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Insights into size, seasonality and biology of a nesting population of the Olive Ridley turtle in northern Australia

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Abstract. The Olive Ridley turtle (*Lepidochelys olivacea*), classed as endangered in Australia, is one of Australia's least studied marine turtles and is little known in the south-east Asian region. This is the first detailed study of the nesting biology and ecology of *L. olivacea* in Australia or south-east Asia, which adds to the regional knowledge of the species and will aid management locally. Daytime surveys of nesting tracks at 14-day intervals in 2004 and irregular surveys in 2005 indicated that the nesting season extended from February to November with peak nesting in April and May. Daily track counts over a 14-day period in April 2004 during peak nesting showed that nesting abundance varied between nights and along the beach. Nightly numbers ranged from 2 to 59 turtles per night over the 10-km beach while, spatially, nesting densities (0.1–6.9 tracks km^{-1} $night^{-1}$) varied between sectors. Nesting in this population was solitary, as opposed to the mass nesting behaviour of *L. olivacea* observed elsewhere in its range, such as in India, Mexico and Costa Rica. The size of nesting *L. olivacea* was normally distributed with a mean curved carapace length of 69.6 ± 2.3 (s.d.) cm (range = 65.0–75.2, n = 85). During the peak of the nesting season dingoes (*Canis lupus dingo*) were responsible for the highest egg mortality (over 14%), followed by varanids (*Varanus* spp., 4.5%) and humans (1.7%). Cyclone Ingrid caused significant egg loss in 2004. Saltwater crocodiles (*Crocodylus porosus*) were a significant predator of adult nesting turtles.

Introduction

Little is known about the biology and ecology of Olive Ridley turtles (*Lepidochelys olivacea*) in Australia or the south-east Asian region. *L. olivacea* occurs in the Atlantic, Pacific and Indian Oceans and although this species has been termed the most numerous of all sea turtle species (Pritchard 1997) its numbers are in decline globally (Limpus 1995) and it is classified as endangered in Australia under the *Environment Protection and Biodiversity Conservation Act 1999* and as endangered internationally by the IUCN Red List (IUCN 2006). The eastern Indian Ocean populations, with an estimated 1000 clutches laid annually, lie between the large mass-nesting populations of India, Mexico and Costa Rica with between 100 000 and 300 000 clutches laid annually in each location (Márquez 1990). Some knowledge of the nesting locations of *L. olivacea* in Australia has been obtained from a combination of on-ground surveys (Cogger and Lindner 1969; Limpus *et al*. 1983; Guinea 1990; Hope and Smit 1998) and broad-scale aerial surveys of beaches throughout the Northern Territory (Chatto 1998). However, a lack of ground-truthed data and no previous detailed studies of *L. olivacea* nesting beaches in the south-east Asian region has resulted in minimal information for management of this endangered species.

Existing information indicates that the nesting range of *L. olivacea* in Australia extends from the western coastline of Cape York, Queensland, in the east (Limpus and Roper 1977; Limpus *et al*. 1983), westward to Fog Bay, Northern Territory (Whiting 1997). No nests have been recorded along the east coast of Queensland or in Western Australia despite records of *L. olivacea* inhabiting the adjacent waters (Harris 1994; Greenland *et al*. 2002; Robins *et al*. 2002). On the basis of current information, the Northern Territory supports most of Australia's *L. olivacea* nesting populations, with major nesting areas including island beaches in Arnhem Land, the Wessel Islands, the Tiwi Islands, and several islands in the Gulf of Carpentaria, including Groote Eylandt (Gow 1981; Chatto 1997, 1998).

Several factors led to the development of this project, including: the lack of knowledge of nesting density and seasonality for this species in Australia; no mention of Australia as supporting nesting by *L. olivacea* in a global sea turtle review (Márquez 1990); the fact that three major regional nesting sites (Anderman Islands, Thailand and Trengganu, Malaysia) have suffered significant declines in nesting numbers in recent years (Limpus 1995); and that *L. olivacea* populations in the Northern Territory are genetically distinct from Asian and eastern Pacific populations (Bowen *et al*. 1997).

The aims of this study were to determine the relative size and seasonality of an Australian *L. olivacea* nesting population,

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obtain basic morphometrics from the population, and assess natural and anthropogenic mortality of eggs, hatchlings and adult female turtles at the nesting beach.

Methods

Study Site

This study was conducted on Cape Van Diemen (11°10.5′S, 130°22.3′E) on the northernmost tip of Melville Island, Tiwi Islands, Northern Territory, Australia (Fig. 1). The Tiwi Islands comprise two main islands (Bathurst and Melville) with a total land area of 7800 km^2 and are located 60 km north of Darwin. The study site was a 10-km-long beach, bordered on both ends by lateritic cliffs. It was divided into seven sectors (Fig. 1) of different lengths based on distinguishable features to help determine which part of the coast was favoured most by nesting turtles. Seagull Island, located 8 km north of Cape Van Diemen, also supports nesting *L. olivacea* (Chatto 1998) and the 1-km-long beach on the western side of the island was included in this study.

