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Vulnerability of sea turtle nesting grounds to climate change

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Abstract

Given the potential vulnerability of sea turtles to climate change, a growing number of studies are predicting how various climatic processes will affect their nesting grounds. However, these studies are limited by scale, because they predict how a single climatic process will affect sea turtles but processes are likely to occur simultaneously and cause cumulative effects. This study addresses the need for a structured approach to investigate how multiple climatic processes may affect a turtle population. Here, we use a vulnerability assessment framework to assess the cumulative impact of various climatic processes on the nesting grounds used by the northern Great Barrier Reef (nGBR) green turtle population. Further, we manipulate the variables from this framework to allow users to investigate how mitigating different climatic processes individually or simultaneously can influence the vulnerability of the nesting grounds. Our assessment indicates that nesting grounds closer to the equator, such as Bramble Cay and Milman Island, are the most vulnerable to climate change. In the short-term (by 2030), sea level rise will cause the most impact on the nesting grounds used by the nGBR green turtle population. However, in the longer term, by 2070 sand temperatures will reach levels above the upper transient range and the upper thermal threshold and cause relatively more impact on the nGBR green turtle population. Thus, in the long term, a reduction of impacts from sea-level rise may not be sufficient, as rookeries will start to experience high vulnerability values from increased temperature. Thus, in the long term, reducing the threats from increased temperature may provide a greater return in conservation investment than mitigating the impacts from other climatic processes. Indeed, our results indicate that if the impacts from increased temperature are mitigated, the vulnerability values of almost all rookeries will be reduced to low levels.

Keywords: adaptive capacity, climate change, exposure, great barrier reef, marine mega-fauna, sea turtles, sensitivity, vulnerability assessment

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Introduction

Climate change will have direct and indirect impacts on a number of species and ecosystems, and in turn will cause considerable challenges for natural resource conservation and management (Pressey *et al*., 2007; Lee & Jetz, 2008; Heller & Zavaleta, 2009; Newson *et al*., 2009; Robinson *et al*., 2009). A particular ecosystem or species may be affected simultaneously by multiple climatic processes, making it difficult for managers to respond to and mitigate these multiple impacts (Halpern *et al*., 2007). Sea turtle nesting grounds will be affected simultaneously by multiple climatic processes (e.g. increased temperature, sea-level rise, and cyclonic activity) at different temporal and geographical scales (see Hawkes *et al*., 2009; Poloczanska *et al*., 2009; Witt *et al*., in press). Increase in temperature is perceived to cause the most impact on sea turtles, because as ectotherms they have life history traits, behavior, and physiology strongly influenced by environmental temperature (Spotila & Standora, 1985; Janzen, 1994). The sand temperature during egg incubation plays a vital role in embryo development, hatchling success, and hatchling sex ratio, thus increases in temperature may alter hatchling attributes and survival (Yntema & Mrosovsky, 1980; Booth & Freeman, 2006). Sea-level rise and cyclonic activity may cause loss and/or alteration of nesting beaches and egg mortality (Pike & Stiner, 2007; Van Houtan & Bass, 2007; Fish *et al*., 2008; Fuentes *et al*., in press a). In addition, nesting beaches, especially reef islands, are likely to be impacted because of ocean acidification, as this will affect carbonate sediment production and in turn the sediment budget and sediment traits at some beaches (Lidz & Hallock, 2000; Mutti & Hallock, 2003; Fuentes *at al*. in press b). This can potentially alter reef-island morphology and sediment characteristics and, in turn, affect sea turtles'

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reproductive output, as they require specific sediment characteristics to incubate their eggs and dig their nests (Mortimer, 1990).

Given sea turtles' potential vulnerability to climate change and the future scenarios of global warming, there has been recent concern over the potential impacts and implications of climate change on them (McMahon & Hays, 2006; Hamann *et al*., 2007; Hawkes *et al*., 2009; Poloczanska *et al*., 2009; Fuentes *et al*., 2009a). A growing number of studies are investigating and predicting how climatic processes will affect sea turtles and their nesting grounds (for review see Hawkes *et al*., 2009 and Poloczanska *et al*., 2009). Most studies predict how increased sand temperature (Hays *et al*., 1999, 2003; Glen & Mrosovsky, 2004; Hawkes *et al*., 2007; Fuentes *et al*., 2010), or sea-level rise (Fish *et al*., 2005, 2008; Baker *et al*., 2006; Fuentes *et al*., in press a) will affect sea turtles or their nesting grounds. Although these studies provide valuable information and insights into how each climatic process can or will affect sea turtles, they are limited by scale because processes are likely to occur simultaneously across a population and cause cumulative and synergistic effects. Consequently, there is a need for a structured approach to investigate how multiple climatic processes may affect the full range of nesting grounds used by a turtle population.

Thus, we used a vulnerability assessment framework to allow assessment of the cumulative impact of multiple climatic processes on sea turtle nesting grounds. The variables from this framework can be manipulated to allow users to investigate how addressing different climatic processes individually or simultaneously can mitigate the vulnerability of the nesting grounds. Thus, by using this framework, managers and scientists will be able to determine which nesting grounds will be the most vulnerable to climate change, which climatic process will cause the most impact to each nesting ground, and how the vulnerability of nesting grounds will change if impacts from specific climatic processes are mitigated. With this information, managers will be better placed to direct and focus management and conservation actions to protect turtle populations.

Methods

The framework

The framework used is based on the environmental vulnerability assessment framework for climate change provided by the International Panel of Climate Change (IPCC, 2007a) and recent studies (Turner *et al*., 2003; Metzger *et al*., 2005; Schroter *et al*., 2005). Our vulnerability assessment was conducted in nine steps; the first three steps were carried out before conducting the modeling and the last six steps were part of the assessment (Fig. 1). We applied the framework to the northern Great Barrier Reef (nGBR) green turtle population; however, if adequate data exist for other nesting populations, the approach is readily transferable to other species and regions. Below we describe each step.

