summer season than during the dry winter. Core areas were centred on riverine habitats within both reserves, with all three herds exhibiting closer distances to rivers and artificial water holes than would be expected if they were moving randomly. There was substantial home range overlap within SSR. In KNP, however, they occupied discrete areas with little overlap. Much of the movement between the two parks occurred along well-defined routes. This study shows that elephant herds depended upon the resources of both SSR and KNP, thus highlighting the importance of ongoing co-operation between wildlife managers from both reserves when forming policy.

## 3.2 Introduction

The complexity of managing African elephants (*Loxodonta africana*) has never been more evident than it is today (Owen-Smith et al., 2006). Identified as a keystone species (Kerley and Landman, 2006) and classified as vulnerable (Blanc, 2008), this species is under threat throughout most of Africa from poaching and human encroachment into their habitat (Glennon, 1990, Osborn and Parker, 2003). In contrast, elephant numbers are steadily growing within the confined reserves of South Africa. This is being attributed to increased artificial water sources, man-made fences restricting the natural movement of elephants outside of these areas and protection from poachers (Slotow et al., 2005, Smit et al., 2007b, van Aarde and Jackson, 2007, Loarie et al., 2009). This increase in elephant numbers has raised concerns about their impact on surrounding vegetation (Jacobs and Biggs, 2002, Codron et al., 2006, Kerley and Landman, 2006, van Aarde et al., 2006, Young et al., 2009). These issues, coupled with the high intrinsic value humans place on this species (Vidya and Sukumar, 2005), intensify the complex wildlife management challenges that wildlife managers face.

Supporting one of the largest confined elephant populations within Africa, both Sabi Sand Reserve (SSR) and Kruger National Park (KNP) are managed autonomously and have very different objectives. KNP is mandated to protect biodiversity and is answerable to a conservation minister (Owen-Smith et al., 2006) while SSR is a private game reserve with shareholders. With no fence between SSR and KNP, elephant movements are unrestricted and, with their population expanding, it is becoming increasingly important that wildlife managers understand elephant behaviour and their use of space between and within regional areas, rather than within individual reserves only (Owen-Smith et al., 2006, van Aarde et al., 2006, Young et al., 2009). Management tools have previously included contraception, culling, translocation and water provision programs . More recent suggestions focus on providing animals in small confined reserves with more space through the creation of megaparks (van Aarde and Jackson, 2007). However, for this to be effective, an improved understanding of the spatial dynamics and landscape preferences of elephants in South Africa is required (van Aarde and Jackson, 2007, Harris et al., 2008).

During the 1990's Whyte (2001) mapped the spatial movement and home range of 29 elephants in KNP using VHF telemetry. He described these elephants as non-migratory and exhibiting a high degree of fidelity to their home ranges. However, because the research was based on an average of only one location point per month, little could be said about factors that influenced their daily and seasonal movements and areas of high use. Whyte's research did not document elephant movements between KNP and SSR.

This aim of this study is to examine the co-dependence of elephants within SSR and KNP irrespective of park boundaries. We provide a long-term spatial dataset on elephant movements between SSR and KNP by following three global positioning system (GPS) collared elephant herds for up to five years. Our specific objectives were to: 1) map annual and seasonal home ranges and calculate the asymptotic level where the maximum home range is reached, 2) identify areas of high use where possible vegetation degradation could be occurring, 3) identify the importance of water resources to these three herds in KNP and SSR, and finally 4) evaluate the technical performance of the three transmitters under field conditions. We considered three aspects of performance; the number of locations obtained (fix success) and whether there were any significant monthly or seasonal differences; whether the number of locations declined as the GPS transmitters approached their theoretical life expectancy; and performance anomalies. This technical performance evaluation will aid in the interpretation of biological results and determine whether the collars functioned efficiently enough to underpin elephant management decisions. The ecological results of this study will reinforce wildlife managers' understanding of the spatial behaviour of herds within and between KNP and SSR and the impact of exogenous factors that influence herd movements. Given that the elephants move freely between the two reserves it is important that, irrespective of the reserves' different management objectives, wildlife managers' plans cater for the needs of fugitive species like elephants.

## 3.3 Materials and Methods

SSR and KNP are located in the north-eastern corner of South Africa with elephant populations estimated at 857 and 12,427 respectively (Blanc et al., 2007). Together they form 20,200 km² of undisturbed savanna, woodland, mountain terrain and riverine forest. The arid bushveld area in the north of KNP has annual rainfall ranging from 500-800 mm contrasted with lowveld bushveld in the south and 500-700 mm annual rainfall (Codron et al., 2006). Seasons were based on long term monthly average rainfall data records within the study area. The wet summer included the months of December, January and February, whilst the dry winter included June, July and August (Thomas et al. 2008).

Within the home range areas of the study herds, the dominant tree species include knob thorn (*Acacia nigrescens*), sickle bush (*Dichrostachys cinerea*) and russet bushwillow (*Combretum apiculatum*) as well as Guinea grass (*Panicum maximum*) (Thomas et al., 2008). The terrain within these home range areas in both SSR and KNP is generally flat containing granitic and basaltic rocks (Codron et al., 2006). There are five rivers relevant to this study, namely the Sabie, Sand, Nwaswitsonso, Nwatswishaka and

Mbyamiti. All are considered main rivers, with the Sabie being perennial and the other four seasonal.

The transmitters used in this study were AST GPS near-real-time data collars (Africa Wildlife Tracking; Pretoria, South Africa). The units weighed 12.5 kg including a 6.5 kg lead ballast to keep the transmitter upright. They were designed to last for 24 months at three readings per day powered by ten D-cell lithium batteries. For this study, they were set to record a single GPS reading per day at midday, thereby extending the lifetime of the batteries to three years.

Three adult female elephants (referred to as Jh1, Jh2 and Jh3) were captured and collared within SSR using standard protocols (Whyte, 2001). Jh2 was tracked for five years from September 2003 to August 2008 with the collar being replaced after three years. Jh1 and Jh3 were tracked for almost three years from February 2007 through to November 2009 with budget constraints preventing their replacement after this time. Led by a single female matriarch, breeding herds can consist of up to twenty adult cows, their daughters and immature male offspring (Archie et al., 2006). Therefore, movement of one adult female may be extrapolated to the movements of a matriarchal group (Galanti et al., 2000). Jh1, Jh2 and Jh3 were members of matriarchal groups of twelve, seven and fifteen members respectively.

The GPS data were retrieved by way of the Inmarsat IOR 3 geostationary satellite system and downloaded using MS Track Pro (© 2008 IQgistics, LLC, Austin, Texas, USA). The Geographic Information System (GIS) software used was ArcGIS® ArcMap® 9.2 (Environmental Systems Research Institute, Redlands, California, USA). GPS collars recorded locations in WGS84, which we transformed to UTM zone 36S for analysis. Local GIS layers including water points, rivers, boundaries and land classification were supplied by the Geographic Information Systems and Remote Sensing Group within South African National Parks and the GIS Department at SSR as at 2009.

The home-range areas (MCP and Kernel) were calculated using the Animal Movement Analyst extension to ArcView (Hooge and Eichenlaub, 1997). MCP estimators are thought to overestimate space use (Douglas-Hamilton, 1998). However, they were used here to enable comparison with other studies as well as to determine the total potential area utilised by each elephant group. As a secondary measure of home range for comparison purposes and to reduce outlier bias, we used kernel-based territory size estimate (using the 95% probability contour). For this analysis we used the least-squares cross validation procedure to determine the smoothing parameter for each kernel distribution. We also used the kernel method (50% probability contour) to calculate core areas. The home range asymptotes were calculated using the cumulative monthly MCP home range values. One-way ANOVA was used to test for significant group mean differences in distance to water sources and a Pearson product-moment correlation coefficient was computed to assess the relationship between the number of locations (N) and time. Minitab® 15 (© 2007 Minitab Inc., State College, Pennsylvania, USA) was used for all statistical analyses.

To analyse the elephants' dependence upon water within their home ranges, for each day we calculated the actual distance to water between their location and the nearest main river or waterhole. These were then compared to distances to water of an equal number of points randomly generated within the MCP boundary of each elephant herd. Distances to water were stratified according to park due to each park's differing management practises and the variation in the waterhole densities between both parks. This stratification acknowledges the greater density of waterholes in SSR (0.67 $km^{-2}$) compared with KNP (0.065 $km^{-2}$). Spatial relationships between the individual elephant groups were analysed by calculating distances between locations recorded on the same day.

## 3.4 Results

### 3.4.1 Elephant movements

The Jh1 herd were in SSR for 31% of their 34-month monitoring period, preferring to remain there during the wet summer months, then moving to KNP during dry winter months (Table 3.1). The Jh2 herd spent 54% of their 60-month monitoring period in SSR, exhibiting a preference for SSR during the dry winter months and KNP during the wet summer months. The third herd (Jh3) spent a larger portion (84%) of their 34-month monitoring period within SSR exhibiting no seasonal preference. The short period of time that they were in KNP was during spring and summer. For all three herds, the brief time spent in other private reserves including Timbavati and Manyeleti, ranged between 1 and 3% with these visits generally occurring during summer and autumn.

**Table 3.1**. Average daily distance, % time spent in each park and home range sizes (MCP and 95% kernel).

| | | Total home range (km²) | | | | SSR home range (km²) | | | | | KNP home range (km²) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Avg dist (km)[1]** | **N** | **MCP** | **Kernel 95%** | **Time (%)[2]** | **Avg dist (km)** | **N** | **MCP** | **Kernel 95%** | **Time (%)** | **Avg dist (km)** | **N** | **MCP** | **Kernel 95%** |
| Jh1 | **Total[3]** | **3.8** | **758** | **1831** | **1251** | **31** | **4.3** | **232** | **420** | **385** | **66** | **3.5** | **500** | **1055** | **552** |
| | Summer[4] | 4.6 | 179 | 1625 | 1559 | 61 | 5.0 | 58 | 231 | 209 | 36 | 4.5 | 103 | 521 | 519 |
| | Winter[5] | 3.1 | 219 | 940 | 590 | 39 | 5.1 | 37 | 217 | 267 | 64 | 2.8 | 182 | 330 | 283 |
| Jh2 | **Total** | **4.1** | **1660** | **3915** | **1366** | **54** | **3.3** | **894** | **591** | **479** | **45** | **4.9** | **739** | **2560** | **926** |
| | Summer | 4.6 | 422 | 3262 | 1549 | 28 | 3.8 | 106 | 399 | 421 | 67 | 4.8 | 302 | 1906 | 807 |
| | Winter | 3.4 | 419 | 1473 | 932 | 72 | 2.9 | 272 | 513 | 354 | 33 | 4.4 | 146 | 467 | 357 |
| Jh3 | **Total** | **4.1** | **1095** | **1609** | **464** | **84** | **3.9** | **915** | **487** | **319** | **15** | **5.0** | **165** | **548** | **276** |
| | Summer | 5.2 | 205 | 924 | 428 | 41 | 5.3 | 183 | 423 | 311 | 54 | 5.0 | 22 | 337 | 545 |
| | Winter | 3.4 | 286 | 810 | 320 | 59 | 3.2 | 263 | 441 | 245 | 46 | 4.4 | 19 | 20 | 77 |

[1] Minimum average daily distance moved within each park and during the wet summer and dry winter seasons.
[2] The total percentage of time spent within each park and during the wet summer and dry winter seasons.
[3] Includes all seasons throughout the year.
[4] Includes the months December, January and February.
[5] Includes the months June, July and August.

The study herds crossed the boundary between SSR and KNP frequently. During a five-year period, Jh2 crossed approximately 25 times, via the same northern or southern route 90% of the time (Figure 3.1). Jh1 and Jh3 were both tracked for three years and crossed between SSR and KNP 13 and 21 times respectively via the same southwest route every time. In fact, neither Jh1 nor Jh3 crossed the SSR eastern boundary at all.

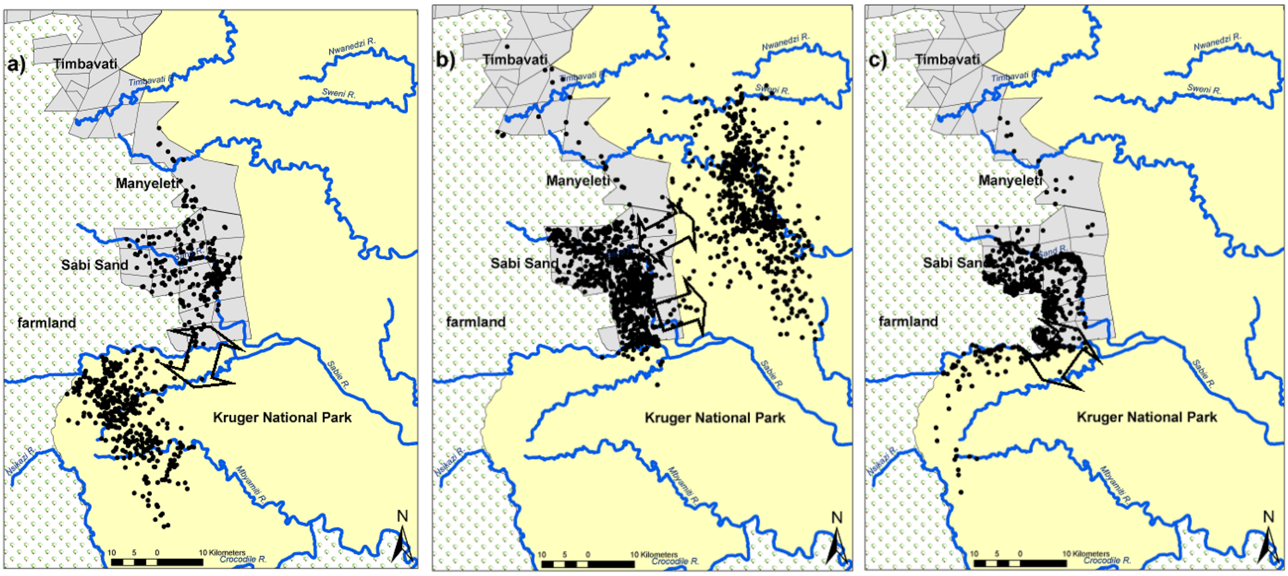


**Figure 3.1.** Study area and daily locations of study elephant. Map of KNP and the adjacent reserves showing the locations of daily GPS fixes from three herds of breeding elephants. a) Jh1 tracked from February 2007 to February 2009 b) Jh2 tracked from September 2003 to August 2008 c) Jh3 tracked from February 2007 to February 2009.

Total home ranges varied between the three herds using both the MCP and kernel methods (Table 3.1). Within KNP, larger home ranges were observed during the wet summer season, while home range sizes within SSR were moderately larger during the dry winter months for two of the three herds. Overall, the herds utilised a larger home range during the wet summer months than the dry winter months.

The mean daily distance moved ranged between 3.8 and 4.1 km (Table 3.1) with the maximum daily distance ranging between 32 and 44 km. All the study herds moved more during the wet summer months ($F = 19.31$; d.f. = 3, 3247; $P < 0.001$) and least during the dry winter.

Based on location points from a duty cycle of one transmission per day, both Jh1 and Jh3 had occupied 95% of their home range within 21 months and almost 100% within 24 months, whilst Jh2 had occupied almost 90% of their home range after 24 months (Figure 3.2). Jh2 then occupied 100% of their home range after 53 months (four and a half years).

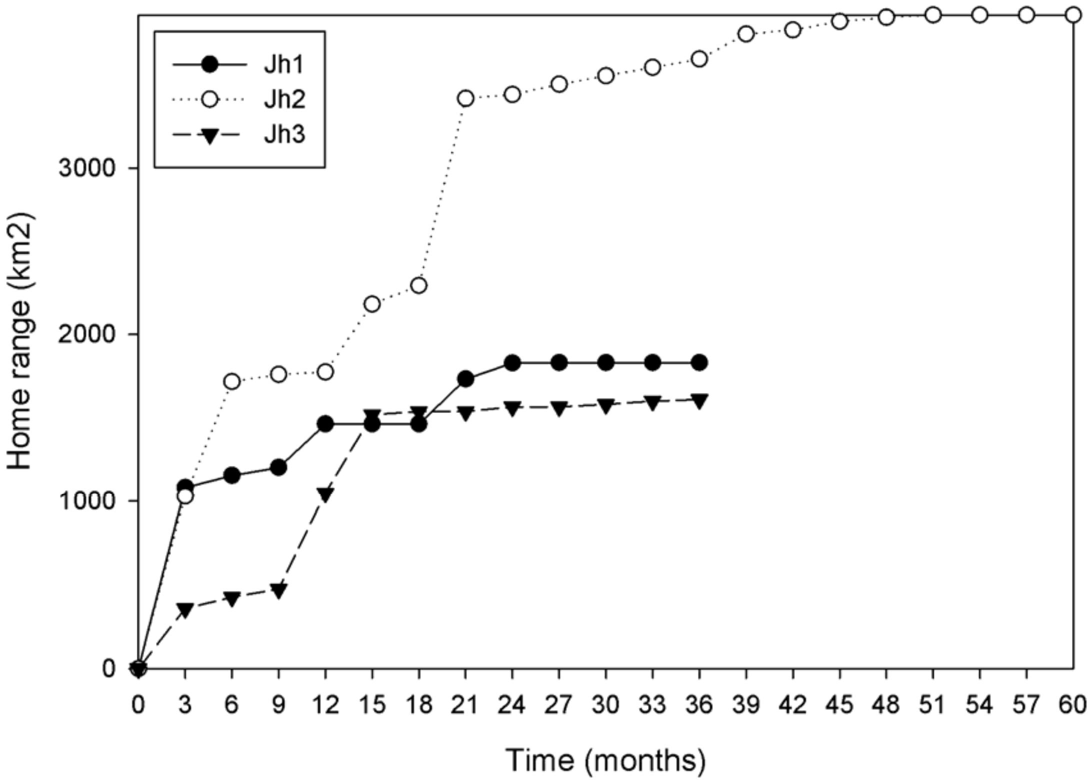


**Figure 3.2.** Asymptote for home range. The home range (MCP) obtained during the study period at three month intervals for all three elephants.

All three herds utilised core home ranges that centred on riverine habitats in KNP and SSR (Figure 3.3). There was range overlap in these high use areas between all study herds along the Sand River in SSR, but none in KNP. Within KNP, Jh2 frequently utilised a 6.5-km section of the Nwaswitsonso River, Jh1 utilised a 12-km section of the Nwatswishaka and 6.5-km section of the Mbyamiti Rivers and Jh3 a short 1-km section of the Sabie River (south of SSR).

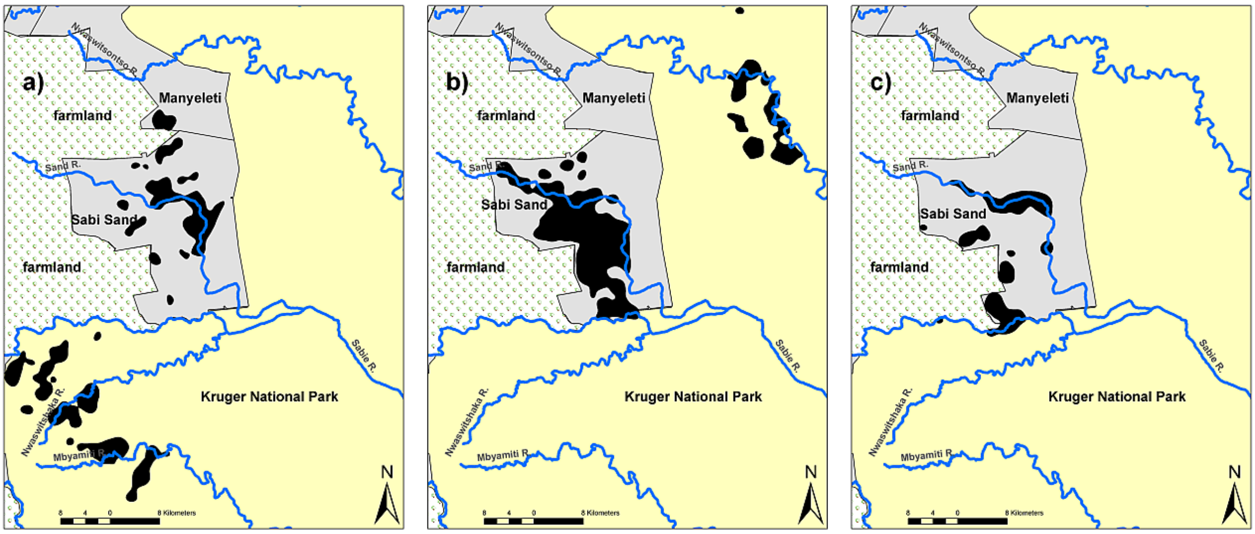


**Figure 3.3.** Core areas (50% contours). The core areas of the three elephant breeding herds within KNP and SSR. a) Jh1 tracked from February 2007 to November 2009 b) Jh2 tracked from September 2003 to August 2008 c) Jh3 tracked from February 2007 to November 2009.

Data reflecting the herds' daily dependence upon both rivers and water holes within their home ranges are presented in Table 3.2. The average distance between the elephants and all water sources in both parks was 2.9 km (± 2.9 km) compared with random locations of 3.5 km (± 3.3 km). Elephants were significantly further from water sources during the wet summer months than during the other seasons (F = 14.95; d.f. = 3, 6886; P < 0.001), significantly closer to waterholes than rivers (F = 21.93; d.f. = 1, 6888; P < 0.001) and significantly closer to water in SSR compared with KNP (F = 1344; d.f. = 1, 6888; P < 0.001). Whilst the average distance to waterholes was farther in KNP than SSR, the distance to rivers was similar in both parks. During the study period, none of the herds were farther than 16 km from water.

**Table 3.2.** Observed and random location distances from water sources.

| | | KNP[1] | | SSR | |
|---|---|---|---|---|---|
| | | **Actual (km)** | **Random[2] (km)** | **Actual (km)** | **Random (km)** |
| River | Jh1 | 2.6 (± 2.2) | 3.1 (± 2.7) | 2.5 (± 2.3) | 3.7 (± 2.5) |
| | Jh2 | 3.4 (± 3.2) | 4.6 (± 3.5) | 2.8 (± 2.2) | 3.6 (± 2.5) |
| | Jh3 | 0.9 (± 1.4) | 2.0 (± 1.5) | 3.8 (± 3.1) | 3.8 (± 2.6) |
| Waterhole | Jh1 | 7.1 (± 2.7) | 7.5 (± 3.5) | 0.7 (± 0.4) | 0.7 (± 0.5) |
| | Jh2 | 4.8 (± 2.4) | 6.1 (± 3.5) | 0.6 (± 0.4) | 0.8 (± 0.6) |
| | Jh3 | 6.5 (± 2.0) | 6.8 (± 2.8) | 0.6 (± 0.4) | 0.9 (± 0.7) |

[1] KNP and SSR are analysed separately as they are managed as autonomous units. SSR has a significantly higher density of waterholes (1 waterhole/1.7 km²) compared to KNP (1 waterhole/162 km²).
[2] Random points were generated within the MCP for the KNP and SSR home ranges. For both observed elephant locations and randomly generated locations, the distance to the nearest watersource, either waterhole or river, was calculated.

### 3.4.2 Tracking performance and reliability

Of the total possible GPS locations expected, 69%, 93% and 86% were received by units Jh1, Jh2 and Jh3 respectively (Table 3.3). In this table a breakdown of 3-D (< 10 m) and 2-D (< 100 m) locations is also shown. No significant differences were identified amongst the mean monthly numbers of successful location attempts for all three herds (F = 0.52; d.f. = 11, 24; P = 0.874) or between the mean numbers of seasonal successful location attempts (F = 0.22; d.f. = 3, 8; P = 0.879).

**Table 3.3**. Technical details describing transmitters used in this study.

| | **Possible locations[1]** | | | **Successful locations** | | | | **Total unsuccessful locations** | |
|---|---|---|---|---|---|---|---|---|---|
| | Start date | End date | Total (N) | Total (N)[2] | Total % | 3D[3] (%) | 2D[4] (%) | Partial communication (%) | No communication (%) |
| Jh1[5] | 27/01/2007 | 09/11/2009 | 1014 | 697 | **69**[6] | 67 | 33 | **5** | **26** |
| Jh2[7] | 26/09/2003 | 16/08/2008 | 1784 | 1658 | **93** | 99[8] | 1 | **1** | **5** |
| Jh3[5] | 27/01/2007 | 09/11/2009 | 1014 | 869 | **86** | 57 | 43 | **7** | **7** |

[1] The total possible number of locations is based on the total number of days between the tracking start date and end date.
[2] The total N values in this table are smaller than those in table 3.1 because this table only calculated a single location for each day, whereas the N in table 3.1 includes the extra locations occasionally obtained each day.
[3] 3D (3-dimensional) fix location obtained from four satellites (accuracy < 10 m).
[4] 2D (2-dimensional) fix location obtained from three satellites (accuracy < 100 m).
[5] Jh1 and Jh3 were refurbished collars.
[6] Bold numbers total 100% to represent total locations.
[7] This was a new collar which replaced the previous collar after three years of tracking. No technical details were obtained from the first collar.
[8] Diagnostic information for this transmitter was only obtained from 19 November 2006. Therefore, the number of 3D, 2D, partial communication and no communication totals have been calculated from this date.

Even as the transmitters approached the end of their theoretical lifespan, they functioned as well or better by the end of the study as they did at the start. Jh2 and Jh3 displayed no relationship between monthly location counts over time, r = 0.039, n = 60, p = 0.765 and r = 0.069, n = 35, p = 0.695 respectively indicating consistent functioning. Jh1 showed a positive relationship, r = 0.485, n = 35, p = 0.003, indicating a general increase in monthly location acquisition over time.

Despite the transmitters being programmed to calculate a noon GPS location each day, occasionally, two or more daily readings were obtained by two of the transmitters, Jh1, 8% (N = 59) and Jh3, 25% (N = 218). These extra locations were deleted from the fix success calculation. Locations were sometimes transmitted several hours after noon, thereby creating uncertainty that locations were in fact calculated at midday.

## 3.5 Discussion

### 3.5.1 Technical effectiveness

Reviewing the reliability and functionality of tracking units can provide important cues to help interpret the data used for ecological analysis.

The higher number of missed readings for Jh1 compared with the other two transmitters in this study may be attributable to habitat variables and/or elephant behaviour. In consultation with KNP, we set the tracking unit to take a single midday reading each day. The noon location time was selected at the start of the study in 2003 and, to ensure consistency of data, the subsequent units were also set to noon transmissions. There has since been evidence to suggest that elephants are least active during the middle of the day and may better be described as crepuscular (Loarie et al., 2009). Noon is generally the hottest time of the day and when elephants may either lie down or shelter from the sun under the cover of dense bush, thereby hindering the transmission (Douglas-Hamilton, 1998). Nonetheless, our results indicated no seasonal effect that would indicate a higher number of missed readings during the hottest months of the year. Transmissions can also be affected by mud on the unit from the elephant having a mud bath or the antenna being fitted too loosely and sliding into a non-functional transmission angle for satellite communication (Douglas-Hamilton, 1998, Harris et al., 2008). During Douglas-Hamilton's (1998) study, most failures occurred between 05.00 to 06.00 hours and between 13.00 and 14.00 hours, the latter possibly due to the animal sheltering from the sun.

A study of stationary GPS location tests reveal an accuracy of 3m to 30m (Lewis et al., 2007), allowing us to accurately map the study animals' long-term daily and seasonal movements. However, upon comparing the geostationary download method we used with other systems, we would recommend that if there is adequate cellular coverage in the area, researchers conducting tracking studies on this or similar species should consider the use of GPS/GSM (cellular) technology as a download method. Whilst weight, size and cost of the equipment were not major issues in our study, GPS/GSM technology offers advantages in all of these areas as well as ease of data download. Another option for obtaining the same type of data as this study and if regular data download is not important, is the use of GPS/store-on-board transmitters. Whilst this would be a cheaper option, the researcher does run the risk of losing all data yet to be downloaded if the elephant's GPS unit is not located.

Technological developments are leading towards smaller GPS units with increasingly powerful transmitters that can penetrate forest canopy and provide real-time continuous data. As this technology improves the trade-off decisions regarding units' weight, size, charging and battery conservation and data acquisition will become less important.

### 3.5.2 Ecological outcomes

Whyte's (2001) radio tracking study of KNP elephants revealed variable MCP home range sizes of between 86 and 2776 km², with an average of 880 km². He suggests that elephants within KNP are non-migratory and have a high degree of fidelity to their home ranges. While all three of our study herds spent time in SSR, Whyte's study does not report on any movement within SSR. This may explain the smaller home ranges he reports in his study compared with this study. Alternatively, the difference could also be attributed to different tracking methods. VHF tracking can underestimate a home range when compared with remotely obtained methods such as GPS tracking (Kochanny et al., 2009) because fewer locations are obtained and the likelihood of acquiring distant locations is lower due to the difficulty of field staff covering large distances. Whyte obtained an average of 41 locations per elephant compared with 1171 in this study.