Surveys

The number of nesting turtles was assessed using two survey methods. The first survey method was designed to determine the timing and duration of the *L. olivacea* nesting season throughout the year. Daytime counts of turtle tracks were conducted at 14-day intervals between March and November in 2004, with additional counts conducted irregularly in 2005. We have termed these extensive surveys because they were conducted in most months throughout the year. Logistic constraints meant sampling could not be conducted during the wet-season months between December and February. Logistic constraints also meant that the entire beach was not sampled on every survey. Therefore, Sector 2 was selected as a subsection of the beach that was surveyed on every occasion and thereby served as an index for nesting seasonality for the entire beach. Surveys were conducted on foot or using a four-wheel motorbike between 0800 and 1200 hours (Table 1). Surveys identified tracks to species (Pritchard and Mortimer 1999) and recorded fresh tracks (previous night), old tracks (all others), hatched nests, depredated nests and other observations within the index sector and within other sectors when possible. Fresh tracks were distinguishable from old tracks because the distinct receding tide lines truncated tracks, indicating their age (days). Counts of old tracks were used to identify recent nesting but were not used for numerical calculations.

The second survey method was designed to identify nightly nesting variability during the peak of the season. These surveys involved counting the number of fresh tracks (plus above parameters) in all sectors during consecutive days and patrolling the beach in Sector 2 during the night. We have termed these 'intensive surveys' because of the increased sampling effort over a short period. Surveys were conducted either on foot or using a four-wheel motorbike, with the longest intensive survey being 14 successive days from 19 April to 3 May 2005, with two shorter periods of three days each (19–21 April 2004 and 19–21 June 2005). The track counts in all sectors was used to determine the spatial variability along the entire beach.

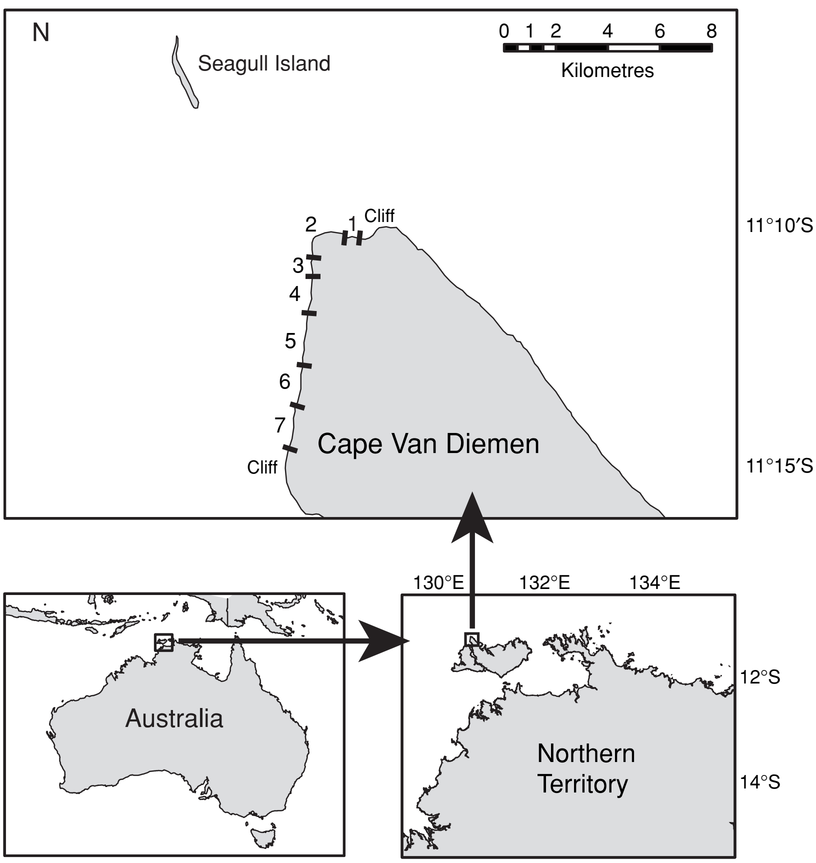

Fig. 1. Location map of Cape Van Diemen, Tiwi Islands, Northern Territory. Sectors are represented by numbers and are separated by black bars.

Table 1. Beach survey days at Cape Van Diemen in 2004 and 2005

Sector 2 was used as the index sector. Numbers against months indicate dates. Italics indicate intensive survey dates

	Sector 1		Sector 2		Sector 3		Sector 4		Sector 5		Sector 6		Sector 7		Seagull Island[B]	
Length (km)	0.46		1.97		0.76		1.45		2.01		1.66		1.63		1	
Turtle access to nesting beach[A]	Good		Good		Good		Poor		Moderate		Good		Good		Good	
	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005
January																
February																
March			11										11			
April		11, 19–30	6, 18, *19–21*	11, *19–30*	6, 20	11, *19–30*	6	11, *19–30*	6	11, *19–30*	6	11, *19–30*	6	11, *19–30*	6, 20	11
May	22	*1–3*	21, *22*	*1–3*	21, *22*	*1–3*	22	*1–3*	22	*1–3*	22	*1–3*	22	*1–3*		
June	23		5, 23	18	23		23		23		23					
July			5, 20	*19–21*	20		20						20			
August			4, 19		4						4, 19		4, 19			
September			2		2						2		2			
October			3													
November			29	7												7
December																
Total 14-day surveys	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	0
Days of intensive survey	0	14	3	17	1	14	0	14	0	14	0	14	0	14	0	0
Days of extensive track counts	2	1	14	3	7	1	4	1	3	1	6	1	7	1	2	2

[A]Access to the beach may be limited by rocks or sand bars.

[B]Seagull island was only sporadically surveyed.

The total number of tracks per year was estimated by fitting a cubic smoothing spline to all track count data for the index sector using a general additive model (GAM) and integrating the predicted total number of nests per year using R 2.2.1 software (R Development Core Team) (Bjorndal *et al*. 1999). Artificial end points of the season were set as 1 January and 31 December and weighted at 1.0, with all remaining points weighted at 0.1; weighting was conducted with confidence in the ends of the season to ensure that the total number of yearly turtles was not overestimated. Estimates for the index sector were extrapolated to give an estimate for the whole beach based on the proportion of nests distributed between sectors observed during the intensive survey period.

