Monitoring of Coastal Sea Turtles: Gap Analysis

1. Loggerhead turtles, *Caretta caretta*, in the Port Curtis and Port Alma region

C.J. Limpus, C.J. Parmenter, and M. Chaloupka

This report should be cited as:

Limpus C.J., Parmenter C.J. and Chaloupka M. (2013). Monitoring of Coastal Sea Turtles: Gap Analysis 1. Loggerhead turtles, *Caretta caretta*, in the Port Curtis and Port Alma Region. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program.

This report has been produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. The study was undertaken under a Consultancy Agreement (CA120021) between Gladstone Ports Corporation and the Department of Environment and Heritage Protection to review all relevant literature on marine turtles for the Port Curtis and Port Alma regions.

This publication has been compiled by the Queensland Department of Environment and Heritage Protection (EHP).

Background
This study has been undertaken to provide a review and summary of available scientific literature and data on marine turtles in Central Queensland, particularly the Port Curtis and Port Alma region, and if required, expand the extent to consider turtle information for Queensland:

- Identify and update baseline data for suitable turtle habitat in the Port Curtis and Port Alma region at a distance of 500km north of Port Alma and south of Port Curtis
- Assess whether the available historical survey data are sufficiently robust to permit trend analyses. If so, undertake a trend analysis; undertake a formal power analysis of the reviewed data, if appropriate;
- Conduct a quantitative analysis of the historical trends in marine turtle numbers for the Port Curtis and Port Alma region; and
- Identify the migratory links between resident foraging turtles in the Port Curtis and Port Alma region and their nesting areas.

Introduction
The loggerhead turtle, *Caretta caretta* (Figure 1), has a global distribution, occurring in all oceans. The biology and conservation status of loggerhead turtles has been reviewed at a global scale by Dodd (1988) and Bolten and Witherington (2003) and within Australia by Limpus (2008a).

Status
Within Australia, the loggerhead turtle is scheduled as an endangered species under both the Queensland and Federal conservation legislation and associated regulations, *Nature Conservation Act 1992* and *Environment Protection and Biodiversity Conservation Act 1999*, respectively.

Data sources
This gap analysis has drawn on information available in the published literature and in the two primary computerised data bases with the Queensland Department of Environment and Heritage Protection (EHP).

Queensland Turtle Conservation (QTC) database

EHP maintains a database that incorporates all tagging records for Queensland, incidental sighting records, nesting distribution and migration data for marine turtles in Queensland.

StrandNet

EHP maintains a database collating reports of sick, injured and dead marine wildlife (Cetaceans, dugong, turtles, threatened sharks and grouper) in Queensland (Biddle and Limpus, 2011). This data base includes turtle mortality from the Queensland Shark Safety Program.

These data sets have been supplemented with data sets managed by Dr Limpus which summarise international nesting and migration.

Index study sites

Nesting:

There are six index nesting beaches for monitoring loggerhead turtle breeding in eastern Australia (Limpus and Limpus, 2003a; Limpus, 2008a)

- Woongarra coast (including Mon Repos beach) via Bundaberg (24.790ºS, 152.438ºE); a major nesting population; total nightly tagging census for the total nesting season, October-March, during 1968-2012.
- Wreck Island (23.300ºS, 151.917ºE); a major nesting population; mid season (last 2 weeks of December) tagging census for the nesting season during most years, 1977-2012.
- Wreck Rock Beaches (24.317ºS, 151.967ºE); a major nesting population; mid season (5 weeks from mid December to third week of January) tagging census for the nesting season during most years, 1978-2012.
- Heron Island (23.433ºS, 151.917ºE); a minor nesting population; total nightly tagging census for the nesting season, December-February, during most years, 1964-2012.
- Lady Musgrave Island (23.900ºS, 152.383ºE); a minor nesting population; mid season (last 2 weeks of December) tagging census for the nesting season during most years, 1972-2012.

- North West Island (23.300ºS, 151.700ºE); a minor nesting population; mid season (last 2 weeks of December) tagging census for the nesting season during most years, 1977-2012.

Foraging

There have been two primary index foraging areas for monitoring loggerhead populations in eastern Australia:

- Southern GBR - Heron & Wistari Reef (23.433ºS, 151.917ºE); annual tagging-recapture sampling of the foraging population during 1984-1999 (Limpus and Limpus, 2003b).
- Moreton Bay (27.35ºS, 153.40ºE); annual tagging-recapture sampling of this foraging population in temperate waters during 1990-2012 (Limpus et al. 1994; Limpus, 2008b).

Stock identification

There have been a series of on going analyses investigating the genetic relationship of loggerhead turtle breeding aggregations at a global scale:

- Bowen *et al*. (1994) established that the loggerhead turtle population that breeds in Queensland (represented by Mon Repos specimens) was genetically distinct from all other tested loggerhead turtle populations, including the Japanese nesting population in the North Pacific Ocean.
- Dutton *et al*. (2002), in a preliminary analysis, identified the eastern and western Australian loggerhead nesting populations as separate stocks.
- Bowen (2003) established that the Queensland nesting population had fixed genetic differences from the separate genetic stocks within the Indian Ocean represented by Oman, South Africa and Western Australia.
- Boyle *et al*. (2009) established that the genetic composition of the southwest Pacific rookeries (Queensland: Mon repos, Heron Island and Swain Reefs cays; and New Caledonia: Bourail) made them distinct from the Japanese rookeries, but not distinct from one another.

From this it is concluded that the eastern Australian and New Caledonian loggerhead turtle nesting populations form a single management unit (genetic stock). Apart from a small but unquantified nesting population in Vanuatu, eastern Australia and New Caledonia account for almost the entire loggerhead turtle nesting population in the South Pacific Ocean (Limpus and Limpus, 2003b).

Nesting population

The loggerhead turtle population breeding in the south-western Pacific Ocean in eastern Australia and New Caledonia represents a globally significant population for the species (Bolten and Witherington, 2003).

Within eastern Australian, the majority of the loggerhead nesting has been aggregated at five sites (Bustard, 1972; Limpus, 1985; Limpus and Reimer, 1994; Limpus, 2008a) surrounded with numerous sites supporting lower densities of nesting (Figure 2):

- Woongarra coast and Wreck Rock beaches on the mainland coast of southeast Queensland.
- Wreck, Tryon and Erskine Islands in the Capricorn Group off Gladstone.

Minor annual nesting concentrations occur more widely:

- On all remaining mainland beaches south from Bustard Head to the Sunshine Coast and on northern ends of Fraser, Moreton and North Stradbroke Islands;
- On the remaining 10 islands of the Capricorn-Bunker Groups of the southern Great Barrier Reef;
- On the islands of the Swain Reefs (especially Pryce Island, Frigate, Bylund, Thomas and Bacchi Cays) and at Bushy Island off Mackay.

Isolated nesting crawls have been recorded beyond this central-south Queensland area, to as far north as the Burdekin Delta beaches in the north and to as far south as central New South Wales. There is no evidence that the isolated loggerhead clutches laid in the Newcastle-Sydney region of central New South Wales successfully incubate to produce hatchling. The failure to hatch can be attributed to beach temperatures at nest depth being below 25ºC, the minium temperature for successful incubation (Miller, 1985).

Isolated loggerhead turtles nest on beaches within the port limits of Port Alma and Port Curtis, but not on an annual basis.

Nesting census and nesting population trend

Figures 3, 4, and 5 summarise the size of the annual female breeding population recorded at the six index rookeries for the eastern Australian stock for varying periods since 1968 (after Limpus, 2008). Those data provide the primary measures of the trends for the loggerhead turtle breeding population in the South Pacific Ocean basin:

- Limpus, (1985) and Limpus and Reimer (1994) estimated the total annual nesting population for Queensland during the 1976-1977 breeding seasons was of the order of 3,500 females.
- Limpus and Limpus (2003) estimated that the annual nesting population in eastern Australia had declined to less than 500 females in the 1999–2000 breeding season.

There has been a marked decline in the number of females breeding annually at all index beaches since the mid 1970s, with "an estimated 50–80% decline in the number of breeding females at the index rookeries up to 1990" (Limpus and Reimer, 1994) and "a decline of approximately 86% by 1999" (Limpus and Limpus, 2003a).

This decline in annual nesting numbers for eastern Australian loggerhead turtles was attributed to primarily the mortality of turtles drowning when captured on prawn trawls of eastern and northern Australia (Limpus and Reimer, 1994).

The Queensland Parks and Wildlife Service responded with a localised management action, declaring the Woongarra Marine Park (WMP) in 1990 with a summer trawl closure over the inshore inter-nesting habitat adjacent to Mon Repos beach. This action resulted in a greatly reduced frequency of strandings of gravid loggerhead turtles on the adjacent coast during the nesting season following the declaration of the WMP (up to 38 stranded gravid females per year before declaration of the WMP; only 3 stranded gravid females during the decade 1990 -2000 along the same length of coast). While this reduced mortality of breeding females resulted in a subsequent reduced rate of decline in the breeding population on the Woongarra Coast after 1990, the WMP did not have a comparable benefit for the nesting populations at other rookeries (Figures 3, 4, 5) – and the Wongarra Coast loggerhead populations continued to decline.

In response to criticism from the fishing industry in the mid 1990s that the decline in loggerhead turtle nesting numbers was the result of research and tourist disturbance, Tryon Island (one of the top five loggerhead turtle rookeries) was selected for monitoring. Tryon Island had been monitored previously by the QTC monitoring team in only one summer, 1977. The Island, having been generally closed to camping over the previous two decades under Queensland Parks and Wildlife Service management, was selected for another census in 1996 after a 19 year 'no research/no tourism" gap. This loggerhead turtle nesting population had declined over those 19 years in the absence of regular tourist disturbance or disturbance by researchers (Figure 4A).

Otter Trawling was listed under the EPBC Act as a key threatening process (KTP) in 2001 because of the level of by-catch of marine turtles. Across the same period, the compulsory use of Turtle excluder devices (TEDs) was regulated in the Northern Prawn Fishery (NPF) in April 2000, East Coast Trawl Fishery (ECTF) in December 2000 and the Torres Strait Prawn Fishery (TSPF) in March 2002. However, TEDs are not compulsory within the trawl fishery in New South Wales in which loggerhead turtles are a known part of the by-catch.

Based on data available in 2004, Limpus (2008a) indicated that "the benefits of a greatly reduced trawl bycatch mortality resulting from the use of TEDs in the NPF, ECTF and TSPF in the early 2000s should be detectible as a slowing in the rate of decline of the population at the east coast nesting beaches within a single breeding cycle of about 5 years for a young adult, i.e. by about 2005." Examination of the trends in nesting numbers for loggerhead turtles at each of the six index beaches (Figure 3) shows that there has been a reversal of the downward trend for nesting numbers since 2001. These data indicate that the use of TEDs have been effective in reducing bycatch mortality in prawn trawls of eastern and northern Australia such that the eastern Australian nesting population is in a recovery mode. The nesting population is still substantially reduced when compared to the population nesting in the mid 1970s.

The down turn in nesting numbers at the index beaches during the 2011-2012 nesting season (Figure 3) is currently unexplained. However, there is a possibility that this reduction in breeding, a year after floods and cyclones during the extreme weather of 2010-2011 has been in response to the resulting damage to coastal habitats in south and central Queensland. The interaction of turtle population dynamics and climate variability warrants close examination given the results of an investigation of Pacific loggerhead turtle nesting population size and sea surface temperature in their respective foraging areas (Chaloupka *et al*. 2008). This study demonstrated that the two Pacific loggerhead turtle stocks (Japan and south-western Pacific) have been exposed to slowly increasing trends in mean annual sea surface temperature in their respective core regional foraging habitats over the past 50 years. They further demonstrated that "irrespective of whether a population was decreasing or increasing there was an inverse correlation between nesting abundance and mean annual sea surface temperature in the core foraging region during the year prior to the summer nesting season".