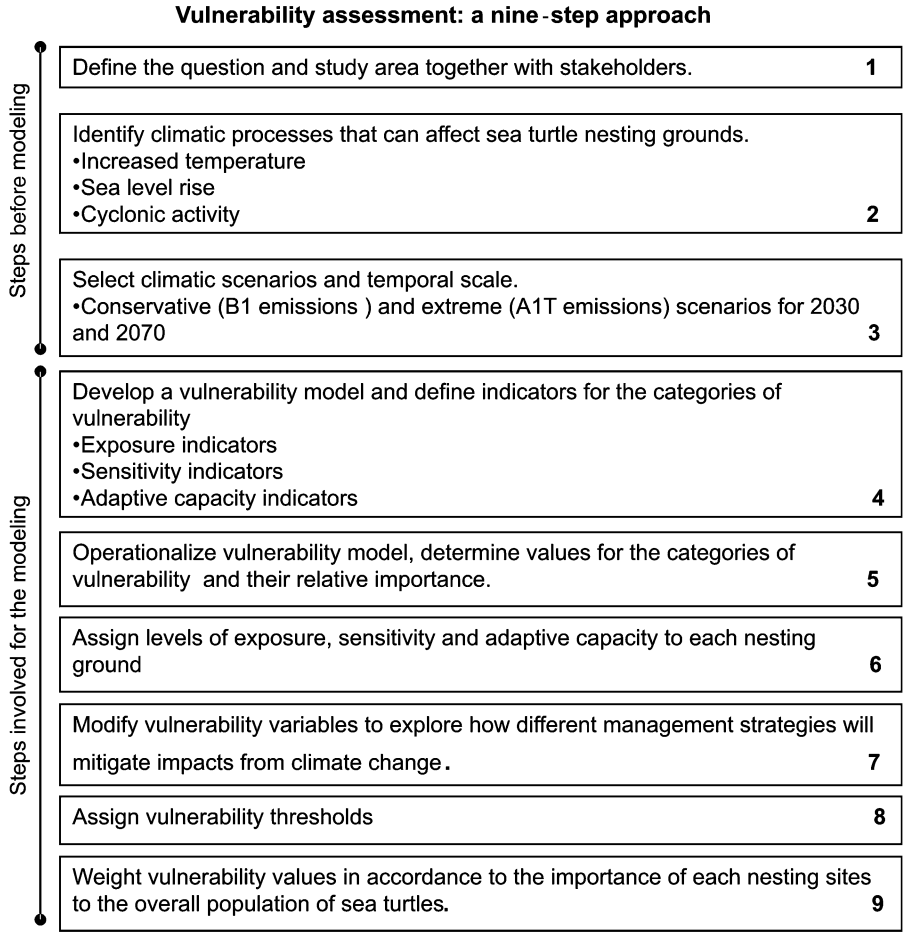
Steps before assessment

Step 1: define the question and study area together with stakeholders. Data from the past 10 years have revealed that the largest green turtle population in the world, the northern Great Barrier Reef, may be in the early stages of decline (Limpus *et al*., 2003). This was indicated in part from poor hatchling production resulting from low nesting success (percentage of females able to successfully lay eggs each night) and low hatching success. To investigate whether climate change will exacerbate these impacts, the Queensland Government agencies managing this population sought information on the vulnerability to climate change of the nesting grounds used by this population. To investigate this we selected nesting grounds that encompass the latitudinal range of important nesting sites used by the population and that represent 99% of nesting for this population (Fig. 2). Selected study sites, in order of importance (according to the average number of females nesting each year), include: (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) Sandbank 7 (13°26′S; 143°58′E), (6) Sandbank 8 (13°21′S; 143°57′E), and (7) Milman Island (11°10′S; 143°00′E) (Fig. 2).

Raine Island and Moulter Cay have the largest portion of nesting with approximately 90% of the nesting occurring at these islands. Subsidiary nesting occurs at Bramble Cay and Dowar Island, which have some of the highest densities of green turtle nesting in Torres Strait (Limpus *et al*., 2003). Minor nesting (50–300 nesting turtles a year) activity takes place at Sandbank 7 and 8 (Limpus *et al*., 2003) and trivial (10–50 nesting females a year), nesting occurs at Milman Island (Dobbs *et al*., 1999) and at approximately 60 other nesting grounds in northern Australia (Fig. 2).

Step 2: identify climatic processes that can affect sea turtle nesting grounds. We conducted a literature review to identify the main climatic process that can affect sea turtle nesting grounds and thus their reproductive output. Increased sand temperature (ST), sea-level rise (SLR) and cyclonic activity (CA) were identified as the main climatic processes that will potentially affect sea turtles' nesting grounds as climate change progresses (Hawkes *et al*., 2009; Poloczanska *et al*., 2009; Fuentes *et al*., 2009a).

Step 3: select climatic scenarios and temporal scale. We conducted our vulnerability assessment under an extreme and conservative scenario of climate change for both 2030 and 2070. The extreme scenario is based on A1T emissions and is described by a future world of very rapid economic growth, global population that peaks in mid-century and declines



Vulnerability assessment: a nine-step approach

Define the question and study area together with stakeholders. 1

Identify climatic processes that can affect sea turtle nesting grounds.
- Increased temperature
- Sea level rise
- Cyclonic activity 2

Select climatic scenarios and temporal scale.
- Conservative (B1 emissions) and extreme (A1T emissions) scenarios for 2030 and 2070 3

Develop a vulnerability model and define indicators for the categories of vulnerability
- Exposure indicators
- Sensitivity indicators
- Adaptive capacity indicators 4

Operationalize vulnerability model, determine values for the categories of vulnerability and their relative importance. 5

Assign levels of exposure, sensitivity and adaptive capacity to each nesting ground 6

Modify vulnerability variables to explore how different management strategies will mitigate impacts from climate change. 7

Assign vulnerability thresholds 8

Weight vulnerability values in accordance to the importance of each nesting sites to the overall population of sea turtles. 9

Fig. 1 A nine step method for assessing the vulnerability of sea turtle nesting grounds to climate change.

thereafter, and rapid introduction of new and more efficient technologies, with high use of nonfossil energy sources (IPCC, 2007b). In contrast, the conservative scenario is based on B1 emissions, which describe a more integrated, convergent and ecologically friendly world with low population growth and global environmental sustainability (IPCC, 2007b). Whereas the A1T world invests its gains from increased productivity and know-how primarily in further economic growth, the B1 world invests a large part of its gains in improved efficiency of resource use ('dematerialization'), equity, social institutions, and environmental protection (IPCC, 2007b).

Steps as part of the assessment

Step 4: develop the vulnerability model and define indicators for the categories of vulnerability. The first step to calculate the cumulative vulnerability (CV) of each nesting ground to climate change was to determine the vulnerability of each of the selected nesting grounds to each climatic process (Vc): (1) increased temperature, (2) sea-level rise, and (3) cyclonic activity. The vulnerability model for each climatic process was described as a function of exposure (E), sensitivity (S), and adaptive capacity (AC) (as per Turner *et al*., 2003; Metzger *et al*., 2005; Schroter *et al*., 2005) (Fig. 3).

Exposure. Exposure was defined as the frequency that each of the selected nesting grounds would be exposed to each climatic process. We identified four levels of exposure to climatic processes that ranged from 'never occurring' to 'constant' (Table 1) (as per Halpern *et al*., 2007).

Sensitivity. Sensitivity refers to the level that each nesting ground will be impacted by the three climatic processes. Sensitivity levels ranged from minimal to severe impact and the categories varied in accordance with each climatic process (Table 1). For example, for sea-level rise, sensitivity ranged from loss of up to 10% of the nesting area of a particular nesting ground to a loss of 85% to 100% of the nesting area.

