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Potential impacts of projected sea-level rise on sea turtle rookeries

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ABSTRACT

1. Projected sea-level rise (SLR) is expected to cause shoreline erosion, saline intrusion into the water table and inundation and flooding of beaches and coastal areas. Areas most vulnerable to these physical impacts include small, tropical low-lying islands, which are often key habitat for threatened and endemic species, such as sea turtles.
2. Successful conservation of threatened species relies upon the ability of managers to understand current threats and to quantify and mitigate future threats to these species. This study investigated how sea-level rise might affect key rookeries (nesting grounds) ($n = 8$) for the northern Great Barrier Reef (nGBR) green turtle population, the largest green turtle population in the world.
3. 3-D elevation models were developed and applied to three SLR scenarios projected by the IPCC 2007 and an additional scenario that incorporates ice melting. Results indicate that up to 38% of available nesting area across all the rookeries may be inundated as a result of SLR.
4. Flooding, as a result of higher wave run-up during storms, will increase egg mortality at these rookeries affecting the overall reproductive success of the nGBR green turtle population. Information provided will aid managers to prioritize conservation efforts and to use realistic measures to mitigate potential SLR threats to the nGBR green turtle population.

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KEY WORDS: sea turtles; green turtles; sea-level rise; habitat loss; climate change; reef island; Great Barrier Reef; Torres Strait

INTRODUCTION

Sea level is anticipated to rise significantly in the future, with a projected sea-level rise (SLR) of 18 to 59 cm by 2100, and a possible additional 10 to 20 cm increase from melting ice sheets and glaciers (Overpeck *et al*., 2006; McInnes and O'Farrell, 2007; Meehl *et al*., 2007). Small, tropical low-lying islands, especially those that are not vegetated or lie on exposed reefs in areas of high tidal range, are the most vulnerable to SLR (Woodroffe *et al*., 1999; Church and White, 2006). Impacts anticipated from SLR include saline intrusion into the water table as well as inundation and flooding of beaches and shoreline erosion of coastal areas (Klein and Nicholls, 1999; Mimura, 1999). Previous studies indicate that the most significant impacts will be at residential and recreational areas, agricultural land (Nicholls, 2002; Snoussi *et al*., 2008), wetlands (Nicholls *et al*., 1999; Nicholls, 2004) and habitats for threatened, endangered and endemic species (Daniels *et al*., 1993; Fish *et al*., 2005, 2008; Baker *et al*., 2006; LaFever *et al*., 2007). This is expected to cause a plethora of biogeophysical and socio-economic consequences producing a cascade of impacts (Klein and Nicholls, 1999). Assessments of the impacts of projected SLR at areas of high human population density, economic importance and/or areas that have high environmental value (e.g. areas important for threatened species), can aid resource management planning and conservation of wildlife that rely on areas at risk (Baker *et al*., 2006; Cowell *et al*., 2006).

Currently, concerns exist regarding the impacts of SLR on the most important rookery, Raine Island, and several of the smaller cays (e.g. Bramble Cay) used by the largest green turtle (*Chelonia mydas*) population in the world: the northern Great Barrier Reef (nGBR) green turtle population. This population nests at rookeries in the far nGBR and Torres Strait region, with an average of 50 000 turtles on a high nesting year (Limpus *et al*., 2003). Over the last 10 years a reduction in

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hatching success has been observed at Raine Island, which is thought to be caused by rising groundwater and other geomorphic processes (e.g. movement of sand) (Limpus *et al*., 2003). It is believed that SLR is likely to exacerbate these processes and the frequency of nest inundation (Limpus *et al*., 2003).