Courtship and mating systems
There have been few studies of loggerhead courtship in eastern Australia.

Limpus (1985) identified that courtship occurred during October and November and that courtship was rarely observed in the immediate vicinity of the nesting beaches. Adult male loggerhead turtles develop a temporary secondary sexual characteristic in the form of a prominent soft area (nuptial pad) in the posterior plastron during spermatogenic preparation for a breeding season (Wibbels *et al*. 1991). This presence of a prominent soft nuptial pad can be used to identify adult male loggerhead turtles preparing to breed while still in their foraging area.

Changes in loggerhead turtle endocrinology associated with preparation for a breeding season and subsequent changes during the breeding season were investigated in a collaborative study between QPWS and a team from Texas A&M University led by Dr David Owens (Wibbels *et al*. 1990, 1992)

That a female mates with multiple partners, stores sperm at courtship and uses this sperm during the following nesting season to fertilise multiple clutches of eggs has been investigated using genetic markers. Harry and Briscoe (1988) demonstrated multiple paternity in loggerhead turtle clutches laid at Mon Repos. More recent studies in progress on loggerhead turtle multiple paternity and sperm storage have been conducted collaboratively between EHP and a Griffith University post graduate student supervised Dr Nancy Fitzsimmons.

There is a general paucity of information on the temporal and spatial distribution of areas where loggerhead turtle courtship occurs and of the biology of the breeding males.

Embryology and temperature dependent sex determination
Miller (1985) has provided a comprehensive description of loggerhead turtle embryology.

Limpus *et al*. (1979); Miller and Limpus (1983) and Harry and Limpus (1989) have investigated movement induced mortality on loggerhead turtle embryos resulting from rotation of the eggs and defined a methodology for safe transportation of eggs to distant incubation sites and laboratories.

The loggerhead turtle of eastern Australia, typical of marine turtles displays temperature dependent sex determination (TSD) (Reed, 1980; Limpus *et al*. 1985):

- This population has a pivotal temperature of 28.6^{o}C;
- Cooler nests producing mostly male hatchlings and warmer nests producing mostly female hatchlings.

The brown sand beaches at nest depth on the mainland (Limpus, 1971; Reed, 1980; Limpus *et al*. 1983; Maloney *et al*. 1990) are on average, warmer than at nest depth on the white sand beaches of the coral cays of the adjacent southern GBR (Bustard, 1972; Limpus *et al*. 1983).

Harry investigated the role of heat shock proteins in TSD in loggerhead turtles (Harry *et al*. 1990), identifying differential growth of male and female loggerhead embryonic urinogenital systems within the sex determining period of incubation (Harry and Williams, 1991).

Georges *et al.* (1994), using controlled temperature laboratory studies, determined that hatchling sex in the loggerhead turtle is determined by the proportion of embryonic development at a temperature, not daily duration of exposure to the temperature.

In response to concerns regarding climate change and increasing beach temperatures, Chu (2008) and Chu *et al*. (2008) investigated loggerhead turtle incubation temperatures, incubation success, hatchling sex ratio and associated hatchling locomotor performance at Mon Repos during the 2005-

2006 and 2006-2007 breeding seasons. They found that the abnormally high nest temperatures of the 2005-2006 breeding season were associated with:

- Approaching 100% female hatchling production;
- No reduction in incubation success but a significant reduction in hatchling emergence success from hotter nests;
- Size of hatchlings was weakly inversely affected by nest temperature;
- Hatchling running ability and swimming force was inversely affected by nest temperatures.

Further collaborative studies with EHP and University of Queensland post graduate students supervised by Dr David Booth are in progress investigating the role of beach temperatures on hatchling sex ratio, incubation and emergence success and hatchling fitness and health of loggerhead turtles breeding on the Woongarra Coast.

Migration

Figure 6A summarises the distribution of foraging areas in Indonesia, Papua New Guinea, Solomon Islands, New Caledonia, Northern Territory, Queensland and New South Wales that have been recorded to supply nesting female loggerhead turtles to eastern Australian rookeries. Limpus (2008) has summarised a number of principles underlying loggerhead turtle migration:

- There is no one path followed by all turtles on their breeding migrations (Limpus and Limpus, 2001).
- Each adult migrates with a high degree of fidelity to its particular feeding area and its rookery (Limpus, 1985, 1989, 1994; Limpus *et al.* 1992; Limpus and Limpus 2001, 2003b).
- Turtles nesting at the one rookery will have migrated from numerous foraging areas (Limpus and Limpus, 2003a).
- Similarly, turtles that live within the same foraging area can be expected to disperse to widely scattered breeding sites (Limpus and Limpus, 2001, 2003b) (Figure 6B).

Adult females can migrate in to breed at eastern Australian rookeries from up to 2,600km distant but the majority appear to migrate from foraging areas within a limited area of the eastern Queensland coast spanning only 6º of latitude (23º to 28º latitudinal blocks) (Figure 7). If this is the case, then most loggerhead turtles breeding in eastern Australia should be migrating to breed from foraging areas less than 500km from their respective rookeries. This concept of a more restricted foraging distribution warrants further investigation.

Loggerhead turtles living within the 23º latitude block of the eastern Australian (in the vicinity of Port Alma and Port Curtis) have been recorded to migrate to breed at many different rookeries in south and central Queensland:

- Swain Reefs cays,
- Capricornia Section of the Southern GBR (Wreck Island, Heron Island, lady Musgrave Island),
- the adjacent mainland coast (Wreck Rock beaches, Moore Park, Woongarra Coast) and
- Fraser Island and
- multiple beaches in New Caledonia (Figure 6B).

Building on previous satellite telemetry studies (Limpus and Limpus, 2001), there are current collaborative studies between EHP and JCU a post graduate student supervised by Dr Mark Hamann investigating inter-nesting habitat usage, migratory corridors between nesting beaches and foraging areas and foraging area home ranges using GPS satellite tags. These tags have been deployed on adult loggerhead turtles nesting at Mon Repos (females) and foraging in Moreton Bay (females and males).

Oceanic pelagic post-hatchling dispersal

Hatchling loggerhead turtles engage in a swimming frenzy to disperse from their natal nesting beaches out to open ocean waters. This phase in their life history has been investigated mostly via laboratory experiments examining blood properties/chemistry and hatchling locomotor performance (Baldwin *et al*. 1989; Pereira *et al.* 2011, 2012a, b). Lemm (1996) and Limpus (2008a) measured very low predation rates by fish and sharks on loggerhead hatchlings as they swam through the immediately adjacent waters off Mon Repos and Wreck Rock beaches. This contrasts with the expected elevated mortality, as recorded for green turtle hatchlings, *Chelonia mydas*, dispersing across coral reef habitats from rookeries in the southern GBR (Gyuris, 1994). During this swimming frenzy period, the hatchling drinks sea water to recover from dehydration that occurred in the nest while digging to the beach surface (Bennett (1983).

Once offshore of the eastern Australian rookeries, the post-hatchling loggerhead turtles initially travel south in the East Australian Current to northern New South Wales before traversing across the Tasman Sea past New Zealand (Limpus and Walker, 1994; Walker 1994). During this dispersal the post-hatchlings feed on macro zooplankton (Boyle and Limpus, 2008).

The subsequent temporal and spatial aspects of their dispersal across the South Pacific Ocean are not documented. However, vast numbers of immature loggerhead turtles are hooked as by-catch in the long-line fisheries of Peru and Chile in the Eastern Pacific Ocean (Kelez, *et al.* 2004; Mangel *et al.* 2011) (Figure 8). Genetic analysis has identified that these post-hatchling loggerhead turtles originate from the south-western Pacific rookeries of eastern Australia and New Caledonia (Boyle *et al*. 2009; Donoso and Dutton, 2010). The mean curved carapace length (CCL) = 57.2 ± 9.2 cm (range = 35.9–86.3, n = 307) off the coast of Peru (Alfaro-Shigueta *et al*. 2011).

On their subsequent return to the western Pacific, the distribution and abundance of the large immature loggerhead turtles that occur in the Coral Sea – Tasman Sea region of the south-west Pacific Ocean (Robins *et al*. 2002, 2007) is unquantified.

Within the total post-hatchling dispersal across the entire south Pacific Ocean, the species is exposed to considerable mortality from ingestion of synthetic debris (Boyle and Limpus, 2008) and long-line fishery by-catch mortality off Peru and Chile (Alfaro-Shigueta *et al.* 2011).

There have been no studies to quantify survivorship of post-hatchlings during this oceanic dispersal phase.

Coastal foraging population

Limpus *et al*. (2008) have summarised habitat use by loggerhead turtles in eastern Australia: "Large immature and adult-sized *C. caretta* from the eastern Australian management unit feed in a wide range of tidal and subtidal habitats including coral and rocky reefs, sea grass meadows, and soft-bottomed sand or mud areas. Their foraging range encompasses the eastern Arafura Sea, Gulf of Carpentaria, Torres Strait, Gulf of Papua, Coral Sea, and western Tasman Sea to southern New South Wales including the Great Barrier Reef, Hervey Bay, and Moreton Bay. The outer extent of their foraging range includes coastal waters in eastern Indonesia, north-eastern PNG (Trobriand Islands and Woodlark Islands), northeastern Solomon Islands and New Caledonia (Limpus, 1985, 1994; Limpus *et al.* 1992, 1994; Speirs, 2002; Bell, 2003)."

Loggerhead turtles also forage in the deeper soft bottom habitats between the coral reefs of the GBR and the mainland and have been most frequently trawled at 6-20 m depth and less frequently to depths up to 40 m (Robins and Mayer, 1998).

Loggerhead turtles recruit from their oceanic pelagic post-hatchling dispersal phase to residency in coastal habitats within the Coral Sea – Tasman Sea region at an estimated age of about 16 yr of age and CCL = 78.6 cm (SD = 4.013, range = 66.7 – 93.9 cm, n = 108. Limpus, 2008a). The size at which they recruit to coastal benthic foraging is independent of the foraging area selected (Limpus and Limpus, 2003)

The loggerhead turtle population is structured similarly at both index foraging sites and all other site sampled in coastal waters (Capricorn Reefs: Limpus, 1985; Limpus and Limpus, 2003. Moreton Bay: Limpus *et al*. 1994; Limpus, 2008a,b. Julian Rocks, NSW: Speirs, 2002):

- Consisting of only large immature and adult turtles.
- Strongly biased to males, approximately 2 males to one female, across all age classes at both index foraging areas:
    - Capricorn Reef: male to female ratio = 1.0 : 0.41;
    - Moreton Bay: male to female ratio = 1.0 : 0.54.

Survivorship, calculated from tagging-recapture analysis for loggerhead turtles resident on coral reefs in the southern GBR, is high (Table 1) (Chaloupka and Limpus, 2002). This is a study site with little direct anthropogenic impact on the turtles.

Adult female loggerhead turtles typically do not breed annually but skip one or more years between breeding seasons (Limpus *et al*. 1994; Limpus and Limpus, 2003). At both index foraging sites, approximately 25% of the adult females prepare for breeding in any one year (Figure 9). There have been approximately constant annual breeding rates recorded in the foraging areas during both the declining and recovery phase of the adult loggerhead breeding population recorded at the nesting beaches. Typically there is a higher proportion of the adult males than females that prepare for breeding from their respective foraging areas in any one year (Figure 9, Table 2).