Measurements and scale counts

During the intensive surveys, turtles encountered in the index sector were tagged with individually numbered titanium tags (Stockbrands Pty Ltd, Perth) (Limpus 1992*a*) and measurements of eggs, nests and adults taken. Adult body measurements included curved carapace length (CCL), curved carapace width (CCW) and plastron length (PL) and were measured using a flexible fibreglass tape (measurement error ±0.5 cm: Limpus *et al*. 1983). Straight measurements were taken to enable comparison to other studies that use this method and included the straight carapace length (notch to tip) (SCL N-T) and straight carapace width (SCW) (Bolten 1999). The straight carapace length (notch to tip) (SCL N-T) was measured from the anterior point of the midline to the tip of the longest supracaudal scale using 127-cm-long Haglöf aluminium tree callipers (estimated measurement error ±0.5 cm). The tail was measured using a flexible tape and included the measurements: carapace to tip of tail (CT), vent to tip of tail (VT) and plastron to tip of tail (PT) (measurement error ±0.5 cm: Limpus 1992*b*). Head lengths (hl) and head widths (HW) were measured using steel dial callipers (instrument error ±0.01 cm). The mass of each turtle was measured by suspending the turtle by ropes attached to a hanging clock-face scale (instrument error ±0.5 kg).

Counts of body and head scales used standard terminology (Pritchard and Mortimer 1999). The following head scales were counted: postorbital (PO), preorbital (PrO), prefrontal (PF) and postparietal (PP). Postparietal scales were described as either symmetrical or asymmetrical. Counts of body scales included precentral (PrC), central (Ce), postcentral (PoC), costal (Co), marginal (M), intergular (IG) and inframarginal (IF).

Eggs, nests and hatching

During the intensive surveys, nests were located at the top of the emerging turtle track and nest success was estimated by assessing the sand and track patterns (Schroeder and Murphy 1999). Nesting success was calculated as the percentage of successful clutches laid from all total emergences. Egg sizes, measured using dial callipers, were calculated as the mean of maximum and minimum diameters of turgid eggs (instrument error ±0.01 cm). Masses of eggs were measured using a 100-g Pesola spring balance (instrument error ±0.5 g: Limpus *et al*. 1983). The depths of nests were measured using a steel tape (estimated measurement error ±0.5 cm) from the natural surface level of the sand to the first egg (top of nest) and to the firm sand in the bottom of the nest (bottom of the nest). Sand temperature at the side of the egg chamber was measured for 12 nests at the top and bottom of the nest in April 2006 using a digital thermometer (±1°C).

Hatched nests were excavated to determine hatching success and emergence success following Miller (1999). Hatching success was the percentage of individuals that hatched from the total number of eggs, while emergence success was the percentage of hatchlings that emerged from the nest from the total number of eggs (Miller 1999).

Nesting behaviour

Behavioural observations were conducted during the intensive survey periods. The nest location was recorded as either below the high-water line, between the high-water line and the first dune, or on the first dune. Nesting success was recorded for each turtle observed during the night. Each stage of the nesting process was timed for one turtle. Lights were used by researchers for safety at Cape Van Diemen to locate saltwater crocodiles (*Crocodylus porosus*) that patrolled the waters' edge and the beach. As turtles can be deterred from nesting because of artificial light (Witherington 1999), turtles at Cape Van Diemen were monitored for any adverse reactions to torch and spotlights on the beach.

Mortality

Evidence of mortality of eggs, hatchlings and adults was recorded throughout the study. Evidence of egg predation included the remains of eggs near freshly dug nests with either dog, varanid, human or crocodile tracks at the top of the nest. Hatchling predation was indicated by the remains of carapaces in dog faeces and bird tracks around freshly hatched nests. Predation by crocodiles on adult turtles was indicated by converging crocodile and turtles tracks, followed by drag marks, sometimes with the remains of turtles. In addition, during the 14-day intensive study in 2005 a sample of freshly laid clutches and fresh partly excavated nests were marked with an individually numbered plastic tag to monitor potential predation by dogs.

Results

Species composition

On the basis of the 14-day intensive survey, the species composition was 99.4% *L. olivacea* and 0.6% *Natator depressus* (flatback turtle). On the basis of all fresh tracks recorded throughout 2004 and 2005 the species composition was 95% *L. olivacea* and 5% *N. depressus*. One hatched nest of *Chelonia mydas* (green turtle) was found in March 2004, indicating at least some nesting by this species.

Seasonality, nightly variability and density

Beach surveys between March and November showed that nesting by *L. olivacea* occurred during 10 months of the year with a peak in the season between April and May (Fig. 2). Nesting by *N. depressus* also occurred during this period, with numbers too low to predict a peak. Old tracks of *L. olivacea* indicated that nesting also occurred in February. One hatched nest of a green turtle found in the middle of March indicated that nesting occurred before mid-January (based on incubation ranges for green turtles in northern Australia) (Limpus *et al*.