The present study uses a geographic information system (GIS) to map the impacts of projected SLR, in terms of inundated area, under four SLR scenarios on a selection of sites used for nesting by this threatened population. The impacts of SLR on sea turtle nesting grounds has previously been quantified in Bonaire and Barbados (Fish *et al*., 2005, 2008), the east coast of the USA (Daniels *et al*., 1993) and the Hawaiian Islands (Baker *et al*., 2006). However, there has been no study in Australia, an area that contains globally significant marine turtle populations. In addition, prior studies, with the exception of Baker *et al*. (2006), focus on the impacts to only one rookery for a particular turtle population. Such an approach does not provide a full understanding of how a genetic stock (management unit) will be affected and respond to SLR. Since sea turtles may shift nesting grounds when nesting habitat is no longer available (Hamann *et al*., 2007) there is also the need to investigate how a variety of nesting grounds for the same population will be affected. Considering this, the impacts of SLR on eight different sites in north-east Australia, representing 99% of nesting activity for the nGBR green turtle population (Limpus *et al*., 2003), were investigated. This ensures that managers will be able to direct and focus management and conservation actions strategically to protect the nGBR green turtle population from impacts of SLR. The ecological impacts of loss and alteration of nesting habitat on the nGBR green turtle population are also discussed.

METHODS

Rookeries

Nesting by the nGBR green turtle population occurs, in order of importance, at : (1) Raine Island (11°36′S, 144°01′E), (2) Moulter Cay (11°26′S, 144°00′E), (3) Bramble Cay (9°09′S, 142°53′E),(4) Dowar Island (9°55′S, 144°02′E), (5) MacLennan Cay (11°22′S 143° 48′E), (6) Sandbank 7 (13°26′S; 143°58′E), (7) Sandbank 8 (13°21′S; 143°57′E) and (8) Milman Island (11°10′S; 143° 00′ E) (Figure 1). The highest concentration of nesting occurs at Raine Island and Moulter Cay, with 90% of the overall nesting for this population (Limpus *et al*., 2003). Smaller, but significant, numbers of nests are laid at both Bramble Cay and Dowar Island in Torres Strait. Nesting at Dowar occurs at three distinct beaches: the north, south and west beaches. Lowest nesting density occurs at Milman Island (Dobbs *et al.,* 1999). Raine Island, Moulter Cay, MacLennan Cay, Sandbank 7 and Sandbank 8 are non-vegetated or vegetated sand cays and Milman Island is a forested cay, located in the nGBR (Figure 1). Bramble Cay is located on a fringing reef around a small volcanic outcrop in the north-east of Torres Strait. Dowar Island is one of the Mer group islands, which are volcanic high islands fringed with Holocene reef. All rookeries are small in size (0.02 to 0.3 km^2).

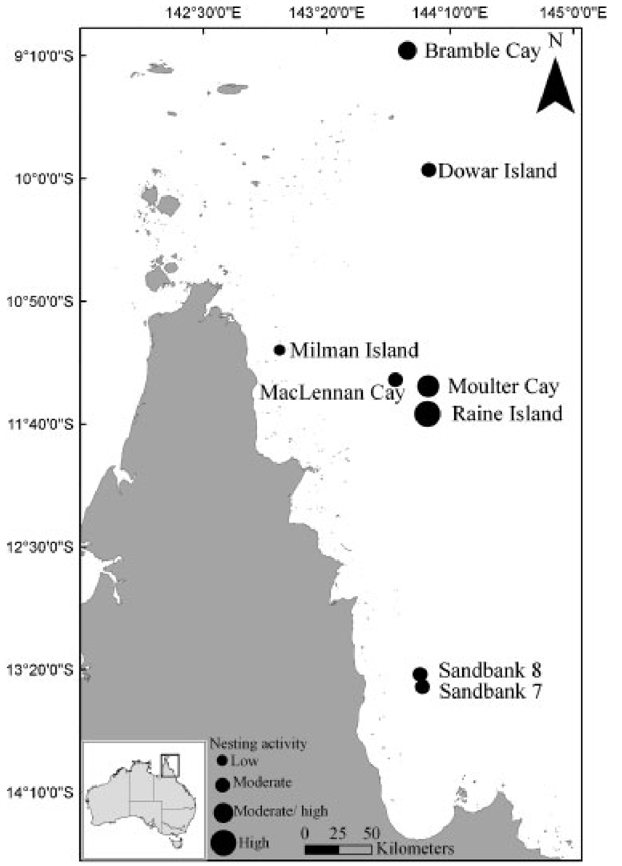

Figure 1. Location of rookeries utilized by the nGBR green turtle population and their relative importance as a nesting ground.