Based on a tagging-recapture analysis of the loggerhead turtle population resident on the coral reefs of the southern GBR, Chaloupka and Limpus (2001) identified that it declined at 3% per year during 1985 to the late 1990s. Because this decline occurred within a foraging population with very high, constant annual survivorship values (Table 1) and within a habitat with few anthropogenic impacts, they hypothesised that the decline was due to failure of recruitment from the post-hatchling oceanic dispersal phase. The decline in numbers of recently recruited immature *C. caretta* captured on these coral reef feeding areas of the southern Great Barrier Reef during the late 1990s (Limpus and Limpus, 2003b) is consistent with this hypothesis. Figure 10 summarises the continuing decline in the proportion of loggerheads recorded in southern GBR and Moreton Bay foraging areas that have recently recruited to residency from the oceanic pelagic dispersal phase beyond that summarised by Limpus and Limpus (2003).

Loggerhead turtles have been recorded within the port limits of Port Alma and Port Curtis. However, no studies have been conducted with this species with the port limits.

Diet

Limpus (2008a) has summarised available data on the diet of loggerhead turtles foraging in eastern Australia coastal waters: "Adult and large immature *C. caretta* are carnivorous, specialised for feeding on hard-bodied, slow-moving invertebrate prey. In eastern Australian coastal waters, while the species has been recorded feeding on about 100 taxa, *C. caretta* feeds principally on benthic gastropod and bivalve molluscs, portunid crabs and hermit crabs (Moody, 1979; Limpus *et al.* 2001)…….. It feeds less frequently on other invertebrates (including jellyfish, anemones, holothurians, sea urchins) and fish (Moody, 1979; Limpus *et al.* 1994; Limpus *et al.* 2001). *C. caretta* forages using a range of strategies including digging within the substrate, picking prey items off the substrate and plucking them from within the water column or at the water surface (Preen, 1996; Limpus *et al.* 2001)."

Ageing studies and relevance to management time scales

A study to determine the age at which loggerhead turtles reach sexual maturity, to determine philopatry to natal beaches and to quantify survivorship to sexual maturity was commenced at Mon Repos during the 1973-1974 nesting season (Limpus, 1885): Over seven breeding season, approximately 130,000 hatchling loggerhead turtle hatchlings were tagged using mutilation tagging (carapace notching) such that each was identified to the beach of its birth and the season in which it was born.

Some loggerhead turtles "tagged" as hatchlings have been recaptured as large immature turtles in their foraging areas (Limpus *et al*. 1994). The first adults that had been marked as hatchlings at the Mon Repos rookery have returned for their first breeding at 29 years of age in the 2003–2004 breeding season (C. Limpus, unpublished data). This study is still in progress.

The size at which loggerhead turtles reach sexual maturity (1^{st} breeding season) has been quantified for turtles foraging on the southern GBR coral reefs using gonad examination to determine commencement of breeding and as nesting turtles at Mon Repos based on long term tagging-recapture and gonad examination to identify recruits to the breeding population (Limpus, 2008a):

- Nesting beach, Mon Repos: CCL = 93.65 cm (SD = 4.25; range = 84.5–103.5 cm; n = 69. Limpus, 1991).
- Feeding area, Heron-Wistari Reefs: CCL = 94.4 cm (SD = 3.45; range = 90.5–101.5 cm; n = 14. Limpus and Limpus, 2003b).

As summarised above, loggerhead turtles recruit to coastal residency from the post-hatchling oceanic pelagic dispersal life history phase at CCL = 78.6 cm.

Immature loggerhead turtles are slow growing. Based on studies, tracking the growth and feeding area fidelity using tagging-recapture studies with flipper tag recoveries, these loggerhead turtles are resident in southern GBR coral reefs for an average of 13 years (SD = 3.7, range = 9–23, n = 15) before they commence breeding (Limpus and Limpus, 2003b). By extrapolation from the above data, these loggerhead turtles are recruiting to coastal residency at about 16 years of age.

Growth of adult loggerhead turtles is extremely slow, of the order of a few millimetres per year (Limpus, 1985).

There is no evidence of further developmental migration of loggerhead turtles once they recruit to a foraging area in eastern Australia. Rather, tagging studies indicate that the turtles continue to maintain fidelity to their respective foraging areas even after they reach maturity and for the remainder of their adult lives.

A species with such extreme delay in age at first breeding will be difficult to management within the time frames of normal Government conservation agency organisation. For example:

- Because coastal trawl fisheries only interact with adults and large immature loggerhead turtles in eastern and northern Australia, the size range that lives in our coastal waters, changes in trawl bycatch mortality can be detected through changes in the size of nesting populations recorded at index nesting beaches within a few years of the management changes in the fisheries.
- However, changes in the mortality of small immature loggerheads (pelagic oceanic post-hatchling life history phase) by oceanic long-line and purse seine fisheries bycatch, as in Peru and Chile, will not be detectable at the nesting population for more than 13 years after the changes occur with the fishing fleets.
- Similarly, changes in egg mortality and associated hatchling production at the nesting beaches will not be detectable in the next generation of nesting turtles for some 30 years or more.

When other aspects of loggerhead turtle life history complexity are considered such, as their vast oceanic dispersal distances, adult breeding migrations and the associated occupancy of a diversity of habitats throughout the life history, there is even greater complexity in implementation of successful conservation management for the species.

On the basis of these timing estimates, impacts of some recent past conservation management will not be detectable in the adult nesting population at this time. If early warnings of population malfunction are to be effective, there is a need for a range of bench mark parameters to be quantified that give a measure of the performance of each life history phase. Some of these parameters include: size of the annual nesting population, recruitment rate to the adult population; rates of clutch loss and incubation success of the remaining clutches; recruitment from pelagic to benthic foraging life history phase; survivorship of immature and adult turtles in representative foraging areas and as breeding adults.

Anthropogenic mortality in coastal waters

Greenland *et al*. (2004) and Biddle and Limpus (2011) have reviewed the incidence of mortality of loggerhead turtles in coastal waters of eastern Queensland from StrandNet records. These data are summarised in Table 3. Given that the strandings summarised in StrandNet are not a complete record of turtle mortality in Queensland, the data in Table 3 can provides only an index of relative importance of mortality factors. The highest recorded mortalities from anthropogenic sources are, on average: boat strike and propeller cuts (6 loggerhead turtles/year reported); entanglement in crab pot float lines (2.1 loggerhead turtles/year reported) and entrapment in Queensland Shark Control Program gear (1.6 loggerhead turtles/year).

Climate change impacts on marine turtle

There has been concern regarding the potential impacts of climate change on marine turtle populations for some two decade (Limpus, 1993). In recent years, there have been two comprehensive reviews of the potential for climate change to impact on marine turtle biology and population dynamics with an emphasis on Australian populations (Hamann et al. 2008; Poloczanska et al. 2009). Both these studies have addressed the issues relevant to loggerhead turtles in eastern Australia.

While there have been some studies investigating particular aspects of climate change impacts on loggerhead turtles in eastern Australia, there have been no management actions implemented to compensate for climate change impacts on the species:

- Increasing sea surface temperature in foraging areas inversely correlated with loggerhead turtle breeding rates (Chaloupka *et al*. 2008).
- Beach temperature impacts on loggerhead hatchling sex ratio, incubation and hatchling emergence success and hatchling vigour (Chu, 2008; Chu *et al*. 2008)

Conservation management
Limpus (2008b) summarised the status of habitat protection for the eastern Australian loggerhead turtle population: “With the combination of > 80% of nesting contained within Queensland Parks and Wildlife Protected Area Estate and 97% of the coastal waters of eastern Queensland contained in Australian and Queensland Marine Protected Areas, the loggerhead turtle population that breeds in eastern Australia has some of the most extensive habitat protection afforded any turtle population globally.”

Significant management actions have continued since the late 1980s that have substantially increased hatchling production from the mainland rookeries. The increased numbers of hatchlings produced through these projects have a strong female sex ratio bias because there are brown sands on the mainland beaches that have nest temperatures that are generally warmer than the pivotal temperature for this population (Limpus *et al*. 1983, 1985; Maloney *et al*. 1990; Reed, 1980).

- The reduction on fox predation of loggerhead turtle eggs on the mainland beaches, including the Wreck Rock beaches, from approximately 90% loss of eggs during the late 1970s – early 1980s to less than 5% egg loss since the late 1980s (Limpus, 2008a). These activities are continuing.
  - EHP and NPRSR staff in collaboration and QTC Volunteers conduct annual baiting for foxes (Fox-off 1080 baits) along mainland beaches of the Woongarra Coast, Skyringville, Moore Park, and Wreck Rock beaches.
  - Queensland Turtle Conservation Volunteers are also placing fox excluder devices (aluminium mesh) over loggerhead turtle nests along the Sunshine Coast (Figure 11A).
- NPRSR staff and volunteers relocate loggerhead clutches laid on northern Fraser Island beaches into heavy duty, aluminium mesh incubation cages to protect them from dingo predation (Figure 11B).
- Rescuing of doomed eggs on the Woongarra Coast to increase hatchling production (Pfaller *et al*. 2008). This project increases loggerhead turtle hatchling production with some 40-50 thousand extra hatchlings being produced along the Woongarra Coast annually.
  - QTC volunteers are rescuing doomed eggs from small numbers of clutches laid along the Moore Park, Sunshine Coast and North Stradbroke Island beaches.

The increased hatchling production from these projects is expected to produce increased adult recruitment into the eastern Australian loggerhead turtle nesting population by about 2020, given the expected age at first breeding for the species. While the increased hatchling production from these two actions will not yet be evident in the current adult nesting population, the increased hatchling production since the late 1980s should have been detectable as increased recruitment from the oceanic pelagic-foraging life history phase into the coastal foraging populations of eastern Australia by about 2005. However this has not occurred (Figure 10). This raises concern regarding the probably excessive mortality of post hatchlings with in the south Pacific Ocean from long-line fisheries by-catch (Alfaro-Shigueta *et al*. 2011) and ingestion of synthetic debris (Boyle and Limpus, 2008) continued decline of the endangered loggerhead turtle in eastern Australia.

An emerging threat to successful loggerhead turtle breeding on the Woongarra Coast is the escalating alteration to coastal light horizons and its potential to cause a decline in loggerhead turtle nesting on this coast and the disruption of hatchling ocean-finding behaviour.

Taking into account the results of study on hatchling ocean finding behaviour of loggerhead turtle and other marine turtles at Mon Repos (Limpus, 1971), QPWS promoted a public education campaign to reduce coastal lighting impacts (Limpus *et al*. 1981) while working with the Woongarra Shire Council to develop the Mon Repos Conservation Park in the early 1980s. Other actions included:

- Revegetation the frontal dunes to create an elevated dark horizon on the inland side of the nesting habitat to shield against distant artificial light horizons of Bundaberg.

- Because of the consistent disruption of ocean-finding behaviour of hatchling turtles at back-lit urban beaches such as Neilson Park and Bargara within the Bargara Township with associated death of hatchlings (Figure 12C), most turtle eggs laid on these particular beaches have been routinely relocated to incubate on a nearby dark beach such as Mon Repos for three decades.