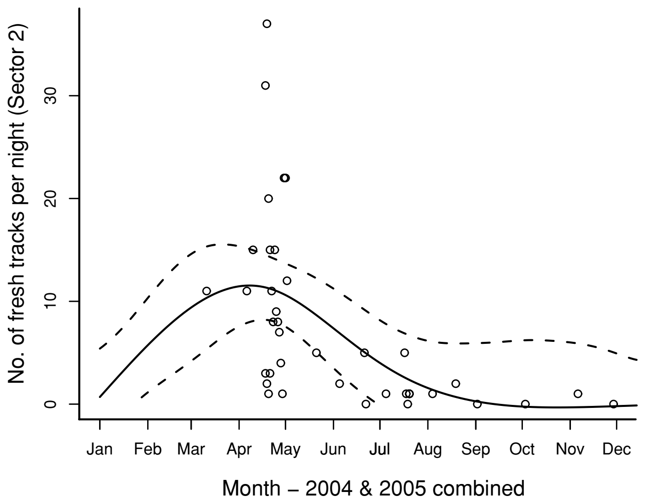

Fig. 2. Number of fresh *L. olivacea* tracks for combined years in Sector 2 with seasonality defined with a GAM smoothing spline with error lines (±2 s.e.).

2001). During the 14-day intensive survey period, the total track count for the entire beach was 327, with nightly track numbers varying between 2 and 59 and variations of between 1 and 37 for Sector 2 (index sector) (Fig. 3).

On the basis of the intensive surveys, spatial variation in nesting density occurred between sectors, with Sector 2 (index sector) having the highest density (6.9 turtles km^{-1} $night^{-1}$) of nesting turtles, followed by Sector 1 (3.1 km^{-1} $night^{-1}$) (Table 2). From three track counts in April 2004 and 2005, Seagull Island had a mean density of 8.7 turtles km^{-1} $night^{-1}$ (±7.4 s.d., range = 3–17).

Using all survey data for 2004 and 2005 the annual number of nesting tracks in Sector 2 was estimated at 1546 (±2 s.e. = 717–3424). Estimates lower and higher than this were calculated for 2004 (1011 ± 2 s.e. = 447–2067) and 2005 (2009 ± 2 s.e. = 845–4768) independently. Using the combined estimate (larger dataset), the Sector 2 estimate was multiplied by 1.67 to extrapolate the data for the entire beach and produced an annual estimate of 2582 *L. olivacea* tracks for the 10-km beach (±2 s.e. = 1197–5718).

Measurements and scale counts of nesting adults

The size (CCL) of nesting turtles was not significantly different from a normal distribution (Shapiro Wilks test = 0.987, $P = 0.6$)

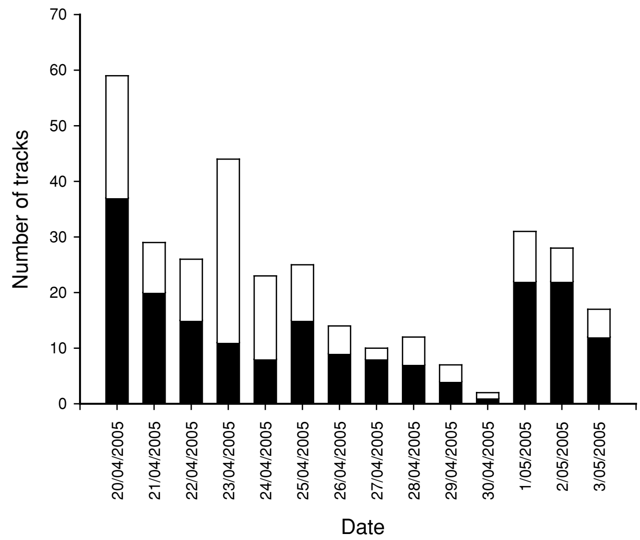

Fig. 3. The numbers of *L. olivacea* tracks counted in all sectors along the Cape Van Diemen Beach during the intensive survey period from 20 April to 3 May 2005. Solid bars represents Sector 2 and open bars represent all other sectors combined.

with a mean size for nesting *L. olivacea* of 69.6 cm CCL (±2.3 s.d., range = 65.0–75.2, $n = 85$) (Table 3, Fig. 4). Length measurements (CCL) were correlated with SCL, SCW, mass and PL (see Table 4). Of all the scale counts, costal scales showed the most variability, with six combinations recorded from 12 turtles (Table 5).

Eggs, nests and hatching

Mean egg size was 3.82 cm (±0.06 s.d., range = 3.73–3.92, $n = 12$), mean egg mass was 31.9 g (±1.5 s.d., range = 29–34, $n = 12$) (see Table 6 for nest depths and temperatures). The mean clutch size of hatched nests was not significantly different (t-test, $t = 1.97$, $P = 0.058$) between those counted at the time of laying (mean = 112.9 ± 24.3 s.d., range = 53–149, $n = 12$) and those counted at the time of hatching (mean = 96.4 ± 23.9 s.d., range = 46–138, $n = 26$) and were pooled. The pooled samples resulted in a mean clutch size of 98.5 (±26.5 s.d., range = 46–149, $n = 38$).

Hatching success and emergence success for *L. olivacea* nests was 81.7% (±22.1 s.d., range = 8.9–98.5, $n = 26$) and 74.8% (±27.0 s.d., range = 8.9–98.5, $n = 26$) respectively.