Characteristics of rookeries

Beach profiles were measured at Bramble Cay, Dowar Island (north, south and west beaches) and Milman Island relative to low water mark at 100 m intervals (except at Dowar where a 50 m interval was conducted), using the dumpy level standard surveying technique (Mwakumanya and Bdo, 2007), where elevation of points (z) along the transect are calculated from slope and ground distances. Waypoints (x and y) were recorded at each elevation point from the profile transects using a global positioning system (GPS) as well as bearings. The x, y and z coordinates for each point from the beach profiles were used to construct triangulated irregular network (TIN) models for each beach using the 3-D analyst tool in ArcGIS®. Data from Raine Island were collected using Real Time Kinematic (RTK) GPS. Beach width, mean and maximum elevation values and area available for nesting for each beach were obtained from the TIN models. Beach profiles for Moulter Cay, MacLennan Cay, Sandbank 8 and 7 were derived from existing information on their elevation profiles and morphology (King and Limpus, 1983; King *et al*., 1983a, 1983b). Spatial information for Moulter Cay was obtained from an aerial photograph taken in 1990 (0.25 m pixel resolution).

Nesting activity

Surveys of nest location were carried out to determine the spatial distribution of nests and the preferred nesting habitat–in terms of

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elevation and distance from high water mark (HWM)–at each rookery. Owing to logistical and time constrains, surveys for turtle nests were carried out only at Bramble Cay, Dowar Island, Milman Island and Raine Island. Monitoring occurred during the 2006/2007 nesting season, which was a high nesting season with up to 21 000 turtles nesting per night at Raine Island (CJL, unpublished data). Monitoring at Raine Island was conducted by Queensland Parks and Wildlife (QPW) as part of their annual monitoring programme, which has taken place since the 1970s (Limpus *et al.*, 2003). Turtles nested on all available un-vegetated beach area and therefore this study assumes that turtles nested everywhere above HWM and below the cliff line and outside any central rock area. Nesting activities at Dowar and Milman Islands were monitored for 10 days during peak nesting and nest locations were recorded with a GPS (Garmin Etrex, Garmin International, Inc. Kansas). Nesting at Bramble Cay was monitored for a single day during the 2006/2007 nesting season, therefore nesting information collected during the 2007/2008 season was also used as an indication of the location of nests at this site. The preferred elevation range, where >70% of nesting takes place, was calculated for each of the rookeries for which nesting information was available, by using zonal statistics (ArcGIS 9.0).

Sea level scenarios and threat to nesting area

Three SLR scenarios (0.18, 0.35 and 0.59 m) were considered for 2100, from the IPCC 2007 (Meehl *et al.*, 2007) and an additional scenario (0.79 m) that accounted for ice melting into the system (0.2 m added to the highest scenario from the IPCC 2007 (Overpeck *et al.*, 2006; McInnes and O'Farrell, 2007).

Similar to other studies (Fish *et al.*, 2005) impacts through inundation of the nesting area were considered. For this, the TIN models were used to identify nesting area below each of the elevations (0.18, 0.35, 0.59 and 0.79 m) and therefore areas that would be inundated by SLR. The area inundated was measured from the HWM. Analyses were conducted using the Surface Volume tool in the ArcGis 9.0 - 3D Analyst Toolbox.

Predicting threat to rookeries where beach profiles were not conducted

Owing to logistical constraints it was not possible to measure beach profiles at Moulter Cay, MacLennan Cay, Sandbanks 8 and 7. To calculate the probable inundation at these rookeries, it was first examined if there was a significant correlation between the maximum elevation at each rookery where a beach profile was conducted and the percentage of area lost for every SLR scenario. After this relationship was established a linear regression model was created to predict the probable percentage of area inundated for the rookeries where profiles were not conducted. To validate the predictive efficiency of the linear model created, paired - t tests were run with the values of percentage of lost area calculated from the beach profile models with the values generated from the linear model for the field study sites (Raine Island, Bramble Cay, Dowar Island and Milman Island).