As both food and water availability influence how elephants use space (van Aarde et al., 2006), some management practices have focused on water manipulation strategies (Smit et al., 2007a, Smit et al., 2007b, van Aarde and Jackson, 2007). Our study herds were always closer to water than if they were randomly distributed (Table 3.2) and had hotspots centred on riverine habitats (Figure 3.3), thus highlighting the impact these water management strategies might have on the distribution of elephant populations (Grainger et al., 2005, Harris et al., 2008). Smit et al. (2007a) suggest that elephants' high dependence upon water is related more to rivers than to water holes, whilst Grainger et al. (2005) note that areas with higher water hole densities lead to smaller elephant home ranges. In our study the distance to rivers was almost equal for both SSR and KNP, but greater for waterholes in KNP (Table 3.2). This may be due to the lower density of waterholes within KNP (1 waterhole/155 km²), compared with SSR (1 waterhole/1.5 km²) but also may be due to seasonal variation where permanent water sources (rivers) become more reliable during the wet summer months. It should be noted that a reduction of waterholes in KNP alone may not be an effective management strategy if elephants can easily move into SSR and find water or if they generally only utilise rivers within KNP anyway.

The three elephant herds in our study were shown to be predisposed to riverine habitats (Figure 3.3), especially along the Sand River in SSR (Figure 3.3). Outside SSR, however, the study herds utilised independent home ranges and rivers. The average and minimum distance between each pair of elephants located together on the same day within SSR was 24 km (± 12) and 1.3 km respectively, whilst for KNP it was 38 km (± 16) and 9 km respectively. The average daily distance moved was < 5 km in this study and is similar to Harris et al. (2008) who suggest elephants move less than a few km a day when essential resources occur locally. Thus, whilst these herds occupy some of the same areas, the distance noted between each herd suggests they seldom do so at the same time. It should be noted, however, that these distances only describe the proximity of our three study herds and that it is likely that other herds overlap the same home ranges.

From the literature there is agreement that elephant home range sizes are likely to be asymptotic with time (Viljoen 1989, De Villiers et al., 1997, Whyte 2001). From our study we found this point was reached within two years (Figure 3.2). Whyte (2001) suggests that an asymptotic relationship may be due to animals occupying a finite home range, therefore elephant home ranges within confined areas such as the KNP/SSR regional area are likely to be smaller than those in unrestricted areas.

Whilst there are no published data suggesting the regular use of a route between adjacent reserves, we found that our study herds regularly utilized the same routes between KNP and SSR (Figure 3.1). Movement between unfenced conservation areas separated by unprotected areas are noted by Galanti et al. (2000), Osborn and Parker (2003) and Douglas-Hamilton et al. (2005). Shadrack et al. (2009) report corridor usage for migration between forested mountain and lowland areas in northern Kenya and like us, noted that elephants moved quickly through the corridor areas compared with non-corridor areas.

GPS technology performed well on this species; however, to take advantage of technological improvements and, coverage permitting, future studies should consider the use of GPS/GSM (cellular) technology. All three elephants were tagged in SSR and this may have influenced our analysis of site specific range use. Had we captured elephants in KNP, the results might have shown different specific home ranges with no inter reserve seasonal movements. Nevertheless, most general features of their ecology would likely remain the same, for example, the greater use of areas close to water. As well as a larger sample size which would allow for statistical inference at the population level, it would be useful for future tracking research to include elephants captured within KNP to ascertain whether capture location has any effect on park use. Further, this study did not include tracking of bulls or bull herds, therefore further understanding of their movement within these parks would also be of benefit.

It is important for wildlife managers to develop an understanding of elephant behaviour and their use of space between and within regional areas rather than individual parks (Scholes and Mennell, 2008; Owen-Smith et al., 2006; van Aarde et al., 2006; and Young et al., 2009). As conservation measures to manage elephant populations such as transfrontier conservation corridors linking KNP to other parks within southern Africa become a reality (Harris et al., 2008; van Aarde et al., 2006, van Aarde and Jackson, 2007), understanding the ways elephants use these corridors is important.

Because of the length of this study, we were able to provide insights into within and between-season movements. We developed detailed maps of the daily movements of the study elephants captured in SSR; from our wet summer season and dry winter home ranges we revealed the study animals' co-dependency upon adjoining parks. This sentiment is underlined by our discovery that, following the removal of the fence between KNP and SSR elephants repeatedly use the same travel routes within a homogenous landscape. These findings are supported by Scholes and Mennell (2008) who speculate that old migration paths are becoming re-established following the removal of these fences. If this proves to be true it should be considered in the wildlife management plans of both parks.

Scholes and Mennell (2008, p. 434) stress that decision-makers must 'be explicit about the spatial and temporal scale of implementation as well as its consequences'. When it comes to strategic management planning, issues of temporal and spatial scale can also extend to mismatches in the human systems associated with conservation areas (Scholes and Mennell 2008). Wildlife managers in our conjoint study area operate under contrasting paradigms – KNP is a National Park whereas SSR is a privately owned and managed wildlife reserve with shareholders. The parks have contrasting land use and management philosophies that are characterised by differences in size, property rights regimes, boundary permeability and environmental management resources. If the managers of these entities do not factor these mismatches into their planning then the consequences of not doing so may manifest at a scale level that was not anticipated in their plans.

## 3.6 Acknowledgements

We gratefully acknowledge the invaluable contribution by the following individuals and organisations: Dr Ian Whyte and Sam Ferreira (KNP Scientific Services), Jonathan Swart, Gavin Hewlett and Johnson Mahluli (Sabi Sand Reserve), Hennie de Waal (pilot), Dr Peter Buss (KNP's Veterinary Services), Douw Grobler (Catchco Africa), Sophie and Martin Haupt (Africa Africa Wildlife Tracking), Mathew Irwin (Massey University, GIS lab) and the Institute of Natural Resources, Massey University.

# CHAPTER 4: Case study two – Home range and habitat use of the New Zealand falcon (*Falco novaeseelandiae*) within a plantation forest: a satellite tracking study

This chapter has been published in the International Journal of Ecology.

## 4.1 Abstract

We tracked two adult and three juvenile New Zealand falcons (*Falco novaeseelandiae*) in Kaingaroa Forest pine plantation from 2002 to 2008 using Argos® satellite technology. The home ranges for both adults and juveniles varied, ranging between 44 and 587 km². The falcons occasionally utilised areas outside the forest, and used stands of all ages within the forest, generally in proportion to their availability. For the most part, the juveniles remained within ca. 8 km of their nests and dispersed at 58, 69 and 68 days after fledging. Falcon movement information was obtained from an average of four location points per tracking day per falcon at a putative accuracy of 350 m. The transmitters, including their solar charge capability, performed well in the forest environment. The use of all stand ages highlights the importance of forestry practises that maintain a mosaic of different aged pine stands.

## 4.2 Introduction

Protected since 1974 and classified as 'Nationally Vulnerable' (Miskelly et al., 2008), the New Zealand falcon (*Falco novaeseelandiae*) is the country's only endemic bird of prey. There are three identified forms distinguishable by their plumage, size, range and habitat preference (Heather and Robertson, 1996), the Bush (c.1300 pairs), Southern (c.400 pairs) and Eastern (c.3150 pairs) forms (Birdlife International, 2009).

Destruction of the New Zealand falcon's habitat is reported to be a key factor leading to the species' decline (Birdlife International, 2009). Historically, the Bush form has bred in tall podocarp forests (Stewart and Hyde, 2004), however, following extensive logging, falcons have been found nesting in clear-cut compartments of pine plantations within the Central North Island (Stewart and Hyde, 2004, Addison et al., 2006). Understanding more about the use of pine forests by falcons in New Zealand is of conservation importance. Plantation forests, if managed appropriately, may provide a suitable habitat for the recovery of this species (Seaton et al., 2008).

Until recently there has been little research on this species. Fox (1977) studied the biology of the Eastern form identifying home range and habitat use within their range on the north-west coast of the South Island. More recent research has focused on the Bush form within exotic forest plantations (Holland and McCutcheon, 2007, Seaton, 2007). Seaton et al. (2008) used ground-based VHF radio telemetry to study the home range, habitat use and dispersal of falcons within Kaingaroa Forest. However, little is known about the year-round habitat use of falcons. This study assembles a long-term record of falcon movement within Kaingaroa Forest, that can be used to enhance policy and species management plans and to inform future researchers on the use of satellite technology for this species.

Argos® satellite telemetry was identified as an effective tool for gathering long-term, continuous location data to map the falcons' use of specific areas. Holland and McCutcheon (2007) undertook the first falcon satellite tracking study in New Zealand when they used an 18-g solar powered satellite transmitter to monitor the movements of a 540-g female New Zealand falcon over a three-year period in Kaingaroa Forest. As an expansion of their pilot project, this paper updates their earlier work by reporting on the results from a further four satellite-tracked falcons in the same forest.

To assemble a long-term dataset and enhance our understanding of falcon movements and habitat use, we deployed five satellite transmitters for up to three years to monitor NZ falcons within Kaingaroa Forest. Specific objectives were to 1) quantify home range size 2) determine seasonal home range patterns for adults 3) determine selection of compartments of different ages 4) describe the pattern of juvenile dispersal, and finally 5) evaluate the technical performance of the five transmitters under field conditions. We considered four components of performance; the number of locations obtained within each accuracy class; the efficiency of the duty cycle (pre-set on/off regime); the accuracy of the system; and the solar charging efficiency within this forest environment. This technical evaluation will aid in the interpretation of biological results to determine whether they functioned efficiently enough to underpin falcon management decisions.

## 4.3 Materials and Methods

Our study examines a breeding population of Bush falcons in Kaingaroa Forest, the oldest and largest softwood plantation forest in the world (Boyd, 1992). Located between Rotorua and Taupo on the volcanic plateau of New Zealand's central North Island, the 189,000-ha Kaingaroa Forest is a mosaic of approximately 1,400 intensively managed compartments of various-aged radiata pine (*Pinus radiata*). These compartments are mostly flat or gently sloping and are approximately 135 ha in size. Harvesting usually occurs at 25-30 years of age, followed by replanting within one year.

In this study, five solar powered Platform Transmitter Terminals (PTT), (Microwave Telemetry Inc., Columbia, Maryland, USA) were used to track falcon movements. PTT's are transmitters that send a signal via the Argos® satellite system (C.L.S, Ramonville Saint-Agne, France). This system consists of polar orbiting satellites located 800 km above the earth equipped with Ultra High Frequency receivers. Each time the satellite passes over a PTT, it has approximately 10 minutes to calculate its location using the Doppler effect. The accuracy of each location point is assessed and assigned one of several Location Classes (LC). The standard deviation of positional error in latitudinal and longitudinal axes is claimed to be 150 m for LC 3, 350 m for LC 2, 1000 m for LC 1 and > 1000 m for LC 0 (Argos User's Manual, 2010). When three or fewer messages are received by the satellite, the accuracy levels are LC A & B (no estimation accuracy) or LC Z (invalid location). Only locations with an Argos® specified accuracy of < 350m (LC 3 and 2) were used for analysis.

Three of the PTT's were set to a 58-hour duty cycle (10 hrs on/48 hrs off) and two set to a 34-hour duty cycle (10 hrs on/24 hrs off). The off part of the duty cycle helped to conserve the batteries and provide enough time for adequate recharging from the solar panel. The PTT cycles were offset from the 24-hour daily cycle to avoid transmission at the same time each day. On periods, therefore, occurred at different times of the day and alternated between nocturnal and diurnal transmissions.

Three juvenile and two adult falcons were captured at nesting sites within Kaingaroa Forest using Bal-chatri and Dho-gaza traps (Bloom et al., 2007). Male falcons weigh between 252-500 g and females between 420-594 g (del Hoyo et al. 1994). Twelve-gram PTT's were fitted to the juveniles and 18-g PTT's were fitted to the adults. Taking body weight into account, the transmitter weights were all less than 5% of the body mass of the falcons. Transmitters were attached to the back of the falcon with a 6-mm Teflon tube harness (Kenward et al., 2001) using a standard backpack configuration.

Between February 2002 and August 2008, the falcon locations were downloaded from the Argos® online data access system and maps were generated using a Geographic Information System (GIS) (ArcGIS® ArcMap® 9.2, Environmental Systems Research Institute, Redlands, California, USA). The data locations were recorded in latitude/longitude WGS84, and transformed to NZGD 2000 New Zealand Transverse Mercator for analysis.

The home-ranges (MCP and Kernel) were calculated using the Animal Movement Analyst extension to ArcView (Hooge and Eichenlaub, 1997). MCP estimators are thought to overestimate space use (Kenward, 2001), however, they were used here to enable comparison with other studies and to map the maximum area potentially required by each falcon. A kernel-based home range utilising the 95% probability contour was used as a second measure to reduce outlier bias. The least-squares cross validation procedure was used to determine the smoothing parameter. We also used the kernel method to estimate compartment selection by identifying the compartments within each 95% kernel area, then calculated the age of each compartment and identified the number of falcon locations within them. Minitab® 15.1.30.0 (© 2007 Minitab Inc., State College, Pennsylvania, USA) was used for all statistical analysis. Unless otherwise noted, all means are expressed as the mean (± s.d.).

## 4.4 Results

### 4.4.1 Falcon movements.

One male and one female adult falcon were continuously tracked for approximately three years. Three juvenile falcons, two male and one female, were tracked for approximately five months each.

The movements of the falcons and locations of their nest sites are presented in Figure 4.1. Their home range sizes are in Table 4.1. The juvenile female's 95% kernel home range was 44 $km^2$ and the juvenile males' were 412 and 12 $km^2$. Their MCP home ranges were 44, 587 and 86 $km^2$ respectively. The adult female utilised a 95% kernel home range of 90 km² and MCP of 147 km², with the adult male utilising an 8 km² kernel home range and 61km² MCP. The kernel home range sizes during the non-breeding and breeding seasons were compared for each adult falcon and were similar for both (Table 4.1).

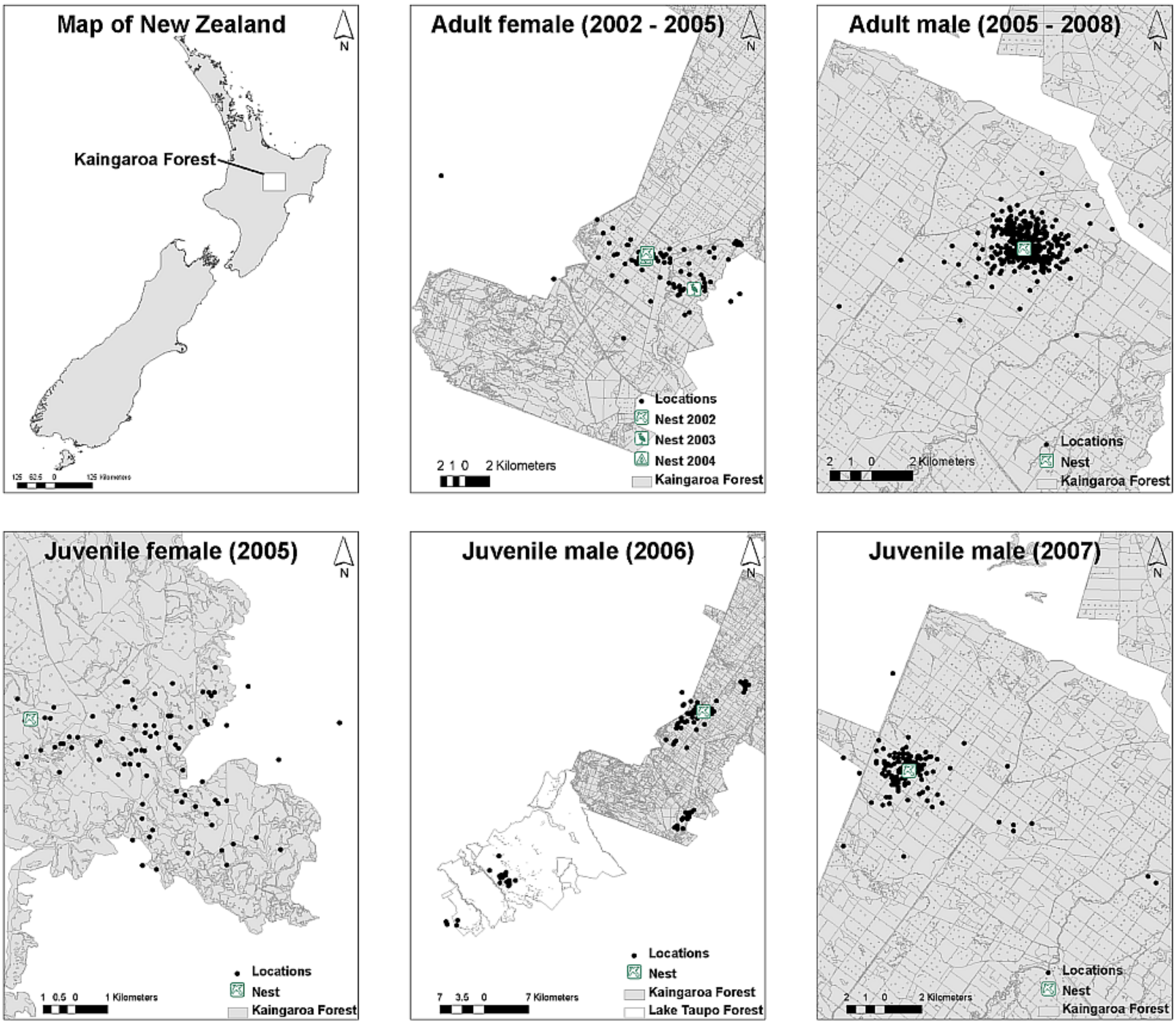


**Figure 4.1.** Locations and nest sites of two adult and three juvenile New Zealand falcons in Kaingaroa Forest, New Zealand.

**Table 4.1.** MCP and kernel home range sizes.

| | MCP (km²) 100% | Kernel (km²) 95% | Year | Non-breeding[1] 95%[3] | Non-breeding[1] 50%[4] | Breeding[2] 95% | Breeding[2] 50% |
|---|---|---|---|---|---|---|---|
| Juv female | 44 | 44 | n/a | n/a | n/a | n/a | n/a |
| Juv male 1 | 587 | 412 | n/a | n/a | n/a | n/a | n/a |
| Juv male 2 | 86 | 12 | n/a | n/a | n/a | n/a | n/a |
| Adult female | 147 | 90 | 2002 | 52 | 11 | n/a | n/a |
| | | | 2002/2003 | n/a | n/a | 78 | 9 |
| | | | 2003 | 41 | 10 | n/a | n/a |
| | | | 2003/2004 | n/a | n/a | 33 | 5 |
| Adult male | 61 | 8 | 2006 | 13 | 3 | n/a | n/a |
| | | | 2006/2007 | n/a | n/a | 10 | 1 |
| | | | 2007 | 6 | 0.5 | n/a | n/a |
| | | | 2007/2008 | n/a | n/a | 6 | 0.7 |

[1] Includes the months of April to September.
[2] Includes the months of October to March.
[3] Using the 95% kernel method.
[4] Using the 50% kernel method.

All falcons except the adult male ranged beyond the Kaingaroa Forest boundaries. Six percent (N = 5) of the adult female locations registered outside the forest, with one location 13 km from the boundary, and the remaining within 2.5 km of it. The juvenile female ranged outside the forest approximately 9% (N = 8) of the time, but all of these locations were within 3 km of the boundary. Juvenile male 2 was located outside the boundary 2% (N = 3) of the time and was never further than 0.5 km from the boundary. Juvenile male 1 however, was tracked outside the Kaingaroa forest boundary 24% (N = 33) of the time, with the majority of these locations being approximately 50 km away in Lake Taupo Forest, a 33,000-ha pine plantation forest (Figure 4.1) managed by New Zealand Forest Managers (NZFM). This falcon made two separate trips to this forest, for a day in March and then again for the month of April 2006.

The juvenile female and juvenile male 2 remained within a distance of ca. 8 km from their nests for the duration of tracking, returning regularly to their nests (Figure 4.2). Juvenile male 1 exhibited this same behaviour for the first two and a half months before leaving the nest area and travelling approximately 50 km over a two-day period to Lake Taupo Forest. He then returned to Kaingaroa Forest, but to an area approximately 16 km from his nest site.

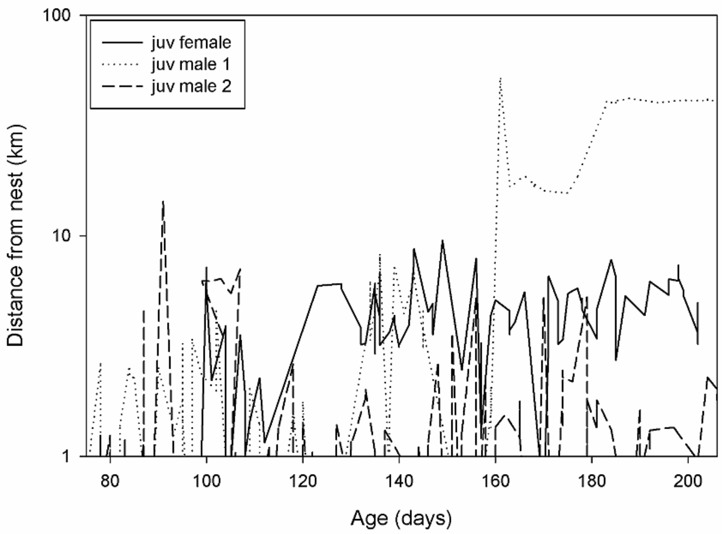


**Figure 4.2.** Distance from nest over time for juvenile falcons.

For this research, dispersal was calculated from when the juvenile left the adult home range. The radius of this adult home range (MCP) was between 4 and 6 km. Using the 4 km radius, the number of days from fledging to when the three juveniles dispersed from their natal territory was 68 days for the juvenile female and 69 and 58 days for juvenile male 1 and 2 respectively.

Table 4.2 illustrates the falcons' use of compartments of different ages. It indicates the use of all compartment ages, used generally in proportion to their availability.

**Table 4.2.** Falcon use of compartments by age category.

| | | < 4 years | | 4 – 9 years | | 10 – 19 years | | > 20 years | |
|---|---|---|---|---|---|---|---|---|---|
| | **Year** | **Area ($km^2$) (%)[1]** | **Use (%)[2]** | **Area ($km^2$) (%)** | **Use (%)** | **Area ($km^2$) (%)** | **Use (%)** | **Area ($km^2$) (%)** | **Use (%)** |
| Juv female | 2005 | 59 | 78 | 8 | 2 | 0 | 0 | 32 | 20 |
| Juv male 1 | 2006 | 11 | 5 | 15 | 23 | 29 | 54 | 45 | 18 |
| Juv male 2 | 2007 | 15 | 26 | 0 | 0 | 50 | 33 | 35 | 41 |
| Adult female | 2002 | 13 | 16 | 11 | 3 | 48 | 42 | 29 | 39 |
| | 2003 | 16 | 18 | 8 | 3 | 44 | 38 | 32 | 41 |
| | 2004 | 13 | 17 | 7 | 5 | 40 | 35 | 40 | 44 |
| Adult male | 2006 | 7 | 26 | 29 | 22 | 29 | 26 | 36 | 26 |
| | 2007 | 3 | 1 | 32 | 45 | 32 | 28 | 32 | 24 |
| | 2008 | 3 | 1 | 21 | 26 | 41 | 46 | 34 | 27 |

[1] The compartments within each falcons' 95% kernel home range were selected and the percentage of available area within each age group was calculated.
[2] The number of Argos locations within each compartment age was calculated as the percentage of use.

### 4.4.2 Performance of the technology.

The technical details for each PTT are presented in Table 4.3. Between 32 – 54% of all recorded transmissions from the five PTT's were LC 3, 2 and 1 (< 1000 m), while 8 – 33 % were LC 3 and 2 (< 350 m). The lowest percentage of useable locations (8%), belonged to the adult female. She was the first falcon to be tracked and her transmitter was the oldest model.

**Table 4.3.** Performance measures/operating details technical details describing all five PTT's.

| | | | | | | Location Class (LC) | | | | | | Battery voltage[2] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Falcon[1]** | **Duty cycle (on/off)** | **Active dates** | **Duration (days)** | **Duration (hours)** | **Total points** | **3 (%)** | **2 (%)** | **1 (%)** | **3, 2, 1 (%)** | **0 (%)** | **A & B (%)** | |
| Juv female | 10/24 | 16/01/05 – 15/05/05 | 118 | 830 | 514 | 4 | 13 | 32 | 49 | 30 | 21 | 3.9 ± .09 |
| Juv male 1 | 10/48 | 18/12/05 – 28/04/06 | 124 | 510 | 495 | 11 | 17 | 26 | 54 | 29 | 17 | 4.1 ± .05 |
| Juv male 2 | 10/48 | 29/01/07 – 17/06/07 | 140 | 580 | 460 | 13 | 20 | 20 | 53 | 24 | 23 | 4.1 ± .13 |
| Adult female | 10/24 | 18/02/02 – 11/12/04 | 1027 | 7240 | 1046 | 1 | 7 | 24 | 32 | 47 | 21 | 3.8 ± .2 |
| Adult male | 10/48 | 18/12/05 – 09/08/08 | 965 | 4000 | 1548 | 11 | 17 | 25 | 53 | 25 | 22 | 3.8 ± .1 |

[1] The adult male and both juvenile males carried the newer PTT's.
[2] Battery (solar) voltage. Minimum value for a transmission is 3.6 volts.

Pre-set duty cycles are intended to regulate transmitter battery usage. It can be useful to analyse how efficiently duty cycle on times are being utilised as an indication of possible bias in the data. All transmitters were equipped with a 10-hour on duty cycle and, using LC 3, 2 and 1 locations, the average time between the first location and last location within this duty cycle on time was four and a half hours or 270 minutes (range 172 – 366 minutes) with the average time between individual locations within the same duty cycle period being 99 minutes (range 86 – 109 minutes). From this duty cycle we got an average of seven locations per tracking day for locations of < 1000 m (LC 3, 2 and 1), and four per tracking day for locations < 350 m (LC 3 and 2).

The average voltage for all transmitters ranged between 3.8 and 4.1 (Table 4.3). The first location within each 10-hour on phase of the duty cycle gave an average reading of 3.93 V (range 3.81 V – 4.17 V) whilst the final location average reading was 3.88 V (range 3.73 V – 4.13 V), leading to an average difference between the first and final reading voltage of 0.048 V (range 0.031 V – 0.081 V). Throughout the tracking period, the adult male and female transmitters showed no decline in voltage, the juvenile male 1 and male 2 showed only very slight declines, with the juvenile female showing a more substantial voltage decline from an average of 3.95 to 3.75 V.

Most locations were obtained between 1600 h and 0600 h and virtually no falcons were located around midday (Figure 4.3). This pattern was also evident when analysing the locations from the two stationary PTT's. These were transmitters that detached from the falcons but continued transmitting for a 30-month and a six-month period. During low PTT acquisition periods, we also observed a deterioration in location quality ratings.

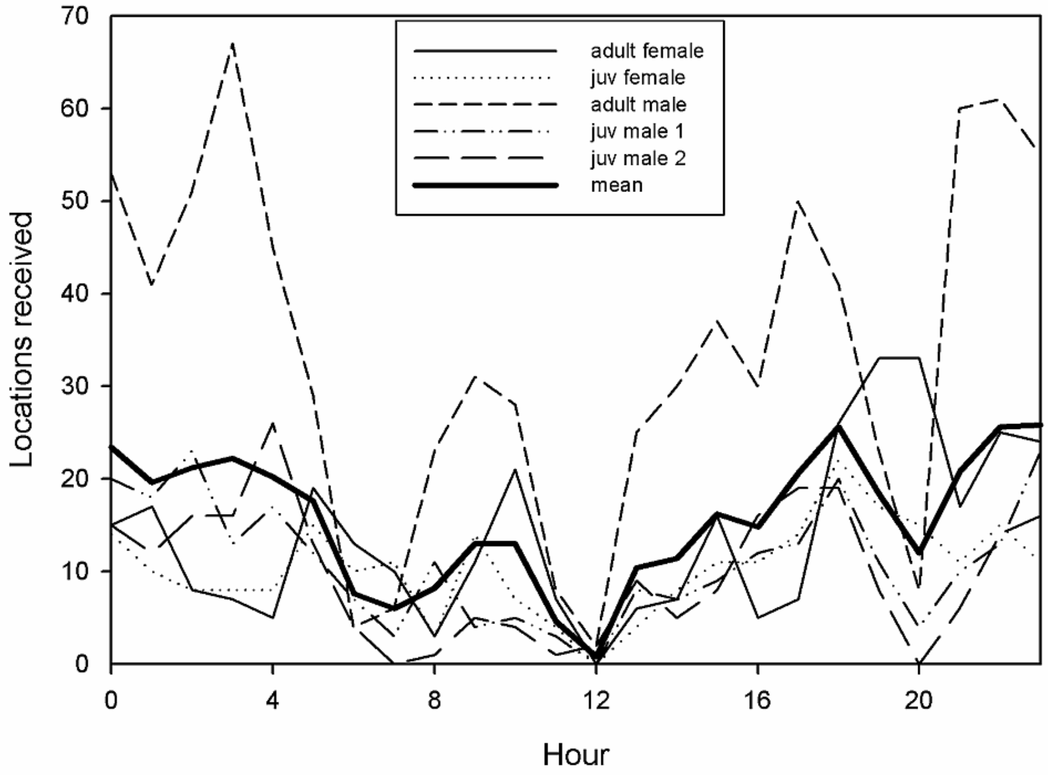


**Figure 4.3.** Locations of all five falcons showing the time of day the location was obtained.

We used the two stationary PTT's to test the accuracy of the system (Table 4.4). The results show the one-standard-deviation accuracy for LC 2 locations (the minimum location class used for ecological analysis in this study) to be 0.8 and 0.6 km, compared to the 0.35 km suggested by Argos®. As one of the transmitters was never recovered, the true position for that transmitter was estimated to be the mean location of the LC 3 (N = 588) locations.