Table 2. Mean nightly density of nesting, hatching and predation for *L. olivacea* in each sector during the 14-day intensive survey period in 2005
Results are shown as mean number of tracks km^{-1} $night^{-1}$ (s.d., range)

Sector	Density of new tracks	Mean hatched nests	Predation on nests			Tracks on beach	
			Dog	Goanna	Human	Dog	Crocodile
1	3.1 (4.4, 0–15.2)	0.0	1.6 (2.5, 0–6.5)	0.0	0.0	4.0 (3.2, 0–10.9)	
2	6.9 (4.7, 0.5–18.8)	0.2 (0.4, 0–1.0)	0.3 (0.7, 0–2.0)	0.0	0.0	0.5 (0.7, 0–1.5)	
3	0.9 (1.4, 0–3.9)	0.0	0.1 (0.4, 0–1.3)	0.4 (1.1, 0–3.9)	0.0	1.9 (2.0, 0–5.3)	
4	0.1 (0.3, 0–0.7)	0.1 (0.1, 0–0.7)	0.1 (0.3, 0–0.7)	0.0	0.0	0.8 (1.0, 0–2.8)	0.1 (0.2, 0–0.7)
5	1.3 (1.7, 0–5.5)	0.0	0.2 (0.4, 0–1.0)	0.0	0.2 (0.4, 0–1.5)	0.8 (0.7, 0–1.5)	0.1 (0.1, 0–0.5)
6	1.3 (1.4, 0–4.2)	0.0	0.2 (0.3, 0–0.6)	0.0	0.0	0.9 (0.9, 0–1.8)	0.0
7	1.6 (1.9, 0–7.3)	0.0	0.7 (1.1, 0–3.1)	0.0	0.0	0.8 (0.9, 0–1.8)	0.1 (0.2, 0–0.6)

Table 3. Morphometric measurements of adult female *L. olivacea*

Measurement	Abbreviation	Mean	s.d.	Range	*n*
Curved carapace length (cm)	CCL	69.6	2.3	65.0–75.2	85
Curved carapace width (cm)	CCW	69.5	2.4	65.3–74.6	84
Mass (g)		37.3	3.7	29.0–43.0	17
Head length (cm)	HL	18.7	0.6	17.8–19.8	12
Head width (cm)	HW	12.2	0.4	11.5–12.8	12
Straight carapace length (cm)	SCL N-T	66.3	2.3	63.8–70.8	12
Straight carapace width (cm)	SCW	59.4	2.2	56.1–62.5	12
Plastron length (cm)	PL	53.6	1.4	51.7–56.2	12
Tail length – carapace to tip (cm)	CT	–0.5	1.3	–2.5–2.5	12
Tail length – plastron to tip (cm)	PT	13.3	2.3	7.0–16.0	12
Tail length – vent to tip (cm)	VT	4.2	0.7	2.8–5.0	12

Hatching success and emergence success for two hatched *N. depressus* nests was 78.4% (range = 69.5–87.3) and 57% (range = 55–59) respectively. The one green turtle nest had a hatchling success of 92.2%, emergence success of 90.6% and clutch size of 64.

Nesting behaviour

L. olivacea usually nested between the high-water line and the first dune (63.5%). In some cases the clutches were laid within 1 m of the spring high-water line. Several clutches laid below the high-water mark were covered by subsequent high tides. Track widths were ~77–83 cm in dry sand and 76–82 cm in wet sand. Most turtles laid eggs in the first nest site selected (92.2%), with an overall nesting success of 98% (188 successful nests from 191 tracks). *L. olivacea* at Cape Van Diemen showed the genus-specific postoviposition behaviour of compacting the sand by repeatedly slamming each side of the body on the sand (Whiting 1997). The whole process usually took less than 1 h. The beginning of each stage of the nesting process for one timed turtle was: emerged from sea, 0 min; turtle reached dry sand and pushed beak into sand, 9 min; body pitting, 13 min; egg chambering, 14 min; laying, 31 min; covering the nest, 45 min; compacting sand by slamming body, 46 min; cover nest using front flippers, 53 min; leaving the nesting site, 57 min; entered the sea, 61 min.

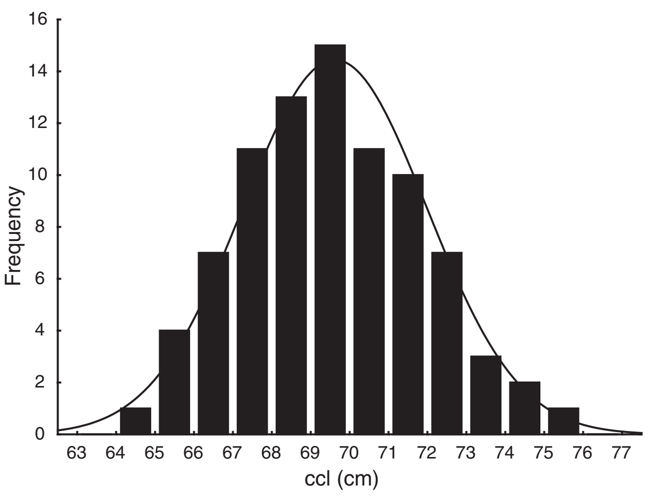

Fig. 4. Size distribution for *L. olivacea* sea turtles. Line shows normal distribution curve. Size distribution of *L. olivacea* was not significantly different to a normal distribution (Shapiro–Wilks test = 0.987, $P = 0.6$).

Turtles were tolerant of human activity on the beach. On some occasions a light was accidentally shone directly on turtles emerging from the water or beginning their nesting process and immediately removed. On no occasion did a turtle stop nesting, return to the water or act adversely after seeing lights or researchers.

Injuries and abnormalities

Only a small percentage of nesting turtles had any substantial damage or injuries: carapace (5.7%), tail (1.1%), front flipper (1.1%) and hind flipper (1.1%). All injuries were healed, with the most severe being a missing front flipper and a wound to the carapace consistent with the conical teeth of a crocodile.