There has been expanding coastal development at the coastal township at Bargara on the Woongarra Coast to the south of Mon Repos in recent decades. This has included increased residential buildings in an expanded urban setting, high rise buildings along the esplanade, flood lighting of night time sports areas, floodlighting of shopping complex parking areas. The combined result of these developments has been to create a brightly illuminated salt spray dome over the township at night. This illuminated sky is now clearly visible from the entire Mon Repos beach (Figure 12A). It is so bright that it now masks the capacity for hatchling turtles to clearly distinguish the natural horizons over the sea that they need to see for successfully dispersing from the beach to the open ocean. Observations at Mon Repos during the February-April 2008 hatchling emergence season demonstrated that lighting from dense coastal development has the capacity for disrupting the natural dispersal of hatchlings from the beach to the sea at distances greater than three kilometres. This was the first time in the history of management of the Mon Repos turtle rookery that hatchlings were regularly observed to walk parallel to the sea and head towards the illuminated glow over Bargara. Studies in the Caribbean with hawksbill turtle hatchlings, *Eretmochelys imbricata*, (Harewood and Horricks, 2008) have demonstrated that beach front lighting can negatively interfere with the swimming performance of hatchlings dispersing out to sea. In addition, they found that hatchlings released from dark beaches were attracted by lights from neighbouring beaches, which only became visible after they were a substantial distance from shore. This illuminated-skyline-trapping of hatchlings in inshore coastal waters and on the beaches parallels the observations made in the past with loggerhead, flatback, and green turtle hatchlings in south Queensland. In the extreme, adult nesting flatback turtles, *Natator depressus*, at Hummock Hill Island have been dis-oriented by the brightly illuminated skyline over the Boyne Island industrial complex that is 18 km away from the beach across the bay (Hodge *et al*. 2007).

In addition, in conjunction with the increasing brightness of the night sky over Kellys Beach since the 1970, there has been a reduction in turtle nesting crawls on that beach. Kellys Beach supported the second highest number of nesting crawls during the late 1960s (15% of the entire nesting crawls for the Woongarra Coast. Limpus, 1985). In recent years it supports only trivial levels of nesting activity (~5% of nesting crawls along the Woongarra Coast). It appears that the nesting turtles are deserting the illuminated beaches to the south of Bargara and shifting to nest on the darker beaches to the north. This would be consistent with observation overseas of female turtles avoiding brightly illuminated beaches for egg laying (summarised by Limpus, 2008).

In response to this increasing threat of light pollution to the Woongarra Coast nesting loggerhead population, NPRSR and EHP have developed a publicity campaign to catalyse change in behaviour and management with regards to lighting along this coast. This has included meetings with the Regional Council, businesses, electricity board, letter drops to the coastal residents, an extension programme with local schools and production of brochures (Figure 12B, D). While the hatchling mortality rates and shift of nesting turtles to other beaches resulting from this illumination of the skyline behind and over the Woongarra Coast nesting beaches remain poorly quantified, the illuminated night sky is a major threat to the maintenance of sustainable turtle nesting populations, including high hatchling production, on this coast.

Kamrowski *et al*. (2012), using satellite imagery of night illumination from the earth's surface, have identified the Woongarra Coast as one of the two most light-polluted areas along the Australian coast and hence posing a high risk to successful marine turtle breeding in the area.

Collaborative studies investigating light horizon impacts on loggerhead turtles are in progress between EHP and UQ post graduate students supervised by Dr David Booth and EHP and a JCU post graduate student supervised by Dr Mark Hamann.

Unless the continued escalation of light pollution from the Woongarra coast is minimised by the *Cut the Glow* Campaign, it may be necessary to consider legislative changes to achieve turtle friendly illumination of this coastline.

Chaloupka (2003) developed a stochastic simulation model for evaluating the population dynamics of loggerhead turtles in the South Pacific Ocean exposed to competing mortality risks. This study identified the most significant mortality factors impacting loggerhead turtles breeding in eastern Australia up to 2000 have been loss of eggs to foxes on the mainland beaches; mortality of large immature and adult turtles in coastal otter trawl fisheries and post-hatchling mortality in oceanic long-line fisheries. This style of modelling provides a valuable management tool for assessing the impact of mortality factors and expected consequences of management options, including the temporal scale over which population response can be expected. Since 2000, fox control and the compulsory use of TEDs in the trawl fisheries have reduced to acceptable levels. It would be appropriate to rerun this model taking these changes into account and addressing the additional risks now identified for the stock: ingestion of synthetic debris by small post-hatchling turtles, altered light horizons impacting hatchling survivorship and climate change impacts on incubation success and sex ratio changes.

References

Alfaro-Shigueta, J., Mangel, J., Bernedo, F., Dutton, P. H., Seminoff, J. A., and Godley, B. J. (2011). Small-scale fisheries of Peru: a major sink for marine turtles in the Pacific. *Journal of Applied Ecology* **doi: 10.1111/j.1365-2664.2011.02040.x**, 1-9.

Baldwin, J., Gyuris, E., Mortimer, K., and Patak, A. (1989). Anaerobic metabolism during dispersal of green and loggerhead turtle hatchlings. *Comparative Biochemistry and Physiology* **94A**, 663-5.

Bell, I. (2003). Turtle population dynamics in the Hay Point, Abbot Point and Lucinda Port areas. *Unpublished report, Queensland Parks and Wildlife Service, Townsville* 1-37.

Bennett, J. M. (1983). Dehydration and drinking in hatchling loggerhead turtles *Caretta caretta*. (Unpublished B.Sc.Vet. thesis: University of Sydney.)

Biddle, T. M. and Limpus, C. J. (2011). Marine wildlife stranding and mortality database annual reports 2005-2010. Marine Turtles. *Conservation Technical and Data Report.* 2010(1):1-124.

Bolten, A. B. and Witherington, B. E. (2003). Loggerhead Sea Turtles. (Smithsonian Books: Washington.)

Bowen, B. W., (2003). What is a Loggerhead Turtle? The genetic perspective. In “Biology and Conservation of Loggerhead Turtles.” (Eds. Bolten, A. B. and Witherington, B. E.) Pp. 7-27. (Smithsonian Institution Press: Washington, D. C.)

Bowen, B. W., Kamezaki, N., Limpus, C. J., Hughes, G. R., Meylan, A. B., and Avise, J. C. (1994). Global phylogeography of the loggerhead turtle (*Caretta caretta*) as indicated by mitochondrial DNA haplotypes. *Evolution* **48**, 1820-8.

Boyle, M. C. and Limpus, C. J. (2008). The stomach contents of post-hatchling green and loggerhead sea turtles in the southwest Pacific: an insight into habitat association. *Marine Biology* **155**, 233-241.

Boyle, M. C., FitzSimmons, N. N., Limpus, C. J., Kelez, S., Velez-Zuazo, X., and Weycott, M. (2009). Evidence for transoceanic migrations by loggerhead sea turtles in the southern Pacific Ocean. *Proceedings of the Royal Society B* **276**, 1993-1999.

Bustard, H. R. (1972). Australian Sea Turtles: Their Natural History and Conservation. (Collins: Glasgow.)

Chaloupka, M. (2003). Stochastic simulation modeling of loggerhead population dynamics given exposure to competing mortality risks in the western South Pacific. In “Biology and Conservation of Loggerhead Turtles.” (Eds. Bolten, A. B. and Witherington, B. E.) Pp. 274-294. (Smithsonian Institution Press: Washington, D. C.)

Chaloupka, M. and Limpus, C. (2001). Trends in the abundance of sea turtles resident in southern Great Barrier Reef waters. *Biological Conservation* **102**, 235-249.

Chaloupka, M., Kamezaki, N., and Limpus, C. (2008). Is climate change affecting the population dynamics of the endangered Pacific loggerhead sea turtle? *Journal of Experimental Marine Biology and Ecology* **356**, 136-143.

Chu, C. T. (2008). “The effects of incubation temperature on morphology and locomotor performance of loggerhead turtle hatchlings (*Caretta caretta*) at Mon Repos, Australia.” M.Sc. Thesis, School of Integrative Biology, University of Queensland.

Chu, C. T., Booth, D. T., and Limpus, C. J. (2008). Estimating the sex ratio of loggerhead turtle hatchlings at Mon Repos rookery (Australia) from nest temperatures. *Australian Journal of Zoology* **56**, 57-64.

Dodd, C. K. (1988). Synopsis of the biological data on the loggerhead sea turtle *Caretta caretta* (Linnaeus *1758). Biological Report* 88(14): 1-109.

Donoso, M. and Dutton, P. (2010). Sea turtle bycatch in the Chilean pelagic longline fishery in the southeastern Pacific: Opportunities for conservation. *Biological Conservation* **143**, 2672-2684.

Dutton, P., Broderick, D., and FitzSimmons, N. (2002). Defining management units: molecular genetics. In “Proceedings of the Western Pacific Sea Turtle Cooperative Research & Management Workshop.” (Ed. Kinan, I.) Pp. 93-101. (Western Pacific Regional Fishery Management Council: Honolulu)

Georges, A., Limpus, C., and Stoutjesdijk, R. (1994). Hatchling sex in the marine turtle *Caretta caretta* is determined by proportion of development at a temperature, not daily duration of exposure. *Journal of Experimental Zoology* **270**, 432-444.

Greenland, J. A., Limpus, C. J., and Currie, K. J. (2004). Queensland marine wildlife stranding database annual report, 2001-2002. III. Marine turtles. *Conservation technical and data report* **2002**.

Gyuris, E. (1994). The rate of predation by fish on hatchlings of the green turtle (*Chelonia mydas*). *Coral Reefs* **13**, 137-144.

Hamann, M., Limpus, C. J., and Read, M. A. (2008). Vulnerability of Marine Reptiles in the Great Barrier Reef to Climate Change. Ch.15. in “Climate Change and the Great Barrier Reef: a vulnerability assessment.” (Eds. Johnson, J. E. and Marshall, P. A.) Pp. 466-496. (Great Barrier Reef Marine Park Authority: Townsville).

Harewood, A. and Horrocks, J. (2008). Impacts of coastal development on hawksbill hatchling survival and swimming success during the initial offshore migration. *Biological Conservation* **141**, 394-401.

Harry, J. L. and Briscoe, D. A. (1988). Multiple paternity in the loggerhead turtle(*Caretta caretta*). *Journal of Heredity* **79**, 96-99.

Harry, J. L. and Limpus, C. J. (1989). Low-temperature protection of marine turtle eggs during long-distance relocation. *Australian Wildlife Research* **16**, 317-320.

Harry, J. L. and Williams, K. L. (1991). Differential growth of male and female urinogenital systems of *Caretta caretta*, within the sex-determining period. *Journal of Experimental Zoology* **258**, 204-211.

Harry, J. L., Williams, K. L., and Briscoe, D. A. (1990). Sex determination in loggerhead turtles: differential expression of two hnRNP proteins. *Development* **109**, 305-312.

Hodge, W., Limpus, C. J., and Smissen, P. (2007). Queensland Turtle Conservation Project: Hummock Hill Island nesting turtle study, 2006. *Conservation Technical and Data Report* **2006**, 1-6.

Kamrowski, R. L., Limpus, C. Moloney J., and Hamann, M. (2012). Coastal light pollution and marine turtles:assessing the magnitude of the problem. *Endangered Species Research* **19**, 85-98.

Kelez, S., Velez-Zuazo, X., and Mamrique, C. (2004). Conservation of sea turtles along the coast of

Peru. (Grupo de Tortugas Marinas - Peru and Associasion Peruana para la Conservacion de la Naturaleza: Unpublished report to UNEP/CMS.)

Lemm, S. (1996). Nest success and hatchling sex ratio of loggerhead sea turtles, *Caretta caretta* at mainland rookeries in Eastern Australia. *MSc thesis, Department of Anatomical Sciences, University of Queensland*.