Adaptive capacity. Adaptive capacity is the ability of nesting sea turtles at each island to adapt to each climatic process. Three levels of adaptive capacity were identified: (1)

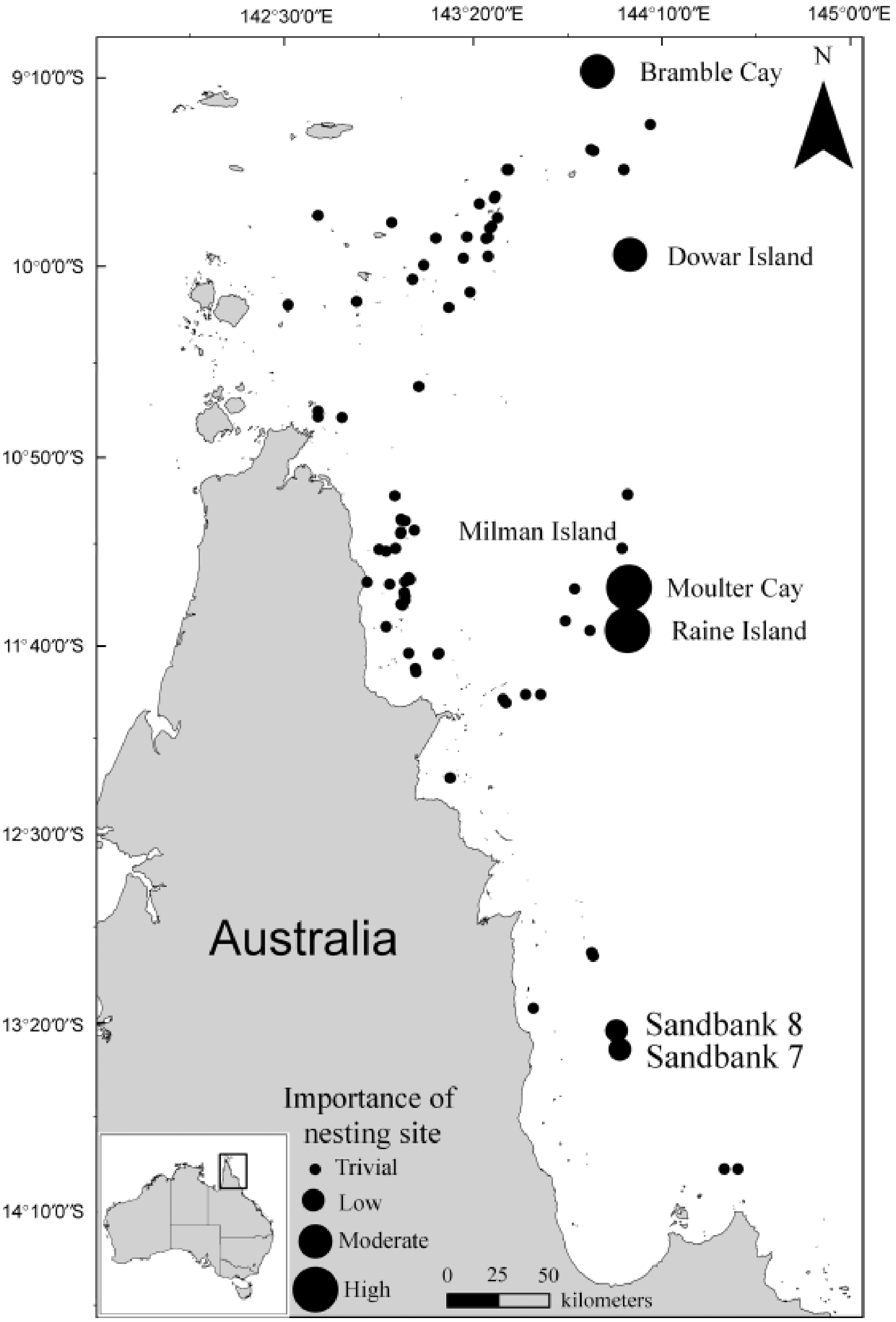


Fig. 2 Map of nesting grounds used by the northern Great Barrier Reef green turtle population. Size of dots indicates importance of each nesting ground: high nesting (+ 1000 turtles nesting a year), moderate nesting (300–1000 turtles nesting a year), low nesting (50–300 nesting turtles a year), and trivial nesting (< 50 turtles nesting a year).

ability to adapt within a nesting season, (2) ability to adapt after a turtle generation, and (3) no ability to adapt (Table 1).

A rank (R), with a maximum value of 4, was given to the different levels of exposure, sensitivity, and adaptive capacity (Table 2) relative to the impact that each level causes (e.g. the lowest value was given to the level that causes least impact and four was given to the level that causes the most impact) (as per Halpern *et al.*, 2007).

Step 5: operationalize the vulnerability model. In Step 4, we developed the vulnerability model and defined levels for each category of vulnerability (exposure, sensitivity, and adaptive capacity). The main aim of Step 5 is to develop overall weight

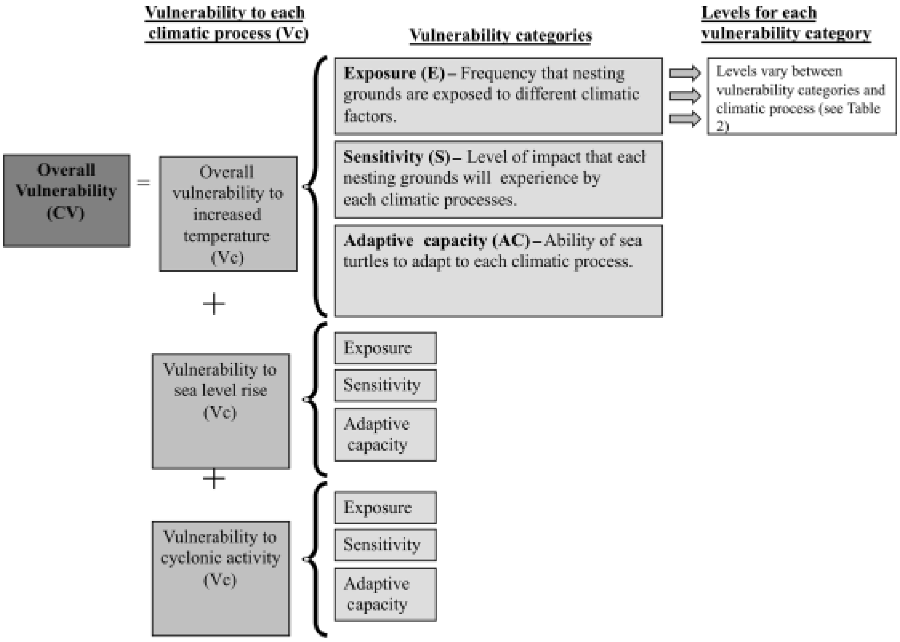


Fig. 3 Cumulative vulnerability model and the relevant vulnerability categories used to asses the vulnerability of nesting grounds to climate change.