**Table 4.4.** Accuracy and precision[1] (km) by Location Class (LC) from two stationary PTT's.

| | Argos | Transmitter 1[2] | | Transmitter 2[3] | |
|---|---|---|---|---|---|
| **LC[4]** | **Precision (km)** | **N** | **Accuracy ± precision (km)** | **N** | **Accuracy ± precision (km)** |
| 3 | ± 0.15 | 588 | 0.24 ± 0.2 | 21 | 0.52 ± 0.2 |
| 2 | ± 0.35 | 456 | 0.55 ± 0.8 | 11 | 1.06 ± 0.6 |
| 1 | ± 1 | 385 | 1.64 ± 2.3 | 6 | 1.95 ± 0.9 |
| 0 | > 1 | 402 | 48.64 ± 268.2 | 3 | 4.22 ± 1.2 |
| A | No accuracy estimation | 342 | 21.93 ± 170.8 | 5 | 1.04 ± 0.96 |
| B | No accuracy estimation | 366 | 17.41 ± 28.4 | 5 | 39.9 ± 50.26 |
| Z | Invalid location | 48 | 147 ± 397.4 | n/a | n/a |

[1] 'Accuracy' (mean) is the offset, or bias, of that mean relative to the true location points, whereas 'Precision' (s.d.) is a measure of the tightness of the grouping, being the clustering of points about the mean of those points (Nicholls & Robertson 2007b).
[2] Transmitter one was tested for two and a half years. The 'true' location was not known so the mean location was calculated using the set of 588 LC 3 locations (-38.82511, 176.58243). This transmitter had 25 locations removed of LC 3, 2, 1, A & B. These locations either had incorrect formats or distances from the mean of > 400 km indicating impossible speeds deeming them to be serious outliers.
[3] Transmitter two was tested for six months.
[4] LC 3, 2, 1 and 0 are available when 4 messages are received per satellite overpass, LC A from 3 messages and LC B from 2 messages. LC Z is considered an invalid location. See methods in text.

## 4.5 Discussion

### 4.5.1 Technical effectiveness.

Understanding how effectively the technology functioned can provide important cues as to the quality of the data used for ecological analysis, hence improving interpretation. It can highlight areas of possible bias in the data as well as times when caution should be exercised when making assumptions that may underpin management decisions.

The number of high confidence PTT locations transmitted during this study is more than that reported for similar studies. Almost 50% of the locations transmitted from four of the five units were LC 3, 2 and 1 (accuracy < 1 km) locations and approximately 25% LC 3 and 2 (accuracy < 350 m) (Table 4.3). Britten el al. (1999) tracked peregrine falcons (*Falco peregrinus anatum*) in Alaska, Utah and Arizona and obtained 11% of LC 3, 2 and 1 locations. This was similar to Soutullo et al. (2007) who tracked golden eagles (*Aquila chrysaetos*) and Bonelli's eagles (*Hieraaetus fasciatus*) throughout the Iberian peninsula obtaining less than 10% of LC 3, 2 and 1 locations. Ganusevich et al. (2004) tracked peregrine falcons in northern Russia and obtained an average of 52% LC 3, 2, 1 and 0 locations, whilst Nicholls et al. (2007) tracked albatrosses, petrels and shearwaters using Argos® and obtained approximately 13% LC 3, 2 and 1 locations. Meyburg and Fuller (2007) report that for most bird tracking studies LC 2 and 3 locations occur approximately 10 – 15 % of the time. If the number of LC 3, 2 and 1 location points is insufficient, it is possible to use LC 0 locations, provided appropriate filtering methods are used (Nicholls and Robertson, 2007b). However, given the frequency of high quality location transmissions in this study, it was not necessary to use LC 0 locations.

For most of the time all the solar-charged batteries remained well charged indicating that the forested environment of Kaingaroa did not impede the charging of the solar array or the efficiency of the duty cycle. The average voltage readings for each of the transmitters (Table 4.3) was higher than required for operating. The difference in the charge of the units between the start and completion of the cycle was low with the transmitters holding an average charge of 3.9 V (range 3.7 V – 4.1 V) for each final location reading. The minimum requirement for successful location acquisition is 3.6 V for both the 12 and 18 g transmitters, therefore it is possible we could have utilised a longer on time during the duty cycle, such as 14 hours on/24 hours off, thereby increasing the number of locations obtained for analysis. With no declines in the units' charge just prior to going offline, it is reasonable to assume that the battery was unlikely to have contributed towards PTT transmission failures.

Most of the location points for this study were recorded between 1600 and 0600 hours (Figure 4.3) even though the interval between NOAA satellite overpasses over Kaingaroa Forest was evenly spaced throughout the day. The one anomaly with the satellite overpasses in this area was reduced satellite reception around local noon, a known phenomenon in the Southern Hemisphere (Nicholls and Robertson, 2007a). As this location acquisition time pattern was observed on both our moving birds and stationary transmitters it would appear that this is likely associated with technical issues related to the Argos system rather than the behaviour of the falcons.

Behavioural issues, however, should still be considered as possible reasons for lower number and quality of locations. There were fewer quality locations received during the day (0600 and 1600 h) when more movement is expected. Consistent with that, Kenward (2001) noted that movement can cause accuracy errors of approximately 100 m for each km $h^{-1}$ of movement, thus the location error could be up to 4 km for a bird flying at 40 km $h^{-1}$. The Argos® system does not correct for this movement error therefore PTT's moving while transmitting may incorrectly report the accuracy class due to instability during location calculation. This issue, along with thick vegetation blocking the signal indicate that bias will tend towards places and activities where the location quality is higher and away from identifying any hunting behaviour when fast flying is occurring or resting sites obscured from satellite reception.

The location accuracy of Argos was tested using two stationary PTT's and the results are presented in Table 4.4. Whilst these reveal a pattern of improvement reflected in the higher confidence LC classes, they show larger errors than those quoted by Argos® (Argos User's Manual, 2010). Transmitter 2 is shown to be more reliable than transmitter 1. However, the true location point calculated from transmitter 1 was estimated from the mean of known Argos® locations rather than identifying its true location. Also, the results may not be representative of moving birds due to the effect on accuracy from fast flying (Kenward, 2001), and that both transmitters were stationary during this test. Thus the error and the Argos® positions for the two stationary transmitters is likely an underestimate of the error for the moving falcons.

Our results compare to Hyrenbach and Dotson (2003) who tracked black-footed albatrosses (*Phoebastria nigripes*) off central California obtaining errors of 0.44 km (LC 3), 0.73 km (LC 2) and 1.53 km (LC 1). Nicholls and Robertson (2007b) who undertook a comprehensive study of the location accuracy of PTT's, found that accuracy and precision errors were also larger than those stated by Argos®. Their analysis revealed that poorer quality locations (LC 0, A, B & Z) resulted from poor satellite reception as well as inaccuracies due to elliptical rather than circular orbits.

For the most part PTT/Argos® technology allowed us to achieve our research objectives. However, there are problems with using Argos® satellite technology for tracking fine scale movements. These result from low and uncertain accuracy, the inability to detect travel speed, the irregularity of acquisition times and possible bias from unsuccessful locations caused by either fast flying movement or rest areas obscured by scrub or bush. Because of these issues it was also difficult to ascertain whether the location of a falcon implied occupation or just a momentary passing over.

For studies that do require finer scale analysis we recommend the use of GPS technology if the field conditions allow for it. GPS technology has the advantage of providing many highly accurate location and speed calculations obtained on a regular schedule. This can enable detailed movement patterns to be identified, and if the Argos® system is used as the download method, it can be very cost efficient over the long-term. However, GPS does require a clear horizon to enable full view of the satellites, which can be compromised by diverse vegetation or mountain ranges (Cargnelutti et al., 2007). Given that Kaingaroa Forest has a number of mature pine compartments that are densely forested, it may not be appropriate for GPS technology to be used in this environment until further advances have been made. In addition to transmission problems, the New Zealand falcon may be too small to wear the slightly heavier GPS transmitters currently available. However, given that the solar charged batteries used in the Argos® transmitters performed well in this environment, the use of future smaller solar units should be considered.

### 4.5.2 Ecological outcomes.

The MCP home ranges of the female and male adult falcons tracked over the three years of this study were 147 and 61 km² respectively, whilst the 95% kernel home ranges were 90 and 8 km² respectively (Table 4.1). The male generally remained within 4 km of his original nest site. The female falcon also remained close to her nest, with each successive nest located on average 5 km apart and no more than 7.5 km apart during the three years. For both the male and female, the home ranges were larger than those suggested by Seaton (2007) who reported the mean adult female and male 95% MCP within Kaingaroa Forest as 6.15 km² and 9.23 km² respectively. The variation in results may be attributed to the use of a different tracking method as well as home range calculation. Seaton et al. (2008) used VHF tracking to obtain a relatively low number of location points during a short time period and this can understate a home range when compared with results from continuous satellite tracking methods. However, our home ranges were similar to those suggested by Fox (1977) who reported the MCP home range of adult Eastern falcon pairs within South Island indigenous forest to be 75 km². It is thought that home ranges within indigenous forests are larger than in pine plantations because prey are less abundant (Clout and Gaze, 1984).

The 95% kernel home range of the three juveniles was 44 km² (female), 412 km² (male 1) and 12 km² (male 2). Juvenile male 1 had an unusually large home range consisting of three distinct high use areas. Two of these were located within Kaingaroa Forest and the third was in a pine forest approximately 50 km away (Figure 4.1). Tracking the falcons revealed that all three juveniles left the forest at some point. This is consistent with Seaton's (2008) finding that 90% of juvenile birds left the forest at some time during their first autumn and winter, mostly on short visits to adjacent farmland.

We had expected this diurnal species to remain near the nest after dark. However, they were not noticeably closer to the nest during the night than at other times and their night-time home ranges were either similar to or larger than during daylight hours. It should be noted, however, that aside from increased movement, the larger home range identified during the night may have resulted from the larger number of locations obtained during this time (Figure 4.3).

Juvenile falcons fledge at around 34 days after hatching (Marchant and Higgins, 1993), with all three juveniles in this study caught and tagged at around 75 days old. During the first month after fledging, juveniles are thought to defend the nest area actively, after which time this defense declines (Marchant and Higgins, 1993). Based on a dispersal distance of > 4 km from the nest, the juvenile female left her natal home range 68 days after fledging and the males at 69 and 58 days. Similarly, Seaton et al. (2008) report that the juveniles tracked in his study dispersed out of the natal home range an average of 76 days after fledging, with the first females dispersing at 56 days and the first males at 42 days. His study, however, used a smaller dispersal distance of > 1.7 km to infer dispersal, due to the apparently smaller adult home ranges in his study. Around the time of natal dispersal, juvenile mortality is high for many falcon species (Newton, 1979). Seaton et al. (2008) suggest that the distances and timing of natal dispersal are highly variable and influenced by factors such as parental aggression, brood size, weather and prey density. There is also evidence to suggest that the dispersal for this species may be initiated later in indigenous forests than plantation forests (Lawrence and Gay, 1991, Barea, 1995). This may be attributable to the higher density of food in plantation forests, allowing for hunting skills to develop at a faster rate within these forests, leading to earlier independence from adults (Seaton et al., 2008).

Seaton (2007) reports that adult falcons prefer stands < 4 years and > 20 years, however, our findings do not support this. We found that falcons use compartments of all ages in proportion to their availability (Table 4.2). This does not mean that selection was not occurring but that more accurate GPS transmitters and a larger sample size are needed to be more confident about falcons' compartment selection behaviour. It is also thought falcons prefer to hunt along the edges of older aged stands due to the high availability of prey along the ecotone between plantation compartments of old and young trees (Seaton, 2007). However, due to the small width size (25 – 30 m) of an ecotone, we would not be able to determine this without the use of finer-scale tracking methods.

From our study we found; home ranges varied for both adults and juveniles; juveniles remain in the forest after dispersal, suggesting that sufficient resources are available; juveniles spend the first two and a half months after fledging within ca. 8 km of their nest; one of the juveniles left Kaingaroa Forest after two and a half months, flew directly to an adjacent plantation forest, before returning to Kaingaroa Forest; the variance in ages of compartments selected by falcons indicates that all stand ages provide important habitat for falcons and whilst four of the five falcons visited areas outside the forest, they all returned to Kaingaroa.

We found that Argos® satellite technology performed well and the collection of continuous data on falcon movement has refined our understanding of the ecology of the species. Our results highlight the importance of plantation forests to the New Zealand falcons and of forestry management practises that maintain a mosaic of different aged pines.

## 4.6 Acknowledgements

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# CHAPTER 5: Case study three – Fledging behaviour of juvenile northern royal albatrosses (*Diomedea sanfordi*): A GPS tracking study

This chapter has been published in Notornis.

## 5.1 Abstract

Using GPS technology, we tracked three juvenile northern royal albatrosses (*Diomedea sanfordi*) as they fledged from Taiaroa Head, Otago Peninsula, New Zealand. All birds flew north along the east coast of New Zealand before undertaking a trans-Pacific easterly migration to Chile. During their 8500-km migration, the maximum daily distance and speed reached were 1047 km and 110 km $h^{-1}$ respectively, and the maximum altitude was 38 m a.s.l. Upon leaving New Zealand waters, the three albatrosses took between 16 to 34 days to reach the coast of Chile where they remained between 23°S and 58°S. The tracked albatrosses generally kept to within 100 km of the coast where the depth of water varied between 1000 and 2000 m. Overall, the tracked albatrosses on the Chilean coast spent 72% of the time resting on the water, primarily between 1800 h and 2400 h local time. Fix success rate of the GPS technology ranged from 56 % to 85%. The use of solar charging and a long attachment period allowed the birds to be followed continuously for 134 to 362 days. Our study confirms the value of GPS technology in uncovering the movements and life history of wide-ranging oceanic birds.

## 5.2 Introduction

Classified as 'endangered' and decreasing in population (IUCN, 2010), the northern royal albatross (*Diomedea sanfordi*) is one of 24 albatross species worldwide (Chambers et al., 2009) and one of 13 species of albatross endemic to New Zealand. The total breeding population is estimated to be approximately 6,500 - 7,000 pairs (Croxall and Gales, 1998). Ninety-nine percent of this population breeds on the Chatham Is (800 km east of New Zealand) with small colonies located on Enderby I (Auckland Is) and Taiaroa Head (Otago Peninsula, New Zealand). The Taiaroa Head colony (45°45´S, 170°44´E) is the only mainland breeding colony of any albatross species in the southern hemisphere and consists of a 5.3 ha grassy Nature Reserve rising to 75 m a.s.l. The population currently is comprised of approximately 140 adult albatrosses (Lyndon Perriman, *pers. comm*). Although it represents only a small proportion of the total population, the ease of access to the colony has led to it becoming an important scientific and tourist attraction.

Prior studies of adult northern royal albatrosses on both the Chatham Is and Taiaroa Head show they forage in the waters over the shelf or shelf edge around New Zealand during breeding. They then migrate across the Pacific Ocean to Chile and Argentina where they remain during the non-breeding season, possibly returning to the breeding grounds via a circumpolar route between 30°S and 45°S (Nicholls et al., 1994, 2002, Waugh et al., 2005, Nicholls, 2007). However, little research has been reported on the movements of any species of juvenile albatross (Birdlife International, 2003, Robertson et al., 2003, Nicholls and Robertson, 2007a) and none at all for the juvenile northern royal albatross. Through banding recoveries, it has been suspected that juvenile northern royal albatrosses fly eastward after fledging to the coast of Chile (Roberston and Kinsky, 1972), but there are no direct data to support this hypothesis. Mortality is thought to be greatest during the first year that juveniles disperse (Warham, 1990). Thus, understanding the movements and life history of juvenile albatrosses is critical to their proper management. The objective of our study was to examine the movements and habitat-use of juvenile northern royal albatrosses during the period immediately after fledging. By documenting the movements during the first year at sea of three juvenile northern royal albatrosses after they fledged, we sought to further understand their post-fledging ecology.

Earlier studies of the distribution of seabirds have employed Very High Frequency (VHF) telemetry (Anderson and Ricklefs, 1987), the Argos® satellite system (C.L.S, Ramonville Saint-Agne, France) (Prince et al., 1992, Nicholls et al., 1994, Nicholls et al., 2002, Walker and Elliott, 2006, Nicholls and Robertson, 2007a), light-based geolocators (Shaffer et al., 2005) and, more recently, the Global Positioning System (GPS) (Weimerskirch et al., 2002, Waugh et al., 2005, Weimerskirch et al., 2007). These methods provide varying accuracy levels, data download intervals, transmitter sizes, weights and costs. The impracticality of using VHF to track seabirds and the location errors of up to a few kilometres of the true location for Argos transmitters (Shaffer et al., 2005, Nicholls, 2007, Nicholls and Robertson, 2007b) make these technologies less than ideal, particularly for small scale analysis. As well, the lower mass (< 10 g) and cheaper features of light-based geolocators have been overshadowed by accuracy issues (errors of 34 to 1,043 km from known locations; Phillips et al., 2004). Although still the heaviest transmitters, GPS technology can provide a way of obtaining very accurate (<5 m) locations (Hulbert and French, 2001) and has been identified as an effective method to gather long-term continuous location data to map albatross movements around the earth (Cohn, 1999, Webster et al., 2002). Regular preset schedules can be programmed and these highly accurate locations can be sent to the researcher without the need for recapture.

Only two previous studies have tracked juvenile albatrosses. Walker & Elliott (2006) followed three juvenile Antipodean albatrosses (*Diomedea antipodensis*) for 9 to 13 months after fledging using Argos satellite tracking. Weimerskirch et al. (2006) used the same method to follow 13 juvenile wandering albatrosses (*Diomedea exulans*) during their first year at sea (2 to 13 months). One reason so few studies have been undertaken with juveniles is that upon fledging, this age group leave the breeding grounds and do not return for five to eight years (Robertson, 1993). As attachment methods and transmitter lifetimes are still considerably less than this time frame, it makes retrieval of the transmitter and tracking of juveniles difficult (Walker and Elliott, 2006).

We used GPS technology to track the movement of juvenile northern royal albatross. Our objectives were to: (1) identify the broad-scale movements during the first year at sea, (2) analyse the daily activity of juveniles, (3) identify areas of high use and (4) evaluate the technical performance of the transmitters under field conditions.

## 5.3 Methods

During our year-long spatial study, we recorded four daily GPS locations of three juvenile northern royal albatrosses (♂ = 2, ♀ = 1) hatched during the 2006/2007 breeding season. This sample size represented approximately 13% of the juvenile population of 23 chicks that fledged from Taiaroa Head during the 2006/2007 season. We considered four aspects of performance: (1) the number of locations obtained (fix success) and whether there were any significant daily, monthly or seasonal differences, (2) whether the number of locations declined as the transmitters approached their theoretical life expectancy, (3) the solar charging efficiency, and (4) the accuracy of the system. The transmitters used in this study were 30-g Solar Argos/GPS PTT-100 with dimensions of 62 x 22 x 21 mm (Microwave Telemetry Inc., Maryland, U.S.A). Between Sep 2007 and Aug 2008, they recorded a GPS location four times a day, every six hours at 0600, 1200, 1800 and 2400 h (local time of the day). These were relayed back to the researcher every sixth day utilising a 12-hour window of the ARGOS® satellite system (C.L.S, Ramonville Saint-Agne, France).

When the albatrosses were nine months old, they were approached whilst on their nests, lightly restrained, tagged and released within 30 to 45 minutes of their capture. The transmitter was attached to dorsal feathers using adhesive tape (Tesa tape 4651), teflon tube and cable ties. The weight of the transmitter and attachment materials was approximately 40 g, which was less than 1% of the body weight of the animal. It was hoped this attachment method would last 12 to 18 months until either failure of the tape or loss of the feathers from moulting. The exact time of moulting is not known; however, the first moult is thought to be around 12 months (Lyndon Perriman, *pers. comm*). The longest known tape attachment lasted approximately 14 months on juvenile Antipodean albatrosses (Walker & Elliott 2006).

While the use of a harness attachment might lengthen the period of tracking, a number of researchers report that this method could lead to mortality, while taped or glued-on transmitters had no discernable effect on foraging efficiency, rates of nest desertion and mortality (Phillips et al., 2003, Walker and Elliott, 2006),.The albatross chicks in our study remained at the colony for three to five weeks after the transmitter was attached and no adverse reaction or change in behaviour was observed.

The data were downloaded from the Argos® online data access system and maps were generated using the Geographic Information System (GIS) ArcGIS® ArcMap® 9.2 (Environmental Systems Research Institute, Redlands, California, USA). The data locations were recorded in latitude/longitude WGS84 and transformed to an equi-rectangular projection for analysis with other GIS layers. Some of the analyses and graphics in this paper were performed with Maptool.

Three data files were received during each download period. The first file contained the GPS location, date, time, speed, course and altitude, obtained as at the set six-hourly times. The second file contained technical information on the internal functioning of the transmitter, such as voltage, ambient temperature and GPS fix time. The third file contained ARGOS® locations for backup purposes. Data from the second and third files were obtained only during the 12-hour Argos download period every sixth day. Error estimates for the GPS latitude/longitude location and altitude were <18 m and < 22 m, respectively. For speed, the error was < 1 km $h^{-1}$ at speeds of > 40 km $h^{-1}$ (Microwave Telemetry Inc., Maryland, U.S.A).

Three stages of juvenile movement were identified during this study, similar to those identified by Nicholls and Robertson (2007a). First, 'fledging' was defined as the period of departure from their Taiaroa Head nest up the east coast of New Zealand just prior to the direct easterly movement. Second, 'migration' involved the period of rapid and consistent direct easterly movement over a longitude range of 175° W to 75° E. Third, 'foraging' was defined as periods of sedentary behaviour on the Chilean continental shelf where the longitude fluctuated over a range of 10°.

Time spent resting on water in this study was determined using locations with speeds of < 9 km $h^{-1}$ to allow for possible surface drift resulting from winds and ocean currents (Weimerskirch et al., 2006). The calculation of the minimum distance was based on the straight line distance moved between consecutive six-hourly locations or the addition of these to account for a daily period. However, albatrosses rarely fly in a straight line, and these distance calculations are minimum values. Both the speed and altitude were calculated by the GPS system, obtained at the same time as the longitude/latitude locations every six hours. The speed and altitude values are also assumed to be minimum values.

We used the kernel-based territory size estimate to calculate the foraging home range at a 95% probability using the Animal Movement Analyst extension to ArcView 3.2 (Hooge & Eichenlaub 1997). The same method using the 50% probability contour was used to calculate core areas during foraging. Upon evaluation of the different effects of the varying smoothing factors (Nicholls et al., 2005), we used the least-squares cross validation procedure to determine the smoothing parameter for each kernel distribution.

## 5.4 Results

### 5.4.1 Dispersal of Albatross

The three juvenile northern royal albatrosses, namely female 1 (F1), male 1 (M1) and male 2 (M2), were tracked for 327, 362 and 134 days respectively. Fig. 5.1 shows the track taken by each during their first year at sea after fledging. Table 5.1 shows the dates and time periods of the three stages during this post-natal year, as well as the distances travelled, speeds and altitude. The total minimum distances travelled during the tracking period were 35,978, 46,066 and 15,149 km for F1, M1 and M2 respectively.

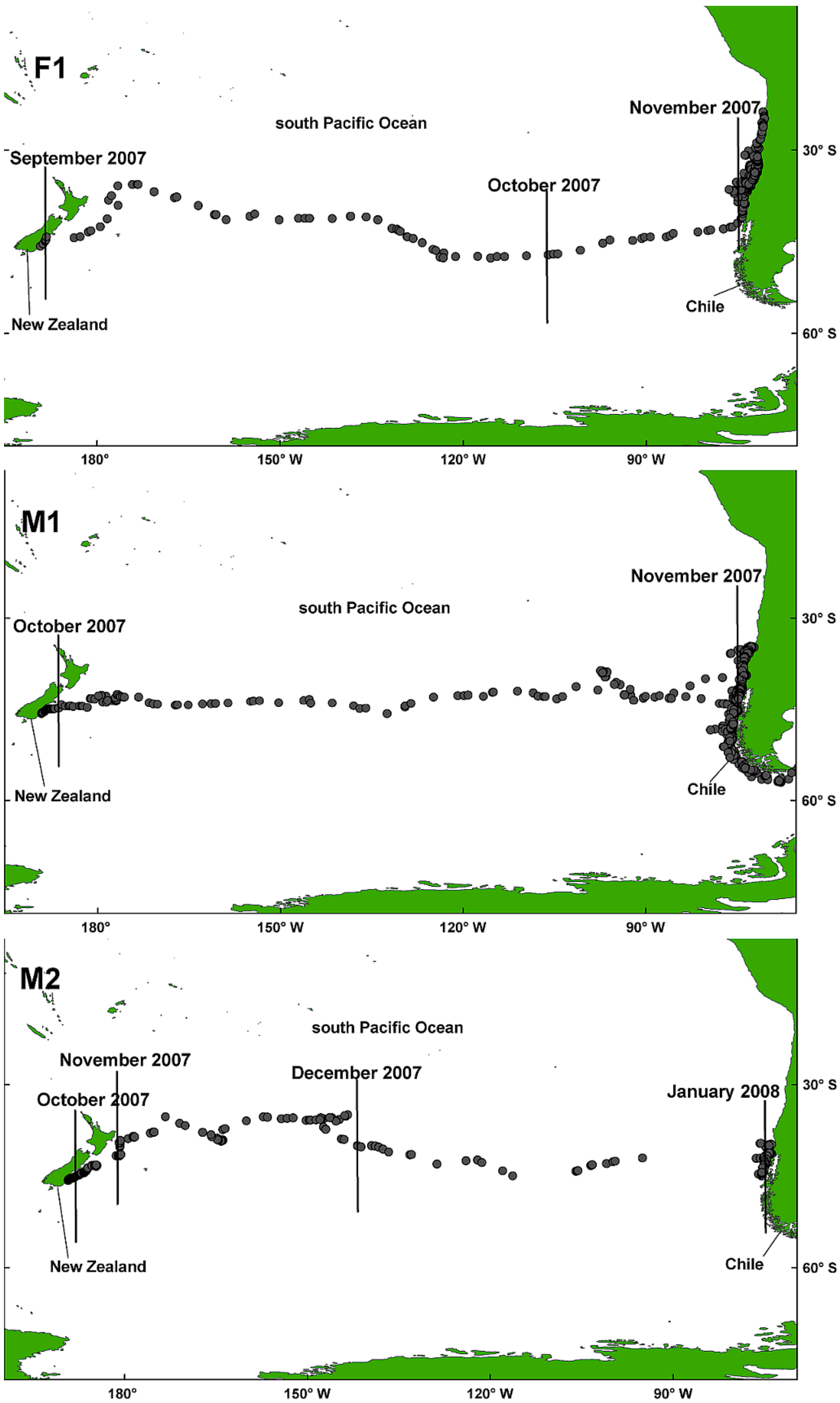


**Figure 5.1.** Tracks of three juvenile northern royal albatrosses (*Diomedea sanfordi*) during their first year at sea taken from six-hourly GPS locations. They all fledged from the Albatross Colony at Taiaroa Head on the Otago Peninsula, New Zealand and flew across to the coast of Chile.