Mortality

During the 14-day intensive survey period, dingoes (*Canis lupus dingo*) and possibly a hybrid of dingoes and wild domestic dogs (*Canis lupus familiaris*) excavated 14.2% of the total nests (percentage of excavated nests to new nests). This ranged from 4.3% in Sector 2 to 100% in Sector 4. Tracks indicated that groups of at least five dogs patrolled the entire length of the beach (all sectors) between late afternoon and late morning. They patrolled and excavated nests on the dunes, beach and intertidal areas. Unfortunately, many of the markers designed to monitor predation were chewed and removed by dingoes within days of them being marked, most with no excavation of the nest. Limited results indicated that dingoes did not excavate every nest every night. From 23 nests monitored for three days, three (13%) were excavated by dingoes. One nest was excavated within 2 h of the eggs being laid. Two other nests that already had been partially depredated were marked, but they were not re-excavated within three days. Of 12 additional marked nests monitored for nine days, three (25%) were excavated by dingoes. Combining these limited data shows that six (17%) of 35 nests were excavated when monitored for between three and nine days. Varanids (*Varanus* spp.) excavated 4.9% of the nests, all in Sector 3, whereas humans harvested 1.7% nests (all Sector 5). One saltwater crocodile excavated one nest (0.3%) nest in Sector 3.

During the extensive survey period, egg harvest by humans was recorded on 13 occasions in Sectors 6 and 7. Bandicoots

Table 4. Linear regression equations ($Y = aX + B$) for significant correlations for length measurements of *L. olivacea* at Cape Van Diemen using $\alpha = 0.05$

Abbreviations are from Table 3

X	*Y*	a	b	*n*	r^2	*F*	d.f.	*P*
CCL	CCW	0.764	16.34	82	0.568	106.5	1,80	<0.001
CCL	SCL N-T	0.818	9.244	12	0.907	87.9	1,10	<0.001
CCL	SCW	0.546	21.310	12	0.370	6.9	1,10	0.027
CCL	PL	0.448	22.275	12	0.979	25.7	1,10	<0.001
CCL	MASS	1.173	–45.080	17	0.962	10852.4	1,15	<0.001
SCL N-T	PL	0.448	22.275	12	0.720	22.3	1,10	<0.001

(*Isoodon* spp.) were recorded as opportunistic predators of nests at the eastern end of Sector 2 near a group of *Casuarina equisetifolia* trees. Predation by bandicoots appeared to increase after the reduction of dogs in April 2004 following a Government baiting program. Pigs were identified by their tracks in Sector 2 but there was no evidence of predation on nests. An extreme event, Cyclone Ingrid, in March 2004 caused substantial egg mortality by removing sand and reshaping the dune system. It is estimated that Cyclone Ingrid destroyed all eggs laid during the seven weeks (based on known incubation period: Whiting 1997) before the cyclone, which accounted for an estimated 75 nests.

Hatchlings were vulnerable to ghost crabs (*Ocypode* spp.) and birds such as beach stonecurlews (*Esacus neglectus*), both of which were observed preying upon *L. olivacea* hatchlings. Fresh tracks of rufous night herons (*Nycticorax caledonicus*) were observed on the dunes and around freshly hatched nests and were a suspected predator. Small (<2 m long) saltwater crocodiles (*Crocodylus porosus*) and dingoes were observed chasing ghost crabs over the intertidal zone on several occasions and both could be considered potential predators to similar-sized but slower-moving sea turtle hatchings. One nest (0.5%) with fully formed hatchings was excavated by dingoes in Sector 2.

Adult turtles were regularly preyed upon by resident saltwater crocodiles. Extensive surveys showed evidence of at least five crocodile attacks on adult *L. olivacea* in Sectors 2, 3 and 7. Evidence included direct observations, remains of turtles on the beach near crocodile tracks and merging crocodile and turtles tracks on the beach, struggle marks and no return turtle tracks. During the 14-day survey period in 2005, one *N. depressus* and two *L. olivacea* were preyed upon in Sector 2. During one of these events, a large 5-m saltwater crocodile was observed walking along the beach with a *N. depressus* (estimated mass 70 kg) in its mouth. Two hours later the same crocodile was holding and consuming an *L. olivacea* (average mass 37 kg – this study) (presumably the first turtle escaped because of observer presence). Saltwater crocodiles were also observed on the beach at Seagull Island. Mortality estimates for the season were obtained by extrapolation to give an indication of the level of mortality in each life stage (Table 7). Dogs and crocodiles at the egg and adult stages, respectively, were the most significant sources of mortality.

Discussion

This study is the first major study on *L. olivacea* in Australia or south-east Asia. From limited information available, the Tiwi Islands (Cape Van Diemen plus other neighbouring beaches) support significant *L. olivacea* rookeries in Australia (Chatto 1998; Limpus, in press) and in the south-east Asian region (Limpus 1997). Although not comparable in population size to the mass-nesting *L. olivacea* populations in India (Ross 1982; Shanker *et al*. 2004), Mexico and Costa Rica (Ross 1982), this population is the most significant recorded in the south-east Asian region and for the Australian genetic stock. However, preliminary surveys (Chatto 1998) show that populations of comparable size may exist across the coast of Arnhem Land in the Northern Territory. The mass-nesting behaviour displayed by *L. olivacea* in other countries such as India, Mexico and Costa Rica (Pritchard 1997) was not observed during this study and has not been reported elsewhere in Australia (Whiting 1997; Hope and Smit 1998).