Table 1 Identified levels of exposure, sensitivity and adaptive capacity for each climatic process to be used on the vulnerability assessments

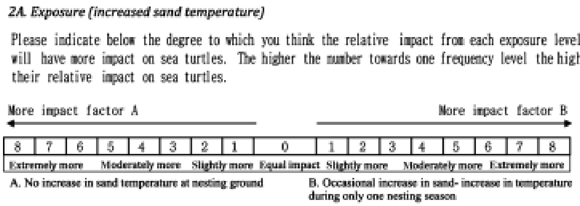
Climatic process	Increased sand temperature	Sea-level rise	Cyclonic activity
Exposure level	No increase in temperature	Sea-level rise never occurs	No cyclonic activity
	Occasionally – increase in temperature during only one nesting season	Occasionally – discrete events of sea level rise, storm surges	Occasionally – 1 cyclone every 30 years
	Often – during one turtle generation (40 years)	Often – sea-level rise over one turtle generation (40 years)	Often – 1 cyclone every 5 years
	Increase in temperature is constant – impacts the stability of the population	Sea-level rise is constant – impacts the stability of the population	Constant – one cyclone every nesting season
Sensitivity level	Temperatures above pivotal temperature (higher % of females)	Loss of up to 10% of current nesting area	Decrease in frequency of cyclones
	Temperature above upper transient range temperature	Loss of 10–35% of current nesting area	Decrease in frequency and more intense cyclones
	Temperatures near the upper thermal threshold	Loss of 35–60% of current nesting area	Increase in frequency of cyclones
	Temperature above upper thermal threshold	Loss of 60–85% of current nesting area	Increase in frequency and more intense cyclones
		Loss of 85–100 % of current nesting area	
Adaptive capacity	Ability to adapt within a nesting season	Ability to adapt within a nesting season	Ability to adapt within a nesting season
	Ability to adapt after a turtle generation	Ability to adapt after a turtle generation	Ability to adapt after a turtle generation
	No ability to adapt	No ability to adapt	No ability to adapt

Table 2 Different levels of exposure, sensitivity and adaptive capacity for each climatic process and their corresponding rank, weight and overall value

Vulnerability category	Rank (R)	Weight (W)	Overall value (OV)
Exposure			
Increased sand temperature			
No increase in temperature	1	0.00	0.00
Occasionally – increase in temperature during only one nesting season	2	0.15	0.30
Often – during one turtle generation (40 years)	3	0.36	1.08
Increase in temperature is constant	4	1.00	4.00
Sea-level rise			
Sea-level rise never occurs	1	0.00	0.00
Occasionally – discrete events of sea-level rise, storm surges	2	0.19	0.38
Often – sea-level rise over one turtle generation (40 years)	3	0.42	1.26
Sea-level rise is constant	4	1.00	4.00
Cyclonic activity			
No cyclonic activity	1	0.00	0.00
Occasionally – 1 cyclone every 30 years	2	0.18	0.36
Often – 1 cyclone every 5 years	3	0.37	1.11
Persistent – constant – one cyclone every nesting season	4	1.00	4.00
Sensitivity			
Increased sand temperature			
Temperatures above pivotal temperature (higher % of females)	1	0.07	0.07
Temperature above upper transient range temperature	2	0.16	0.32
Temperatures near the upper thermal threshold	3	0.38	1.14
Temperature above upper thermal threshold	4	1.00	4.00
Sea-level rise			
Loss of up to 10% of current nesting area	0.8	0.06	0.048
Loss of 10–35% of current nesting area	1.6	0.10	0.16
Loss of 35–60% of current nesting area	2.4	0.20	0.48
Loss of 60–85% of current nesting area	3.2	0.44	1.40
Loss of 85– 100 % of current nesting area	4	1.00	4.00
Cyclonic activity			
Decrease in frequency of cyclones	1	0.11	0.11
Decrease in frequency and more intense cyclones	2	0.24	0.48
Increase in frequency of cyclones	3	0.39	1.17
Increase in frequency and more intense cyclones	4	1.00	4.00
Adaptive capacity			
Increased sand temperature			
Ability to return to adapt within a nesting season	1.33	0.11	0.14
Ability to adapt after a turtle generation	2.66	0.30	0.80
No ability to adapt	4.00	1.00	4.00
Sea-level rise			
Ability to adapt within a nesting season	1.33	0.16	0.21
Ability to adapt after a turtle generation	2.66	0.39	1.03
No ability to adapt	4.00	1.00	4.00
Cyclonic activity			
Ability to adapt within a nesting season	1.33	0.16	0.21
Ability to adapt after a turtle generation	2.66	0.31	0.82
No ability to adapt	4.00	1.00	4.00

(W) values for each level of the vulnerability categories, to indicate their relative impact in relation to each other. As no quantitative data exist on the relative impact of each level of exposure, sensitivity, and adaptive capacity, we used expert knowledge to fill this gap. The use of expert knowledge to quantify how different threats affect various ecosystems has been widely used in other studies (e.g. Sala *et al*., 2000; Halpern *et al*., 2007; Grech & Marsh, 2008; McClanahan *et al*., 2008; Newson *et al*., 2009; Robinson *et al*., 2009).

We identified potential respondents for this study through (1) the Web of Science for Literature, by selecting scientists that have conducted research on sea turtles and climate change and with extensive knowledge of Australian's sea turtles; and (2) from government agencies responsible for marine turtle management in northern Australia, by selecting managers with extensive knowledge of north Queensland's sea turtles, their management, and some of the potential threats they may face in relation to climate change. We identified 30 potential respondents and 22 experts (11 managers and 11 scientists) responded to the survey. Respondents were from 10 different agencies including the Great Barrier Reef Marine Park Authority, Torres Strait Regional Authority, Queensland Department of Environment and Resource Management, James Cook University, University of Queensland, University of Sydney, University of Melbourne, Charles Darwin University, and Southern Cross University. Experts were asked to complete 50 pair-wise comparison matrixes based around each category level and climatic process (see example in Fig. 4) to indicate scores for their perception of the relative severity of each category level. Weights (w) were calculated from the scores given in the matrices using Analytical Hierarchy Process calculation software available at http://www.isc.senshu-u.ac.jp/ ~ thc0456/EAHP/AHPweb.html (Saaty, 1980).



2A. Exposure (increased sand temperature)

Please indicate below the degree to which you think the relative impact from each exposure level will have more impact on sea turtles. The higher the number towards one frequency level the higher their relative impact on sea turtles.

More impact factor A ← → More impact factor B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
Extremely more			Moderately more			Slightly more		Equal impact	Slightly more			Moderately more			Extremely more	

A. No increase in sand temperature at nesting ground

B. Occasional increase in sand- increase in temperature during only one nesting season

Fig. 4 Example of a pair-wise comparison matrix given to respondents to complete.

We averaged the weighting (w) from all the experts to calculate the overall weighting (W) for each level of exposure, sensitivity, and adaptive capacity (as per McClanahan *et al.*, 2008, 2009) (see Table 2 for overall weight). The overall weight was then multiplied by the corresponding rank value (R) to obtain the overall value (OV) for each level of the vulnerability categories (exposure, sensitivity, adaptive capacity) (Table 2 and Fig. 5).

