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Home range and movement patterns of an Estuarine Crocodile *Crocodylus porosus*: a satellite tracking pilot study

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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 of 63 km^2 and a 95% kernel area of 8 km^2. 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, with an increased number of location readings occurring between 2000 and 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.

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. porosus* 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 3,000. The import and export of crocodile skins and products was banned in 1971 which effectively ended this exploitation (Messel & 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 to 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 (Leach *et al.* 2009). An understanding of crocodile home range and movement patterns could provide information for improving these programs and be a basis for developing sound management strategies. Unfortunately, aggressiveness of the species and the 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 & Connors 2006).

Prior to 2001, all data on movement of Estuarine Crocodiles were obtained using mark and recapture methods (Webb & 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 an area near Darwin, as well as to test the attachment of a transmitter and evaluate the effectiveness of satellite technology for monitoring this species. 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.

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.

Methods

The research area was the Adelaide River, located approximately 100 km east of Darwin, Northern Territory (Figure 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.

Platform Transmitter Terminals (PTTs) send a signal via the Argos® satellite system (CLS, 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, 1 km for LC 1 and >1 km for LC 0 (Collecte Localisation Satellites 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 <1 km (LC 3, 2 and 1) were used for analysis.

The tracking unit measured 120 mm (L) x 32 mm (W) x 24 mm (H); it weighed 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 had other battery preservation features, including a salt water switch activated by

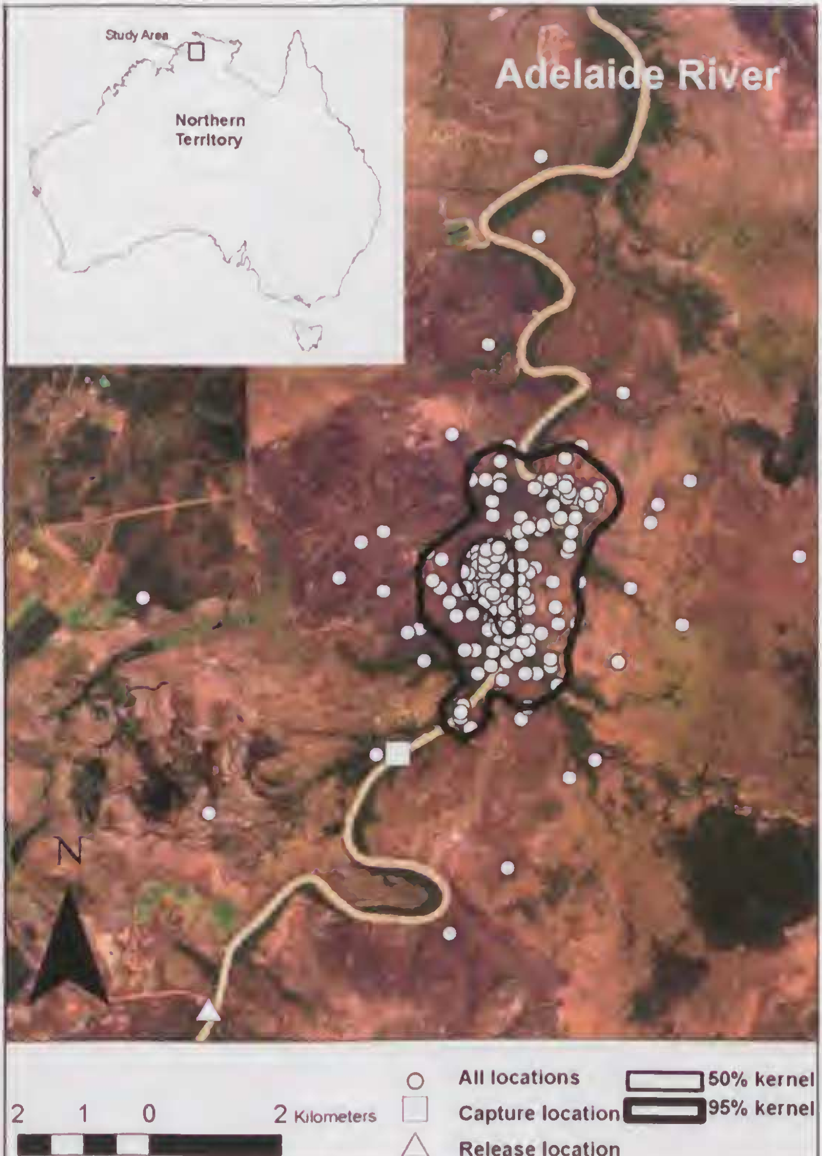

Figure 1. Satellite image map showing LC 3, 2 and 1 locations of *Crocodylus porosus* in the Adelaide River area, approximately 100 km east of Darwin, between 13 July and 31 December 2005. The capture location was *c.* 80 km inland from the mouth of the river. Accuracy of locations is LC 3 ± 150 m, LC 2 ± 350 m and LC 1 ± 1 km.

salinity levels. This prevented transmission when the transmitter was submerged in water, or it was out of water for longer than 4 hours, and allowed transmission to resume upon resurfacing or re-entering 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.