**Table 5.1.** Tracking details of three juvenile northern royal albatrosses that fledged from Taiaroa Head, New Zealand.

| | | Dates | Days | Total distance (km) | Average daily distance (km) | Maximum daily distance (km) | Average speed (km $h^{-1}$) | Maximum speed (km $h^{-1}$) | Average altitude (m a.s.l.) | Maximum altitude (m a.s.l.) |
|---|---|---|---|---|---|---|---|---|---|---|
| Female[1] | Attachment | 30-Aug-07 | - | - | - | - | - | - | - | - |
| | Fledge | 4-Oct-07 | 15 | 1619 | 96 | 177 | 13 | 83 | 4 | 6 |
| | Migration | 19-Oct-07 | 17 | 9039 | 517 | 730 | 31 | 110 | 6 | 36 |
| | Forage | 6-Nov-07 | 295 | 25,320 | 88 | 283 | 13 | 87 | 1 | 37 |
| | End tracking | 31-Aug-08[2] | | | | | | | | |
| | **Total** | | **327** | **35,978** | **109** | **730** | **14** | **110** | **2** | **37** |
| Male 1[3] | Attachment | 30-Aug-07 | - | - | - | - | - | - | - | - |
| | Fledge | 22-Sep-07 | 19 | 1508 | 104 | 290 | 8 | 90 | 8 | 27 |
| | Migration | 11-Oct-07 | 16 | 8993 | 553 | 1047 | 43 | 109 | 7 | 38 |
| | Forage | 27-Oct-07 | 327 | 35,565 | 127 | 690 | 19 | 104 | 3 | 38 |
| | End tracking | 24-Sep-08 | | | | | | | | |
| | **Total** | | **362** | **46,066** | **158** | **1047** | **20** | **109** | **3** | **38** |
| Male 2[4] | Attachment | 30-Aug-07 | - | - | - | - | - | - | - | - |
| | Fledge | 25-Sep-07 | 45 | 1796 | 51 | 205 | 4 | 56 | 5 | 26 |
| | Migration | 10-Nov-07 | 34 | 10,559 | 219 | 534 | 18 | 105 | 4 | 29 |
| | Forage | 14-Dec-07 | 55 | 2,794 | 83 | 194 | 12 | 80 | 7 | 36 |
| | End tracking | 9-Feb-08 | | | | | | | | |
| | **Total** | | **134** | **15,149** | **112** | **534** | **11** | **105** | **5** | **36** |

[1] Weight just prior to fledging was 6.8 kg. Age at time of fledging was 248 days.
[2] This is the date the transmitter stopped working.
[3] Weight just prior to fledging was 9.2 kg. This was Toroa, the 500th chick to be successfully hatched at Taiaroa Head. Age at time of fledging was 240 days.
[4] Weight just prior to fledging was 11 kg. Age at time of fledging was 242 days.

***Movements after fledging***

During the first two weeks after fledging, the three juveniles flew north-east off Taiaroa Head staying within 150 km of the New Zealand coastline over the coastal continental shelf before heading east towards the Chatham Rise (Figure 5.2). The maximum depth of the ocean in this region is 1000m. F1 and M2 then veered north of the Chatham Rise into deeper oceanic waters (up to 4000 m), whilst M1 continued towards the Chatham Is, reaching to within 20 km of the coast. F1 and M1 stayed within 650 km of the New Zealand coast for 15 and 19 days respectively (Table 5.1) before undertaking a direct easterly migration. M2 remained within approximately 350 km of the New Zealand coast for 46 days before beginning its direct easterly migration.

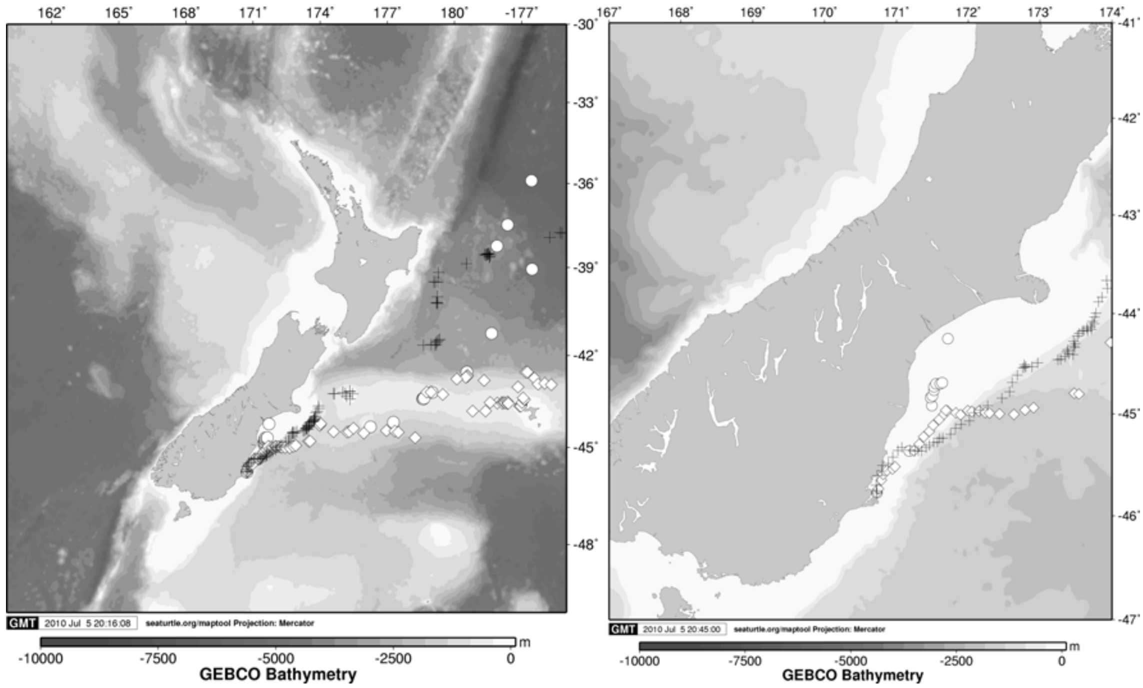


**Figure 5.2.** Six-hourly GPS locations of three fledging juvenile northern royal albatross (*Diomedea sanfordi*) F1 (circle), M1 (diamond) and M2 (cross) within New Zealand waters. On the right is an enlarged image of the South Island coast, New Zealand.

#### *5.4.1.2 Migration*

Upon leaving the coastal area of New Zealand all three albatrosses flew east across the Southern Ocean in a corridor between 34°S and 48°S. F1 and M1 flew directly across with no backtracking. M2, however, appeared to back-track up to 450 km on two occasions (Fig. 5.1). It took 18, 16 and 34 days for F1, M1 and M2, respectively, to cross the ocean. The maximum daily distance (and fastest speed in parenthesis) attained during this stage were recorded at 730 km (110 km $h^{-1}$), 1047 km (109 km $h^{-1}$) and 534 km (105 km $h^{-1}$) for F1, M1 and M2, respectively (Table 5.1). Maximum altitudes recorded during this stage ranged from 36 to 38 m a.s.l. (Table 5.1). With the exception of altitude for M2, for all three albatrosses, speed, altitude and average daily distance were greater during migration than during both fledging and foraging (Figure 5.3). Throughout the tracking period, the albatrosses flew at speeds over 80 km $h^{-1}$ only 3% of the time, with more than half of these higher speeds occurring during migration.

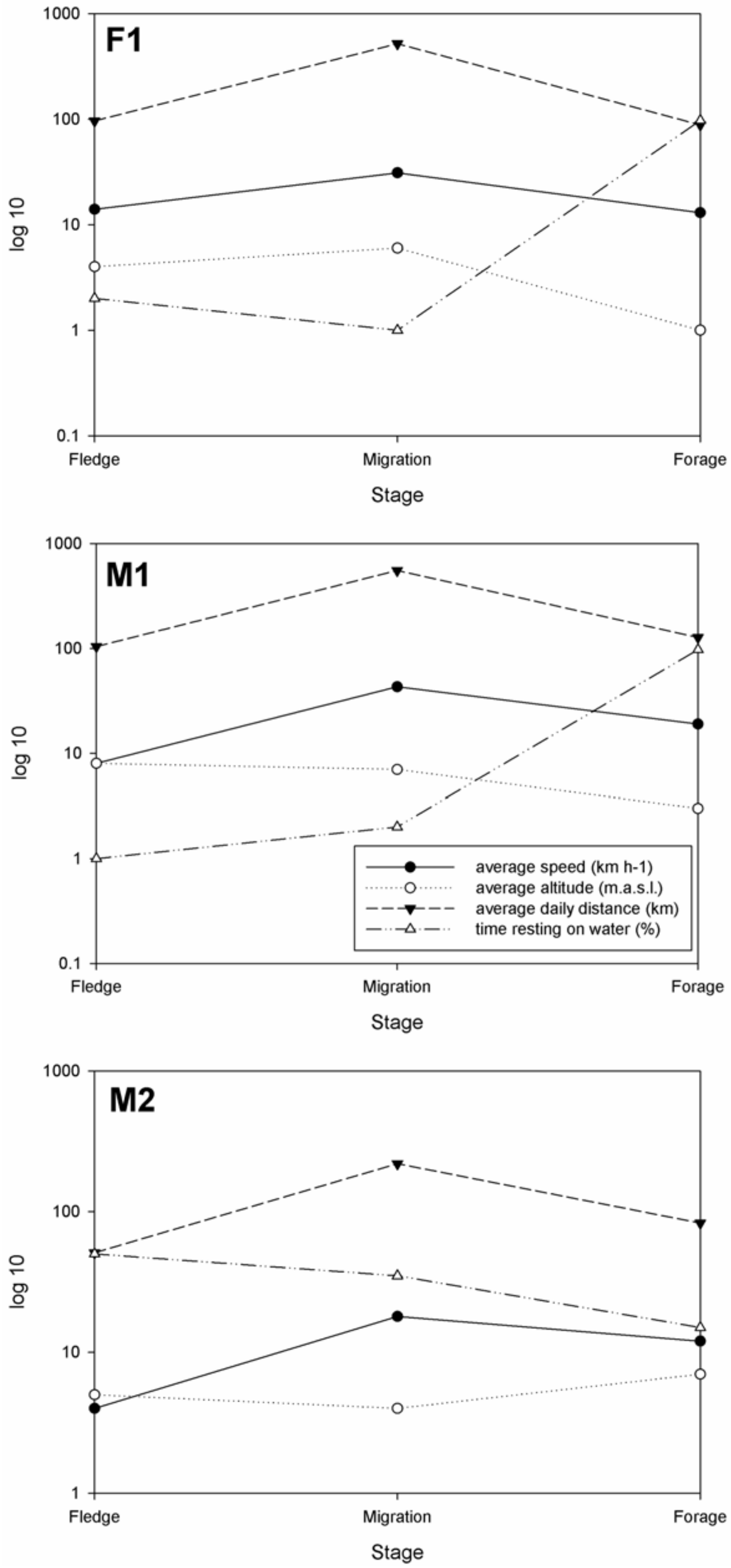


**Figure 5.3.** Average speed, altitude, daily distance and time spent resting on the water of each stage during the first year at sea for three juvenile northern royal albatrosses (*Diomedea sanfordi*).

#### *5.4.1.3 Foraging*

All three albatrosses reached South America at different times (Table 5.1) at latitudes between 40°S and 44°S, before dispersing along the narrow Chilean continental shelf edge between 23°S and 58°S (Figure 5.1). The estimated area of the foraging ranges off the coast of Chile was 145,000, 950,000 and 115,000 km² for F1, M1 and M2, respectively. The albatrosses largely remained within 100 km of the coast, over the shelf edge in waters between 1000 and 2000 m deep. Occasionally, they were located up to 200 km from the coast in 4000 m deep water, but were rarely located further than 200 km from the coast where depths reached 5000 m. Only rarely were locations recorded over the Peru-Chile Trench where depths reached 6000 m. None of the albatrosses were located closer than 5 km from the coast during the study period.

F1 ventured the furthest north, foraging between 23°S and 38°S off the coast of Valparaiso (33°S), Chile. At one point it ventured 270 km off the coast at an ocean depth of 4000 m. M2 remained within 39°S and 45°S in depths of 1000 m during its time on the coast, displaying the least movement of all three albatrosses. M1 ranged between 34°S and 57°S and generally remained no further than 150 km from the coast, constantly moving up and down the coastline. It flew rapidly southwards on three separate occasions, once on a two-month trip between 20 Jan and 25 Mar 2008. On this trip it travelled at least 7500 km reaching the very southern tip of the Patagonian coast (170 km from the Falkland Is) before returning north to the starting point. The other two southward return flights included a 1200 km trip over 16 days in May and another 49-day trip starting in early June where the albatross travelled 3800 km southwards and back. In Aug 2008, it also made a 2000-km trip directly westward into the southern ocean on a reverse heading of his migration flight.

For each albatross, the core area identified during foraging on the coast of Chile was approximately one fifth to one tenth the size of the entire home range during foraging. The core areas spanned a large area of latitude (31°S to 50°S) and whilst the entire core area of M2 overlapped with a portion of the core area of M1, there was no other overlap at all (Fig5.4).

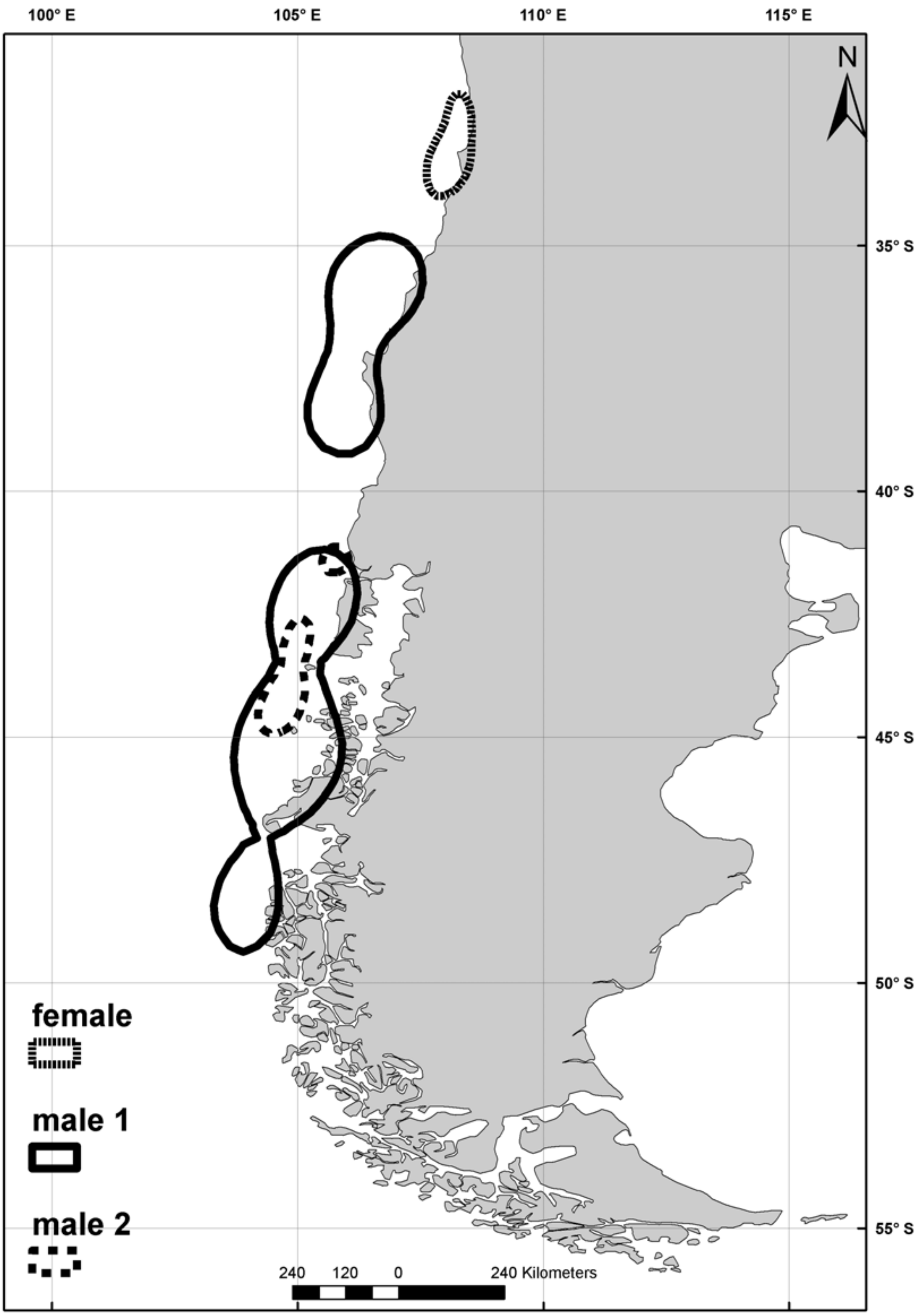


**Figure 5.4.** Core areas (50% kernel) of three juvenile northern royal albatrosses (*Diomedea sanfordi*) foraging off the coast of Chile during their first year at sea.

#### *5.4.1.4 General behaviour*

During the year-long tracking period, the three albatrosses spent on average 72% (± 7.9, range 63 – 79%) of their time resting on the water. Resting on the water varied according to their dispersal stage (Figure 5.3). Based on individual averages, the birds rested the most during fledging (range 74 – 94%), followed by foraging (range 63 – 75%), and the least during migrating (range 39 – 67%) ($F$ = 6.6; $df$ = 2, 6; $P$ = 0.031). The percentage of time spent resting on the water for both F1 and M1 was biased towards foraging; however, the time spent resting on the water by M2 was spread over all three stages (Figure 5.3). There was no significant variation in time spent resting on the water by time of day ($F$ = 0.85; $df$ = 3, 8; $P$ = 0.505); however, a larger percentage of resting locations was obtained at 2400 h (range 31 – 45%). The remaining resting locations were evenly spread over the other time periods (range 10 – 25%) showing a decrease toward the evening (Figure 5.5).

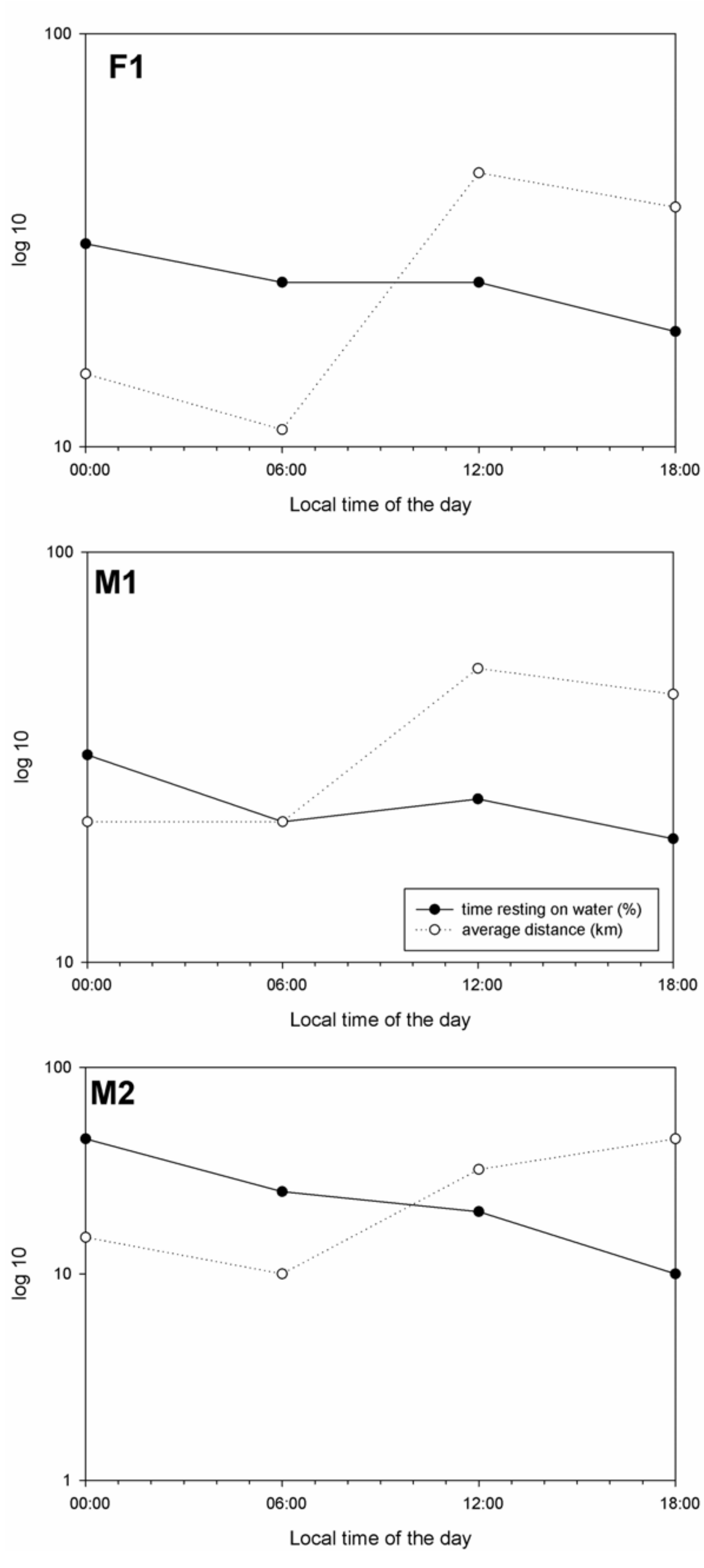


**Figure 5.5.** Average distance travelled and time spent resting on the water by time of day during the first year at sea for three juvenile northern royal albatrosses (*Diomedea sanfordi*).

The average daily distance flown varied significantly by stage ($F = 9.82$; $df = 2, 6$; $P = 0.013$), with the highest recorded during migration, followed by foraging, and fledging (Table 5.1). The average distance travelled between two consecutive location points varied according to the time of day ($F = 16.8$; $df = 3, 8$; $P = 0.001$) with larger average distances being covered between 0600 h and 1800 h. Over the course of the day, overall average distances per six-hour period ranged from 32 to 52 km, compared with 10 – 22 km between 1800 h and 0600 h (Figure 5.5). The corresponding pattern of percentage of time spent resting on the water during the night with increased movement during the day is further shown in Figure 5.5.

There was some evidence of M1 reacting to the Chaiten volcano eruption on 2 May 2008 which produced a plume of volcanic ash and steam nearly 17 km high. On that day, M1 was located approximately 160 km directly west of the volcano and had been at this location for three weeks. Between 0600 and midday on 2 May 2008, it began the second of his rapid southward movement travelling 80 km during these six hours. It continued south for a further nine days travelling 1100 km before turning around to head up north again and returning to near the same location 160 km west of the volcano on approximately 20 May. Winds pushed the major ash plumage directly east into Argentina so he probably did not react directly to the ash. Although based on a single observation, this suggests that these birds may react to small changes in air pressure, smell, temperature or even underground tremors associated with a volcanic eruption.

### 5.4.2 Performance of the system

GPS transmitter locations were verified by a hand-held Garmin Etrex Vista GPS unit (Garmin International Inc.; Olathe, KS, USA). During the three to five week period between attachment and fledging, the differences between nest locations recorded by the GPS tracking units and the hand-held GPS unit were 25 m (± 15), 24 m (± 10) and 16 m (± 8) for F1, M1 and M2 respectively. Location fix success of the GPS tracking units prior to fledging and whilst the albatrosses were still on their nests was 42% (n = 56), 80% (n = 80) and 92% (n = 92) for F1, M1 and M2 respectively.

From the time of fledging until the end of tracking, the three transmitters registered 85% (n = 1107), 81% (n = 1169) and 56% (n = 299) location fix success rates for F1, M1 and M2, respectively, with 66 to 83% of these location points accurate to 18 m. Transmitter acquisition rates were higher during migration (70 to 99%) than during the fledging or foraging periods (Table 5.2). There was no significant difference between seasonal ($F$ = 0.49; $df$ = 3, 6; $P$ = 0.7) or monthly location fix rates ($F$ = 0.93; $df$ = 11, 18; $P$ = 0.536). Acquisition success did not vary by time of day ($F$ = 0.04; $df$ = 3, 8; $P$ = 0.987). The median time required for the transmitter to acquire the satellites ranged from 66 to 77 seconds, and the 5$^{th}$ to 95$^{th}$ percentiles of time to fix for all transmitters ranged between 39 to 125 seconds. On average, five satellites were acquired for each successful GPS location.

**Table 5.2.** Location fix success of GPS transmitters

| | | Days tracked[1] | Possible locations[2] | Successful locations | % | 3D[3] | % | 2D[4] | % | Voltage (V) Average (± *sd*) | Temp (°C) Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Female | Fledge | 15 | 60 | 22 | 37 | 16 | 73 | 6 | 27 | 3.7 (*0.1*) | 23 |
| | Migration | 17 | 68 | 67 | 99 | 58 | 87 | 9 | 13 | 4.1 (*0.1*) | 17 |
| | Forage | 295 | 1180 | 1018 | 86 | 845 | 83 | 173 | 17 | 4.0 (*0.2*) | 22 |
| | **Total** | **327** | **1308** | **1107** | **85** | **919** | **83** | **188** | **17** | **4.0 (*0.2*)** | **22** |
| Male 1 | Fledge | 19 | 76 | 64 | 84 | 56 | 89 | 7 | 11 | 3.8 (*0.0*) | 23 |
| | Migration | 16 | 64 | 63 | 98 | 54 | 86 | 11 | 17 | 4.1 (*0.1*) | 19 |
| | Forage | 327 | 1308 | 1042 | 80 | 752 | 72 | 289 | 28 | 4.0 (*0.1*) | 33 |
| | **Total** | **362** | **1448** | **1169** | **81** | **862** | **74** | **307** | **26** | **4.0 (*0.1*)** | **19** |
| Male 2 | Fledge | 45 | 180 | 103 | 57 | 75 | 73 | 28 | 27 | 3.8 (*0.1*) | 27 |
| | Migration | 34 | 136 | 95 | 70 | 76 | 80 | 19 | 20 | 4.1 (*0.1*) | 22 |
| | Forage | 55 | 220 | 101 | 46 | 47 | 47 | 54 | 53 | 3.9 (*0.2*) | 20 |
| | **Total** | **134** | **536** | **299** | **56** | **198** | **66** | **101** | **34** | **3.9 (*0.2*)** | **22** |

[1] The days tracked is the number of days the transmitters were active.
[2] The possible locations were calculated using the days tracked times 4 as there were 4 locations per day.
[3] Three dimensional fix based on more than three satellites.
[4] Two dimensional fix based on three satellites only.

Even as the transmitters approached the end of their theoretical lifespan, they functioned as well, or better, than at the start. There was no significant change in the number of locations per month for any of the three birds (M1, r = -0.169, n = 13, $P$= 0.581); (M2, r = -0.156, n = 6, $P$= 0.767); (F1, r = 0.314, n = 12, p = 0.321). The minimum required operating battery voltage for the transmitters used in this study was 3.6 V. Table 5.2 shows the average battery charge held by each transmitter and was similar for the three birds. The voltage of the solar-charged batteries varied by season ($F$ = 126.35; $df$ = 3, 927; $P <$ 0.001), with the lowest reading in winter (3.8 ± 0.1 V) and highest in summer (4.0 ± 0.1 V). The effect of movement stage on solar charge was also statistically significant ($F$ = 70.67; $df$ = 2, 928; $P$ < 0.001) with the highest average voltage readings occurring during migration (4.1 ± 0.07).

The total average temperature measured by the tracking units was also similar for the three birds (Table 5.2). However, there were differences between the temperature taken during the three stages, in that migration had the lowest average temperatures for both F1 and M1, while M2 had the lowest during foraging. The average temperature during foraging for M1 was exceptionally high, at 33° C.

Seventy-five percent of the failed satellite acquisition attempts occurred for one of three reasons. Firstly, 'no fix' was obtained when the receiver turned on at the designated time and timed out after a two-minute period. Secondly, 'battery drain' occurred when the receiver turned on to get a fix, but the battery voltage then dropped too low to continue after 15 seconds. Finally, failure occurred through a 'low voltage' signal, which was obtained if the battery voltage was too low to attempt a fix and the GPS receiver did not turn on. Of all the failed transmission attempts, most were due to 'no fix' readings (range 46 – 80%) when the average battery charge was 3.9 V, a high enough voltage for a successful reading. For a period of 18 days during Oct 2007, we received no locations from M2. The voltage reading at the start of this black out was 3.56 V and when it started up again it was 3.95 V, indicating that this blackout may have been due to insufficient battery charge.

## 5.5 Discussion

### 5.5.1 Technical effectiveness

It is important to know the limits of the technology and quality of the data because they reveal the sources of potential bias which can affect interpretation of the data. The field test showed the accuracy of the three GPS units ranged from 16 to 25 m. Lewis et al. (2007) report that most stationary test locations have an accuracy of < 30m but that they can be accurate to < 3m. Awkerman et al. (2005) attained a ground truthing average of 4.6 m (± 2.8 m) during their study of waved albatrosses (*Phoebastria irrorata*). It is thought that the juvenile northern royal albatrosses may move 5 to 50 m while at the nest colony (Christopher Robertson, *pers.comm*), which may account for some of the GPS error in our study.