Vulnerability as a result of rookeries characteristics

The relationship between threat to nesting area and different physical attributes of each rookery (i.e. beach width, nesting area as well as maximum and mean elevation) was also investigated. For this, the proportion of beach under threat from an intermediate sea-level rise scenario (0.35 m) was considered as a measure of vulnerability (modified method from Fish *et al.*, 2005), and Pearson's Correlation was used to examine the effects of each physical attribute and vulnerability to SLR.

Threat to nesting area during storm events

As it is anticipated that waves will penetrate even further inland during episodic storms (Gornitz, 1991; Fletcher III, 1992; Church *et al.*, 2006), it was also explored how nests and nesting areas will be impacted during storms under an intermediate SLR scenario of 0.35 m rise. Due to lack of storm tide predictions previous highest astronomical tide (HAT) measurements were used as an indication of possible intrusion by storm-wave run-up. Using data from the Environmental Protection Agency, Australian Bureau of Meteorology website (http://www.bom.gov.au/index.shtml) and Seafarer tides, HAT was calculated to be 1.0 and 0.45 m above mean spring high tide level in Torres Strait and the nGBR region correspondingly. As HAT data are only available at a regional level, these are used only as an indicative measurement. It was then assumed that nesting area under 1.35 m (0.35 m SLR+1.0 m run-up) and 0.8 m (0.35 m SLR+0.45 m run-up) in Torres Strait and nGBR, respectively, would be affected by wave run-up during storm events and consequently the nests laid in this area would be inundated.

RESULTS

Rookeries characteristics and nesting activity

Raine Island, Moulter Cay, Milman Island and north Dowar provide the largest available nesting areas, and conversely, western Dowar provides the smallest area for turtle nesting (Table 1). The highest elevations were found at north Dowar and Raine Island (9.13 m and 4.9 m, respectively), while the lowest nesting beaches were at Sandbank 7, MacLennan Cay, Sandbank 8 and west Dowar (Table 1). Preferred nesting habitat varied at each rookery (Table 2), turtles at north Dowar nest at higher elevation and turtles at west Dowar nest at lower elevations (Table 2). Preferred nesting elevation was found to be a result of the elevation range found at each rookery, as the mean nest elevation was significantly and positively correlated with maximum and mean elevation at

Table 1. Characteristic of rookeries during the 2006/2007 nesting season. Rookeries are listed in order of importance

Rookery	Width (m)	Nesting area (m^2)	Mean elevation (m)	Maximum elevation (m)
Raine Island	90	152 247	1.2	4.9
Moulter Cay	N/A	78 200	N/A	3.0
Bramble Cay	44.4	21 980	1.34	4.08
North Dowar	37.5	36 719	2.36	9.13
South Dowar	28	8803	1.021	3.9
West Dowar	19.4	3844	0.77	2.09
MacLennan Cay	38	24 000	N/A	1.05
Sandbank 7	45	22 000	N/A	0.76
Sandbank 8	60	32 000	N/A	1.36
Milman Island	17	58 648	1.8	4.28

N/A = not available.

each rookery ($r^2 = 0.959$, $n = 5$, $P = 0.01$ and $r^2 = 0.989$, $n = 5$, $P = 0.001$, respectively). Mean distance of nest to HWM also varied between rookeries (Table 2), with mean nest distance being positively correlated with beach width ($r^2 = 0.855$, $n = 5$, $P = 0.001$).