Limpus, C. J. (1971). Sea turtle ocean finding behaviour. *Search* **2**, 385-387.

Limpus, C. J. (1985). A study of the loggerhead turtle, *Caretta caretta*, in eastern Australia. *PhD thesis, Zoology Department, University of Queensland*.

Limpus, C. J. (1989). Foraging area fidelity following breeding migrations in *Caretta caretta*. *National Oceanic and Atmospheric Administration Technical Memorandum Southeast Fisheries Center* **232**, 97-9.

Limpus, C. J. (1991). Puberty and first breeding in *Caretta caretta*. *National Oceanic and Atmospheric Administration Technical Memorandom National Marine Fisheries Service Southeast Fisheries Center* **278**, 81-3.

Limpus, C. J. (1993). A marine resource case study: climate change and sea level rise. Probable impacts on marine turtles. In “Climate change and sea level rise in the south pacific region.” (Eds. Hay, J. and Kaluwin, C.) P. 157. (South Pacific Regional Environment Programme: Apia).

Limpus, C. J. (1994). The loggerhead turtle, *Caretta caretta*, in Queensland: feeding ground selection following her first nesting season. *National Oceanographic and Atmospheric Administration Technical Memorandum National Marine Fisheries Service Southeast Fisheries Science Center* **351**, 78-81.

Limpus, C. J. (2008a). A biological review of Australian marine turtles. 1. Loggerhead turtle *Caretta caretta* (Linneaus). (Queensland Environmental Protection Agency: Brisbane.)

Limpus, C. J. (2008b). Status of the eastern Australian loggerhead turtle, *Caretta caretta*, population, November 2008. (Department of Environment and Resource Management, Brisbane).

Limpus, C. J., Baker, V., and Miller, J. D (1979). Movement induced mortality of loggerhead eggs. *Herpetologica* **35**, 335-8.

Limpus, C. J., Carter, R. W., and McLean, S. (1981). Lights and hatchling turtles: an education program. *Marine Turtle Newsletter* **19**, 11.

Limpus, C. J., Couper, P. J., and Read, M. A. (1994). The loggerhead turtle, *Caretta caretta*, in Queensland: Population structure in a warm temperate feeding area. *Memoirs of the Queensland Museum* **37**, 195-204.

Limpus, C. J., de Villiers, D. L., de Villiers, M. A., Limpus, D. J., and Read, M. A. (2001). The loggerhead turtle, *Caretta caretta*, in Queensland: observations on feeding ecology in warm temperate waters. *Memoirs Queensland Museum* **46**, 631-645.

Limpus, C. J. and Limpus, D. J. (2001). The loggerhead turtle, *Caretta caretta*, in Queensland: breeding migrations and fidelity to a warm temperate feeding area. *Chelonian Conservation and Biology* **4**, 142-153.

Limpus, C. J. and Limpus, D. J. (2003a). The loggerhead turtle, *Caretta caretta*, in the equatorial and southwest Pacific Ocean: a species in decline. In “Biology and Conservation of Loggerhead Turtles.” (Eds. Bolten, A. B. and Witherington, B. E.) pp. 199-209. (Smithsonian Institution Press: Washington, D. C.)

Limpus, C. J. and Limpus, D. J. (2003b). The biology of the loggerhead turtle, Caretta caretta, in southwest Pacific Ocean foraging areas. In “Biology and Conservation of Loggerhead Turtles.” (Eds. Bolten, A. B. and Witherington, B. E.). Pp. 93-113. (Smithsonian Institution Press: Washington, D. C.)

Limpus, C. J., Miller, J. D., Parmenter, C. J., Reimer, D., McLachlan, N., and Webb, R. (1992). Migration of green (*Chelonia mydas*) and loggerhead (*Caretta caretta*) turtles to and from eastern Australian rookeries. *Australian Wildlife Research* **19**, 347-58.

Limpus, C. J., Reed, P., and Miller, J. D. (1983). Islands and turtles. The influence of choice of nesting beach on sex ratio. In “Proceedings of Inaugral Great Barrier Reef Conference, Townsville, 28 Aug - 2 Sept 1983.” (Eds. Baker, J. T., Carter, R. M., Sammarco, P. W., and Stark, K. P.) Pp. 397-402. (JCU Press: Townsville)

Limpus, C. J., Reed, P. C., and Miller, J. D. (1985). Temperature dependent sex determination in Queensland sea turtles: intraspecific variation in *Caretta caretta*. In “Biology of Australian Frogs and Reptiles.” (Eds. Grigg, G., Shine, R., and Ehmann, H.) Pp. 343-351. (Surrey Beatty and Sons: Sydney)

Limpus, C. J. and Reimer, D. (1994). The loggerhead turtle, *Caretta caretta*, in Queensland: a population in decline. In “Proceedings of the Australian Marine Turtle Conservation Workshop.” (Compiler: James, R.) Pp. 39-59. (Australian Nature Conservation Agency: Canberra)

Limpus, C. J., Walker, T. A., and West, J. (1994). Post-hatchling sea turtle specimens and records from the Australian Region. In “Proceedings of the Marine Turtle Conservation Workshop, Seaworld Nara Resort, Gold Coast, 14-17 November 1990” (Compiler: James, R.) Pp. 95-100 (Australian Nature Conservation Agency: Canberra).

Maloney, J. E., Darian-Smith, C., Takahashi, Y., and Limpus, C. J. (1990). The environment for development of the embryonic Loggerhead turtle (*Caretta caretta*) in Queensland. *Copeia 1990* 378-387.

Mangel, J. C., Alfaro-Sigueto, J., Witt, M. J., Dutton, P. H., Seminoff, J. A., and Godley, B. J. (2011). Post-capture movements of loggerhead turtles in the southeast Pacific Ocean assessed by satellite tag. *Marine Ecology Progress Series* **433**, 261-272.

Miller, J. D. (1985). Embryology of Marine Turtles. In “Biology of the Reptilia.” Vol 14. Development A. (Eds. Gans, C., Billett, F., and Maderson, P.) Pp. 270-328. (John Wiley and Sons: Sydney)

Miller, J. D. and Limpus, C. J. (1983). A method for reducing movement-induced mortality in turtle eggs. *Marine Turtle Newsletter* **26**, 10-1.

Moodie, E. G. (1979). Aspects of the feeding biology of the loggerhead turtle (*Caretta caretta*). B.Sc.Hon. Thesis, James Cook University of North Queensland, Townsville.

Pereira, C. M., Booth, D. T., and Limpus, C. J. (2011). Locomotor activity during the frenzy swim: analysing early swimming behaviour in hatchling sea turtles. *Journal of Experimental Biology* **214**, 3972-3976.

Persira, C. M., Booth, D. T., and Limpus, C. J. (2012a). Swimming performance and metabolic rate of flatback *Natator depressus* and loggerhead *Caretta caretta* sea turtle hatchlings during the swimming frenzy. *Endangered Species Research* **17**, 43-31.

Pereira, C. M., Booth, D. T., Bradley, A. J., and Limpus, C. J. (2012b). Blood concentrations of lactate, glucose, and corticosterone in dispersing hatchling turtles. *Biology Open* **doi:10.1242/bi.20123046**.

Pfaller, J. B., Limpus, C. J., and Bjorndal, K. A. (2008). Nest-site selection in individual loggerhead turtles and consequences of doomed-egg relocation. *Conservation Biology* **23**, 72-80.

Poloczanska, E. S., Limpus, C. J., and Hays, G. C. (2009). Vulnerability of marine turtles to climate change. *Advances in Marine Biology* **56**, 151-211.

Preen, A. R. (1996). Infaunal mining: a novel foraging method for loggerhead turtles. *Journal of Herpetology* **30**, 94-6.

Reed, P. C. (1980). The sex ratio of hatchling loggerhead turtles - progeny of two nesting adult females. (B.Sc.Hon. Thesis, James Cook University of North Queensland: Townsville, Australia.)

Robins, C. M., Bache, S. J., and Kalish, S. R. (2002). Bycatch of sea turtles in pelagic longline fisheries - Australia. (Fisheries Research and Development Corporation: Canberra.)

Robins, C. M., Bradshaw, E. J. and Kreutz, D. C., (2007) Marine Turtle Mitigation in Australia's Pelagic Longline Fisheries. Fisheries Research and Development Corporation Final Report 2003/013, Canberra, Australia.

Robins, J. B. and Mayer, D. G. (1998). Monitoring the impact of trawling on sea turtle populations of the Queensland East Coast. *DPI Project Report Series* **Q098012**, 1-59.

Speirs, M. (2002). A study of marine turtle populations at the Julian Rocks Aquatic Reserve, northern New South Wales . *Unpublished B.Sc.Hon. thesis, School of environmental Science and Management, Southern Cross University* 1-119.

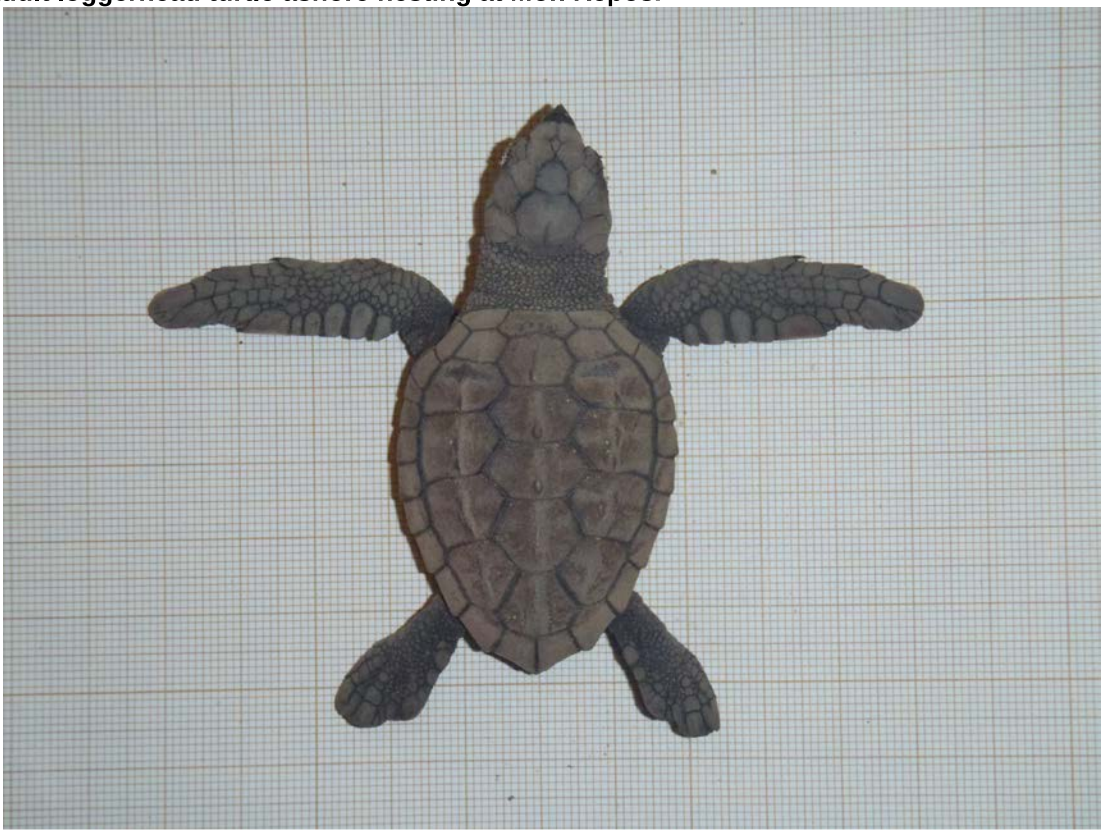
Walker, T. A. Post-hatchling dispersal of sea turtles. James, R. Proceedings of the Marine Turtle Conservation Workshop, Seaworld Nara Resort, Gold Coast, 14-17 November 1990 , 79-94. 1994.