The mean rates of successful transmissions in this study (Table 5.2) are similar to those of Kawakami et al. (2006) who tracked black-footed albatrosses (*Diomedea nigripes*) in southern Japan using GPS technology. The lack of statistical significance between fix success and seasonal, monthly or daily time differences in our study indicates there was little bias in data acquisition. The higher location acquisition rates achieved during migration (Table 5.1) over the ocean may be attributable to extended periods when the wings of the albatrosses were spread leaving the solar panels unobstructed and able to fully charge. In contrast, during fledging and foraging periods, more time is spent resting on the water with wings closed, covering the solar panels. It should be noted that two of the three transmitters had a similar or higher location fix success whilst still at their nests, when the wings might be covering the transmitter for much of the time. However, because there was no difference in fix success with time of the day, we suggest that in general, a transmitter obstructed by albatross wings may have a reduced solar charge, but the effect is not apparent within the short-term or daily time periods.

Solar charging of the transmitters provided an adequate voltage for the duration of the study (Table 5.2). Whilst we could not measure direct sunlight, we found a seasonal effect on the solar levels, with a mean winter charge of 3.8 V (± 0.12 V) compared with summer when the charge averaged 4.0 V (± 0.14 V). Many factors can affect the regularity and extent of charging, such as number of daylight hours, intensity of the sun, amount of cloud cover. At the equator our transmitters would require four hours of direct sunlight to fully recharge. However, as birds (and thus their transmitters) move towards the poles, a longer charging period is needed due to the lower intensity of the sun.

It is unlikely the temperature taken by the transmitter is solely ambient temperature. Given the range of values, it would seem that this temperature is being modified by the albatrosses' body temperature as it sits sheltered under the albatross wings. This can also be seen as average temperatures appear to drop during migration when the wings would be spread leaving the transmitter exposed (Table 5.2). In contrast, the average temperatures are at their highest during the more sedentary times. However, the temperatures taken by the transmitter whilst the albatrosses were still at their nests were no different to those taken during other times, during the most sedentary time of all.

We obtained a high level of fix success for two of the transmitters and they all functioned well with no significant decline over the tracking period. However, we recommend that consideration be given to the choice of duty cycle or transmission schedule. The GPS location schedule in this research (every six hours) did not provide locations with enough frequency to correlate with oceanographic predictors such as Sea Surface Temperature (SST), chlorophyll concentration and wave height. The accuracy of GPS technology is sufficient to perform that kind of analysis, so if the frequency of data acquisition increases, an accurate understanding of fine-scale habitat use can be obtained. Depending on the specific research objectives, for the size of transmitter and solar array (30 g) that we used, we recommend that the location schedule be increased to six per day (every four hours) and downloading via the Argos system every fourth day. However, increasing the location acquisition schedule could shorten the life of the transmitter or require more battery/solar power, which would require a larger solar array and increase the size of the transmitter. It should be noted that there can be a data storage limit, after which time the locations are over-written. For our transmitters, a maximum of 24 locations could be stored, necessitating the six-day download schedule. Given the large size of albatross, we could have used a 45 g GPS transmitter, increasing the location schedule even further to every two or three hours, downloading to Argos every second or third day. However, we chose to reduce the transmitter load to a minimum, following the advice of Phillips et al. 2003. As Argos costs are dictated by the amount of time used by that system, an increase in the data download schedule will increase costs. Continued reductions in the size of GPS transmitters and improvements in solar technology are rapidly paving the way for this technology to surpass other telemetry options in every way.

### 5.5.2 Ecological outcomes

The three fledging juvenile northern royal albatrosses in this study dispersed from Taiaroa Head, migrating across the south Pacific Ocean to Chile in South America where they remained off the coast. They each behaved differently during their first year at sea (Table 5.1).

#### *5.5.2.1 Post-fledging movements*

After fledging, the albatrosses remained in New Zealand waters for 15 (F1), 19 (M1) and 46 (M2) days, and all spent some of this time over the Chatham Rise. This is an undersea platform in 500 to 1000 m of water approximately 1000 km from the New Zealand coast and an important feeding area for seabirds (Waugh et al., 1999). It lies beneath the subtropical front, a convergence zone for warm subtropical surface waters from the north and cold subantarctic waters from the south, creating nutrient-rich waters ideal for plankton and many animals that feed on them. This tracking stage comprised the first two to seven weeks after fledging and it is likely that these initial weeks were spent developing flying and foraging skills (Burger, 1980).

#### *5.5.2.2 Migration*

The migration period in this study ranged from 16 to 34 days for the three juvenile albatrosses. This was also the period when the greatest distances and speeds were achieved. This behaviour was similar to adult northern royal albatross which also migrate rapidly across the Southern Ocean to the coast of Chile (Nicholls 2007). The influence of wind on albatross movements is well documented (Weimerskirch et al., 2000, Shamoun-Baranes et al., 2003), and the start of the long westerly migration was likely caused by the seasonally predictable prevailing westerly winds that dominate the Southern Ocean between 30°S and 60°S. Weimerskirch et al. (2000) noted that albatrosses do not wander aimlessly across the Southern Ocean. Rather they travel in flyways created by favourable winds that enable them to cover large distances with little effort by 'storm riding' (Catry et al., 2009). The changes in wind regime and variability that are predicted with possible future climate changes (Pachauri and Reisinger, 2007), could mean that the increasing frequency of storm events may have a biological consequence for this species, potentially interrupting migration patterns and reducing food stocks (Weimerskirch et al. 2000).

The variable flight speed patterns for juvenile northern royal albatrosses in this study are similar to those recorded for other albatrosses. Chatham albatrosses (*Thalassarche* eremita) tracked by Nicholls et al. (2007) had consistent differences in flight speeds between their trans-ocean migrations and their 'rest and recreation' phases. Flight speeds for adult wandering albatrosses (*Diomedea exulans)* have been recorded at 135 km $h^{-1}$ (Weimerskirch et al. 2002), whilst in this study maximum speeds of 110 km $h^{-1}$ were reached. The difference may be due to variation in tracking methods. The high speeds reported for wandering albatrosses were calculated based on the use of the Argos system. Apparently, speeds were determined by dividing the distance between two Argos locations by the intervening time interval, thus confidence in the reported speeds can be compromised if the location inaccuracy is high (Hays et al., 2001). In contrast, the speed was calculated by the GPS transmitter at a set time in our study, and is thought to comprise an error of < 1 km $h^{-1}$ at speeds of > 40 km $h^{-1}$.

#### *5.5.2.3 Foraging*

Banding studies show that young (< 1 years) southern royal albatrosses were commonly found during summer on the highly productive coastal area of Chile at 30° to 40°S, with few recovered between 45° to 50°S latitudes (Roberston and Kinsky 1972). Our results, however, show that our juvenile northern royal albatrosses were between 23°S and 58°S on the coast of Chile. The juveniles were often over the shelf edge where the ocean depth was 1000 to 2000 m, and rarely where depths exceeded 2000 m. Adult northern royal albatrosses are reported to prefer shelf feeding in 200 to 1000 m waters (Nicholls et al. 2002, Walker and Elliott 2006).

The high use areas of M1 and M2 overlapped, but M1 and the female occupied areas of different sizes and locations on the coast. The variation in range between the juveniles was similar to that for the three juvenile wandering albatrosses (*D. antipodensis*) tracked by Walker et al. (2006) indicating that albatrosses of the same species may use different areas of the Chilean cost. The high-use areas may be attributable to foraging activity, prevailing wind patterns, roosting and commuting (Nicholls et al., 2005).

#### *5.5.2.4 General behaviour of fledglings*

The satellite technology allowed us to estimate time spent on different activities. During the study, 75% of all locations were identified as resting points on the water with one third of these obtained at 2400 h. This coincides with an increased average distance per six-hour period between 0600 h and 1800 h, suggesting a division between resting at night and foraging during the daytime.

Dispersal behaviour of albatrosses upon fledging in our study was similar to that of the juvenile wandering albatrosses (*D. exulans*) studied by Weimerskirch et al. (2006). Upon fledging, the juveniles in their study immediately landed on the water and drifted for one to 15 days until southerly winds started to blow. The juveniles then flew directly east, crossing the subtropical convergence 600 km north of the Crozet Is, before continuing onto the sub-tropical waters (Weimerskirch et al. 2006). They also found that female juvenile *D. exulans* flew further than males each day, covering an average of

183,800 km during their first year. Whilst their general pattern of dispersal is similar to our three juveniles, the distance covered by our study birds during the first year was substantially lower (15,000 to 46,000 km). However, variation in distance travelled between the two studies may be attributed to a different tracking method. Their distances calculated by Weimerskirch et al. (2006) were based on the use of the Argos system, known to provide locations with a larger error (Nicholls et al. 2007), and potentially providing inflated distances.

Albatrosses are reported to frequent nutrient-rich areas of high productivity, transition and convergence zones, as well as areas of upwelling where prey are pushed to the surface and become concentrated and accessible to surface feeders (Waugh et al. 1999). The nutrient-rich Chatham Rise and the coastal area of Chile were both utilized by our study birds. This coastal area of Chile is a well-known foraging area for other age groups of northern royal albatross (Nicholls et al. 2002, Nicholls 2007) and for other albatross species (Imber, 1999, Spear et al., 2003, Nicholls and Robertson, 2007a).

The Humboldt Current is a cold, low-salinity ocean current flowing along much of the coast of Chile. It is one of the most highly productive (>300 $gC/m^2$-yr) marine ecosystems of the world (Paulik, 1981). Albatrosses feed on surface planktonic crustaceans, squid and pelagic fish (Marchant & Higgins 1993). Southern royal albatrosses (*Diomedea epomophora*) are thought to have a preference for the greater hooked squid (*Moroteuthis ingens)* (Imber 1999). These squid are distributed on the continental shelf break and inner slope of southern New Zealand, Chile and Argentina, and this might be one of the reasons for different albatross species migrating between the two areas. Robertson et al. (2003) suggest that knowledge of good feeding locations is learned during the long period of adolescence.

Bycatch of seabirds by pelagic and demersal longline fishing boats has been implicated in the decline of many seabird species in the Southern Ocean (Prince et al., 1992). However, a study of birds caught by trawlers and longliners within New Zealand waters show numbers of northern royal albatross are small in comparison with numbers of other species caught (Robertson et al., 2004). Whilst the literature reports no connection between the decline of this species and bycatch in New Zealand waters, juvenile ranges analysed in this study spatially overlap with areas of substantial longline fishing in New Zealand, Chile and the south Pacific Ocean. Therefore, it is possible they are still at risk of becoming bycatch. Fleets from Japan, Taiwan, Korea, New Zealand, Argentina and Chile fishing for southern blue fin tuna (*Thunnus maccoyii*), albacore tuna (*T.* alalunga), ling (*Genypterus blacodes*), hake (*Merluccius hubbsi*) and Patagonian toothfish (*Dissostichus eleginoides)* (Tuck et al., 2003) are frequent in the areas traversed by the three juvenile albatrosses. As well, the Chatham Rise is New Zealand's most productive and important commercial fishing ground, providing 60% of the national catch. Although spatial overlap is highly likely, temporal overlap is far more difficult to ascertain and is beyond the scope of this study.

Although we tracked only three birds, we found differences between individuals. For example, M2 behaved consistently differently from the other juveniles. He took longer to leave New Zealand, took longer to migrate across the Pacific Ocean (backtracking on two occasions), had the lowest average daily distance, provided more locations spent resting on the water spread throughout all three stages, had the lowest percentage of successful GPS locations and went offline seven months earlier than F1. Whether this was due to transmitter problems or behavioural problems is unclear. He was noticeably heavier prior to fledging, therefore the longer periods during fledging and migration may have been due to his weight and/or indicate that he was not as strong as the other two juveniles. This would require that he rest more often during these stages which would have in turn meant more time with the wings covering the solar panels of the transmitter. However, his transmitter reported only a slightly lower average voltage (Table 5.2).

In order to raise awareness of this species, New Zealands' Department of Conservation developed a publicity campaign. M1, known as Toroa the 500th chick, was selected as one of the juveniles to track to support this initiative. His lineage was well known to the public after his grandmother successfully raised 13 chicks during her 61 years at the colony. Updates of the albatross locations from this study were made public via a website (http://www.albatross.org.nz/toroa.html), and along with the media reporting of the tracking study, the educational interest and profile of the species were increased.

The GPS technology enabled us to achieve our research objectives and we would recommend its use. From our study we found that these juvenile northern royal albatrosses flew up the New Zealand coast before beginning a direct easterly migration across the Pacific Ocean to the Chilean coast to forage for up to one year. Their behaviour showed similarities to both breeding and non-breeding adult northern royal albatrosses, which also traverse across the Southern Ocean from breeding grounds in or near New Zealand to the continental shelf area of Chile as well as the Patagonian coast of Argentina (Nicholls et al. 2002, Nicholls 2007), before migrating back to their breeding grounds. This study has provided useful movement information for this species, but there still remains an information gap of approximately four years between the ages of one year and adulthood, where their movement is unknown. Whilst the GPS technology performed well during this study, we recommend that future studies consider using a duty cycle with more frequent locations as this would allow researchers to take advantage of remote sensing data to improve fine-scale analysis. As well, improvements in long-term attachment methods may contribute to addressing the information gap between one year and adulthood.

This study is the first to report on the first year-at-sea movements of juvenile northern royal albatrosses. The precise tracking of the movement of these juvenile study birds over a one-year period has improved our understanding of their preliminary dispersal patterns. Because northern royal albatross disperse to the economic zones of other nations and may interact with international commercial fisheries, the results of our study will contribute towards effective transboundary conservation strategies to protect this species.

## 5.6 Acknowledgements

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# CHAPTER 6: Case study four – Home range and movement patterns of an estuarine crocodile (*Crocodylus porosus*): a satellite tracking pilot study

This chapter has been published in the Northern Territory Naturalist.

## 6.1 Abstract

The number of Estuarine Crocodiles *Crocodylus porosus* in the Northern Territory, Australia is increasing. This has led to an increase in interaction with humans and livestock. Whilst there have been a number of studies on the distribution and movement of crocodiles in Australia, little has been recorded detailing movement patterns, and less evaluating the technical effectiveness of employing satellite tracking technology on this species. We attached an Argos satellite transmitter to a 4.2 m male Estuarine Crocodile captured in the Adelaide River, approximately 100 km east of Darwin, Northern Territory, Australia. During the six month study period (July to December 2005), the crocodile showed definite signs of home range fidelity, staying within a Minimum Convex Polygon (MCP) area of 63 km² and 95% kernel area of 8 km². The average daily movement was 5.9 km day$^{-1}$ with increased movement during the month of December. A high percentage of useable locations (65%) were received from the Platform Terminal Transmitter (PTT), with an increased number of location readings occurring between 2000 – 0700 hours. Given the aggressiveness of this species and the hostile environments in which they live, the Argos system is a useful method for tracking their movement. The results of this study have provided preliminary information improving our understanding of the home range and behaviour of a large male crocodile.

## 6.2 Introduction

The Estuarine or Saltwater Crocodile (*Crocodylus porosus)*, is endangered in many parts of the world. In the Northern Territory, Australia, however, numbers of *C. pororus* have increased markedly over the last 35 years. During the 1950s and 60s, crocodile numbers in this area decreased severely due to an intensive skin trade, leading to non-hatchling population estimates in the early 1970s of as low as 3000. The import and export of crocodile skins and products was banned in 1971 which effectively ended this exploitation (Messel and Vorlicek, 1986). Subsequently, crocodile numbers rebounded sharply and by 2001 populations were estimated at more than 75,000 (Webb, 2002).

Caldicott et al. (2005) estimate that crocodiles in Australia have been responsible for 62 unprovoked attacks on humans between 1971 and 2004, with 63% of these taking place in the Northern Territory. They link an increasing incidence of crocodile attacks in northern Australia to recovery of the crocodile population and increase in housing, agricultural and recreational activities adjacent to, or within, crocodile habitats. It is believed that as interactions with this once low numbered and endangered species begin to increase, the public's sympathy with conservation measures may begin to decline. This situation places more pressure upon management agencies to continue developing species management plans that balance conservation concerns for the species, public needs, and budgetary restrictions of conservation agencies.

Programs are currently underway to manage increasing crocodile numbers, for example, public education initiatives, 'problem crocodile' removal, warning signs at high-risk swimming areas, and sustainable use such as wild egg harvest (Parks and Wildlife Service of the Northern Territory, 2005). An understanding of crocodile home range and movement patterns could provide information for improving these programs and as a basis for developing sound management strategies. Unfortunately, the aggressiveness of the species and hostile environments in which they live make crocodiles difficult to study using conventional methods. Thus, until recently, virtually nothing was known about the movements of estuarine crocodiles (Caldicott et al., 2005, Letnic and Connors, 2006).

Prior to 2001, all data on movement of estuarine crocodiles were obtained using mark and recapture methods (Webb and Messel, 1978). The first telemetry tracking study of the estuarine crocodile was undertaken by Kay (2004a) who used Very High Frequency (VHF) technology to carry out land-based tracking of crocodiles between October 2001 and May 2003 in the Cambridge Gulf region of Western Australia. Following this, Brien et al. (2008) used VHF to track five males and eight females during 2003 and 2004 in Lakefield National Park, Northern Queensland. Mark and recapture methods provided baseline information on the movements of saltwater crocodiles and VHF telemetry improved our understanding of home range and seasonal movement patterns. However, there are a number of shortfalls associated with these techniques including high recurrent costs due to the intensive fieldwork as well as the risk of potentially modifying the animal's behaviour due to observer presence (Kenward, 2001). More recently, Read et al. (2007) captured and tracked three large male estuarine crocodiles in northern Queensland using Argos telemetry, demonstrating the potential this technology can have for remotely obtaining large amounts of long range movement data.

As no satellite tracking movement studies have previously taken place on this species in the Northern Territory, this pilot study aimed to contribute preliminary biological information related to crocodile movement within the surrounding Darwin area as well as test the attachment and effectiveness of satellite technology on this species. These results will be used to enhance management plans and public safety programs and for future research on the use of this technology on this species.

Therefore, to enhance our understanding of crocodile movement we deployed a satellite transmitter to monitor a crocodile in the Northern Territory, Australia. Specific objectives were to 1) quantify home range size 2) identify areas of high use 3) describe daily and seasonal movement patterns 4) identify correlation between movement and meteorological variables and finally 5) evaluate the technical performance of the transmitter under field conditions. This fifth objective will aid in the interpretation of biological results to help determine whether the technology functioned efficiently enough to underpin crocodile management decisions.

## 6.3 Materials and Methods

The research area was the Adelaide River, located approximately 100 km east of Darwin, Northern Territory (Figure 6.1). We chose this river because of its known crocodile population and the belief that some members of this population move out into the Darwin Harbour area (Mike Letnic, Parks and Wildlife Service Northern Territory, pers. comm.). Based on a high number of recreation activities that take place in the Darwin Harbour and an increased incidence of human interaction, crocodile movement in this area was of particular interest.

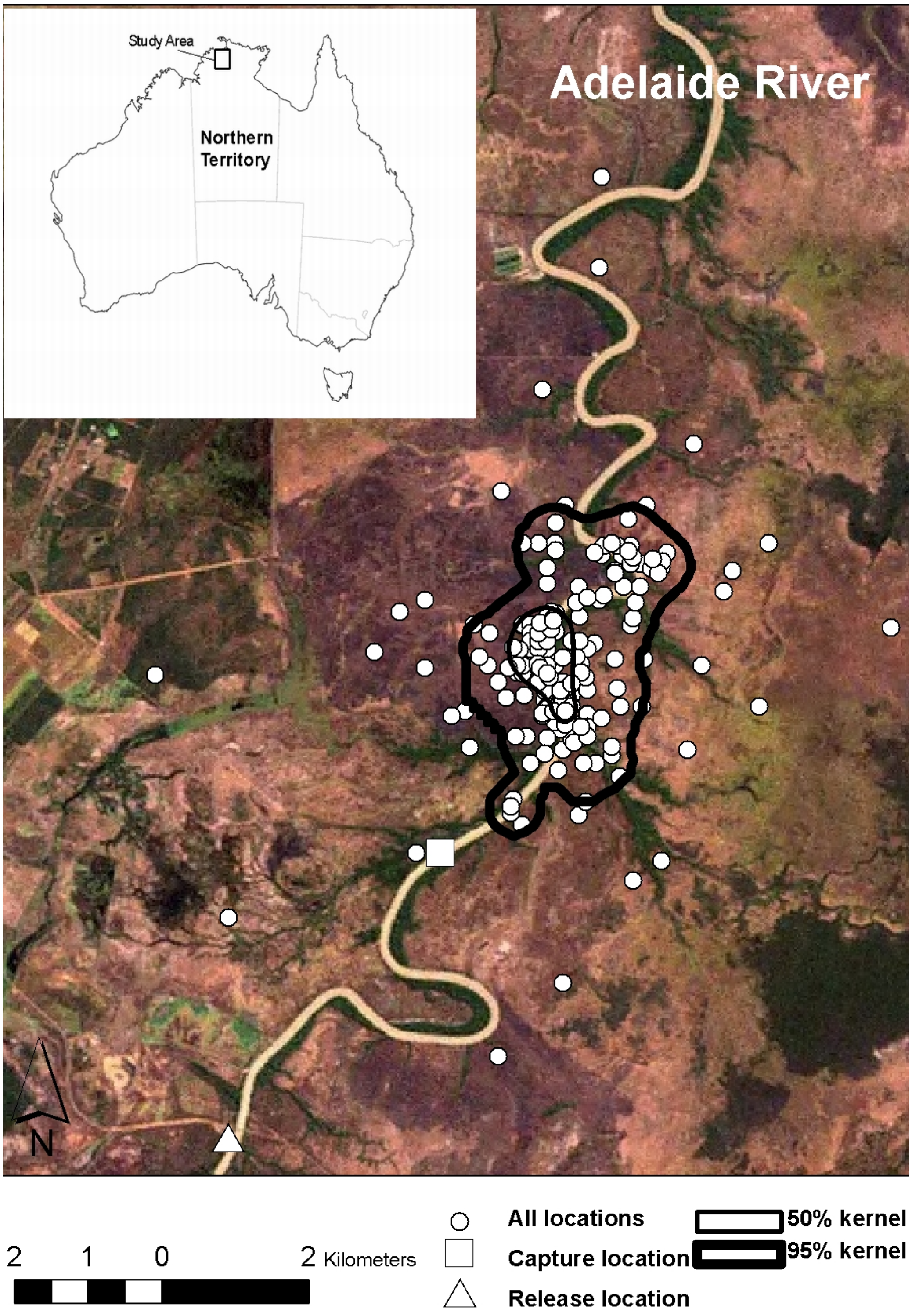



**Figure 6.1**. Satellite image showing LC 3, 2 and 1 locations of C. porosus from 13 July 2005 until 31 December 2005 within the Adelaide river, located approximately 100 km east of Darwin. The capture location was approximately 80 km inland from the mouth of the river.

Platform Transmitter Terminals (PTT's) are transmitters that send a signal via the Argos® satellite system (C.L.S, Ramonville Saint-Agne, France). The PTT used was the Kiwisat 101 designed and customized by Sirtrack (Sirtrack Wildlife Tracking

Solutions; Havelock North, New Zealand) with the help of Queensland Parks and Wildlife Service (QPWS). This system consists of polar orbiting satellites located 800 km above the earth equipped with Ultra High Frequency receivers. Each time the satellite passes over a PTT, it has approximately 10 minutes to calculate its location using the Doppler effect. Each location point is classified and assigned one of several Location Classes (LC), depending on the accuracy of the location estimate. In this study, we assumed the standard deviation of positional error in latitudinal and longitudinal axes to be 150 m for LC 3, 350 m for LC 2, 1000 m for LC 1 and > 1000 m for LC 0 (Argos User's Manual 2010). When three or fewer messages are received by the satellite, the accuracy levels are LC A & B (no estimation accuracy) or LC Z (invalid location). Only locations with an Argos specified accuracy of < 1000 m (LC 3, 2 and 1) were used for analysis.

The dimensions of this tracking unit were 120 mm (L) x 32 mm (W) x 24 mm (H) with a weight of 300 g, well below the recommendation of no more than 3 – 5% of the body weight of the animal (Kenward 2001). The PTT was powered by a single lithium C cell battery and set to a duty cycle of 24 hours on followed by 96 hours off. It was on for approximately 34 hours a week giving it an expected life of around 450 days. The PTT was designed with additional battery preservation features. These included the use of a Salt Water Switch (SWS), activated by the salinity levels in salt water with the ability to cease transmissions when the transmitter was submerged in water or out of water for longer than 4 hours, then resume transmission upon resurfacing or re-entering of the water. A VHF transmitter was also incorporated into the PTT so the device could be found using conventional radio tracking if necessary. Argos tracking technology was chosen for this research because of its ability to provide remote location data to help understand the behaviour of a dangerous animal living in an inaccessible area at a reasonable cost. The specific unit selected for this research was chosen because of its size, shape, durability and energy efficiency features.

We captured a 4.2 m male crocodile at approximately 2300 h on 12 July 2005. The capture location was 80 km from the Adelaide River estuary. Experienced crocodile handlers from the Parks and Wildlife Service, Northern Territory (PWSNT) captured the selected crocodile using the live capture skin harpoon method (Department of the Environment, Water, Heritage and the Arts, Australian Government). It is generally agreed that this is a quick, efficient and low stress method of capturing different sized crocodiles. The harpoon consists of a 3 m pole with a three-pronged detachable harpoon with barbed points attached to a hand spool of parachute cord. The preferred target is the dorsal area of the neck which is very muscular and relatively free of bones. Once harpooned, the crocodile was initially allowed to pull away and then slowly retrieved in much the same way as catching a fish. The crocodile was then brought to the side of the boat where a noose was placed over its neck, its snout bound and it was sedated with valium. Because the crocodile was too large to pull into the boat, it was secured to the side and taken to an attachment/release location on the river bank approximately 8 km further upstream from the capture location (Figure 6.1). Here the eyes were covered to reduce visual stimulation, the rear legs were bound alongside the body with nylon webbing, the harpoon was removed and the PTT was attached.

The attachment team, led by Mark Read from the QPWS, secured the transmitter using a variation of the Winston Kay method (2004b). This method has been tried and tested on a number of tracked crocodiles in northern Queensland. After capturing and restraining the crocodile, the nuchal shield area was cleansed using chlorhexidine scrub and rinsed with 70% ethanol. A local anaesthetic (lignocaine) was used to anaesthetize the nuchal shield area. This was administered using multiple intra-muscular injections of 1.5 to 3 mls which were placed around the base of the nuchal shield. After approximately 20 minutes the anaesthetized area was stimulated to check for a reaction from the crocodile. When no reaction was observed a portable drill fitted with a sterilized 3 mm drill-bit was used to drill two holes into each of the four large nuchal shields. The transmitter was then placed between the nuchal shields and two pre-cut lengths of plastic coated stainless steel wire (100 kg breaking strain) were used to secure the transmitter by threading the wire through the holes and then through the attachment loops fixed to the lateral face of the transmitter (Figure 6.2). The wire was then secured by using standard lead crimps that degrade over time to release the transmitter and wire.


**Figure 6.2**. Image showing the study animal (*Crocodylus porosus)* during the attachment of the PTT. The plastic coated stainless steel wire is being threaded through the holes in the nuchal shields. (Photographed by Derek C. Robertson).

Prior to release, the rear legs and snout were unbound and the eyes uncovered. The crocodile was visually monitored for signs of disorientation and other abnormal behaviours for approximately one hour. After this period it turned and crawled back into the river.

This study was expected to provide data for at least one year (July 2005 to July 2006), however, transmission ceased after six months, covering movement during the dry and build up to the wet seasons. Therefore, between July 2005 and December 2005, the crocodile locations were downloaded using an Argos telnet connection and maps were generated using a Geographic Information System (GIS) (ArcGIS® ArcMap® 9.2, Environmental Systems Research Institute, Redlands, California, USA). The data locations were recorded in latitude/longitude WGS84, and transformed to Universal Transverse Mercator (UTM) zone 53 S for analysis and location time was converted from Greenwich Mean Time to Darwin local time, which was a difference of + 9½ hours. Local GIS layers for the study area were supplied by the Geographic Information Systems Group from PWSNT.

The home-range areas, Minimum Convex Polygon (MCP) and Kernel, were calculated using the Animal Movement Analyst extension to ArcView (Hooge and Eichenlaub 1997). MCP estimators are thought to overestimate space use (Kenward 2001), however they were used here to enable comparison with other studies as well as to indicate the maximum area potentially required by the crocodile. A kernel-based home range utilising the 95% probability contour was used as a second measure to reduce outlier bias. The least-squares cross validation procedure was used to determine the smoothing parameter. Minitab® 15.1.30.0 (© 2007 Minitab Inc., State College, Pennsylvania, USA) was used for all statistical analysis. Unless otherwise noted, all means are expressed as the mean (± s.d.).