Each vulnerability category (exposure, sensitivity, adaptive capacity) was then multiplied by each other to obtain the vulnerability (Vc) value for each climatic process (Fig. 5).

Step 6: assign levels of exposure, sensitivity, and adaptive capacity to each nesting ground. In the previous steps, we determined the overall value for each level of exposure, sensitivity, and adaptive capacity for each of the three climatic processes. The aim of this step is to assign one level of exposure, sensitivity, and adaptive capacity to each nesting ground. To illustrate this process, we provide a working example of how we determined Bramble Cay's overall vulnerability to increased temperature for 2030 under a conservative scenario of climate change (Fig. 6).

Exposure. To assign an exposure value for each nesting ground we assumed that increases in temperature and sea-level rise would be constant for all nesting grounds over all years and for all climatic scenarios. For example, to calculate the OV of Bramble Cay's exposure to increased temperature, we multiplied the rank of constant exposure (4) by its corresponding weight (1) (Table 2 and Fig. 6). To calculate the exposure values for cyclonic activity, we assumed that cyclonic activity would occur occasionally at nesting grounds in the Torres Strait region and often at

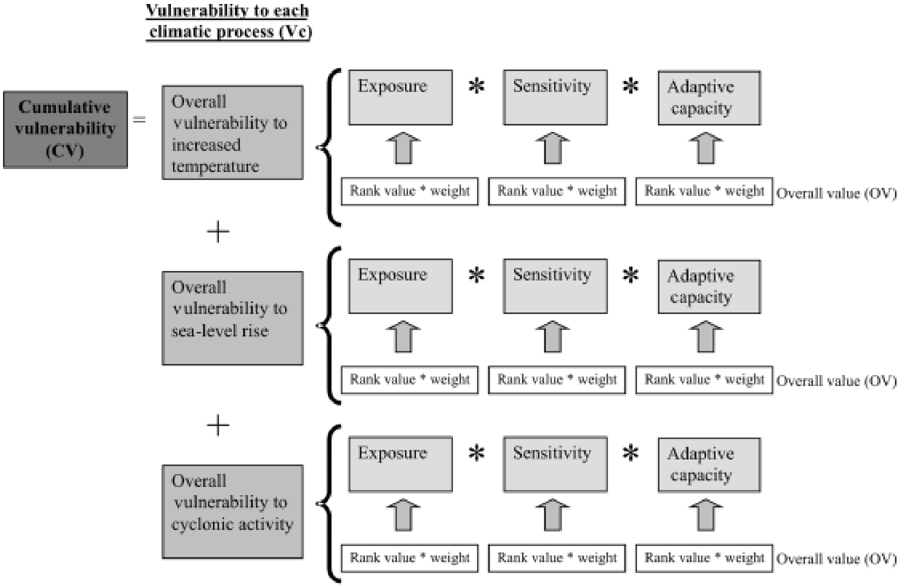


Fig. 5 Vulnerability model, vulnerability categories and an expression of how the overall value for each vulnerability category was determined.

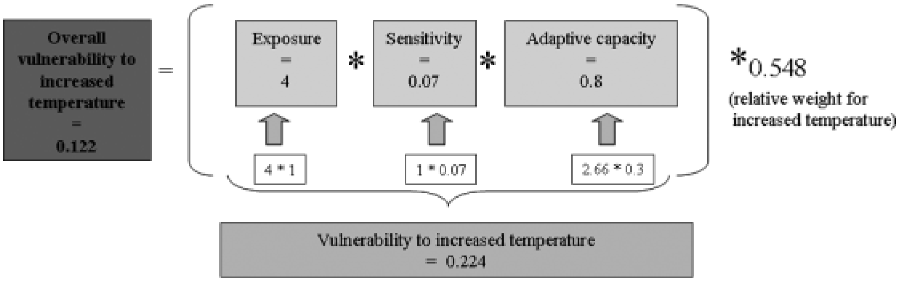


Fig. 6 Worked example of how Bramble Cay's vulnerability to increased temperature for 2030 under a conservative scenario of climate change was determined.

nesting grounds in the nGBR. Cyclone values were based on past cyclonic activity in the study region (information from the Australian Bureau of Meteorology, 2008).

Sensitivity. Values for the sensitivity of each nesting ground to increased temperature and sea-level rise were assigned based on published projections from Fuentes *et al.* (2009b, 2010 and in press a) (see summary in Table 3). For example, Fuentes *et al.* (2009b and 2010) predict that by 2030 under a conservative scenario of climate change, Bramble Cay will experience temperatures above the pivotal temperature. Consequently, to determine Bramble Cay's sensitivity value to increased temperature we multiplied 1, which is the rank for temperatures above the pivotal temperature (see Table 2), by 0.07, which is the corresponding weight, and obtained 0.07 as the OV of sensitivity for Bramble Cay for 2030 under a conservative scenario (Fig. 6). In line with recent studies, we assumed that cyclonic activity will decrease in frequency and increase in intensity (Webster *et al.*, 2005; IPCC, 2007b; Emanuel *et al.*, 2008).

Adaptive capacity. Assigning a value to the capacity of sea turtles to adapt to the impacts of different climate processes on their nesting grounds was more challenging as no empirical data exist. Indeed, reviews and published research on sea turtles and climate change highlight the need for further investigation of sea turtles' adaptive capacity (see Hawkes *et al.*, 2009; Fuentes *et al.*, 2009a). Nevertheless, based on the knowledge that sea turtles have adapted to past climate changes (see Hamann *et al.*, 2007; Limpus, 2008; Poloczanska *et al.*, 2009), we assumed that sea turtles would have the ability to adapt to climate change after a turtle generation. Therefore, to assign Bramble Cay an overall value of adaptive capacity to increased temperature we multiplied 2.66 (rank value) by 0.3 (weight value) (Tables 2 and 3 and Fig. 6). As more data become available, the adaptive capacity value can be easily modified.

Overall vulnerability

After we calculated the vulnerability of each nesting ground for each climatic process, emission scenario, and year, the next step was to calculate the overall vulnerability of each nesting ground to climate change. We first had to determine the relative impact of each climatic factor. We took a similar approach to determining the relative impact values for each level of the vulnerability categories (Step 5) and consequently used the same expert panel, analysis, and type of questions to determine weights and thus the relative impact of each climatic process as per Step 5. After the weights for each climatic process were determined, they were multiplied by the corresponding vulnerability value from each climatic process to obtain an overall vulnerability (Vc) Eqn (1). We then calculated the cumulative vulnerability (CV) for each nesting ground by adding the Vc values for each climatic process. Thus, the CV at each nesting ground is described as (also see Figs 3 and 6):

$$\mathrm{CV} = \mathrm{Vc}\,(\mathrm{ST}) \times 0.548 + \mathrm{Vc}\,(\mathrm{SLR}) \times 0.269 + \mathrm{Vc}\,(\mathrm{CA}) \times 0.183, \quad (1)$$

where CV is the cumulative vulnerability, Vc the vulnerability to a climatic process, ST the increased temperature, SLR the sea-level rise, and CA is the cyclonic activity.