Threat to nesting area

Validation of methods for rookeries where beach profiles were not conducted

As a significant correlation existed between the maximum elevation at each rookery and percentage of area lost for every SLR scenario, for the beaches for which there were beach profiles (except scenario 3) (scenario 1, $r^2 = -0.831$, $n = 6$, $P = 0.041$; scenario 2, $r^2 = -0.842$, $n = 6$, $P = 0.035$; and scenario 4, $r^2 = -0.863$, $n = 6$, $P = 0.027$), a linear regression model was created to predict the probable percentage of area inundated for the beaches for which it was not possible to measure profiles (Moulter Cay, MacLennan Cay, Sandbank 8 and 7). Paired *t*-tests validated the linear models, as there was no significant difference between the values from the beach profiles and the values calculated from the linear models for all four SLR scenarios (all pairs, $t = 0.001$, df = 5, $P > 0.999$).

Vulnerability and rookeries characteristics

Between 8% and 38% of the total area available for nesting (438 441 m^2) across the beaches studied are predicted to be inundated under the various SLR scenarios (Figure 2). Sandbank 7 is predicted to lose the greatest amount of beach (12 to 49%), followed by west Dowar, MacLennan Cay and Sandbank 8 where approximately 11 to 47% of their area is predicted to be lost. Similarly, Milman Island is predicted to lose 10 to 42% of its nesting area. North Dowar is predicted to be the least vulnerable rookery with a predicted area inundated of 3–15% (Figure 2).

Beaches with lower elevation were, not surprisingly, found to be more susceptible to SLR as inundation was significantly and negatively correlated with maximum elevation under all SLR scenarios (scenario 1, $r^2 = -0.91$, $n = 10$, $P < 0.000$; scenario 2, $r^2 = -0.91$, $n = 10$, $P < 0.000$; scenario 3, $r^2 = -0.88$, $n = 10$, $P = 0.001$ and scenario 4, $r^2 = -0.92$, $n = 10$, $P < 0.000$) (Figure 3).

Threat during storm events

During storm events the nesting habitat at west Dowar is predicted to be under the greatest threat, with up to 75% of available nesting habitat inundated, potentially affecting 90%

Table 2. Characteristic of preferred nesting habitat at each rookery during the 2006/2007 nesting season

Rookery	Preferred elevation range (m)	Mean nest elevation (m)	Percentage of nesting at preferred nest elevation	Mean distance from HWM (m)
Bramble Cay	1.5–3.5	2.1	77.0	19.6
North Dowar	2.5–4.5	3.3	73.4	24
South Dowar	1.0–2.5	1.6	82.1	13
West Dowar	1.0–2.0	1.2	71.4	8
Milman Island	2.0–3.5	2.4	75.2	11.5

Rookeries are listed in order of importance. Data for Raine Island, Moulter Cay, MacLennan Cay, Sandbank 7 and 8 are not available. Preferred elevation range is where >70% of nesting takes place at each rookery. Elevation is measured from high water mark (HWM).