Species composition

Nesting activity by sea turtles on Cape Van Diemen was dominated by *L. olivacea*, with a small percentage of *N. depressus* turtles and one record of *C. mydas*. Several other beaches on the northern coast of Melville Island also support *L. olivacea* and *N. depressus* nesting, while the southern coast of the Tiwi

Table 5. Scale counts of twelve adult turtles

PF = prefrontal, PrO = preorbital, PP = postparietal, PrC = precentral, Ce = central, PoC = postcentral, Co = costal, M = marginal, IG = Intergular, IF = inframarginal; whole numbers = scale counts; divided numbers = counts on left and right side of the body; numbers in parentheses are percentages

PF	PrO	PO	PP	PrC	Ce	PoC	Co	M	IG	IF
2 prs (100)	0/0 (100)	3/3 (83.3)	2 (75)	1 (91.6)	6 (69.2)	2 (100)	7/7 (33.3)	12/12 (100)	2 (100)	4/4 (100)
		4/3 (8.3)	3 (25)	2 (8.3)	5 (15.4)		6/5 (16.7)			
		4/4 (8.3)			7 (15.4)		6/7 (16.7)			
							6/6 (8.3)			
							8/7 (8.3)			
							7/8 (8.3)			

Table 6. Egg and nest parameters of *L. olivacea* at time of laying in June 2005

Parameter	Mean	s.d.	Minimum	Maximum	*n*
Clutch size (count)	112.9	24.3	53	149	12
Egg diameter (cm)	3.82	0.06	3.73	3.92	12
Egg mass (g)	31.9	1.5	29	34	12
Depth of nest top (cm)	25.7	6.13	12	35	12
Depth of nest bottom (cm)	41.5	4.4	35	48	12
Nest temperature, top of nest (°C)	31.2	0.6	30.3	32.2	12
Nest temperature, bottom of nest (°C)	32.1	0.4	31.7	33.0	12

Islands is dominated by *N. depressus* nesting (Chatto 1998). Other nearby beaches are dominated by *N. depressus* (Bare Sand Island: Whiting and Guinea 2006) and by *N. depressus* and *C. mydas* (Cobourg Peninsula: Hope and Smit 1998).

Seasonality, nightly variability and density

L. olivacea nested for at least 10 months of the year, from February until November, with a perceived peak in April and May. The peak nesting abundance is not well defined and may extend over a longer period. Nesting by *L. olivacea* on Cobourg Peninsula in February and March (Cogger and Lindner 1969) indicates at least some nesting during the hottest months of the year also.

Nesting density varied between sectors, indicating that *L. olivacea* selects for nesting sites along the coast. Sector 2, with a northern aspect and exposure to wave and wind action, had the highest track density. Seagull Island, with similar exposure to wind and waves, had nesting densities similar to that of Sector 2. Nesting site fidelity is thought to be weaker for solitary-nesting *L. olivacea* compared with mass-nesting *L. olivacea* (Plotkin 2003). The level of fidelity both within and between seasons could not be determined as this would require intensive surveys in all sectors. However, three out of eight individuals tracked with satellite transmitters from Cape Van Diemen in 2004 and 2005 showed strong fidelity by renesting approximately two weeks later only tens of metres from their previous location (Whiting *et al*. 2007). The other five individuals did not renest for that season. Between-season nesting fidelity was shown by one individual that was tracked to its foraging ground 400 km away in 2004 and was recognised by its titanium tag while nesting again in Sector 2 in 2005.

Estimates of annual fresh tracks for Sector 2 of 1546 (±2 s.e. = 717–3424) seem plausible when considering that 191 tracks were recorded in Sector 2 within 14 days. Extrapolating this estimate to the whole beach resulted in an estimate of 2582 fresh tracks per year, which is also plausible given that 327 tracks were recorded in the 14-day intensive period. Based on a mean of 1.5 nests per female per season (Márquez 1990), there are ~1700 (±2 s.e. = 798–3812) *L. olivacea* females visiting Cape Van Diemen each year. The estimated number of clutches laid on this beach is more than the estimate for the entire eastern Indian Ocean (Márquez 1990). Considering Cape Van Diemen (this study), Cobourg Peninsula (Cogger and Lindner 1969) and other known locations such as the Wessel Islands and Groote Eylandt (Gow 1981; Chatto 1998), northern Australia may represent a stronghold for this species in the eastern Indian Ocean and south-east Asian region. This is especially true considering that the two sites (Trengganu, Malaysia and the Andaman Islands, Thailand) recognised for *L. olivacea* nesting in the region have suffered serious declines due to egg harvest (Ross

Table 7. Summary of mortality sources for *L. olivacea* on Cape Van Diemen
Estimates are based on observations from total 11 km of beach

Life stage of turtle	Type of mortality	Mortality estimate	Notes
Eggs	Dogs/dingoes (empirical data)	23 clutches per week (peak of season)	Based on two-week field trip and notes from track counts in 2004
	Varanids	8 clutches per week	Based on two-week field trip
	Human	1–2.5 clutches per week	Based on two-week field trip
	Bandicoots	0–1 clutches per week	Based on extensive surveys
	Cyclone Ingrid	75 clutches for 2004 season	Based on 1.5 nests laid per night for 6 weeks before Cyclone Ingrid
	Crocodile	1–5 per season (estimate)	One nest was excavated by a crocodile
Hatchlings	Dogs/dingoes	1–2 per week (unknown – estimate only)	Dog tracks on beach. One full-term nest excavated by dogs and live hatchlings scattered on sand
	Ghost crabs	Hundreds of hatchlings	Predation by crabs observed on several nights in 2005
	Birds	Hundreds of hatchlings	Beach stone-curlews and herons observed on beach and in dunes regularly
	Crocodile	Tens of hatchlings	Small crocodiles were observed chasing ghost crabs on the intertidal sand flats at low tide. It is likely that hatchling sea turtles are within their diet
Adult female	Crocodile	1–2 per week	Based on observations from 2004 and 2005
	Dogs/dingoes	Not witnessed	Possible predator

1982; Limpus 1995). The number of clutches laid at Trengganu have dropped from 1000–2000 to ~20 annually (Limpus 1995). The rookeries of south-east Asia and northern Australia are small in comparison to the mass-nesting populations of India (300 000 clutches annually), Mexico and Costa Rica (both with 200 000 clutches annually) (Márquez 1990). However, this region may represent an important geographical link between the two mass-nesting regions for this species.