Step 7: modify vulnerability variables to explore how different management strategies will mitigate impacts from climate change. To investigate how the CV of each nesting ground will alter as the impact of different climatic processes is addressed (by management strategies), we manipulated some of the vulnerability categories. To investigate the degree to which the vulnerability of the nesting grounds would change if the impacts from increased temperature are mitigated, we altered the increased temperature exposure value for all nesting grounds to 'no increase in temperature' (level rank 1 and weight 0.0 – as per Table 2) and the sensitivity value to 'temperatures above pivotal temperature' (category 1 and weight 0.07 – as per Table 1). Similarly, to investigate the changes in the vulnerability of the nesting grounds if sea-level rise is addressed, we changed the sea-level rise exposure value for all nesting grounds to 'no sea-level rise' (category 1 and weight 0.0 – as per Table 1) and the sensitivity value to 'loss of up to 10% of the nesting area' (category 0.8 and weight 0.06 – as per Table 1). The reason we used this sensitivity category, even though sea-level rise would be mitigated, is that loss of nesting area can still occur from either or both aperiodic cyclonic activity and storm surges.

Table 3 Categorical values for each vulnerability category for conservative (C) (based on B1 emission scenario of the IPCC, 2007b) and extreme (E) (based on A1T emission scenario of the IPCC, 2007b) scenarios for 2030 and 2070

	Increased sand temperature				Sea-level rise				Cyclonic activity
	2030 C	2030 E	2070 C	2070 E	2030 C	2030 E	2070 C	2070 E	2030 and 2070 E and C
Bramble Cay north	Temperature above pivotal	Temperature above UTRT	Temperature near the UTT	Temperature above the UTT	Up to 10%	Up to 10%	10–35%	10–35%	Decrease in frequency and more intense cyclones
Dowar north	Temperature above pivotal	Temperature above UTRT	Temperature near the UTT	Temperature near the UTT	Up to 10%	Up to 10%	Up to 10%	10–35%	Decrease in frequency and more intense cyclones
Dowar south	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	Temperature above UTRT	Up to 10%	Up to 10%	10–35%	10–35%	Decrease in frequency and more intense cyclones
Milman north	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	Temperature above the UTT	10–35%	10–35%	10–35%	10–35%	Decrease in frequency and more intense cyclones
Milman east	Temperature above pivotal	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	10–35%	10–35%	10–35%	10–35%	Decrease in frequency and more intense cyclones
Milman south	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	Temperature near the UTT	10–35%	10–35%	10–35%	10–35%	Decrease in frequency and more intense cyclones
Milman west	na	na	Temperature above pivotal	Temperature above UTRT	10–35%	10–35%	10–35%	10–35%	Decrease in frequency and more intense cyclones
Moulter Cay north	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	Temperature near the UTT	Up to 10%	Up to 10%	10–35%	10–35%	Decrease in frequency and more intense cyclones
Raine Island south	Temperature above pivotal	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	Up to 10%	Up to 10%	10–35%	10–35%	Decrease in frequency and more intense cyclones
Sandbank 7 north	Temperature above pivotal	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	Up to 10%	10–35%	10–35%	35% to 60%	Decrease in frequency and more intense cyclones
Sandbank 7 south	na	na	Temperature above pivotal	Temperature above pivotal	Up to 10%	10–35%	10–35%	35% to 60%	Decrease in frequency and more intense cyclones
Sandbank 8 north	Temperature above pivotal	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	Up to 10%	10–35%	10–35%	10–35%	Decrease in frequency and more intense cyclones

Categories were assigned based on published material; categories for increased temperature we assigned according to Fuentes *et al*. 2009b, 2010, categories for sea-level rise were assigned based on Fuentes *et al*. in press a, and categories for cyclonic activity were assigned based on Webster *et al*. 2005. Pivotal temperature refers to the temperature where a 50 : 50 male to female sex ratio is produced, TRT refers to the transitional range of temperature and is the range of temperature where sex ratio shifts from all male to all females, the UTRT refers to temperatures above the TRT and when only females are produced, and UTT refers to upper thermal threshold.

Step 8: assigning vulnerability thresholds. To aid the interpretation of the results, we created four vulnerability categories (low, intermediate, high, and extreme). The categories were determined in accordance with the sensitivity values (Table 1) for each climatic factor. The exposure values (Table 1) and adaptive capacity values (Table 1) were kept constant – as described in Step 6. For example, a low vulnerability value was obtained by using the lowest sensitivity category for increased temperature and sea-level rise and using the value for cyclonic activity as decreasing in frequency but intensifying. Similarly, for the extreme category, we used the highest values for increased temperature and sea-level rise and again for cyclonic activity we used the value for activity as decreasing in frequency but intensifying. The other vulnerability categories were determined in the same way with the respective sensitivity category.

Step 9: weight vulnerability values according to the importance of each nesting site to the overall population of sea turtles. A particular sea turtle population uses several sites to nest, with some sites having more importance (proportional to the number of turtles nesting) than others. This is the case for the nGBR green turtle population as discussed in Step 1. Because of the variability in the importance of each of these sites, we weighed the vulnerability scores of each nesting site according to the importance of each nesting site to the population. The weights were based on the percentage of nesting that occurs at each site in relation to the overall nesting across these sites. Consequently, the following weights were attributed: Raine Island (0.50), Moulter Cay (0.40), Dowar Island (0.025), Bramble Cay (0.03), Sandbanks 7 and 8 (0.02) and Milman Island (0.005). This will allow investigation of the relative impact on the overall population.

Results

Vulnerability to increased temperature

The nesting grounds studied here will start to be vulnerable to increase in temperature by 2070. Before that, most rookeries will have temperatures that are between the pivotal temperature and above the upper transient range, and thus in 2030 will have only low vulnerability scores (Table 4). However, by 2070 rookeries will be much more vulnerable to increased temperature and the nesting grounds will experience temperatures above the upper transient range and the upper thermal threshold. Bramble Cay and the northern facing beach at Milman Island are the nesting areas most vulnerable to increased temperature (Table 4).