Wibbels, T., Owens, D. W., Licht, P., Limpus, C. J., Reed, P. C., and Amoss, M. S. (1992). Serum gonadotropins and gonadal steroids associated with ovulation and egg production in sea turtles. *General and Comparative Endocrinology* **87**, 71-78.

Wibbels, T., Owens, D. W., Limpus, C. J., Reed, P. C., and Amoss, M. S. (1990). Seasonal changes in serum gonadal steroids associated with migration, mating and nesting in loggerhead sea turtle (*Caretta caretta*). *General and Comparative Endocrinology* **79**, 154-164.

Wibbels, T., Owens, D. W. M., and Rostal, D. (1991). Soft plastra of adult male sea turtles: an apparent secondary sexual characteristic. *Herpetological Review* **22**, 47-49.

A. Adult loggerhead turtle ashore nesting at Mon Repos.



B. Hatchling loggerhead turtle at Mon Repos (millimetre scale grid)

Figure 1. Loggerhead turtle, *Caretta caretta*, in eastern Australia.

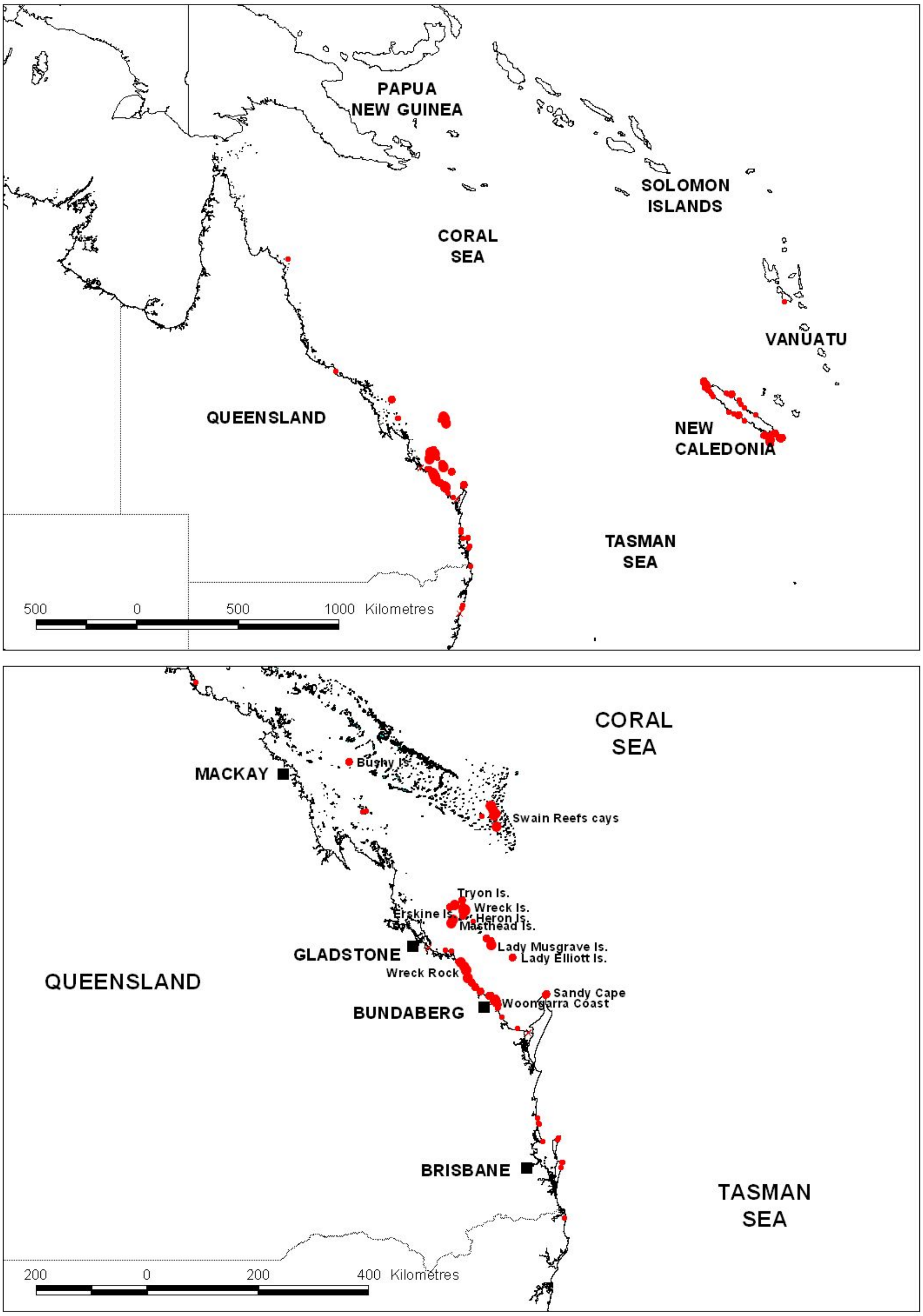
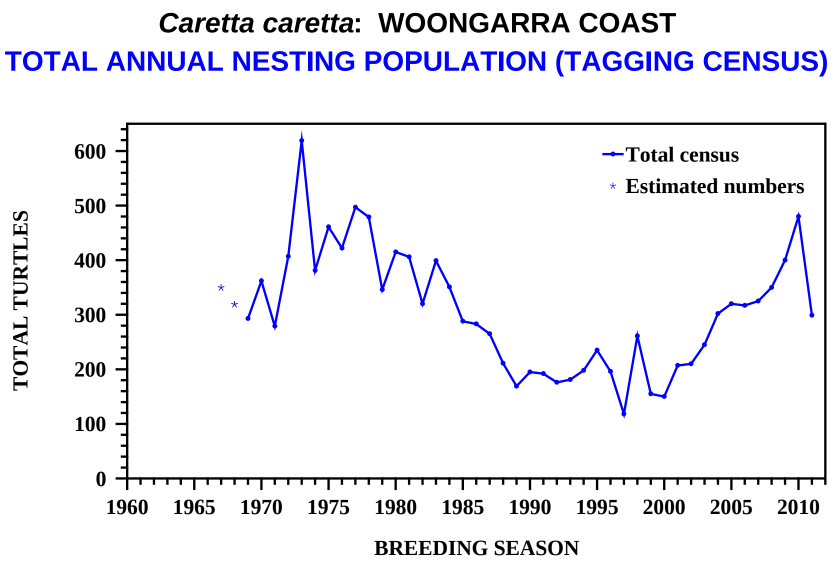
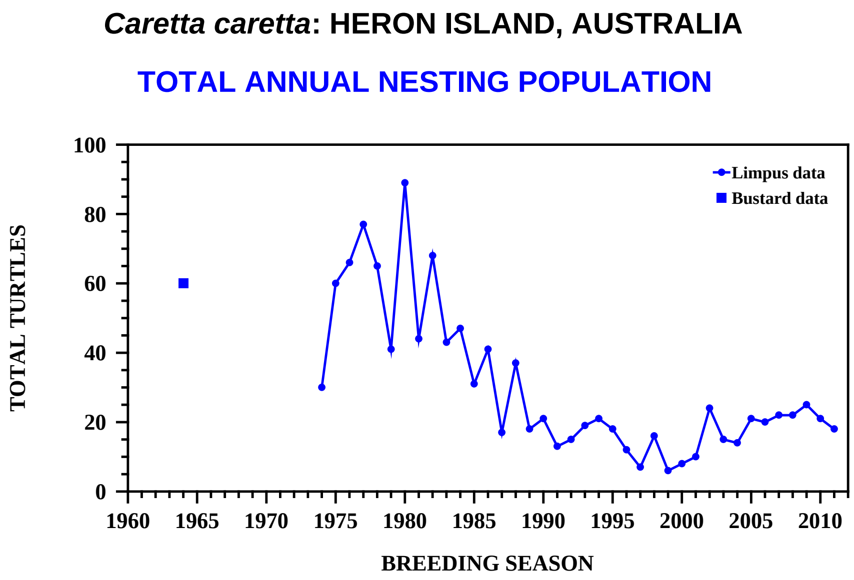


Figure 2. Loggerhead turtle, *Caretta caretta*, nesting distribution within the south-Pacific management unit (genetic stock) in eastern Australia and New Caledonia. Red dots denote recorded nesting localities.

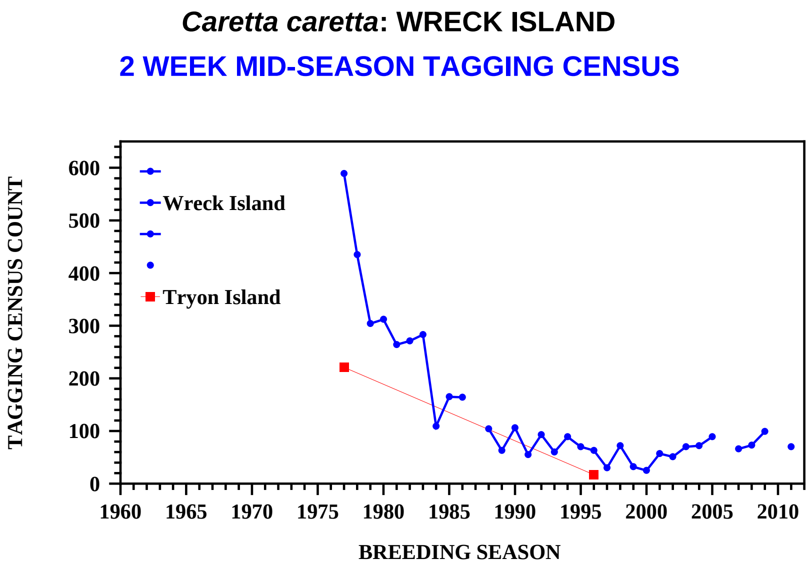


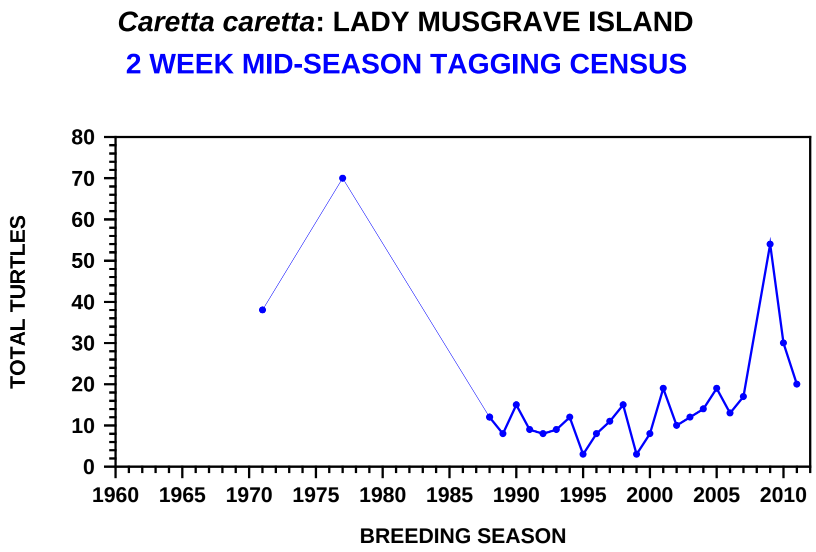


A. Woongarra Coast, including Mon Repos

B. Heron Island

Figure 3. Total annual loggerhead turtle, *Caretta caretta*, nesting population at index rookeries measured by total annual tagging census.