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 (DEWHA 2003). 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 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 (Kay 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 a 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 ml 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 2). The wire was then secured by using standard lead crimps that degrade over time to release the transmitter and wire.

Figure 2. Image showing the study animal (*Crocodylus porosus)* during the attachment of the Platform Terminal Transmitter. The plastic coated stainless steel wire is being threaded through the holes in the nuchal shields. (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), but transmission ceased after six months. Movement during the dry and build up to the wet seasons was therefore covered. Between July 2005 and December 2005, locations of the crocodile 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). Data locations were recorded in latitude/longitude WGS84, and transformed to Universal Transverse Mercator (UTM) zone 53 S for analysis. 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 area of the home range, Minimum Convex Polygon (MCP) and kernel were calculated using the Animal Movement Analyst extension to ArcView (Hooge & Eichenlaub 1997). MCP estimators are thought to overestimate space use (Kenward 2001), but 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 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, to allow 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 was the ratio of distance travelled (metres) 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 precipitation during the 24 hours prior to 0900 h local time on the day of the location; this was 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 0900 reading, and locations falling between midday and midnight were assigned the 1500 reading.

Results

Performance of the technology

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

The transmitter, with its pre-programmed duty cycle, was activated at 0020 h on 13 July 2005. The transmitter performed well, sending in 24 hours of data every fifth day without fail, which equated to 34 download periods or full days of tracking. A higher number of LC 3, 2 and 1 locations were received between the hours of 2000 and 0700 than at other times (Figure 3). The time of the first location obtained during each 24 hour download period ranged from 0026 to 1706 h, 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 to 13 hours.

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, but also non-significant relationship was seen with battery voltage levels over time (r^2 = -0.025).

Crocodile movements

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

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

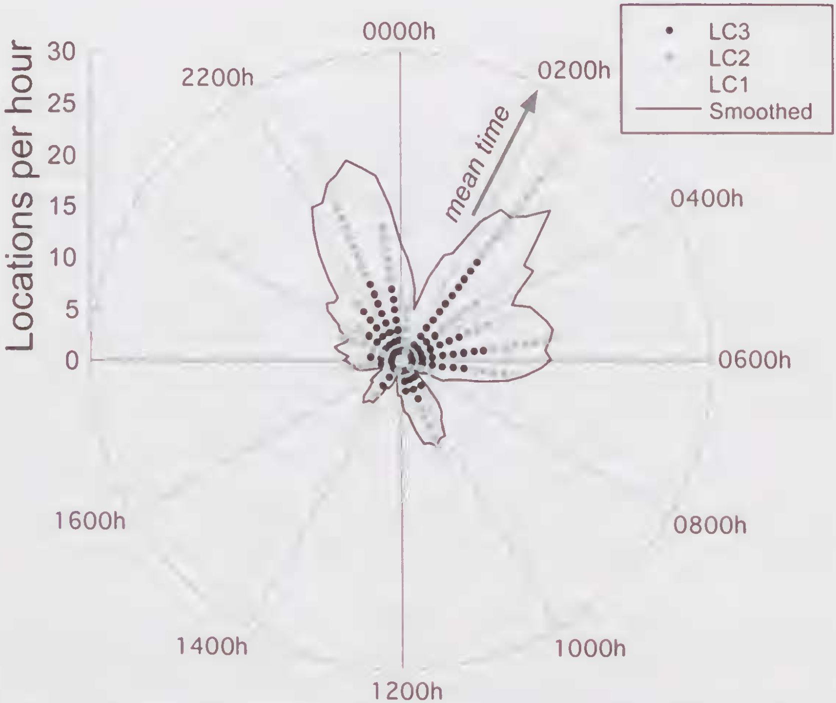

Figure 3. Circular plot showing the number of LC 3, 2 and 1 locations received at various times of the day. Locations were received on 34 days from 13 July to 31 December 2005. The locations are summarized in 24 one-hour bins. For example, the 0200-0300 h bin shows there were 12 LC 3, 10 LC 2 and 5 LC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

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 27 ± 3.5 °C, humidity of 58 ± 21 % and air pressure of 1009 ± 3.4 hPa. Using fitted line regression analysis, no relationships were identified between the movement patterns of the crocodile and the four meteorological variables analysed. However, it may be that the crocodile displayed a time lag in response to environmental conditions of, for example, up to 15 days after a big rainfall. To test this hypothesis, we analysed the data further and, whilst it may be possible that more movement was identified 10-15 days after each significant rainfall, this was not certain.