Vulnerability to sea-level rise

In the long term (by 2070) the vulnerability to sea-level rise of the nesting grounds studied here is relatively low compared with their vulnerability to increased temperature (Table 4). However, some nesting grounds in the nGBR will experience higher levels of vulnerability to sea-level rise in the short term (by 2030) than they will to increased temperature. Nevertheless, the

Table 4 Overall vulnerability of the nesting grounds to different climatic processes under conservative (C) (based on B1 emission scenario of the IPCCb) and extreme (E) (based on A1T emission scenario of the IPCC, 2007b) scenarios of climate change by 2030 and 2070

	Vulnerability to increased temperature				Vulnerability to sea-level rise				Vulnerability to cyclonic activity			
	2030 C	2030 E	2070 C	2070 E	2030 C	2030 E	2070 C	2070 E	2030 C	2030 E	2070 C	2070 E
Bramble Cay north	0.12	0.56	2.00	7.02	0.05	0.05	0.18	0.18	0.03	0.03	0.03	0.03
Dowar north	0.12	0.56	2.00	2.00	0.05	0.05	0.05	0.18	0.03	0.03	0.03	0.03
Dowar south	0.12	0.12	0.56	0.56	0.05	0.05	0.18	0.18	0.03	0.03	0.03	0.03
Milman north	0.12	0.12	0.56	7.02	0.18	0.18	0.18	0.18	0.08	0.08	0.08	0.08
Milman east	0.12	0.12	0.56	2.00	0.18	0.18	0.18	0.18	0.08	0.08	0.08	0.08
Milman south	0.00	0.00	0.12	0.56	0.18	0.18	0.18	0.18	0.08	0.08	0.08	0.08
Milman west	0.12	0.12	0.56	2.00	0.18	0.18	0.18	0.18	0.08	0.08	0.08	0.08
Moulter Cay north	0.12	0.12	0.56	2.00	0.05	0.05	0.18	0.18	0.08	0.08	0.08	0.08
Raine Island south	0.12	0.12	0.12	0.56	0.05	0.05	0.18	0.18	0.08	0.08	0.08	0.08
Sandbank 7 north	0.12	0.12	0.12	0.56	0.05	0.18	0.18	0.54	0.08	0.08	0.08	0.08
Sandbank 7 south	0.00	0.00	0.12	0.12	0.05	0.18	0.18	0.54	0.08	0.08	0.08	0.08
Sandbank 8 north	0.12	0.12	0.12	0.56	0.05	0.18	0.18	0.18	0.08	0.08	0.08	0.08

Vulnerability values were obtained as described in steps 1–7. Threshold values for increased temperature, sea-level rise and cyclonic activity, respectively are: low (>0.13, >0.05, and >0.02; white), intermediate (between 0.13 and 0.56, 0.05 and 0.18, and 0.02 and 0.08; light grey), high (0.56 to 1.99, 0.18 to 1.58, and 0.08 to 0.19; dark grey), and extreme (above 7, 4.48, and 0.65; darker/black grey) (see step 6 for how vulnerability values where assigned).

vulnerability of rookeries to sea-level rise will not be exacerbated or achieve high levels by 2070. Only Sandbank 7 is likely to have high levels of vulnerability to sea-level rise by 2070 (Table 4).

Vulnerability to cyclonic activity

The vulnerability of the nesting grounds to cyclonic activity was found to be low. This is a reflection of the low predicted cyclonic activity in the study region (Table 4).

Cumulative vulnerability

The cumulative vulnerability of the nesting grounds studied is relatively low in the short term (2030). However, by 2070 the cumulative vulnerability of the nesting grounds will increase considerably (Table 5). Under a conservative scenario, all rookeries studied will experience at least intermediate vulnerability values by 2070, with the nesting grounds in Torres Strait, Milman Island, and Moulter Cay experiencing the highest vulnerability values (Table 4). Results are more drastic under an extreme scenario of climate change, as most rookeries are predicted to experience high vulnerability values, with Bramble Cay and the north-facing beach at Milman experiencing extreme vulnerability values (Table 5).

Changes in cumulative vulnerability with different management strategies

Addressing the impacts from increased temperature will cause the greatest reductions in the cumulative vulnerability of nesting grounds to climate change. If the impacts from increased temperature are mitigated, all rookeries will experience very low levels of cumulative vulnerability in the future, with the nesting grounds in Torres Strait experiencing the lowest level of vulnerability and Sandbank 7 experiencing the highest level of vulnerability (Table 5). Addressing the impacts from sea-level rise will not be as effective as reducing the threats from increased temperature, especially in the long term (2070). By 2070, a reduction of the impacts from sea-level rise may not be sufficient, as rookeries will still experience high cumulative vulnerability levels resultant from increased temperature (Table 5).

Cumulative vulnerability of nesting grounds in relation to importance to the overall population

If the importance of each nesting ground is taken into account, Raine Island, Moulter Cay, and Bramble Cay will be the nesting sites with the highest cumulative vulnerability scores (Table 5). In fact, these sites are the only sites that will have significant cumulative vulnerability values by 2030 (Table 5).

Table 5 Cumulative vulnerability of nesting grounds to climate change with different management responses under conservative (C) (based on B1 emission scenario of the IPCC b) and extreme (E) (based on A1T emission scenario of the IPCC, 2007b) scenarios by 2030 and 2070

	Cumulative vulnerability with no management response				Cumulative vulnerability with management of temperature				Cumulative vulnerability with management of sea-level rise				Cumulative vulnerability, in relation to overall population*, with no management response			
	2030 C	2030 E	2070 C	2070 E	2030 C	2030 E	2070 C	2070 E	2030 C	2030 E	2070 C	2070 E	2030 C	2030 E	2070 C	2070 E
Bramble Cay north	0.20	0.64	2.21	7.23	0.08	0.08	0.20	0.20	0.15	0.59	2.03	7.05	0.006	0.019	0.066	0.216
Dowar north	0.20	0.64	2.08	2.21	0.08	0.08	0.08	0.20	0.15	0.59	2.03	2.03	0.005	0.016	0.052	0.055
Dowar south	0.20	0.20	0.77	0.77	0.08	0.08	0.20	0.20	0.15	0.15	0.59	0.59	0.005	0.005	0.019	0.019
Milman north	0.38	0.38	0.82	7.28	0.26	0.26	0.26	0.26	0.20	0.20	0.64	7.10	0.001	0.001	0.004	0.036
Milman east	0.38	0.38	0.82	2.26	0.26	0.26	0.26	0.26	0.20	0.20	0.64	2.09	0.001	0.001	0.004	0.011
Milman south	0.26	0.26	0.38	0.82	0.26	0.26	0.26	0.26	0.08	0.08	0.20	0.64	0.001	0.001	0.001	0.004
Milman west	0.38	0.38	0.82	2.26	0.26	0.26	0.26	0.26	0.20	0.20	0.64	2.08	0.001	0.001	0.004	0.011
Moulter Cay north	0.26	0.26	0.82	2.26	0.13	0.13	0.26	0.26	0.20	0.20	0.64	2.08	0.104	0.104	0.320	0.904
Raine Island south	0.26	0.26	0.38	0.82	0.13	0.13	0.26	0.26	0.20	0.20	0.20	0.64	0.130	0.130	0.190	0.410
Sandbank 7 north	0.26	0.38	0.38	1.18	0.13	0.26	0.26	0.62	0.20	0.20	0.20	0.64	0.005	0.007	0.007	0.023
Sandbank 7 south	0.13	0.26	0.38	0.74	0.13	0.26	0.26	0.62	0.08	0.08	0.20	0.20	0.002	0.005	0.007	0.014
Sandbank 8 north	0.26	0.38	0.38	0.82	0.13	0.26	0.26	0.26	0.20	0.20	0.20	0.64	0.005	0.007	0.007	0.016

Low vulnerability is highlighted in white (>0.19), intermediate values are between 0.19 and 0.82 (light grey), high values are between 0.82 and 3.76 (dark grey) and extreme values between 3.76 and 12.13 (in darker grey).