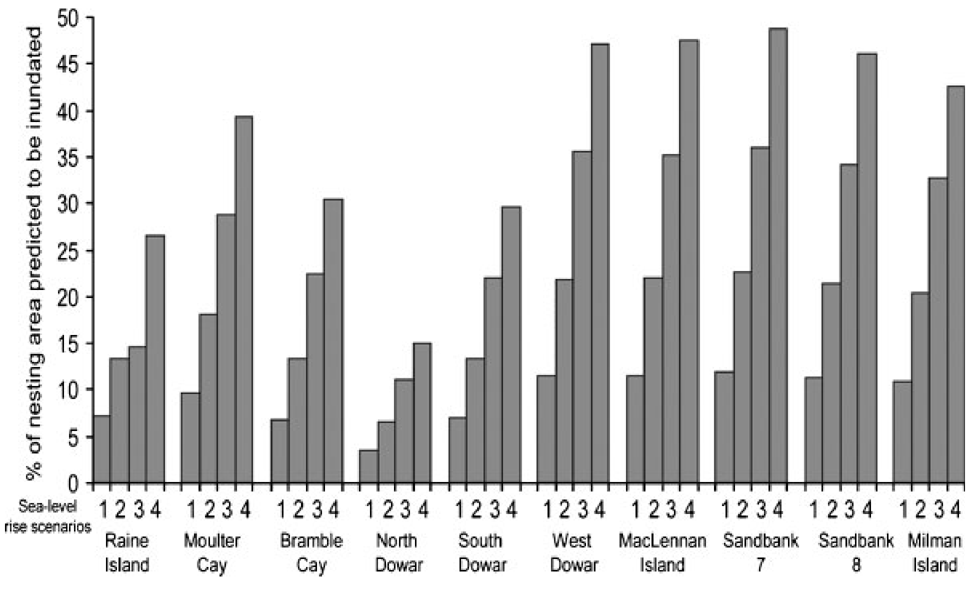

Figure 2. Area predicted to be inundated after sea-level rise scenarios of (1) 0.18 m rise, (2) 0.35 m rise, (3) 0.59 m rise, and (4) 0.79 m rise at each rookery used by the nGBR green turtle population.

of nests laid. Milman Island, Moulter Cay, Bramble Cay, MacLennan Cay and Sandbank 8, Sandbank 7 and Milman Island are also predicted to have large amounts (>50%) of their nesting area inundated during storm events, with Bramble Cay and Milman Island potentially having up to 30% of their nests inundated. Raine Island is expected to have up to 30% of the available nesting area inundated during storm events (Figure 4).

DISCUSSION

Threat of sea-level rise

To successfully conserve and manage sea turtles as climate change progresses managers will need to identify, understand, predict and mitigate any future impact on these endangered species (Hamann *et al*., 2007). This study quantified the area of rookeries, utilized by the largest green turtle population in the world that will potentially be susceptible to projected SLR scenarios. It is predicted that under the most extreme SLR scenario proposed by IPCC (2007)–a 0.59 m rise–27.7% of the total nesting area available for the nGBR green turtle population could be inundated. The extent of inundation of individual beaches ranges from 11% to 36%, with the beaches that support the highest levels of nesting being the least vulnerable to inundation. Similar results are predicted for sea turtle rookeries in the Caribbean region where 26% and 32% of the nesting area in Barbados and Bonaire, respectively, are predicted to be inundated with a 0.5 m sea level rise (Fish *et al*., 2005, 2008).

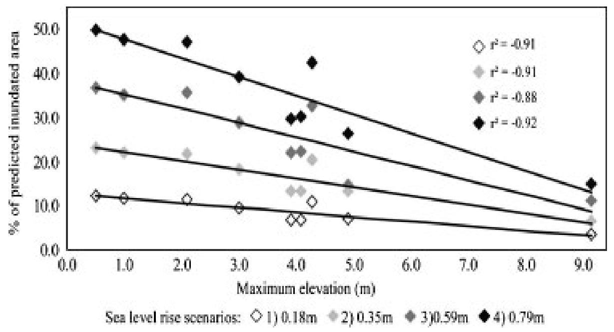

Figure 3. Relationship between maximum elevation at each rookery and area predicted to be inundated after sea-level rise scenarios of (1) 0.18 m rise, (2) 0.35 m rise, (3) 0.59 m rise, and (4) 0.79 m rise.

Reduction of available nesting area will amplify density-dependent issues at nesting grounds, potentially increasing nest infection (Fish *et al*., 2008) and destruction of nests by co-specifics (Bustard and Tognetti, 1969; Girondot *et al*., 2002; Limpus *et al*., 2003). This already occurs at Raine Island, Moulter Cay, Dowar and Bramble Cay during high density nesting years. Higher nesting density at a particular rookery may also reduce the total reproductive output as increased disturbance by nesting co-specifics could result in premature use of somatic energy stores and resorption of ovarian follicles (Hamann *et al*., 2002; Limpus *et al*., 2003). Another outcome of SLR is increased impact of storm events, causing periodic beach erosion and washing away and flooding of nests (Gornitz, 1991; Fletcher III, 1992; Church *et al*., 2006). This will increase egg mortality affecting the overall reproductive success of the nGBR green turtle population.