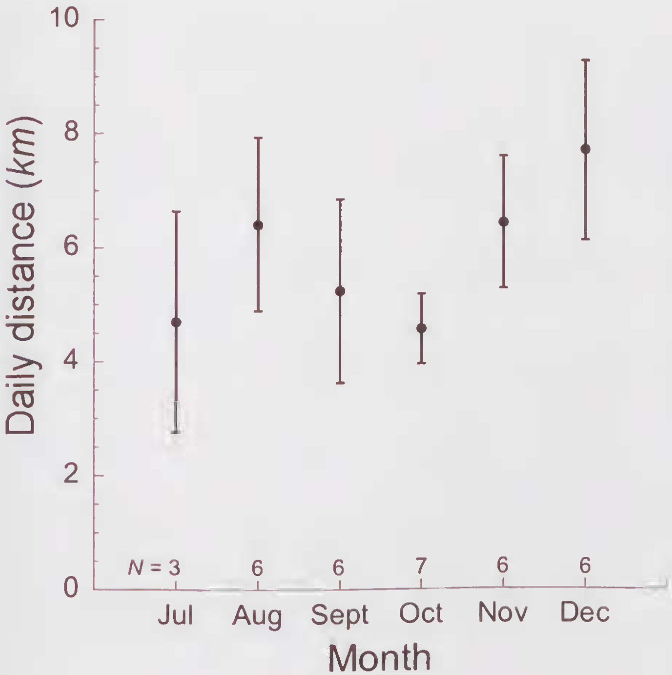

Figure 4. Plot showing the daily distances (mean ± s.e.) moved by the tagged crocodile during each month of the study.

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 south-east of the previous point, indicating a speed of 3.25 km h^{-1}. The remote weather station data show that about 75 mm of rain fell during the two weeks prior, but only 0.2 mm fell during the immediately preceding 24 hours; relative humidity at the nearest available time was 73%, whilst the temperature as indicated by the tranmitter was 29.4°C. 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. As this point was the last for that 24 hour period, no consecutive following point was available for calculation of speed. The meteorological data indicated very little rainfall prior to this with only 1 mm during the month of July, with a corresponding relative humidity of 21% and temperature of 32.4°C.

Discussion

Technical effectiveness

Reviewing the reliability and functionality of tracking units can provide important information to help with interpretation of data used for ecological analysis.

The tracking unit performed well with 65% of locations obtained from the PTT being usable. This was higher than the performance obtained by Read *et al.* (2007), whose percentage of similar useable locations ranged from 32-53%. The crocodiles in the Read study had the same transmitter and duty cycle as in this study, but 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 of location.

Many more locations were received between 2000 to 0700 h than at other times of the day (Figure 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 have been most active from late afternoon (1500-1800 h) until midnight. Thus, the difference in the number of day and night locations is probably a product of crocodile behaviour and its effect on transmissions. It is likely that the crocodile was submerged in the river or within mangroves during the day, and moved on the surface in more open water, or was on open ground, at night. Although the aerial antenna on the transmitter is 185 mm in length, submerging may have covered the transmitter, making transmission difficult during the day, as it cannot 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 related to three attributes: functioning of the transmitter, performance of the Argos system and behaviour of the species being tracked. Notwithstanding the obvious advantages apparent with a system that allows remote data collection, identifying where the fault lies can often be difficult when problems do occur, due to the large distances between the researcher, the animal and the satellite system.

Until transmissions ceased halfway through the project there were no PTT or satellite receiver problems. This reduced transmission time may have been due to animal mortality, depletion of batteries, premature detachment, antenna damage or failure of the salt-water switch (Hays *et al.* 2007). 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 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 such as a Global Positioning System tracking unit with an accuracy level of < 5 m (Hulbert and French 2001). Use of this kind of unit would have permitted 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. A more accurate unit would also have provided locations at pre-set time intervals, useful for analysing variables such as distance or speed. The lower accuracy of the Argos tracking system (Yasuda & Arai 2005) makes 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.

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 seasons, but that this difference was not apparent during the dry season. They also concur with Kay (2004a) in that crocodiles in their study exhibited considerable home range overlap. Read *et al.* (2007) captured and relocated three male Estuarine Crocodiles in northern Queensland and 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, before taking 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 & 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 & 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 midstream 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). They reported midstream linear ranges of

10.64 ± 2.86 ha in the late dry/mid wet season (July to January) compared with 3.20 ± 1.02 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 & 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 & Walker 2007), the short observation period of this study or to the problems inherent in aligning the set daily schedule 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 an area near Darwin. Whilst the sample size precludes any statistical inference being drawn at a population level, our study was intended as a pilot to provide preliminary information about the home range and behaviour of a large male *C. porosus* in a tidal area. This has enabled us to refine our understanding of the attachment and use of Argos satellite transmitter and tracking technology as it relates to *C. porosus*.

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Saltwater Crocodile *Crocodylus porosus*. (top left, Jon Clark; top and centre right, Ruchira Somaweera; below and bottom, Tissa Ratnayeke).