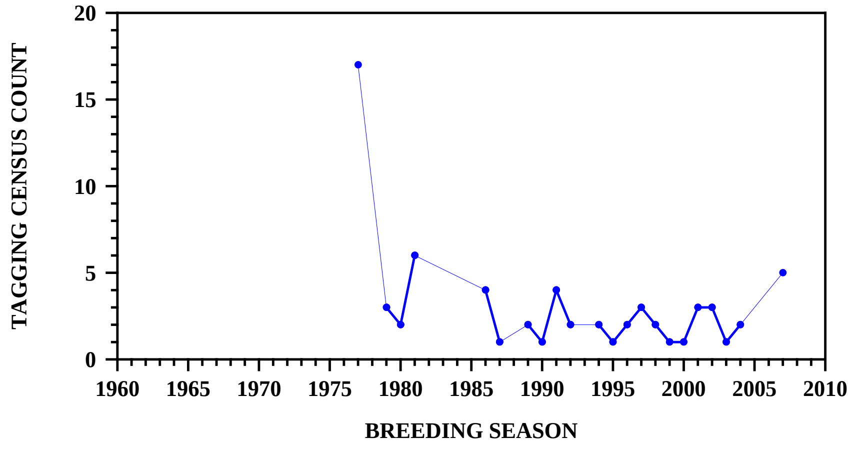




A. Wreck Island and Tryon Island

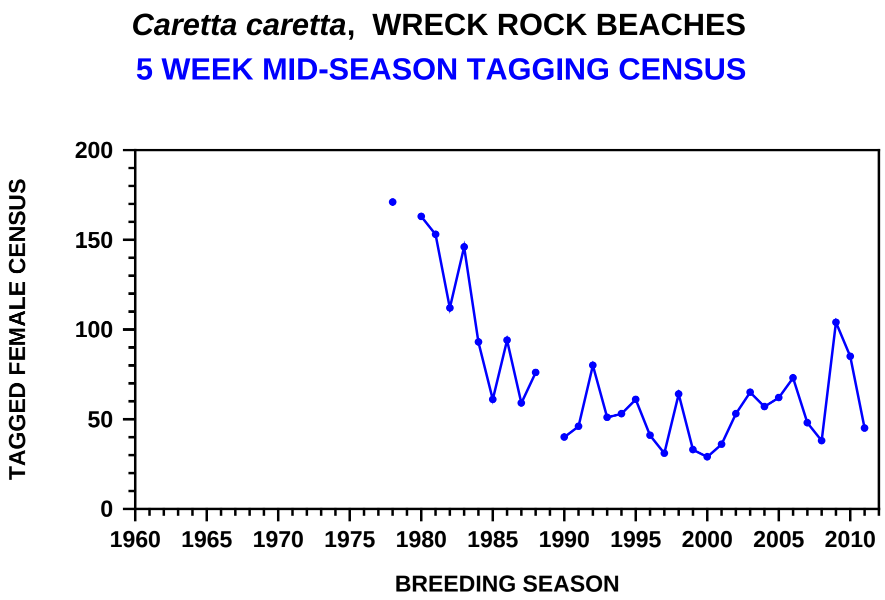
B. Lady Musgrave Island

Figure 4. Annual number of loggerhead turtles, *Caretta caretta*, recorded nesting at index rookeries measured by tagging census at the peak nesting season census period during the last two weeks of December.



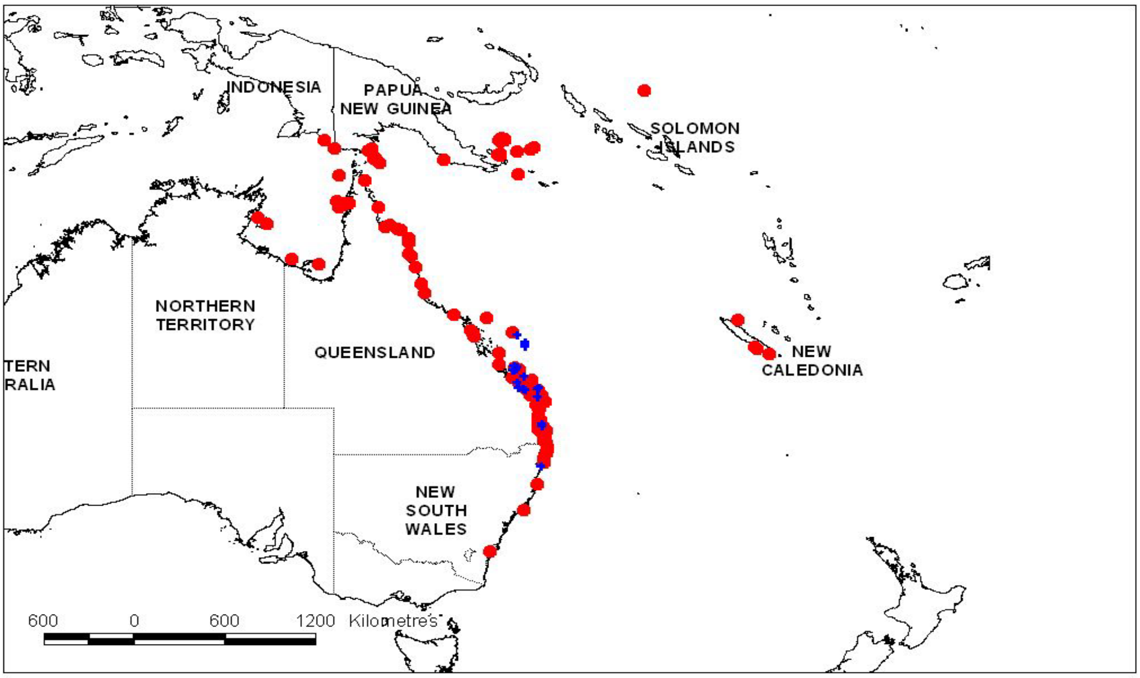
C. Northwest Island

Figure 4. Continued.

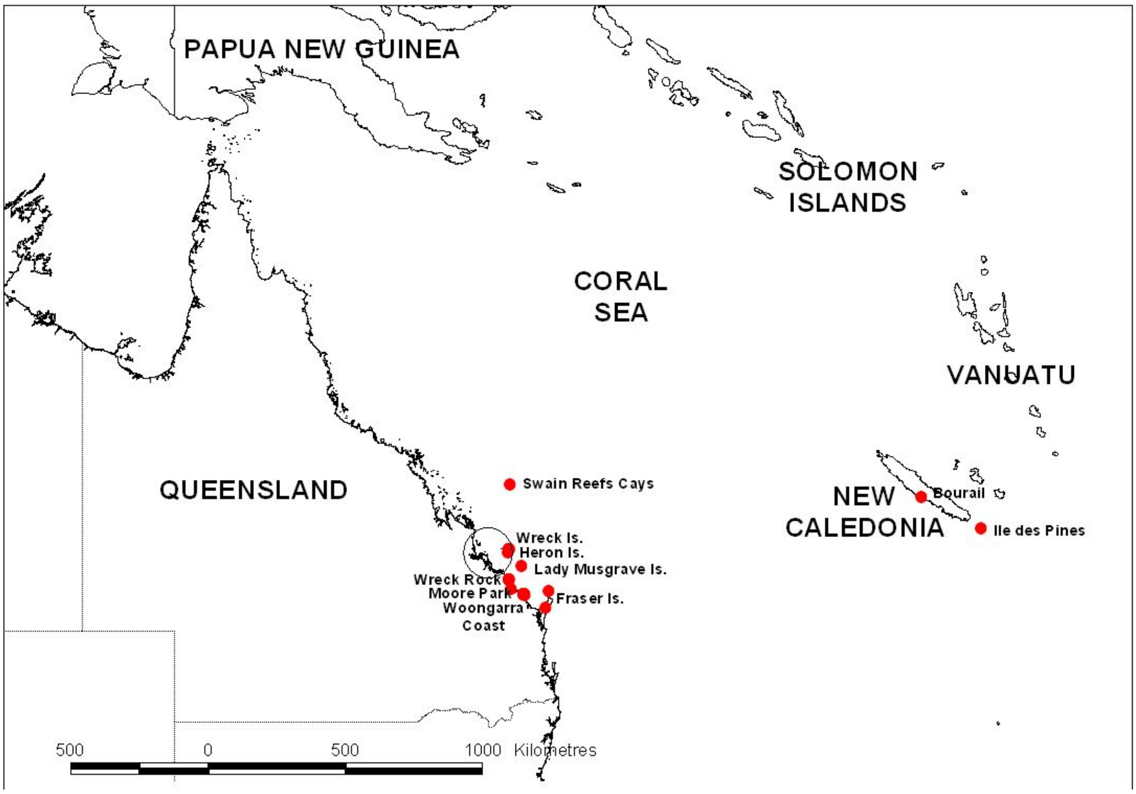


A. Wreck Rock Beaches

Figure 5. Annual number of loggerhead turtles, *Caretta caretta*, recorded nesting at an index rookery measured by tagging census at the peak nesting season census period during five weeks in December and January.



A. Migration to/from breeding areas (crosses) within Australia and distant foraging areas (red dots).



B. Migration between foraging areas adjacent to Gladstone and distant breeding sites (red dots).

Figure 6. Migration of adult loggerhead turtles, *Caretta caretta*, between breeding areas and foraging areas based on flipper tag recoveries and satellite telemetry.

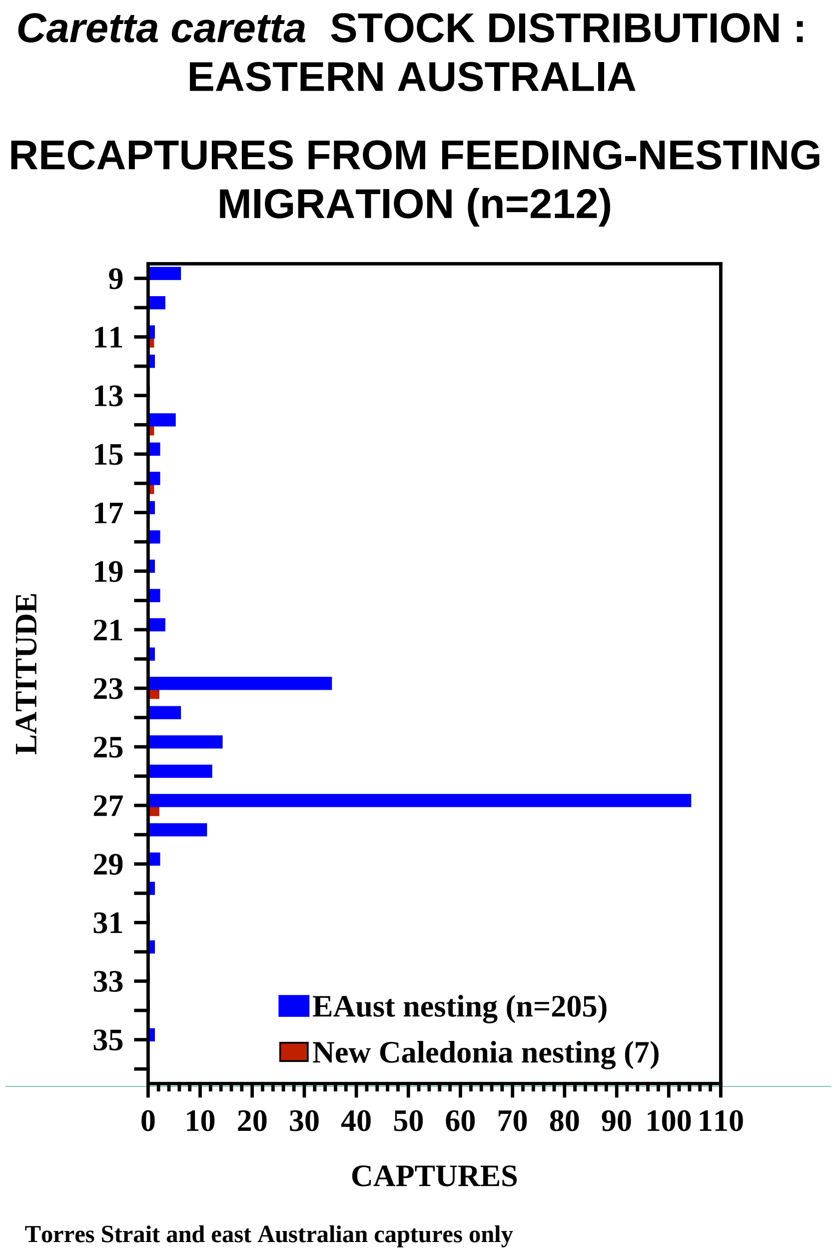


Figure 7. Distribution of foraging area records by 1º latitude blocks along the eastern Australian coast for loggerhead turtles, *Caretta caretta*, recorded at nesting sites in the south-western Pacific Ocean (After Limpus, 2008b).