Distance was calculated using the Postdist function within Microsoft Excel 2003 and allowing for the four-day gap between each data download period, was calculated using consecutive locations within each 24 hour download period only. We assumed straight-line movement between consecutive points. Speed was calculated in a similar way using consecutive locations in the same data download period and calculating the ratio of distance travelled (meters) to the time interval (seconds).

The temperature (°C) used was obtained from the transmitter at the time of each location. Rainfall (mm), humidity (%) and air pressure (hPa) were obtained from the Australian Bureau of Meteorology (BOM) using the nearest remote weather station to the study area, the Middle Point AWS (#14041) located at (12.605°S, 131.2983°E). Rainfall comprised total precipitation during the 24 hours prior to 0900 h local time on the day of the location, then assigned to crocodile locations obtained on that day. Humidity and air pressure were both taken at 0900 and 1500 h each day and assigned to locations depending on the time of the location. Locations falling between midnight and midday were assigned the 9am reading, and locations falling between midday and midnight were assigned the 3pm reading.

## 6.4 Results

### 6.4.1 Performance of the technology

The PTT was tested prior to attachment and confirmed to be operating correctly. Locations of all classes were received from 13 July 2005 to 31 Dec 2005 (n = 305, 172 days), equating to 27% (83) LC 3, 22% (67) LC 2, 16% (48) LC1 with the remaining 35% (107) of locations designated as LC 0, A, B or Z. Of the total locations, we obtained an average of nine locations per 24 hours or for useable locations (LC3, 2 and 1) six locations per 24 hours.

The transmitter incorporated a pre-programmed duty cycle and was activated at 0020 h on the 13 July 2005. The transmitter performed well sending in 24 hours of data every fifth day without fail, equating to 34 download periods or full days of tracking. Using only LC 3, 2 and 1 locations, there was a higher number of locations received between the hours of 2000 – 0700 (Figure 6.3). The time of the first location obtained during each 24 hour download period ranged from 0026 to 1706 hours, with an average time of 0356 h. The last location obtained during each 24-hour period ranged from 1845 to 0017 h, with an average time of 1923 h. The average time difference between two consecutive locations within a 24 hour period was approximately 6 hours ranging from 1 hour to 13 hours.

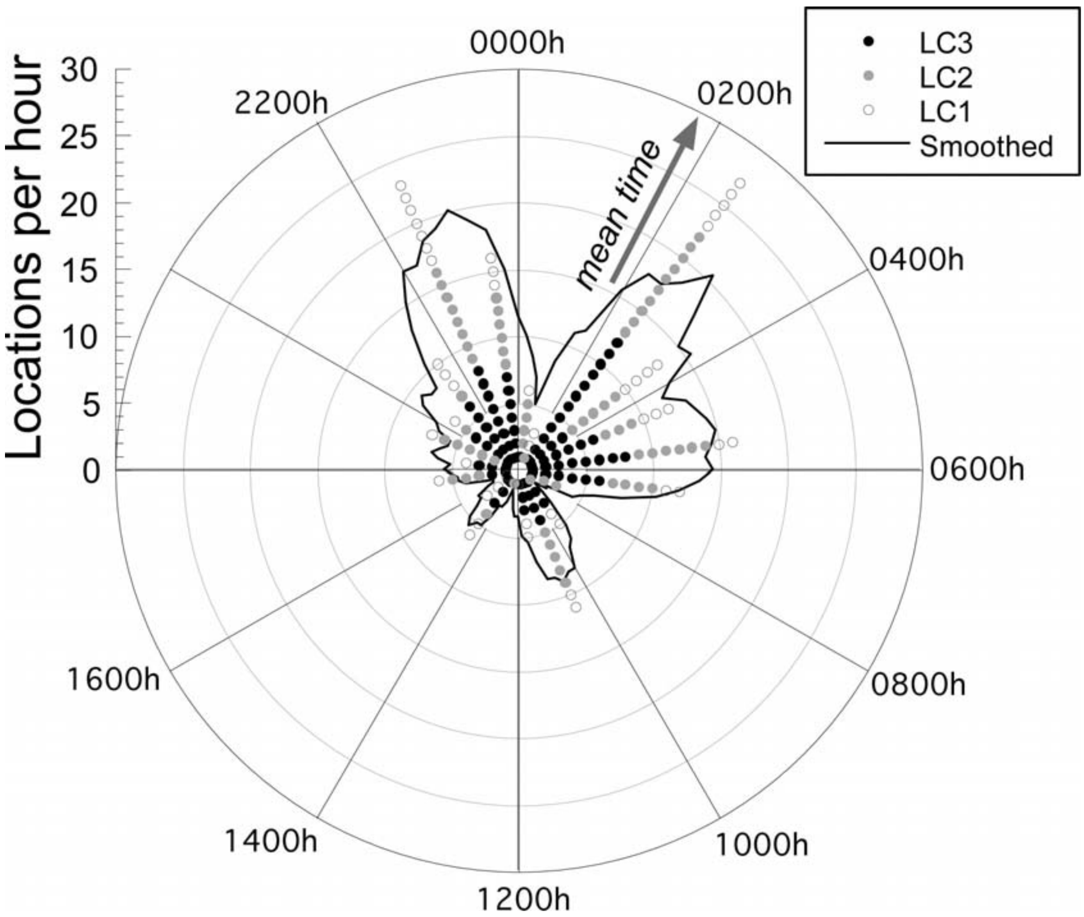



**Figure 6.3.** Circular plot showing the number of LC 3, 2 and 1 locations received at various times of the day. Locations were received on 34 days from 13 July to 31 December 2005. The locations are summarized in 24 one-hour bins. For example, the 0200 – 0300 h bin shows there were 12 LC3, 10 LC2 and 5 LC1 locations. The smoothed line shows the moving average over a two-hour sliding window. The mean time of all locations was 0147 (± 5.4 hours, circular standard deviation). Accuracy of locations is LC3 (± 150 m), LC2 (± 350 m), and LC1 (± 1 km).

We identified a slightly negative relationship ($r^2 = - 0.038$) between the number of acquired locations and time as the PTT approached the end of its theoretical lifespan, but this was not significant. A similar relationship was seen between the battery voltage levels over time ($r^2 = - 0.025$), and was also non-significant.

### 6.4.2 Crocodile movements

Successive positions from the satellite data allowed us to estimate the crocodile's home range (Figure 6.1). Using all LC 3, 2 and 1 locations (n = 198), the MCP home range was 63 km², the 95% kernel home range was 8 km² and the mid-stream linear range was 24 km. A high use area calculated using the 50% kernel home range is also shown in Figure 6.1. This equates to an area of approximately 1 km².

The mean daily distance moved was x = 5.9 ± 3.2 s.d. km $day^{-1}$ with a maximum daily distance of 13 km $day^{-1}$. This maximum daily distance was observed during the month of September with most movement occurring during December (Figure 6.4). The mean distance moved between two consecutive locations was x = 1.2 ± 1.2 s.d. km. The maximum distance was 7.8 km, calculated over a time period of almost 4 hours in the early hours of 26 September 2005. The mean speed between consecutive locations was x = 2 ± 1.2 s.d. km $h^{-1}$ with the fastest speed of 3.6 km $h^{-1}$ recorded on 26 October 2005 calculated over a distance of 4.5 km between 2149 and 2308 h.

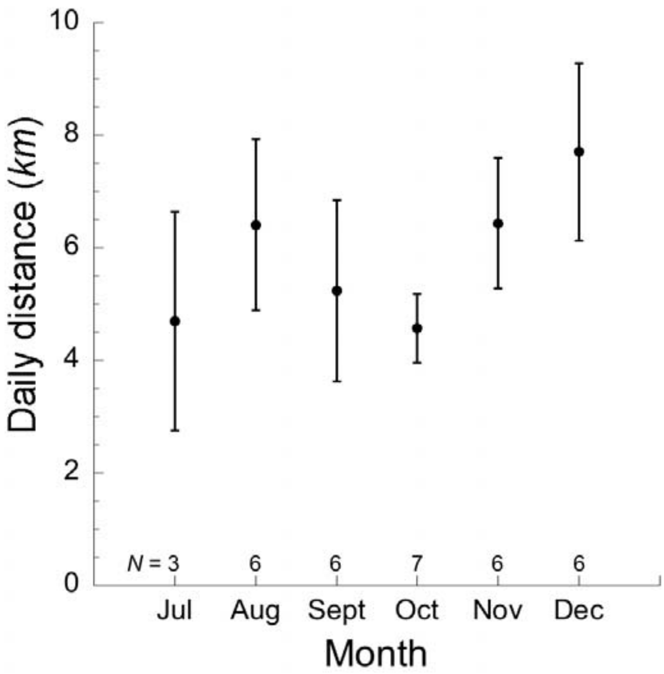



**Figure 6.4.** Boxplot showing the mean ± S.E. of the daily distances moved by the tagged crocodile during each month of the study.

No unusual weather events occurred during the study period with monthly rainfall from July to December 2005 ranging from 0.4 mm to 156 mm, a mean temperature of x = 27 ± 3.5 s.d. °C, humidity of x = 58 ± 21 s.d. % and air pressure of x = 1009 ± 3.4 s.d. hPa. Using fitted line regression analysis, no relationships were identified between the movement patterns of the crocodile and the four meteorological variables analyzed, temperature, rainfall, humidity and air pressure. However, it may be that the crocodile may display a time lag in response to environmental conditions of for example up to 15 days after a big rainfall. Upon considering this we analysed the data further and whilst it may have been possible that more movement was identified 10 – 15 days after each significant rainfall, it was not with any certainty.

The furthest point from the river was an LC 1 location 4.8 km directly west from the river edge on 25 November 2005 at 0116 h. The following location was an LC 2 located at 0254 h that same day right on the river edge, 5.3 km slightly southeast of the previous point, indicating a speed of 3.25 km/hr. In this study the remote weather station data show there was about 75 mm of rain during the two weeks prior to this, but only 0.2 mm during the 24 hours prior to this date, with a temperature of 29.4°C and relative humidity of 73%. The next furthest point from the river was an LC 2 on 2 August 2005 at 2213 h, located 4.3 km directly east of the river. This point was the last for that 24-hour period so no consecutive point was obtained for a speed calculation. The meteorological data indicated very little rainfall prior to this with only 1 mm during the month of July, a temperature of 32.4°C and relative humidity of 21%.

## 6.5 Discussion

### 6.5.1 Technical effectiveness

Reviewing the reliability and functionality of tracking units can provide important cues to help interpret the data used for ecological analysis.

The tracking unit performed well with 65% of the locations obtained from the PTT usable, which was higher than those obtained by Read et al. (2007), whose percentage of similar useable locations ranged from 32 – 53%. The crocodiles in the Read study used the same transmitter and duty cycle as this study with slightly varying periods of attachment. The slightly higher percentage of quality readings in this study may be attributed to the crocodile moving smaller distances, thereby allowing the transmitter to acquire improved satellite fixes, and hence, accuracy.

Many more locations were received during the time from 2000 to 0700 h than during other times of the day (Figure 6.3). Satellite passes over the Darwin area were relatively evenly spaced throughout the day (J. Trede, Argos/Satellite IT Pty Ltd, pers. comm.). Brien et al. (2008) report the crocodiles in their study to be most active from late afternoon (1500 – 1800 h) until midnight. Thus, the difference in the number of day and night-time locations is probably a product of crocodile behaviour and the effect on the transmissions. It is likely the crocodile was submerged in the river or within the mangroves trees during the day and moved on the surface in more open water and on open ground at night. Although the aerial antenna on the transmitter is 185 mm in length, this submerging may have covered the transmitter, making transmission difficult during the day, as it can't transmit through water or when obscured by thick bush (Kenward 2001). To overcome these constraints, other methods including acoustic and archival tracking could also be used, potentially providing useful behavioural and physiological data for species living in aquatic environments (Franklin et al., 2009).

Generally, the effectiveness of Argos technology can be attributed to three areas, the functioning of the transmitter, the performance of the Argos system and the behaviour of the species being tracked. Notwithstanding the obvious advantages apparent with a system that allows remote data collection, it can often be difficult identifying where the fault lies when problems do occur due to the large distances between the researcher, the animal and the satellite system.

Until the transmissions ceased halfway through the project there were no PTT or satellite receiver problems. This reduced transmission time may have been attributed to either animal mortality, depletion of batteries, premature detachment, antenna damage or failure of the salt-water switch (Hays et al. 2001). When transmission ceased, an attempt was made to search for the transmitter using the VHF aerial, but this was not successful.

Because the subject of this research project inhabited a smaller home range than was expected, it may have been more appropriate to have used a tracking technology with increased accuracy levels. A Global Positioning System (GPS) tracking unit is afforded with an accuracy level of < 5 m (Hulbert and French 2001), which would have allowed for an understanding of variables such as time spent in the river, time spent on the riverbanks and time spent outside the river system, all of which could have provided valuable behavioural information. It would also have provided consistent locations taken at pre-set time intervals, useful for analysing variables such as distance or speed. The lower accuracy levels afforded to the Argos tracking system (Yasuda and Arai, 2005) make analysing these kinds of variables problematic.

In addition to the direct benefits wildlife managers enjoy from satellite-based tracking systems, there are also indirect benefits such as increased public awareness and educational initiatives. This study was the first of its kind in the Northern Territory and enjoyed local, national and international media coverage. The results of the study were updated on a dedicated website every five days to enable scientists, park managers and members of the public to follow the project's progress. There was strong support for the project from both Australian and international viewers.

### 6.5.2 Ecological outcomes

Previous studies describe the abundance and distribution of crocodiles in the Northern Territory and Queensland where it has been suggested that rainfall may be an important factor influencing crocodile movement (Webb & Messell 1978). Kay (2004a) noted that male and female crocodiles in the Ord River, Western Australia, exhibited different movement patterns. He suggested that males have substantial range overlaps and that territoriality is not an important behavioural characteristic. Brien et al. (2008) found that males occupied larger home ranges than females during the late dry/mid-wet season, but that this difference was not apparent during the dry season. They also concur with Kay (2004a) in that the crocodiles in their study exhibited considerable home range overlap. Read et al. (2007) captured and relocated three male estuarine crocodiles in northern Queensland, then used Argos tracking to study their behaviour, in particular, their homing instinct. Their study confirmed that all three crocodiles behaved similarly upon release by making small and random movements around their release sites for periods of 10 to 108 days, then took the most direct coastal route home. All three travelled up to 10 – 30 km a day, along the coast and demonstrated definite homing instincts. A tag and recapture study of juvenile crocodiles in rivers in Arnhem Land, Northern Australia, revealed that 57 – 93% of crocodiles aged from hatchling to 4 years old returned to within 10 km of the original capture site (Webb and Messel 1978). Walsh and Whitehead (1993) confirmed homing behaviour during a study on the relocation of 'problem' crocodiles in Arnhem Land.

In this study, the crocodile was relatively sedentary with high site fidelity and a defined home range. Read et al. (2007) reported similar site fidelity for their three crocodiles once they returned to their capture locations. It is believed that the distribution of crocodiles upstream is similar to that of Barramundi (*Lates calcarifer*) in the area (Letnic and Connors 2006). The high site fidelity shown in this study would most likely indicate that the crocodile had sufficient food within the area of his home range.

According to Kay (2004a), the mid-stream linear range for male crocodiles ranged from 11 – 87 km compared to 24 km in this study. The higher rate of movement in December (the beginning of the wet season), recorded during this study conforms with that reported by Brien et al. (2008), who report mid-stream linear ranges of 10.64 ± 2.86 s.d. ha in the late dry/mid-wet season (July to January) compared with 3.20 ± 1.02 s.d ha in the dry (May to August). Kay (2004a), showed a higher mean rate of movement during the summer wet season (December to March), of 4.0 km day-1, followed by late dry movements (September to November) of 1.6 km day-1, dry movements (June to August) of 1.3 km day-1 and post wet movements (April to May) of 1.1 km day-1. Flooding of the plains adjacent to the river banks during periods of increased rain are believed responsible for this increase in movement (Webb and Messel 1978).

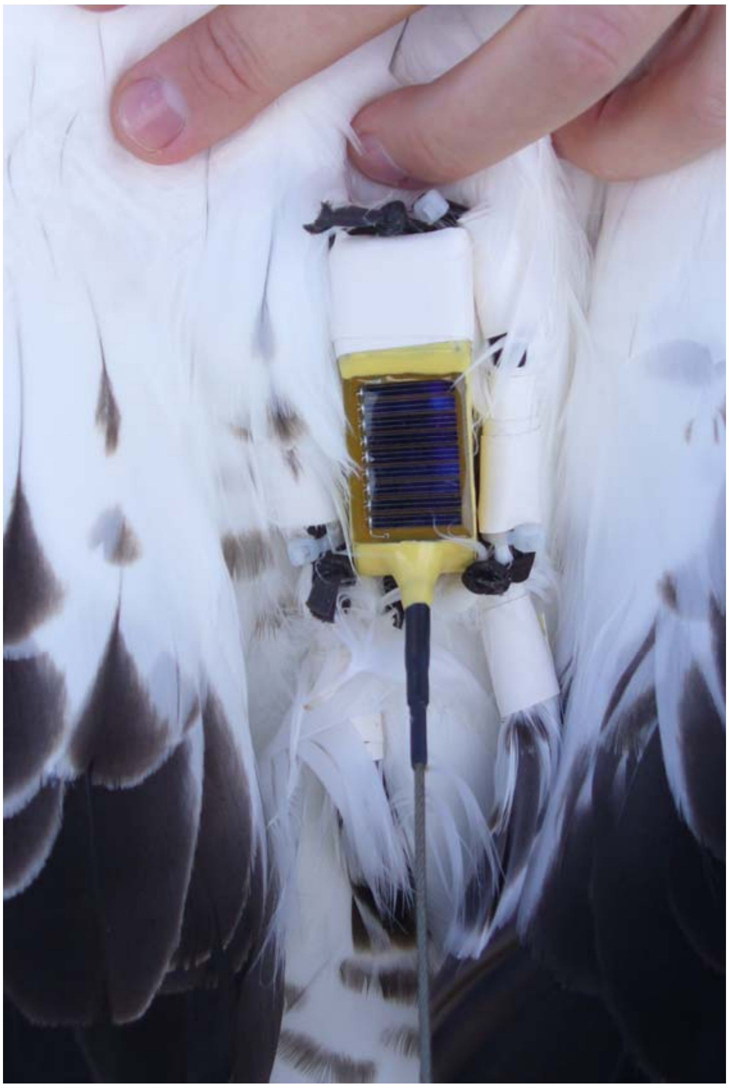
Whilst increased movement was recorded during the month of December in this study, the correlation between movement and meteorological variables was not significant. This may be attributed to either the low sample size (Lindberg and Walker, 2007), the short observation period of this study or to the problems inherent in aligning the set daily times of meteorological readings with variable location times.

This study is the first in the Northern Territory to report on the continuous movement of a crocodile within the surrounding Darwin area. Whilst the sample size of this study excludes any statistical inference to be drawn at a population level, the aim of this study was to provide preliminary information about the home range and behaviour of a large male *C. pororsus* in a tidal area as per a pilot study, enabling us to refine our understanding of the attachment and use of this technology as it relates to *C. porosus*.

## 6.6 Acknowledgements

This research was a collaboration between Massey University in New Zealand, the Parks and Wildlife Service Northern Territory (PWSNT) and the Queensland Parks and Wildlife Service (QPWS). The invaluable contributions of Mike Letnic, Tom Nichols (Parks and Wildlife Service, Northern Territory), Garry Lindner (Kakadu National Park) and Mark Read (Queensland Parks and Wildlife Service) are gratefully acknowledged. We are also grateful for technical guidance from Kevin Lay (Sirtrack Wildlife Tracking Solutions) and Mathew Irwin (Massey University, GIS lab) and for financial support from the Institute of Natural Resources, Massey University. Ethics approval to capture,

sedate and attach the transmitter to a single crocodile was obtained from the Animal Ethics Committee at Charles Darwin University, Northern Territory, Australia.



# CHAPTER 7: Wildlife satellite tracking; technology choices and cost considerations

This chapter has been submitted to Wildlife Research.

## 7.1 Abstract

Identifying the options for satellite tracking for a particular project involves an analysis of the costs and benefits of different methods against a rapidly evolving and expanding set of technologies and manufacturers. We developed a set of guidelines for assessing the technology options to help wildlife researchers choose the best tracking solution for their needs. We offer our own experience with tracking four very diverse species as both an illustration and test of our guidelines.

## 7.2 Introduction

Wildlife biologists are now using satellite technology to gather animal behaviour data that a short while ago was considered impossible to obtain (Cohn, 1999, Cargnelutti et al., 2007). These data, combined with others such as meteorological or Geographical Information System (GIS) layers, enable bio geographic hypotheses to be tested and provide important information to improve wildlife and ecosystem management decision making. This synergy between science and technology is fostering the emerging discipline of movement ecology (Cagnacci et al., 2010).

Movement ecology and the development of biotelemetry began in the early 1960's with the advent of Very High Frequency (VHF) tracking (Cochran and Lord Rexford T. Jr, 1963). Satellite tracking followed in the early 1970's when, for example, Craighead et al. (1971) tracked a single elk (*Cervus canadensis*) using a transmitter linked to the Interrogation, Recording and Location System (IRLS) on board the NIMBUS 3 satellite that was originally designed to monitor geophysical, oceanographic and meteorological data. Since then, satellite transmitters have made use of the Argos® satellite system. Animal tracking using Global Positioning System (GPS) technology began its development in the early 1990's in response to researchers' need to collect fine scale location data for far-ranging species (Rodgers et al., 1996).

Ecological studies using satellite tracking technology have evolved from describing the movements of only a few individuals to more complex analysis and problem solving (Webster *et al*. 2002). Wildlife researchers now have the ability to understand more about the behaviour of a wide range of diverse endangered species by answering an increasing number of ecological questions. Hebblewhite and Haydon (2010) identify a number of ecological or conservation objectives that are addressed using satellite tracking technology. These include but are not limited to behaviour, migration, home range, human-wildlife conflict and climate change.

Continued scientific and commercial demand for long-distance remote tracking has resulted in the development of a variety of satellite tracking technologies. Whilst spoilt for choice, it is important to understand the strengths and weaknesses of the different options to ensure the selected system matches the ecological or conservation research objectives and the animal being tracked (Bradshaw et al., 2007). Frair *et al*. (2010) suggest that previous knowledge on species movement behaviour and precision of GPS locations is important when designing satellite tracking studies.

In the final analysis, the choice of which tracking system to use requires consideration of functionality and cost. Because satellite tracking technology is expensive to purchase, deploy and monitor (Mourao and Medri, 2002, Lindberg and Walker, 2007), and budgets frequently constrain the technical tools available to conservation researchers, understanding and considering all the associated costs is also important (Franco et al., 2007). In this paper we present: 1) guidelines for choosing the best wildlife satellite tracking technology 2) assessment and validation of these guidelines based on four case studies 3) assessment of the cost of each technology.

## 7.3 Methods

Descriptions of location acquisition and data download methods used for satellite tracking wildlife are presented in Table 7.1. These methods include descriptions of both the location acquisition methods and data download methods, two stages of wildlife tracking technology. Location acquisition refers to the method used to calculate the position (longitude/latitude). Four location acquisition methods are presented, two satellite and two non-satellite methods. Whilst the main focus of this paper is satellite tracking, other non-satellite methods are presented. GPS, Argos satellite Doppler-based positions (Argos) and VHF are commonly used location acquisition methods, while light-based geolocation methods are less common. The choice of location acquisition method will affect both location accuracy and the frequency of collection. Data download, on the other hand, refers to the methods used to transfer locations (and biological data) from the tracking device to the researcher. The data download method influences the regularity of data transmissions, data transfer method (satellite or non-satellite) and data format. Three of the four location acquisition methods (Argos, VHF and geolocation) are restricted to a single data download method, whilst GPS has a number of data download options. It should be noted that geolocation data can be downloaded using satellite technology as in marine animals (pop-up archival tags, in combination with Argos) but marine tracking is beyond the scope of this study.

**Table 7.1.** Description of wildlife tracking methods used in this study

| Location acquisition method | Description |
|---|---|
| Argos satellite Doppler-based positions (Argos) (satellite) | A Platform Transmitter Terminal (PTT) transmits a pulse detected by Argos® polar orbiting satellites located 800 km above the earth. The satellite passes over the PTT and has approximately 10 minutes to receive the frequency data (Doppler effect) and time stamps required. This data is then downlinked and processed at the Argos processing centres and locations are calculated. The accuracy of each location point is assessed and assigned one of several Location Classes (LC). The standard deviation of positional error in latitudinal and longitudinal axes is claimed to be 150 m for LC 3, 350 m for LC 2, 1000 m for LC 1 and > 1000 m for LC 0 (Argos User Manual). When three or fewer messages are received by the satellite, the accuracy levels are LC A & B (no estimation accuracy) or LC Z (invalid location). The location is transferred to the researcher using the Argos® system. |
| Global Positioning System (GPS) (satellite) | GPS tracking devices transmit and receive transmissions from a constellation of approximately 24 satellites located at 20,000 km above the earth (NAVSTAR). When four or more satellites are in view, GPS provides a location accuracy of approximately < 30 m (Tomkiewicz et al. 2010). The location is then transferred to the researcher using one of the data download methods described below. |
| Very High Frequency (VHF) (non-satellite) | VHF transmitters emit a radio frequency signal. These signals are located by a researcher using an antenna and receiver from a plane, a vehicle or on foot. Signals can also be acquired using an automatic VHF tower. The location of the animal is calculated manually when the researcher triangulates multiple bearings or visually sights the animal or automatically using a VHF tower. This method provides a variable accuracy dependent on local conditions, instruments used and on the skill of the operators to acquire locations. Precision of 200 – 600 m has been reported for locations of VHF devices acquired via triangulation and homing (Zimmerman and Powell 1995). |
| Light-level geolocation (non-satellite) | An archival tag is capable of storing data on light levels (sunrise and sunset times) and measuring the current light levels. A comparison of the two is used for location calculation. The locations are obtained by retrieving the archival tag and downloading the data manually. This method provides a location accuracy of 34 – 1,043 (Phillips et al. 2004) |
| **Data download method** | **Description** |
| GPS/Argos | GPS is used for location acquisition and the Argos® system for remote data download. |
| GPS/Iridium | GPS is used for location acquisition and the Iridium satellite system for remote data download. |
| GPS/Globalstar | GPS is used for location acquisition and the Globalstar satellite system for remote data download. |
| GPS/Geostationary (GEO) | GPS is used for location acquisition and a geostationary satellite system for remote data download. |
| GPS//Global System for Mobile Communications (GSM) | GPS is used for location acquisition and a cellular network for remote data download. |
| GPS/VHF | GPS is used for location acquisition and a VHF receiver/antenna used by a researcher to download the data manually in the field. |
| GPS//Store on board (SOB) Ultra High Frequency (UHF) | GPS is used for location acquisition storing the locations on the tracking device. An Ultra High Frequency (UHF) receiver is used by a researcher to download the data manually in the field. |
| GPS/SOB drop-off | GPS is used for location acquisition storing the locations on the tracking device. The data is then downloaded when the collar drops off at a pre-set time for manual retrieval in the field. |
| GPS/SOB recapture | GPS is used for location acquisition storing the locations on the tracking device. The data is downloaded upon recapture of the animal and retrieval of the transmitter manually in the field. |

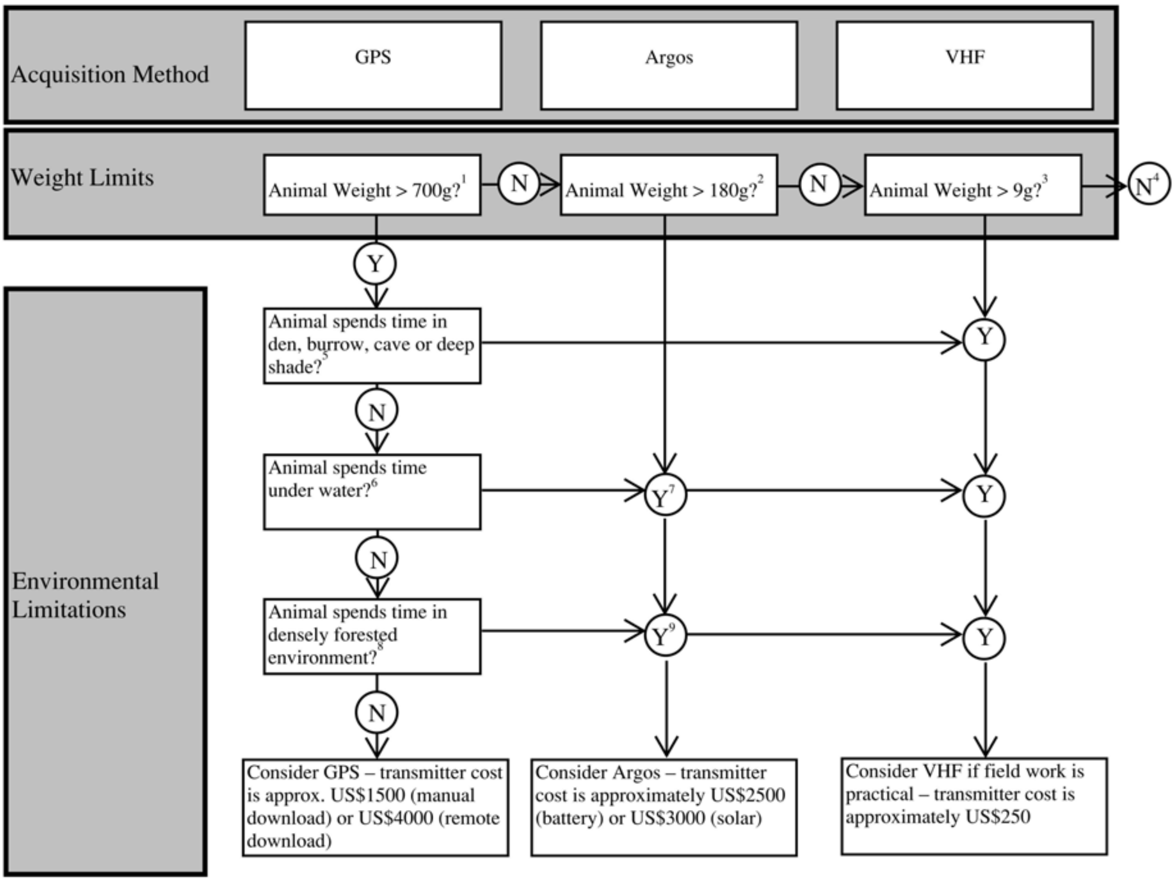
Choosing the tracking method best suited for a project requires; 1) clearly specifying the data required to meet project objectives, 2) understanding the constraints imposed by the study species and its environment, and 3) calculating the net cost per datum of the various tracking methods available. Based on these criterion, this paper develops a technology choice decision guide to assist wildlife scientists select an optimal tracking technology.