Further flooding of sea turtle nests and impacts on the reproductive output of sea turtles can occur through a raised water table as a result of SLR (Titus *et al*., 1991; Ross *et al*., 1994). Raine Island, in particular, is more susceptible to this as it already experiences water level problems (Hamann *et al*., 2007). On occasion, groundwater level has been so high at Raine Island that pooled water has been observed in depressions and body pits made by turtles (Limpus *et al*., 2006). A recent study by Guard *et al*. (2008) has initiated

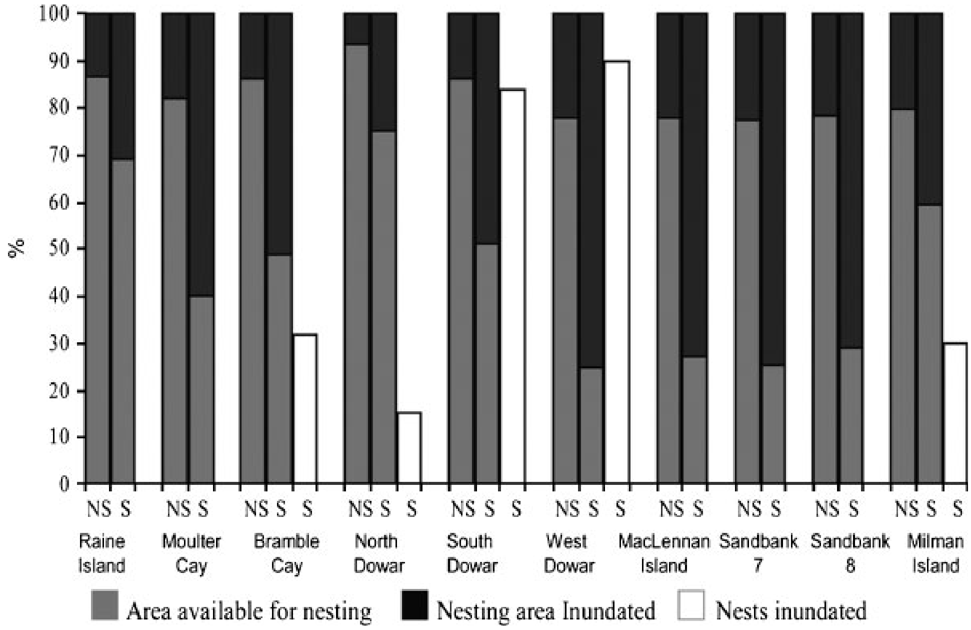

Figure 4. Percentage of nesting area and nests inundated, at rookeries for the nGBR green turtle population, under an intermediate sea-level rise of 0.35 m both during storms (S) and when storm events are not occurring (NS). Information on nest inundated is only available for rookeries where we conducted nesting monitoring.

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exploration of the water table dynamics at Raine Island in order to provide models of water table response to tidal oscillations. Further investigation and expansion of this study may provide more quantitative insights into the impacts of SLR on groundwater dynamics and therefore the impact of SLR on the reproductive output at Raine Island.

Possible responses by turtles and consequences of SLR

Sea turtles may be able to adapt to SLR by shifting nesting up the beach, away from the high tide (Fish *et al*., 2005; Limpus, 2006). However, such a shift is constrained at small low-lying islands and where urban development restrains landward beach recession (Fish *et al*., 2008). As the nGBR green turtle population nests on beaches where little urban development exists, a landward shift in nesting is a potential response for this population. This is not the situation, however, for populations nesting at beaches developed for tourism in the Caribbean region (Fish *et al*., 2005, 2008).

Some nesting beaches may become fully inundated as sea level continues to rise above 1 m beyond 2100 (Turner and Batianoff, 2007). Turtles nesting at these or at beaches that have no more elevated nesting habitat, as may occur at west Dowar and Sandbank 7, will need to seek out new nesting sites (Limpus, 2006; Hamann *et al*., 2007). For example, if nesting is no longer possible at west Dowar, higher density nesting may occur at the southern and northern beaches–which provides more suitable habitat–or turtles may shift to nest at nearby Mer or Waer Islands. There is also the possibility that turtles will shift their nesting to new beaches that may develop/or stabilize in the region as a result of SLR (Hamann *et al*., 2007).