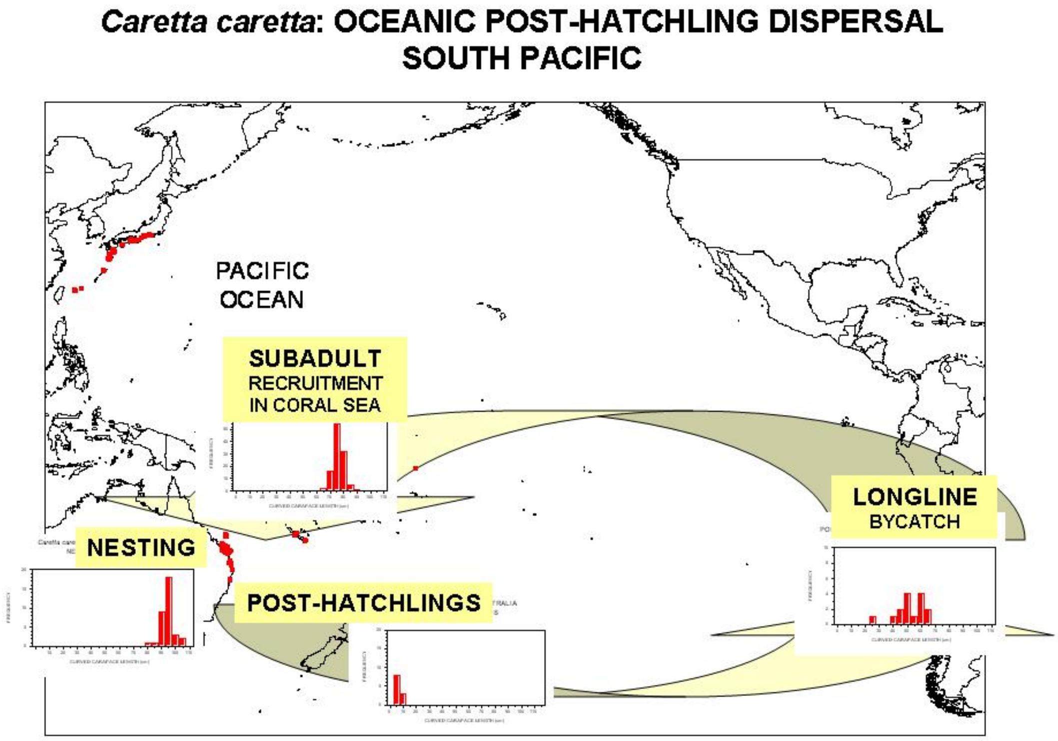


Figure 8. Generalised dispersal of life history stages of loggerhead turtles, *Caretta caretta*, in the South Pacific Ocean.

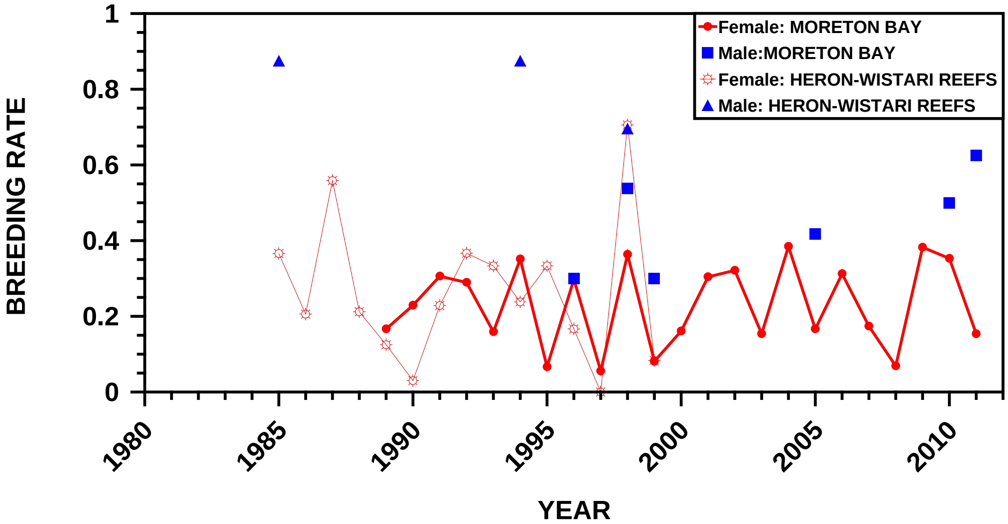
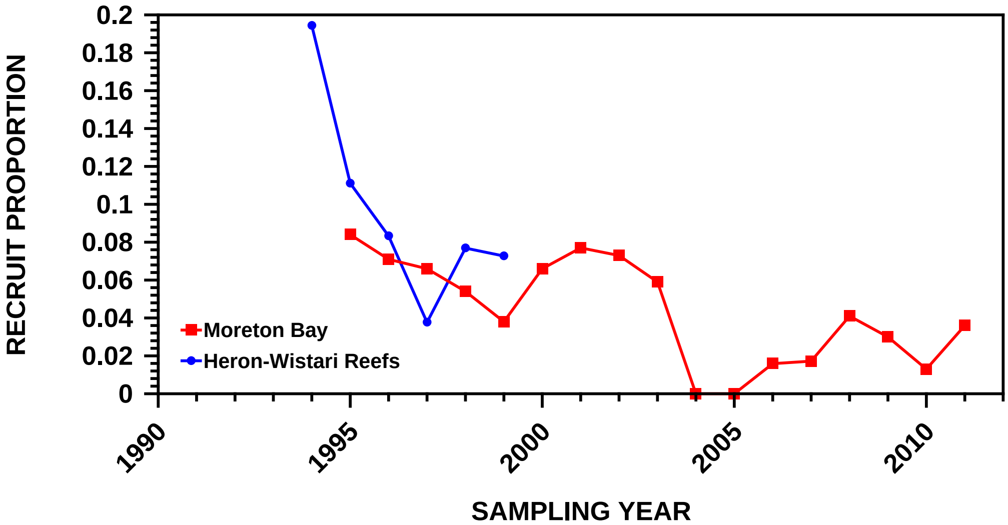


Figure 9. Annual proportion of adult loggerhead turtles, *Caretta caretta*, that prepare for breeding, measured by gonad examination while in the foraging area or by observed breeding at a nesting beach (QTC Marine Turtle data base).



Comprehensive recording of this parameter began in 1994 in the GBR and 1995 in Moreton Bay

Figure 10. The proportion of loggerhead turtles, *Caretta caretta*, recorded in coastal foraging areas that had recently recruited to residency from the oceanic pelagic dispersal phase (QTC marine turtle data base).

	
A. Aluminium fox excluder used for protection of marine turtle clutches laid on the Sunshine Coast. Photo by curtesy of Julie O'Connor.	**B. Aluminium mesh incubation cage used to exclude dingo predation of loggerhead clutches on Fraser Island. Photo by curtesy of Aub Strydom.**

Figure 11. Predator exclusion devices used at loggerhead turtle nesting beaches in south east Queensland.

A. Night time illumination of the sky over Bargara on during new moon phase. Photograph taken from midway along Mon Repos beach in January 2012.

B. Light switch sticker distributed to coastal residents on the Woongarra Coast within the *Cut the Glow* campaign.

C. Road-killed loggerhead hatchlings at Neilson Park following disruption of ocean-finding behaviour and the hatchlings heading inland to artificial lighting sources, April 2012.

D. Competition brochure within the *Cut the Glow* campaign.

Figure 12. Issues and examples materials used in the Cut the Glow public awareness campaign

Table 1. Summary of annual survivorship estimates for loggerhead turtle, *Caretta caretta,* resident in coral reef habitats of the southern Great Barrier Reef (Chaloupka and Limpus, 2002) where there is very little anthropogenic impact on the turtles.

Life history stage	Size range (CCL)	Annual survival rate		
		Mean	**SE**	**95% confidence interval**
Adult	ca.92 cm	0.875	0.0179	0.84–0.91
Immature (all)	< ~95 cm	0.859	0.0146	0.83–0.89
Immature (corrected for possible transients)		0.918	-	0.88–0.96
All sizes combined and not corrected for transients	> ~70 cm	0.861	0.0116	0.84–0.88

Table 2. Summary of the annual proportion of adult loggerhead turtles, *Caretta caretta*, that were recorded preparing to breed from their respective foraging areas, measured from gonad examination or observations of nesting behaviour (QTC turtle research data base).

Sampled subsets	Annual breeding rate			
	Mean	**SD**	**Range**	**Sample size**
Moreton Bay				
Female	0.233	0.113	0.056 – 0.406	23
Male	0.446	0.126	0.300 – 0.625	8
Heron-Wistari Reefs				
Female	0.253	0.181	0 – 0.706	17
Male	0.861	0.125	0.696 – 1.0	4

Table 3. A summary of reported loggerhead turtle, *Caretta caretta*, strandings and mortality by year and identified strandings and mortality from anthropogenic sources in Queensland. See Greenland and Limpus (2004, 2008) and Biddle and Limpus (2011) for a description of the stranding database from which these records are drawn. These turtles are presumed to represent only a portion of the total mortality from these sources. R denotes turtles released alive.

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Total
Boat Strike	8	10	8	5	3	5	6	5	5	4	10	3	72 (6/yr)
Dredging		1	1	3				2	1				8 (0.6/yr)
Shark Control Program	4	1	2		1	1	3	1	1	4		1	19 (1.6/yr)
Crab pot entanglement	6	4		1	2	2	3	1	1	2	$1+2^{R}$	$2+3^{R}$	25 (2.1/yr)
Fishing line/rope entanglement	1	1		2		2		1		3			10 (0.8/yr)
Ingestion of foreign bodies									2			1	3 (0.3/yr)
Undetermined										1	1		2 (0.2/yr)
Total	19	17	11	11	5	10	12	10	10	14	14	11	