We undertook four satellite tracking case studies involving avian, aquatic and terrestrial species living in diverse environments of the world, namely, (1) three African elephants (*Loxodonta africana)*, Kruger National Park, South Africa, (2) five New Zealand bush falcons (*Falco novaeseelandiae*), central North Island, New Zealand, (3) one estuarine crocodile (*Crocodylus porosus*), Darwin, Australia and (4) three northern royal albatrosses (*Diomedea sanfordi*), Taiaroa Head, New Zealand. We use these case studies to validate and test the technology choice decision guide and to calculate the cost effectiveness of alternative tracking methods.

## 7.4 Results

### 7.4.1 Technology

When comparing satellite tracking technologies, researchers are confronted by a plethora of complex information that can be overwhelming. We developed a tracking technology choice decision guide to assist researchers (Figure 7.1). The guide ultimately leads to the selection of one of three more commonly used location acquisition methods, GPS, Argos or VHF. Ignoring cost considerations, the guide acknowledges GPS as the method of choice, except when constrained by the animal or its environment. This is because it can acquire accurate locations in rapid succession (Witt et al., 2010). The guide also considers the technical aspects of each location acquisition method. The choice of location acquisition method dictates the data download options. To further assist wildlife researchers with decision making, a comparison between the commonly used data download methods is presented in Table 7.2.




Technical Requirements[10]

| | GPS | Argos | VHF |
|---|---|---|---|
| Required location accuracy?[11] | High | Low | Medium |
| Number of Locations Required | High | Medium | Low |
| Accuracy of speed required?[12] | High | Low | Low |
| Altitude Required?[13] | Yes | No | No |
| 24 hour coverage required? | High | Medium | Low |
| Impact of human presence to animal?[14] | Low | Low | High |
| On-board location storage? | Yes | No | No |
| Number of download options? | High | Low | Low |

**GPS data download options and cost**

| Options[15] | Type | Frequency | Cost |
|---|---|---|---|
| Argos, Globalstar, Iridium, UHF or VHF | Satellite, satellite, satellite, non-satellite, non-satellite | Daily | Decreasing ↓ |
| Argos, Globalstar, Iridium, UHF or VHF | Satellite, satellite, satellite, non-satellite, non-satellite | Weekly | |
| Argos, Globalstar, Iridium, UHF or VHF | Satellite, satellite, satellite, non-satellite, non-satellite | Monthly | |
| SOB drop off | Non-satellite | No recovery | |
| SOB recapture | Non-satellite | On recovery | |
| GSM or GEO | Satellite | Daily, weekly, monthly | |

**Argos data download options and cost**

| Options | Type | Frequency | Cost |
|---|---|---|---|
| Argos | Satellite | Daily | Decreasing ↓ |
| Argos | Satellite | Weekly | |
| Argos | Satellite | Monthly | |

The data must be acquired using either a manual receiver or automatic VHF tower

**Figure 7.1.** Technology choice decision guide.

[1] The weight of a transmitter should be no more than 3 – 5 % of the body weight of the animal (Kenward 2001). The smallest GPS tracking device weighs 22 g, therefore, based on a an estimate of 3%, the animal must be at least approximately 700 g to wear one. Note: the 22 g GPS tracking device refers to a unit with satellite download capability (as per our case studies). However, smaller GPS tracking devices are available, weighing 5 g (recapture required for data download) and 15 g (download via Bluetooth but only have a 50 – 100 m range). If these technologies are viable, the weight restrictions should be adjusted accordingly.
[2] The smallest Argos transmitter (PTT) weighs 5 g, therefore the animal must be at least approximately 170 g to wear one (3% of body weight).
[3] The smallest VHF transmitter weighs 0.26 g, therefore the animal must be at least approximately 9 g to wear one (3% of body weight).
[4] Animals weighing less than 9 g are currently too small to track.
[5] Neither GPS or Argos transmissions can penetrate solid surfaces and could waste valuable battery power trying. Therefore, an estimation of the period of time spent in these black out areas should be made. It is possible for a duty cycle to be set in an attempt to target likely times outside of these areas. VHF is still not guaranteed but may provide more successful transmissions in these situations.
[6] Neither GPS or Argos transmissions can penetrate water. However, it may be that the research animal does not spend much time under water or the transmitter can be placed on the animal where it predominantly stays above water. An example of this is the estuarine crocodile where the transmitter was placed on the back of the neck, an area on the crocodile which stays above the water for much of the time.
[7] There are transmitters (pop-up archival) used in marine studies which utilize light-levels to calculate the location, then automatically release and transmit their data via Argos once above water. These kinds of transmitters can also calculate underwater dive depths. VHF is still not guaranteed but may provide more successful transmissions under water.
[8] GPS transmissions cannot always penetrate densely forested environments and there is a known effect on fix rate and signal precision from canopy closure and topographic complexity (Frair *et al*. 2010). However, newer GPS receivers have an improved sensitivity which may penetrate dense forest.
[9] Argos and VHF are still not guaranteed but may provide more successful transmissions in a densely forested environment.
[10] These requirements should be based on research objectives.
[11] Where a balance between weight and power requirements is necessary (small animals), it is possible you may not require the higher accuracy of the heavier GPS tracking devices, but rather your objectives are such that the lower accuracy from the smaller Argos will be sufficient. A good understanding of your project objectives should clarify this. For example, for small scale habitat analysis of 1 – 10 km, high accuracy is required. However, if only a large scale understanding of the home range is required, then a lower accuracy is sufficient. Whilst it would be prudent to always choose a high accuracy where possible, often due to weight restrictions or cost this is not possible. As well, when the animals' weight is borderline between use of either GPS or Argos tracking devices (around 700 g), if high accuracy is not required, then any undue stress on the animal due to a heavy transmitter should be avoided.
[12] GPS tracking devices are capable of calculating speed at the time of the location with a high level of accuracy. Speed and can still be calculated from Argos and VHF using point to point distance divided by time, however, the location error afforded by these technologies affects this.
[13] GPS tracking devices are capable of calculating the altitude at the time of the location.
[14] This disruption refers to the level of field work required.
[15] These are all options for downloading the data from GPS tracking devices. In contrast to Argos/UHF or VHF where an increase in download frequency increases cost, there is no change in cost for using the GSM or GEO option as a monthly fee is charged for these regardless of the number of downloads.

**Table 7.2. Features of** data download systems used with Global Positioning System (GPS) wildlife positioning tracking devices

| Feature | Argos | Iridium | Globalstar | GSM | GEO | VHF | UHF | Recapture | Drop-off |
|---|---|---|---|---|---|---|---|---|---|
| Remote data download | Yes | Yes | Yes | Yes | Yes | No | No | No | No |
| Automatic variable download frequency (eg. Daily, weekly or monthly) | Yes | Yes | Yes | Yes | Yes | No | No | No | No |
| Data download only possible in-field | No | No | No | No | No | Yes | Yes | No | No |
| Potential time-lag for data download[1] | Low | Low | Low | Low | Low | Moderate | Moderate | High | High |
| Disruption to animal | Low | Low | Low | Low | Low | High | High | Moderate | Low |
| Cellular coverage required | No | No | No | Yes | No | No | No | No | No |
| Geostationary satellite coverage required | No | No | No | No | Yes | No | No | No | No |
| Antenna/receiver required | No | No | No | No | No | Yes | Yes | Yes[2] | Yes[2] |
| 2-way capability to modify transmitter settings (eg. duty cycle) | No | Yes | No | No | Yes | No | No | No | No |
| Ease of animal location for sighting or if recapture required | Low[3] | Moderate[4] | Moderate[5] | Moderate[6] | High[7] | Moderate[8] | Moderate[9] | Moderate[8] | Moderate[7] |

[1] The time lag is the time between transmitter attachment and data download. Researchers using VHF and UHF methods often sight or capture animals for other reasons and can download data during those times.

[2] Only required for re-locating the animal and/or the collar.

[3] Often supplied with a VHF transmitter for locating the animal in the field but the battery for this may not last as long as the GPS or Argos transmission battery. However, depending on the regularity of the data download, it may be possible to locate the animal based on the latest GPS location.

[4] Often supplied with a VHF transmitter for locating the animal in the field but the battery for this may not last as long as the Iridium transmission battery. However, depending on the regularity of the data download, it may be possible to locate the animal based on the latest GPS location.

[5] Often supplied with a VHF transmitter for locating the animal in the field but the battery for this may not last as long as the GPS or Globalstar transmission battery. However, depending on the regularity of the data download, it may be possible to locate the animal based on the latest GPS location.

[6] Often supplied with a VHF transmitter for locating the animal in the field but the battery for this may not last as long as the GPS or cellular transmission battery. However, depending on the regularity of the data download, it may be possible to locate the animal based on the latest GPS location.

[7] Often supplied with a VHF transmitter for locating the animal in the field but the battery for this may not last as long as the GPS or geostationary transmission battery. However, it is possible to 'poll' these transmitters which can supply a GPS location within minutes. It is necessary to either have a networked laptop in the field or to have the location sent to a mobile phone for this to be effective.

[8] Location in the field using either a VHF receiver or by visual sighting is required to download the data.

[9] Location in the field using the UHF receiver used to download the data is required.

Tracking devices are powered by batteries that can be recharged with solar panels to extend the transmitter life or increase the regularity of locations. A guide to assist the researcher when deciding between solar or simple battery charge is presented in Figure 7.2.

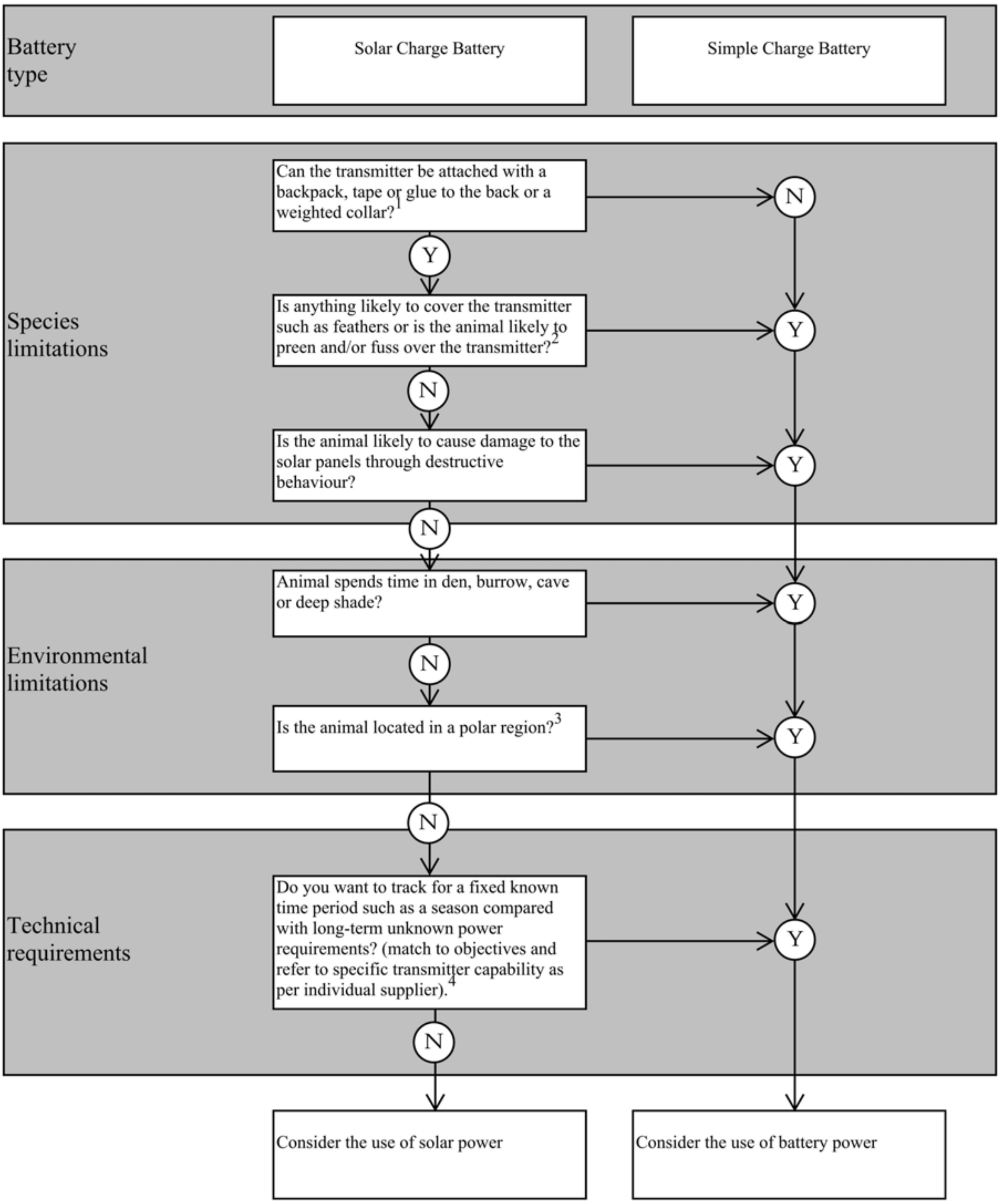



**Figure 7.2.** Technology choice decision guide for solar or simple battery charge.

[1] The solar panels on a transmitter need to be held upright at all times during attachment for maximum solar charge

[2] Solar panels need to remain clear of obstruction at all times during attachment for maximum solar charge.

[3] Solar panels are difficult to charge in the polar regions due to the low angle of the sun.

[4] Due to the risks involved in solar panel obstruction during attachment, where possible, battery should be used. If you only have short-term tracking requirements or longer-term (generally a year) with a duty cycle, a battery transmitter might be sufficient. However, for long-term studies (between 1 – 3 years), and where the risk of obstruction is minimal, solar transmitters could be suitable.

The African elephant study (Table 7.3) was designed to provide daily locations for five years in order to trace movement between two adjacent wildlife parks. The GPS/Geostationary (GPS/GEO) technology performed well for our purposes and we would choose it again based on the guide in Figure 7.1. However, due to the limited capacity of the built-in battery and the extended length of the project, we were limited to acquiring a single daily location thereby precluding any analysis of within-day movements. A solar powered battery would be ideal but current solar designs would likely not withstand the rigors associated with elephant behaviour and habitat.

**Table 7.3**. Total cost and cost per data point of wildlife satellite tracking case studies

| Species | Location | Tracking device | Total Cost per animal (US$)[1] | Cost per data point | Data points | Accuracy | Duty cycle | Data downloaded |
|---|---|---|---|---|---|---|---|---|
| Estuarine crocodile (*Crocodylus porosus*) | Northern Territory, Australia | Argos battery (300 g) | $8,545[2] | $51 | 166 | < 150 m | 24/96 | Every 6th day |
| New Zealand falcon (*Falco novaeseelandiae*) | Central North Island, New Zealand | Argos solar (18 g) | $8,260[3] | $55 | 150 | < 150 m | 10/48 | Every 3rd day |
| African elephant (*Loxodonta africana*) | Kruger National Park, South Africa | GPS/GEO (12.5 kg)[4] | $9,000[5] | $25 | 365 | < 20 m | One per day | Daily |
| Northern royal albatross (*Diomedea sanfordi)* | Taiaroa Head, New Zealand | GPS/Argos (30 g) | $7,000[6] | $5 | 1460 | < 20 m | 4 per day | Every 6th day |

[1] The costs used in this table were calculated as at the time of each case study between 2006 and 2009.

[2] Estuarine crocodile total cost includes transmitter $2200, capture/boat staff $1170, attachment materials $75, Argos tracking $1600, statistical analysis $3500. The manufacturer of this tracking device was Sirtrack Wildlife Tracking Solutions; Havelock North, New Zealand.

[3] New Zealand falcon total cost includes transmitter $3150, capture/attachment $350, Argos tracking $1260, statistical analysis $3500. The manufacturer of this tracking device was Microwave Telemetry Inc.; Columbia, Maryland, USA.

[4] Half of the weight of this collar (6.5 kg) consisted of a lead weight designed to keep the GPS receiver upright.

[5] African elephant total cost includes transmitter $3000, capture/attachment $4000, satellite time $500, statistical analysis $1500. The manufacturer of this tracking device was Africa Wildlife Tracking; Pretoria, South Africa.

[6] Northern royal albatross total cost includes transmitter $4000, capture/attachment $900, satellite time $600, statistical analysis $1500. The manufacturer of this tracking device was Microwave Telemetry Inc.; Columbia, Maryland, USA.

For our study of New Zealand falcons (Table 7.3) we required locations over a three-year period within a plantation forest. Adult and juvenile falcons weigh between 250 to 600 g, so we chose Argos. The solar panel powered devices performed well, despite the densely forested area. Had the transmitter been light enough, GPS would have been the preferred technology.

The objective of the estuarine crocodile study (Table 7.3) was to track movement within a riverine environment for at least one year. We used Argos which was consistent with the technology successfully used to track crocodiles by researchers in Queensland (Read et al. 2007). However, in hindsight and based on the guide in Figure 7.1, the GPS location acquisition technology would have been the preferred technology. This crocodile was large enough to have carried the heavier GPS transmitters and the environment was conducive to successful transmissions. The transmitter was placed on the back of the crocodiles neck, which generally remains above the water. Whilst solar charging the batteries would have been ideal to extend the life of the study, the aggressive nature of this species, coupled with the extremely harsh environment in which they live, makes this option unviable.

In another study we tracked the migration route of juvenile northern royal albatrosses from fledging through their first year at sea (Table 7.3). The solar charged transmitter provided four locations per day. The project was successful and the tracking devices with the Argos data download option functioned extremely well. The albatrosses were big enough to carry a heavier transmitter with a larger solar array which would have provided more positions per day, giving more detail of movements throughout the day, but our decision was to minimise the weight wherever possible.

### 7.4.2 Costs

We found that the total cost of tracking each of our study species for one year was similar, ranging between US$7,000 – US$9,000, depending upon which satellite tracking technology we used (Table 7.3). However, the cost per data point fluctuated widely, with the high number of locations in the albatross case study translating to the lowest cost per data point (US$5.00). By comparison, this was 25 % of the cost per data point of the GPS/GEO technology used on the African elephant and 10 % of that for the Argos tracking devices used on crocodiles and falcons. Longer term studies can reduce the tracking device costs further. The New Zealand falcon was tracked for three years, reducing the cost per data point from $53 in the first year to $38 in the third year. The African elephant was tracked for five years and the cost per data point declined from $25 after the first year to $12 by year five.

One year of data costs from each of our studies was compared with cost estimates of alternative tracking methods using the same number of locations (Table 7.4). We found Argos technology to be the most cost effective for tracking New Zealand falcons and the estuarine crocodile over one year, followed by GPS/Argos, whilst VHF and GPS/VHF were the least effective options. GPS/Global System for Mobile Communications (GSM) was identified as the most cost effective option for tracking the elephant, followed by the GPS/GEO, GPS/Argos and Argos options. Geolocation tracking technology was the most cost effective option for tracking the northern royal albatross, followed by GPS/Argos and Argos. In all our case studies, the use of VHF as either the location acquisition or data download method gave a cost per data point at least three times greater than that of alternative options. Despite the low initial cost of VHF transmitters, this method also requires high labour costs to support a tracker in the field.

**Table 7.4.** Total cost and cost per data point of wildlife satellite tracking case studies.

| | Cost per data point by technology option (US$)[1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Species** | **Argos** | **GPS/Argos** | **GPS/GEO** | **GPS/VHF** | **GPS/UHF** | **GPS/GSM** | **VHF** | **Geolocation** |
| Estuarine crocodile (*Crocodylus porosus*) | **51**[2] | 56 | n/a | 142 | n/a | n/a | 126 | n/a |
| New Zealand falcon (*Falco novaeseelandiae*) | **53** | 55 | n/a | 105 | n/a | n/a | 167 | n/a |
| African elephant (*Loxodonta africana)* | 26 | 26 | **25** | n/a | 287 | 21 | 4,018 | n/a |
| Northern royal albatross (*Diomedea sanfordi)* | 5 | **5** | n/a | n/a | n/a | n/a | n/a | 3 |

[1] These calculations are based on tracking the animal for one year and as near as possible obtaining the same number of data points and using the same data download frequency. The Iridium and Globalstar data download options are not included in this table because they were not available at the time of these case studies.
[2] Bold values indicate the technologies used in the case study.

Not all studies require a large sample of animal location points. For studies that require fewer than 15 locations, VHF is usually the most cost effective option because of low fixed costs, followed by Argos (Figure 7.3). For studies requiring a larger sample, GPS is the most cost effective tracking method. For our elephant study GPS/GSM was the most cost effective option, however, Argos, GPS/GEO and GPS/Argos were only marginally more expensive. For tracking the albatross, geolocation technology was the most cost effective option. After eight months, the GPS/Argos option becomes more cost effective than Argos.

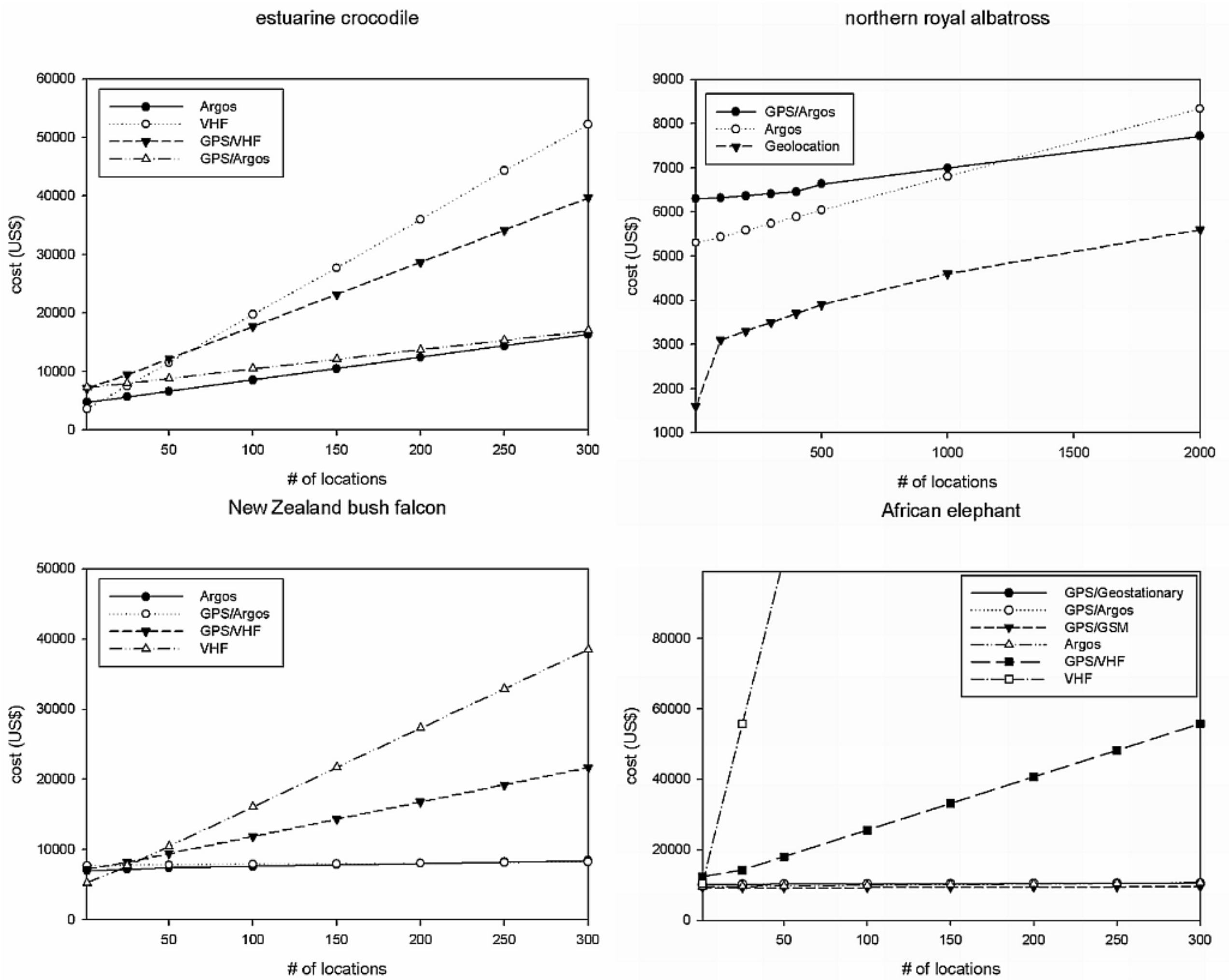



**Figure 7.3.** Cost comparisons between various tracking options.

## 7.5 Discussion

### 7.5.1 Technology

Free ranging animals can be tough on satellite tracking transmitters. Even where they remain attached to the animal, they are subject to extreme conditions and impact. Each species imposes its own challenges and each study requires varied performance. The uncontrollable nature of wild animals means the decisions in Table 7.1 and 7.2 do not always involve a simple yes or no response. Thus, knowledge of the behaviour of an animal is necessary to gauge the likely effect of that on the functioning of the transmitter. While transmitter success is never guaranteed, failure can be minimised with proper consideration of the variables and forethought.

Whilst GPS may be a preferred choice of tracking system, there are some exceptions. When field work is confined to a small area or where only a small number of locations are required, then VHF may be a better option. This is due to low transmitter costs, easy site accessibility and reduced operational costs. Potential other limitations to using GPS include their relatively heavy weight and potential effect on fix rate and signal precision from canopy closure and topographic complexity (Frair et al. 2010). However, newer GPS receivers have an improved sensitivity which may allow them to penetrate dense forest.

Sometimes the benefits of using GPS are outweighed by an animal's physiology or environmental limitations. In these cases we suggest that it may be necessary to compromise on the objectives, or that tracking may not be an appropriate use of conservation funding. For example, the researcher may require a very high location accuracy, but the guide may suggest the use of Argos due to the weight of the animal. A compromise may involve no longer expecting high accuracy locations for fine-scale analysis, which may be possible for a long distance migrant. Another option may be to select a larger member of the species such as an adult to enable the use of GPS. Argos transmitters are smaller and lighter than GPS but with a lower accuracy (Britten et al., 1999). A limitation of the Argos technology is the evidence of reduced satellite performance in Southern Europe and Central Asia (Dubinin et al. 2010). Despite this, Argos transmitters are especially effective when tracking avian species and for transmitting data related to marine species (Hays et al. 2001). VHF has the least functionality of all options and is the most disruptive to the animal due to human presence (Cooke et al., 2004). However it is the lightest and smallest tracking device of the three and is still used to track very small animals or those with a small home range (Naef-Daenzer et al., 2005). This low weight, however, is offset by variable accuracy due to the dependence on both instruments and the skill of the operators to acquire locations.