*Vulnerability values were weighted in accordance to the percentage of nesting that occurs at each site in relation to the overall nesting for the nGBR green turtle population (see Step 9).

Discussion

Multiple climatic processes (e.g. increased temperature, sea-level rise, and cyclonic activity) will impact sea turtle nesting grounds at different intensities and geographical scales Hawkes *et al.*, 2009; Poloczanska *et al.*, 2009; Fuentes *et al.*, 2009a; Witt *et al.*, in press). Knowledge of which climatic factor will cause the most impact, and which regions will be most impacted, can aid management strategies and responses (Pressey *et al.*, 2003; Kappel, 2005; Halpern *et al.*, 2007; Higgason & Brown, 2009; Mazaris *et al.*, 2009). Our study indicates that in the long term (by 2070), increased temperature will cause the most impact to the nesting grounds used by the nGBR green turtle population. Therefore, if sea turtles continue to use the same nesting grounds in the future, reducing the threats from increased temperature may provide a greater return in conservation investment than mitigating the impacts from sea-level rise or cyclonic activity. Indeed, our results indicate that if the impacts from increased temperature are mitigated, the vulnerability values of almost all rookeries will be reduced to low levels. Some of the potential options to mitigate the impacts of increased temperature include changing the thermal gradient at beaches (e.g. nest shading, revegetation programs, sand coloring, and habitat modification), nest relocation, and artificial incubation (Naro-Maciel *et al.*, 1999; Hawkes *et al.*, 2007, 2009; Fuentes *et al.*, 2009a).

The best management options will be site specific and dependent on a series of factors, including feasibility, risk (interaction and impact on other species and ecosystems), cost, constraints to implementation (both cultural and social), and probability of success in relation to selected sites (Pressey & Bottrill, 2009). Thus, a 'toolbox' with various strategies may be needed to address the impacts of increased temperature across the nesting sites used by the nGBR green turtle population. For example, the best management strategy at Dowar Island might be to relocate nests to cooler areas, as periodic monitoring of the beaches is conducted by turtle and dugong rangers. However, this strategy is not feasible for other nesting grounds, such as Bramble Cay, that are remote and have no constant monitoring.

Implementing any strategy, even at small spatial scales, will be costly and time intensive (Fuentes *et al.*, 2009b). Hence, if we consider the limited resources available, managers may also need to prioritize the nesting grounds on which they focus their management and resources. Thus, knowledge of the extent that nesting grounds will be affected is essential to guide management decisions. According to our results, impacts from climatic changes to Raine Island, Moulter Cay, and Bramble Cay will cause the most impact to the overall nGBR green turtle population. Consequently, managers may decide to focus their management in these regions. From a governance perspective, both Raine Island and Moulter Cay are protected (the Environmental Protection Agency manages the islands and surrounding intertidal areas and the Great Barrier Reef Marine Park Authority has jurisdiction over the waters below mean low water), but Bramble Cay is not protected by any legislation (Limpus, 2008). However, considering the ecological importance of Bramble Cay, there might be scope to protect it as an Indigenous Protected Area (an area of Indigenous-owned land or sea where traditional owners have entered into an agreement with the Australian Government to promote biodiversity and cultural resource conservation) another option may be to declare Bramble Cay a nature refuge (where land owners – traditional owners in this case – can enter in a formal agreement with the Australian Government).

Protection of nesting grounds that are currently less important than these three sites and that will be less impacted has also been suggested as a strategy. Regardless of the priorities and goals (e.g. protect the most threatened vs. the most ecologically important site) of different agencies and groups, the framework used here can provide valuable guidance for management decisions. Our method provides the first systematic and comprehensive framework to assess how sea turtle nesting grounds will be affected by climate change. The framework used here can easily be adapted if new information is obtained, and can be transferable to different sea turtle populations and sea turtle life cycle phases (e.g. adult sea turtles, foraging) provided the necessary data exist. The framework is not meant to be a rigid prescription of a specific technique, but rather an approach for managers and scientists to address the impacts of climate change to sea turtles. However, we strongly suggest that the framework is applied to multiple areas (e.g. nesting areas) used by a single population, so that an understanding of a population level (management unit) can be obtained. It is also important that the models are updated as new information becomes available and the experts' knowledge changes. For example, as further understanding of sea turtles' adaptive capacity is gained and the experts' opinions potentially change, the new scores should be altered and incorporated into the model.

Indeed, our understanding of sea turtles' adaptive capacity to climate change is likely to increase, since several studies have highlighted the need for further research on this topic (Hamann *et al.*, 2007; Hawkes *et al.*, 2009; Fuentes *et al.*, 2009a; se). A way to move forward may be to develop a method to measure sea turtles' adaptive capacity to climate change and acquire further understanding of the geomorphology processes at each nesting ground and their capacity to adapt. Some indication of sea turtles' ability to adapt to climate change at each nesting site may be provided by information on their current status, trend, the threats they face (e.g. predation, harvest), the awareness and legislative compliance at a local level, and the morphological stability of their nesting sites. Including these additional parameters in the framework has the potential to refine and add ecologically important information to vulnerability assessments.

Similarly, if an understanding of how sea turtles may potentially shift their nesting ground as climate change progresses, as an adaptation response (as suggested by Hays *et al*., 2001), is gained the vulnerability assessment conducted here should be conducted at the areas that may serve as potential nesting grounds to sea turtles in the future. This will provide insights into areas that managers may need to focus their resources and management strategies.

Another important incorporation in future studies is the impacts of synergetic (amplifying) effects and interactions from different climatic processes (Brook *et al*., 2008; Brooks *et al*., 2009). Climate processes will not act in isolation and they may produce unexpected changes to ecosystems when combined with local conditions and other threats (Harley *et al*., 2006; Emily & Isabelle, 2008). For example, sea-level rise may reduce the area available for sea turtles to nest; this will amplify density-dependent issues at nesting grounds, potentially increasing nest infection (Fuentes *et al*., in press a), destruction of nests by cospecifics (Bustard & Tognetti, 1969; Girondot *et al*., 2002; Limpus *et al*., 2003; Tiwari *et al*., 2006), and predation (Tiwari *et al*., 2006). It is likely that most threat interactions will amplify their impacts; however, the nature and magnitude of these synergies are unknown for most threats and ecosystems (Halpern *et al*., 2007) and could potentially be beneficial. For instance, increased temperature may negatively impact on the wild pigs and goannas that predate on turtle eggs and may reduce their numbers or change their distribution, resulting in a decrease in the predation of sea turtle nests. Unfortunately, the prevalence and magnitude of these interactions remain one of the largest uncertainties in projections of future ecological change (Emily & Isabelle, 2008). Thus, further research on this issue is warranted.

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