Survey methodology on year-round, remote nesting beaches is difficult because of financial and logistic constraints. The survey methods used in this study were reviewed in hindsight in regard to logistic constraints and objectives. A combination of intensive and extensive surveys provided information about the functioning of this year-round, nesting population located in a remote area. Intensive studies that require constant observer presence throughout the complete nesting season are almost impossible for populations with long nesting seasons, but this type of survey allowed for estimates of spatial distribution and provided nightly variations in nesting numbers. Extensive surveys conducted throughout the year allowed the peak in the season to be estimated and also enabled estimates of population size. However, there are several limitations to extensive periodic one-day surveys throughout the year, which include nightly variation in nesting numbers and tracks being erased owing to sand erosion by strong winds. Nightly variability ranged from 1 to 37 tracks in the index sector during the intensive survey period. This means that one-day track counts every 14 days may under- or over-represent mean values for that period. Similarly, strong winds experienced on the nesting beach during the intensive period revealed that some tracks were erased within several hours, which means that one-day track counts may under-represent track counts at some times of the year and on some sections of the beach. Errors may be reduced by more surveys over consecutive days throughout the season or more intensive survey periods where every turtle and its track are viewed during night patrols. High nesting success (98%) by *L. olivacea* means that counts of fresh tracks gives a good indication of clutches laid.

Measurements of adults, nests, eggs and hatchlings

This is the first comprehensive morphometric dataset on *L. olivacea* in Australia. Curved carapace lengths and masses of adult turtles encompassed those reported elsewhere in Australia (Cogger and Lindner 1969; Limpus *et al*. 1983; Whiting 1997; Hope and Smit 1998) and were similar to ranges reported outside Australia (Márquez 1990). Adult scale counts are the first for Australia and should be used to compare spatially disjunct populations, such as the one on Cape York when data become available in the future.

Clutch sizes and egg sizes were within the ranges of the few data available (Cogger and Lindner 1969; Whiting 1997) and were similar to ranges reported outside Australia (Márquez 1990). *L. olivacea* lays eggs in shallow nests (mean depth to top egg 25. 7 cm: Table 6) compared with *N. depressus* (mean depth to top egg 36.1 cm: Limpus *et al*. 1983), which makes the species more susceptible to predation by dingoes and varanids. Hatching and emergence success was high for those nests that had greater than zero hatching success. Without marking nests it was impossible to detect nests that had zero emergence success, thus a marked sample would substantially refine these estimates. During the 14-day intensive survey period, only three hatched nests of *L. olivacea* were found for the entire beach. This low number of hatched nests was most likely attributed to Cyclone Ingrid, which passed over the area several weeks before and caused extensive beach erosion. This would have removed most clutches laid in the previous seven weeks.

Nesting behaviour

L. olivacea is a relatively fast nester compared with other species, such as *C. mydas*, which can take an average of three hours (Bustard 1972). The behaviour of *L. olivacea* whereby it slams its body on the ground to compact the sand produced vibrations and audible sounds. Further investigation is needed to determine whether these cues are used by crocodiles to locate turtles on beaches at night.

Injuries and mortality

A low percentage of injuries were recorded from *L. olivacea* on Cape Van Diemen considering that crocodiles commonly patrol the beach and surrounding waters. Crocodile damage to the carapace of one *L. olivacea* provided evidence that not all attacks are fatal.

Wild dogs should be considered potential predators to adult nesting *L. olivacea* as they patrol the beach in packs and dogs have already been listed as predators of this species (Márquez 1990). Dingoes were the major predator of eggs and accounted for 68% of recorded egg mortality. However, more detailed studies are required to refine this estimate as nests were not permanently marked and some depredated nests may have been missed. In addition, predation rates were calculated as the percentage of depredated nests against the number of new nests. Thus the comparison was of daily depredated nests against daily number of fresh nests, which would produce a time lag that may be as long as the incubation period. The predation rates from the nests that were marked (for between one and nine days) was higher (17%) than that produced by the survey counts (14%). If these markers had lasted the full incubation period of seven weeks (Whiting 1997) then predation rates may have been several magnitudes higher. In addition, these studies were conducted at the peak of the nesting season when the number of nests available was at its highest. If the predators are stable throughout the year, then a higher percentage of nests would be excavated early and late in the season when turtle nests are at their fewest. Islands, such as Seagull Island, that support sea turtle nesting across northern Australia are usually free from feral animals and provide habitat free from this type of mortality. Cape Van Diemen is located 20 km from the nearest Aboriginal community and customary harvest was displayed on several occasions by locals. This accounted for only 1.7% of recorded egg mortality and occurred only in Sector 5 during the intensive study and in Sectors 6 and 7 at other times. Following a community and school camp, which focused on sea turtle conservation in 2005, this beach was informally declared a restricted area within the community for sea turtle education and conservation.

This study provides the first detailed information on nesting *L. olivacea* in Australia or the south-east Asian region and provides a baseline for ongoing monitoring of the Australian genetic stock. Given its accessibility, and moderately sized nesting population of *L. olivacea*, Cape Van Diemen is well suited to serve as an index beach for the long-term monitoring of this species in northern Australia.

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