New developments over the last few years have seen the testing and use of new wildlife satellite tracking options not available at the time of our case studies. 'Fastloc' is a type of GPS unit that does not require GPS ephemeris or almanac information, allowing animal location data to be obtained almost instantly, particularly useful for the marine environment. Two satellite systems, Globalstar and Iridium, have recently been incorporated with wildlife GPS tracking devices as remote data download options, providing an alternative to Argos (Tomkiewicz et al. 2010). However, whilst the smallest GPS/Argos tracking device weighs 22g, the smallest GPS/Globalstar and GPS/Iridium devices range between 600 to 800g, making them suitable for large terrestrial species only.

It should be noted that as transmitter weights decline, the species weight restrictions in Figure 1 should be adjusted accordingly. At the time of this research, the smallest Argos PTT satellite transmitter available weighs 5 g and the smallest GPS transmitter available with satellite data downloading capability weighs 22 g, limiting the weight of tracked animals to 170 g. They will continue to reduce in size as technology improves, increasing accuracy, location acquisition and data download frequency, whilst also reducing in price.

#### 7.5.2 Costs

Wildlife tracking technology costs vary considerably. Whilst this paper discusses cost per animal and cost per location, the total cost of a tracking project is predominantly influenced by the number of animals to be tracked, dependant on the project objectives. Some studies suggest a minimum sample size of 30 as optimal and that the number of individuals not the number of locations per individual is important for making statistical inference at a population level (Aebisher et al. 1993; Hebblewhite et al. 2010).

Tracking device costs can also be reduced when more than one animal is being tracked. With larger sample sizes, the highest cost savings would be from VHF because the marginal costs of field work decline as study animal numbers rise (as long as animals are in the same general area). When using Argos or GPS, the cost of tracking additional animals would not significantly reduce the cost per animal. This does not mean that VHF tracking is always cheaper or even feasible when more animals are being tracked, just that cost savings may accrue.

The total cost of VHF tracking studies can be difficult to calculate because in addition to the fixed cost of the tracking devices, the field work costs required for calculating the location can be variable and change with each project (Girard et al., 2006). When using

GPS, however, the marginal cost to finding additional location points is effectively nil. For tracking the albatross and elephant, increases in the number of locations would not have resulted in an increase in cost; rather, the number of locations acquired were limited by the battery capacity and storage size. The cost of calculating locations using an Argos system would generally be between the cost of VHF and GPS methods. Users of the Argos system pay for the 'on' time or time used to calculate positions. Therefore, an increase in the number of locations in the crocodile and falcon studies would have increased the total project cost. Part of this added functionality, in terms of the capability to calculate positions for no extra cost, such as with GPS, is directly realised within the initial transmitter cost. Whilst GPS tracking devices have no location acquisition cost, they are the most expensive.

Both Argos and VHF location acquisition methods use inbuilt download systems. For GPS location acquisitions, however, there are several download options and cost savings may be made here. For research that does not require locations to be downloaded regularly, a manual download method such as VHF, GPS/Store on Board (SOB) drop-off or recapture is likely the most cost effective. It should be noted, however, in addition to the risk of data loss associated with irregular downloads, there can be added cost if there is difficulty in locating an animal or its drop-off collar (Lizcano and Cavelier, 2004). For research requiring a regular download schedule, a remote method such as GSM, GEO, Argos or more recent systems such as Iridium or Globalstar are suggested. Both our crocodile and falcon studies utilised Argos transmitters and any increase in the data download frequency would have increased costs. The falcon data were downloaded every third day and the crocodile every sixth day, because of the transmitter's battery charge. It should be noted that although the use of light-based geolocation would have been a cheaper option for tracking the albatross, this method has questionable location accuracy and downloading the data can be difficult for some researchers, possibly requiring additional analysis (Shaffer et al. 2005), thereby increasing the total costs. Further, the albatross would have had to be recaptured to download the data. This can be difficult for juveniles who can take five to eight years to return to their breeding ground.

The geostationary satellite system used to download the data in the elephant study incurred a monthly charge irrespective of the transmission rate. For the elephants, it was possible to remotely reconfigure (2-way) the download schedule with the only limitation being the life span of the batteries. The albatross GPS data were downloaded every sixth day (using Argos) because the transmitter's memory could only store the last 24 location points (four per day). This limitation can dictate the regularity of data downloads, however GPS tracking devices with manual data download options do not have these limitations and are often able to store a higher number of locations on board (Tomkiewicz et al., 2010).

The more recent satellite download options of Iridium and Globalstar were not compared directly in Table 4 as they were not available at the time of these case studies. However, their current costs are likely to make them the cheapest data download options for GPS data but their heavier weights still restrict them to very large terrestrial animals only.

In some instances, researchers have reduced costs by manufacturing their own GPS tracking devices. Zucco and Maurao (2009) developed GPS harnesses to track pampas deer in Brazil for half the cost of a commercial tracking device. They spent US$2,262 to deploy four adapted GPS radio collars on 19 deer, obtaining 31,596 fixes at five minute intervals, giving a cost per data point of US$0.07. Mourao and Medri (2002) also developed a GPS tracking device to track a giant anteater (*Myrmecophaga tridactyla*) in Brazil and spent US$490 (including GPS and VHF), obtaining 1373 fixes over 215 hours. Limited budgets often force researchers from developing countries to use alternative materials and adapt tracking devices that are bought off the shelf. However, when costs of researcher built systems are compared to commercial systems, it is important that the cost of design, build and test are is also included by the researcher. Unexpected transmitter failure can cause significant increases in total research costs, not to mention lost time and data. Thus, more expensive systems may be more cost effective over all if they are robust and provide more accurate data.

## 7.6 Conclusions

In this paper we presented guidelines for choosing the best wildlife satellite tracking technology, assessed them based on four case studies and discussed the cost of each technology. It is not intended that the specific details discussed and used for comparison of different tracking methods be the focus, rather the emphasis is on the process and considerations necessary for selecting the most appropriate technology.

GPS technology is generally preferable to other wildlife tracking methods due to its ability to provide more frequent and precise locations (Dodd et al., 2007). It also has a higher number of data download options. However, its limitations include greater size and weight, and reduced performance under forest canopies, underwater and underground. Where these limitations prevent the use of GPS, alternatives such as Argos or VHF are usually adequate, notwithstanding their lower accuracy and transmission rates.

GPS technologies can be very cost effective over medium and long-term studies. Nevertheless, VHF is still the cheapest option for very short-term studies where a low number of locations is needed or when field work is practical and required anyway. However, consideration of the costs and benefits of alternative methods can be complex and should be assessed on a project by project basis.

This paper is very time sensitive. With new advancements such as GPS ‘fastloc’, SS technologies, new data download options, continued weight reductions in satellite technology and increased sensitivity of satellite technology, the decision making process of how to choose the best technology for a research project will simplify. Costs will also continue to change and impact cost per data point and overall project costs. As the technology becomes more cost effective and accessible, the amount of data on animal movement and behaviour will increase. It will then be the responsibility of the researcher to ensure that the appropriate data analysis is conducted to ensure important ecological and conservation objectives can be addressed.

## 7.7 Acknowledgements

We gratefully acknowledge the Institute of Natural Resources, Massey University and the New Zealand Lotteries Grants Board. As well, we acknowledge the invaluable contributions of the organisations involved in each case study. These include Kruger National Park, South Africa; Sabi Sand Game Reserve, South Africa; Wingspan Bird of Prey Trust, New Zealand; Raptor Association of New Zealand; Kaingaroa Timberlands Ltd, New Zealand; Department of Conservation, New Zealand and the Parks and

Wildlife Service, Northern Territory, Australia. The individual contributors are acknowledged within each case study publication.

# CHAPTER 8: Conclusions and recommendations

## 8.1 Introduction

The aim of this study was to assess the technology and conservation benefits derived from satellite tracking diverse endangered species. To achieve this aim, four case studies were undertaken providing an assessment of the conservation benefits and technical effectiveness of satellite tracking.

Through these case studies, this research has revealed important ecological insights on the *in situ* movement and behaviour of the African elephant (*Loxodonta Africana*), Kruger National Park, South Africa, the New Zealand bush falcon (*Falco novaeseelandiae*), Central North Island, New Zealand, the estuarine crocodile (*Crocodylus porosus*), Darwin, Australia and the northern royal albatross (*Diomedea sanfordi*), Taiaroa Head, New Zealand and Chile. This research has also identified and discussed the strengths and weaknesses of the different types of satellite tracking technology currently available and compared its cost effectiveness with alternative tracking options. Guidelines were developed to assist wildlife managers in selecting the most appropriate technology to achieve their research objectives.

Each case study had unique aims and objectives that combine to give a larger message, offering useful insights for wildlife managers and researchers. In addition, papers in twenty-two peer reviewed wildlife conservation journals published between 1999 and 2009 were reviewed. This search identified 150 published papers where satellite tracking had been used, as shown in Appendix 1. Insights from the assessment of these papers are used to supplement this larger message.

In this chapter, the research is placed into a wider context to allow for conclusions and recommendations on the use of wildlife satellite tracking technology and its contribution to conservation. Suggestions for further work are also made based on this research.

## 8.2 Conclusions

The conclusions arising from this research relate to the contribution to conservation, limitations and the future development possibilities of satellite tracking technology.

### 8.2.1 Contribution to conservation

This section focuses on how the application of satellite tracking technology can contribute to species management and to increased education and public awareness of endangered species.

#### *8.2.1.1 Species management*

Wildlife satellite tracking is making a substantial contribution to species management and conservation. Whilst this technology is only one tool available to wildlife researchers, it is a powerful one. Alternatives are often constrained by low accuracy, effects of the disruptive human presence in an animals' territory and high field costs. Satellite technology can provide cost effective, consistent and highly accurate locations on a free-ranging animal during the day and night, throughout all seasons and in almost any environment.

Ecological studies have evolved from describing the movements of only a few individuals to more complex analysis and problem solving (Webster et al., 2002) and wildlife researchers now have the ability to understand more about the behaviour of a wide range of diverse endangered species. These include dangerous and aggressive species (Chapter 6), far-ranging pelagic species located in inaccessible environments (Chapter 5), large socially developed terrestrial species in confined areas (Chapter 2 and 3) and small avian species adapting to plantation forests (Chapter 4).

The wide range of species tracked with GPS and Argos technology vary from small avian species, such as the New Zealand falcon (*Falco novaeseelandiae*) to large terrestrial animals such as the African elephant (*Loxodonta Africana*). The most commonly tracked species include the albatross (11 different species) followed by bear (*Ursus maritimus, Ursus americanus and Ursus arctos*), wolf (*Canis Lupis, Chrysocyon brachyurus and Canis lycaon*), deer (*Odocoileus virginianus, Capreolus capreolus, Ozotoceros bezoarticus and Odocoileus hemionus*), elephants (*Loxodonta africana and*

*Loxodonta cyclotis*) and eagles (*Haliaeetus leucocephalus, Aquila chrysaetos, Hieraaetus fasciatus, Haliaeetus pelagicus and Aquila nipalensis*) (Appendix 1). GPS was the most common method employed to track larger terrestrial animals and Argos systems were the most popular technology choice to track smaller avian species (Appendix 1). As GPS units are larger and heavier than the Argos systems, these results suggest that generally, other researchers have applied this technology on the appropriate species.

The increase in use of animal tracking systems such as those used in this study has lead to an increase in the number of ecological questions being answered. In addition to the ability to identify specific behaviour and movement patterns, the application of this technology is being used with increasing success to investigate activities such as migration, human-wildlife conflict, relocation/reintroduction and species-prey interaction (Appendix 1). In particular, we now have the ability to obtain scientific evidence on a range of issues such as response to natural gas development, fisheries and oceanic pollutant concentrations as well as scientifically perplexing questions like homing instinct and geomagnetic capability.

Where this technology is used appropriately and effectively, an improved understanding of how and why animals move and use resources can be expected, enabling us to answer important ecological questions, contributing to wildlife conservation.

#### *8.2.1.2 Education and public awareness*

In addition to the direct ecological contributions to conservation obtained from satellite-based tracking information, there are also additional benefits such as increased education and public awareness. Conservation organizations' objectives often include these indirect benefits, whereby they try to promote conservation and educate the public on endangered species issues. The estuarine crocodile study was the first of its kind in the Northern Territory and had local, national and international media coverage. The results of the study were updated on a dedicated website every five days to enable scientists, park managers and members of the public to follow the project's progress.

There was also public interest in the website dedicated to tracking 'Toroa', one of the juvenile northern royal albatross tracked at the Taiaroa Head albatross colony. The lineage of this particular bird was of interest to the public because his grandmother was well known, having successfully raised 13 chicks during her 61 years at the colony. The media took interest in the research and the tracking results were regularly updated on the internet, increasing the profile of this species as well as the conservation issues it faces. Both of these satellite tracking projects received interest and questions from schools, families and other members of the public.

As well as the near real-time data generated by satellite tracking projects, the visual and interactive presentation of the locations can significantly improve information exchange and access and ultimately learning. These characteristics are not only beneficial to researchers interpreting the results, but for the dissemination of this information for other educational programs, such as schools. Increasing education and public awareness of any conservation issue can lead to increased support of conservation initiatives and policies.

### 8.2.2 Limitations

This section focuses on potential limitations of satellite tracking technology related to species size, sample size and fieldwork.

#### *8.2.2.1 Species size*

The technology used in this study allowed us to track a variety of species ranging in weight from a 250 g falcon to a 6500 kg elephant, providing an immense wealth of ecological information. However, due to the generally accepted rule-of-thumb that transmitters weigh no more than 3 – 5% of the weight of the animal (Kenward 2001), currently only animals weighing more than 170 g can be tracked with satellite transmitters. Other tracking methods used on these smaller animals include VHF, fluorescent powder tracking (Violaine and Marc, 2007) and light-based geolocation (Shaffer et al., 2005). However, there are concerns about the accuracy of these methods and the usefulness of them when the animal is located in inaccessible terrain or moves over long distances.

#### *8.2.2.2 Sample size*

Sample size has a direct effect on the strength of population inferences and due to the high cost of satellite tracking equipment, the sample size per tracked population can be low (Hebblewhite and Haydon, 2010). Webster et al. (2002) recommend that where population level conclusions are made from small sample sizes, that they be supported with additional information such as surveys, other forms of marking (banding) or genetics data. Lindberg and Walker (2007) suggest that if the correct sample size cannot be obtained due to burgeoning costs, the researcher should either change the research objective or use the money for other biological studies.

#### *8.2.2.3 Fieldwork*

Notwithstanding the benefits associated with remote tracking technology in obtaining wildlife movement data in otherwise inaccessible terrain, the importance of fieldwork should not be underestimated (Coelho et al., 2007, Lindberg and Walker, 2007). Relying solely upon remotely acquired animal location data only explains a part of an animal's biology. Location data needs to be augmented with environmental and behavioural information that comes from field observations of the animal, digital sources such as Geographic Information Systems (GIS) data layers and remotely sensed digital images. There are unique ecological benefits to be gained from time spent in the environment of the research animal that cannot be obtained from satellite tracking technology.

### 8.2.3 Future of satellite tracking technology

Wildlife satellite tracking technology is yet to reach its full potential. It is still developing towards miniaturised real-time GPS tracking units. Transmitters with additional functions like video cameras and sound recorders are likely to be common features in the future. It is likely there will be low cost units small enough to fit on any animal.

GPS transmitters show the most promise for the future, and the technology is establishing itself as the chosen location acquisition method, not just within wildlife tracking applications, but in many other parts of every day life. Fastloc™ is a type of GPS unit, specially designed for use on species within the marine environment. Fastloc™ does not require GPS ephemeris or almanac information to operate and, consequently, does not have the long cold and warm start times of traditional GPS receivers. Therefore, it allows animal location data to be obtained almost instantaneously, for example, during a brief ocean surfacing period.

Two satellite systems, Globalstar and Iridium, have recently been incorporated with wildlife GPS tracking devices as remote data download options, providing an alternative to Argos (Tomkiewicz *et al*. 2010). Only a few companies build tracking devices with these options, Northstar Science and Technology, LLC, Virginia, USA and Lotek Wireless Inc., Ontario, Canada for Globalstar and Advance Telemetry Systems, Minnesota, USA and Lotek for Iridium. However, whilst the smallest GPS/Argos tracking device weighs 22g, the smallest GPS/Globalstar and GPS/Iridium devices range between 600 to 800g, making them suitable for large terrestrial species only. Being able to remotely change the settings of the tracking device (2-way communication) is currently available with Iridium and Argos, but this functionality makes these devices heavier.

Alternative methods for data download are still being developed and trialled. Cellular technology is already being used and holds substantial promise for the future as coverage to remote parts of the world improves. Juang et al. (2002) have trialled a wildlife GPS tracking unit that downloads its data via a wireless sensor network using ‘peer-to-peer’ networking techniques without using a cellular phone service or other widely available telecommunications support. Schwartz et al. (2009) have trialled a new data download method whereby GPS locations are downloaded with a new system of data transmission that uses spread spectrum (S-S) technology utilising the 902–928 MHz bandwith range. This technology takes advantage of spreading information across many channels, potentially providing an improvement over narrow-band frequency methods such as VHF or UHF and other tracking systems such as cellular and satellite (Argos).

At the time of this research, the smallest Argos PTT satellite transmitter available weighs 5 g and the smallest GPS transmitter available with satellite data downloading capability weighs 22 g, limiting the weight of tracked animals to 170 g. They will continue to reduce in size as technology improves, increasing accuracy, location acquisition and data download frequency, whilst also reducing in price. There is also a 15 g GPS transmitter available, however it utilises Bluetooth technology for the remote download of the data, limiting its’ range to 50 – 100 m. More recently, 2.5 and 5 g GPS transmitters have become available but are limited to one location per day and do not allow for remote download.

Whilst satellite tracking technology is not a panacea for solving all wildlife management issues, it is providing wildlife researchers with a significant library of once unexplained ecological behaviours of many diverse endangered species. By incorporating these into management plans we can reduce the knowledge gaps and contribute to high level conservation goals.

## 8.3 Recommendations

The recommendations arising from this research relate to the use of the technology, the importance of collaboration, making the results available to the public and suggested future research.

### 8.3.1 Technology

Choosing between the varied wildlife tracking options whilst taking into consideration the cost effectiveness of each can be difficult. For medium to long-term studies, this research recommends that GPS technology is the preferable location acquisition method because it can consistently acquire accurate locations (Witt et al. 2010). This option also provides the most data download options.

However, while GPS usually provides more frequent and accurate locations, it is limited by battery size and weight and the signal can be blocked by environmental obstructions. Where these limitations prevent the use of GPS, technologies with less functionality can be used, such as Argos or VHF.

GPS technologies can be very cost effective over medium and long-term studies, however, VHF is still the cheapest option for studies of a short duration, where fewer locations are needed or when field work is required.

### 8.3.2 Collaboration

Collaboration between organizations and individuals is key to the success of wildlife satellite tracking projects. In this study these included national parks, government conservation agencies, research institutions, technology manufacturers, satellite service providers, veterinarians and field rangers.

Due to the remote nature of the areas where this technology is employed, the research area is often not accessible to researchers. In these situations, collaboration with the local conservation agencies can provide vital information on the status of the animal and tracking device.

In a wider context, due to the global nature of this technology, many migratory or far ranging species can cross a number of international boundaries. In such instances, collaboration between governments may be necessary.

Collaboration in these research projects is often mutually beneficial. Access to sensitive areas and endangered species along with experience in capturing and handling species is often provided to researchers, whilst the agencies managing these areas can derive benefit from specialised knowledge and the use of expensive technical equipment and analysis software. Agencies managing these remote areas can be in isolated areas and from developing countries where funding is a serious issue. In these instances, this kind of collaboration provides access to funds, information and tools they might otherwise not have. Other benefits of collaboration include expert and local advice when interpreting movement data, improved access to local digital GIS layers for analysis, the exchange of new ideas and increased sample sizes.

Collaboration can be encouraged in a number of ways. These include contacting the relevant agencies prior to project initiation, acquiring the appropriate permits, providing regular location data updates to the local agencies and making the results available on completion of analysis.

### 8.3.3 Disseminate tracking results into the public domain

Due to the potential for increased education and public awareness of conservation issues from using this technology, it is also recommended that researchers and/or conservation organizations make the tracking data available to the public in a non-scientific format. This may be via dedicated websites, media or directly through conservation agencies. Whilst this does require extra time, it is necessary to take full advantage of the potential conservation benefits this technology can provide.

As well as making the scientific results available to the researchers involved in species and park management, it may also be useful to make these available to the more discerning members of the public. Open access journals are becoming an important medium for providing access to scientific peer-reviewed research findings to a wider audience due to there being no cost involved in accessing the papers.

### 8.3.4 Suggested further work

Below are suggestions for future work which may improve the application of satellite tracking technology for the researcher and tracked species, benefiting the overall conservation goals.

#### *8.3.4.1 Continued Research and Development*

Whilst efforts are always made to reduce the impact on individual animals from carrying tracking devices, the reality is that it can only be minimised but not avoided. Therefore, the continual development of this technology to reduce the size and enhance the functionality is important for animal welfare considerations.

Researchers can play an important role in this by including an analysis of the *in situ* technical effectiveness of this technology in their study within reports and published work, and make recommendations for improvement. This will provide manufacturers with valuable feedback on the current effectiveness of this technology and ideas for future developments.

#### *8.3.4.2 Create a centralised database*

The creation of a centralised global database to promote collaboration and data sharing of spatial species movement data would be of significant benefit to researchers. The raw data or the metadata associated with satellite tracked species could be supplied and maintained within a central location. This could increase sample size and encourage the reuse of data in situations where another researcher may have improved analysis skills. If researchers could accurately verify the spatial data that has already been obtained by others and highlight any information gaps related to their research species, they would be better equipped to tailor their data needs to avoid repetition, wasted funds and time.

Some isolated initiatives to collate large volumes of geospatially referenced data on certain types of species are already in use. The OBIS-SeaMAP programme (http://seamap.env.duke.edu/) is a database repository of historical tracking and survey data for birds, reptiles and marine mammal studies. Coyne et al. (2005) and the Tagging of Pacific Pelagics (TOPP; http://toppcensus.org/) created a database combining tracking data from marine mammals, birds, sea turtles, fish and shark species, with remotely sensed environmental data such as Sea Surface Temperature and Chlorophyll content available to its' users. By using a set of standardised data processing criteria, Birdlife International have integrated spatial albatross data from many different studies, encouraging data sharing and collaboration between researchers. This has enabled them to identify specific species and specific age groups of albatross whereby tracking data is missing, directing efforts to those areas.

#### *8.3.4.3 Focus on eco-regions*

Conservation agencies, such as Conservation International (Conservation International 2010) believe that preservation efforts should focus on two types of territories; tropical wilderness areas untouched by humanity, and 'biodiversity hot spots', areas rich in animal and plant species. Brooks et al. (2002) found that if priority and conservation funding was placed on protecting the world's biodiversity hotspots, over half the worlds species could be protected. Olson & Dinerstein (1998) maintain that conservation priorities should focus on protecting the eco-regions, rather than on single species. Whilst the designation of a protected area can be based on the habitat requirements of a single species, such as umbrella, keystone or indicator species ((Mills et al., 1993, Caro and O'Doherty, 1999, Mac Nally and Fleishman, 2002), the use of satellite tracking technology can divert the attention of researchers to focus on a single species rather than biodiversity as a whole. Therefore, further work could focus on large scale projects involving large eco-regions where a range of species could be identified and this technology used to learn about their behaviour individually and their interactions as part of the eco-region.

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# Appendix 1

Review of twenty-two peer reviewed wildlife conservation journals (150 published papers) with articles published between 1999 and 2009 where satellite tracking had been used.

| Main research objective[1] | Studies where GPS tracking technology was used (N)[2] | References[3] | Studies where Argos tracking technology was used (N)[4] | References |
|---|---|---|---|---|
| Behaviour[5] | 20 | *1, 6, 13, 16, 17, 19, 28, 30, 52, 52, 55, 67, 69, 70, 94, 98, 100, 105, 113, 138* | 19 | *11, 20, 29, 34, 54, 58, 59, 62, 77, 78, 82, 83, 91, 107, 116, 122, 134, 140, 141* |
| Homing[6] | 6 | *9, 25, 26, 41, 86, 146* | 2 | *8, 93* |
| Migration | 1 | *42* | 18 | *2, 32, 57, 61, 65, 73, 74, 76, 80, 81, 84, 89, 99, 101, 103, 124, 128, 133* |
| Movement[7] | 12 | *4, 10, 15, 31, 43, 63, 64, 88, 92, 114, 118, 119* | 8 | *56, 63, 79, 85, 108, 127, 129, 145* |
| Population dynamics[8] | 1 | *106* | 4 | *3, 33, 102, 117* |
| Relocation/reintroduction | 2 | *66, 120* | 1 | *125* |
| Response to human activity[9] | 6 | *7, 38, 50, 87, 112, 126* | 9 | *36, 37, 40, 60, 95, 130, 136, 137, 143* |
| Species-prey interaction[10] | 11 | *23, 24, 27, 39, 44, 45, 51, 110, 111, 135, 147* | 1 | *144* |
| Technical evaluation[11] | 23 | *5, 12, 14, 18, 21, 22, 35, 46, 47, 48, 49, 68, 71, 72, 75, 90, 97, 109, 115, 121, 131, 132, 142* | 5 | *96, 104, 123, 131, 139* |
| **Species Type[12]** | | | | |
| Albatross | 1 | *131* | 19 | *36, 37, 60, 93, 96, 104, 116, 122, 131, 137, 140, 141, 144* |
| Bear | 13 | *31, 44, 45, 46, 47, 55, 72, 75, 109, 115, 126, 138* | 4 | *3, 77, 78, 85* |
| Deer | 14 | *1, 7, 12, 18, 22, 27, 35, 68, 97, 112, 113, 149* | 0 | |
| Eagle | 2 | *121* | 8 | *82, 83, 84, 89, 91, 133, 134* |
| Eider | 0 | | 4 | *99, 101, 102, 103* |
| Elephant | 8 | *10, 17, 30, 42, 50, 70, 118, 119* | 4 | *11, 29, 125, 136* |
| Elk | 5 | *23, 24, 28, 39, 147* | 0 | |
| Falcon | 0 | | 5 | *56, 81, 123, 124, 128* |
| Goose | 0 | | 4 | *57, 58, 75, 117* |
| Osprey | 0 | | 6 | *2, 32, 76, 127, 128* |
| Petrel | 0 | | 6 | *8, 34, 40, 130, 143* |
| Pigeon | 6 | *9, 25, 26, 41, 86, 146* | 0 | |
| Wolf | 13 | *4, 6, 21, 27, 51, 87, 88, 90, 110, 111, 142* | 2 | *63, 139* |
| Other | 31[13] | | 23[14] | |

[1] The main objective of each study was identified.
[2] Fifty-two percent of the total studies used GPS tracking technology.
[3] A full reference list is below.
[4] Forty-eight percent of the total studies used Argos tracking technology.
[5] This group includes research on faecal marking, mating strategy, social structure, social dynamics, reproduction, mortality, survival, habitat selection, search effort, seed dispersal, foraging success, edge association, emotional connection, biomechanics, corridor use and highway permeability.
[6] This group includes research on geomagnetic field importance and trained bird homing.
[7] This group includes research on home range, spatial distribution, ranging patterns, seasonal analysis, wind selectivity, identification, important sites, grazing and directed movement.
[8] This group includes research on structure, estimates, boundaries and DNA.
[9] This group includes research on natural gas development, response to military activity, response to land-use types, human presence conflict, hunting pressure, fisheries interaction and locations of oceanic pollutant concentrations.
[10] This group includes research on locations of kill sites and predation risk.
[11] This group includes research on location accuracy, location fix success, comparison of analysis methods, testing new technology and attachment success.
[12] The species type for each study was identified. The numbers associated with this are the number of species. This is more than 150 due to some studies involving more than one species eg. species-prey interaction studies or more than one sub-species eg. albatross.
[13] The 'other' species group tracked using GPS technology includes anteater (N = 1, Reference # *92*), baboon (1, *98*), bison (2, *16, 38*), bobwhite (1, *52*), booby (1, *131*), brant (1, *132*), buffalo (1, *5*), bull (1, *13*), caribou (2, *51, 63*), cattle (3, *43, 105, 114*), chickadee (1, *53*), cougar (1, *67*), giraffe (1, *64*), goat (2, *71, 106*), horse (3, *66, 100, 120*), kangaroo (1, *19*), lion (1, *135*), moose (2, *48, 49*), nightingale (1, *94*), panther (1, *69*), sheep (1, *105*) and zebra (2, *14, 15*).
[14] The 'other' species group tracked using Argos technology includes bat (N = 1, reference # *107*), buzzard (2, *128, 148*), crane (2, *65, 133*), flamingo (2, *80*), flying fox (1, *33*), fox (1, *29*), frigatebird (2, *145*), gazelle (1, *61*), golden-eye (1, *108*), ibis (1, *73*), leopard (1, *79*), mollymawk (1, *95*), murre (2, *54*), puffin (1, *54*), spoonbill (1, *133*) and stork (4, *20, 59, 62*).


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