Nest placement has been shown to affect hatchling success and sex ratio in the GBR green turtle population (Miller and Limpus, 1981; Morreale *et al*., 1982) and any shift in their rookeries may influence this. Changes in nesting locations may also have severe implications and cause further conservation challenges if they are forced to nest where even fewer conservation measures are in place or management is logistically difficult. Conversely, changes may result in improved population performance as turtles may start nesting in areas with more favourable nesting and incubating condition and/or areas with less anthropogenic threats, such as traditional hunting of turtle meat and eggs as occurs at the rookeries in Torres Strait. Longer-term consequences associated with changes in nesting distribution include the development of new genetic stocks and thus differentiation in biological parameters (e.g. turtle stocks with different breeding phenology and different size adult females) (Limpus, 2008). This has been suggested to have occurred with the historical (Pleistocene) population of flatbacks, *Natator depressus*, which developed into two distinct current (Holocene) populations (Limpus, 2008).

Further impacts of SLR and uncertainties

Turtle nesting beaches may be further affected by SLR through shoreline erosion, which is dependent on a series of factors such as wave energy, tidal currents, island and reef morphology, sediment type and sediment supply, among others (Cooper and Pilkey, 2004; Woodroffe, 2008). Developing appropriate models to successfully predict shoreline response to SLR is challenging (Cooper and Pilkey, 2004; Fish *et al*., 2005). The most common and widely used model is the 'Bruun rule' (Bruun, 1962) (see Cooper and Pilkey (2004) for a compiled list of studies), which assumes a continuous equilibrium of sand transport between beach and nearshore (Woodroffe, 2008) and therefore it is not applicable for the systems studied here. In addition, this model has been criticized for its restrictive assumptions, omission of important variables and erroneous concepts (Cooper and Pilkey, 2004). To overcome some of the issues Cowell *et al*. (2006) recently suggested incorporating probabilistic components to model outputs to allow greater freedom in quantifying some of the input parameters; however, owing to lack of specific data, especially on the coastal processes and changes in beach profiles at each nesting ground, this model could not be applied.

As assessing the quantitative impacts of shoreline erosion, rise of water table and potential accretionary events was beyond the scope of this study and therefore not incorporated into the results presented here, it is important to consider that influences from these factors could lead to greater or lesser habitat loss. Several other studies (Daniels *et al*., 1993; Fish *et al*., 2005; LaFever *et al*., 2007) have used a similar approach to this study, and only quantified the impact of SLR caused by inundation. As with many other predictions of beach response to SLR, the current approaches include uncertainties (Cowell *et al*., 2006). In this study uncertainties arise from (1) predicted SLR scenarios, (2) assumptions of how beaches will respond to SLR (in terms of their sea level and wave climate), and (3) the models used to quantify the impacts and response of SLR to selected beaches (Cowell *et al*., 2006). Possible errors from these uncertainties were minimized by (1) utilizing a range of SLR scenarios consistent with IPCC 2007 as well as incorporating possible increases in SLR through ice/glazier melting and increase in wave-run up, and (2) by using similar assumptions and methodology to other studies that address comparable questions. Nevertheless, the results presented here provide the first insights and the best current available assessment of the potential effects of SLR on the nGBR green turtle rookeries. Studies of this nature, which assess the potential impacts of SLR on endangered megafauna, are extremely important, as they can potentially aid managers to prioritize management efforts and to use realistic measures to mitigate potential SLR threats to these ecologically important species. Some potential management measures to mitigate the impacts of inundation and erosion from SLR include (1) 'hard engineering structures' (e.g. seawalls, groynes), (2) 'soft methods' (e.g. beach nourishment, dune building), and (3) retreat and setback regulations (Nicholls and Tol, 2006; Fish *et al*., 2008). In order to determine the most realistic and efficient solution to use, a cost benefit analysis of each strategy will be necessary as well as information on any ethical, ecological and practical issues associated with implementing them.

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