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Resilience of marine turtle regional management units to climate change

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Abstract

Enhancing species resilience to changing environmental conditions is often suggested as a climate change adaptation strategy. To effectively achieve this, it is necessary first to understand the factors that determine species resilience, and their relative importance in shaping the ability of species to adjust to the complexities of environmental change. This is an extremely challenging task because it requires comprehensive information on species traits. We explored the resilience of 58 marine turtle regional management units (RMUs) to climate change, encompassing all seven species of marine turtles worldwide. We used expert opinion from the IUCN-SSC Marine Turtle Specialist Group (n = 33 respondents) to develop a Resilience Index, which considered qualitative characteristics of each RMU (relative population size, rookery vulnerability, and genetic diversity) and non climate-related threats (fisheries, take, coastal development, and pollution/pathogens). Our expert panel perceived rookery vulnerability (the likelihood of functional rookeries becoming extirpated) and non climate-related threats as having the greatest influence on resilience of RMUs to climate change. We identified the world's 13 least resilient marine turtle RMUs to climate change, which are distributed within all three major ocean basins and include six of the world's seven species of marine turtle. Our study provides the first look at inter- and intra-species variation in resilience to climate change and highlights the need to devise metrics that measure resilience directly. We suggest that this approach can be widely used to help prioritize future actions that increase species resilience to climate change.

Keywords: climate change adaptation, conservation planning, expert opinion, flatback turtle, green turtle, hawksbill turtle, leatherback turtle, loggerhead turtle, olive ridley turtle, sea turtle

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Introduction

Climate change is a major threat to biodiversity (Bellard *et al.*, 2012) that has already impacted species globally, with projections for further impacts on species distributions, physiology, phenology, behavior, and reproduction (Gitay *et al.*, 2002; Walther *et al.*, 2002; Root *et al.*, 2003; Maclean & Wilson, 2011). Although climate change may have a positive influence on some species (e.g., by increasing prey availability or expanding suitable habitat), it may also impact on species interactions, community composition, and ecosystem services (Walther *et al.*, 2002; Walther, 2010).

In response to the anticipated widespread negative impacts of climate change, the forefront of current research focuses on strategies that mitigate these potential threats (Heller & Zavaleta, 2009; Mawdsley *et al.*, 2009). These strategies seek to do the following: 1) mitigate the threat by reducing global greenhouse emissions (Hannah *et al.*, 2002); 2) adaptively manage impacts from climate change by increasing population persistence (Peterson *et al.*, 1997); and 3) employ actions that build biodiversity resilience, such as addressing current non climate threats (Chambers *et al.*, 2005; Heller & Zavaleta, 2009; Mawdsley *et al.*, 2009). Reducing emissions is perhaps the biggest challenge, but even immediate reductions will not stop the already apparent and unavoidable impacts of climate change (Peterson *et al.*, 1997). Adaptive management is constrained by risks associated with implementing mitigation strategies (e.g., species relocations, manipulations or management actions that improve habitat) and a lack of understanding of how effective these strategies will be at reducing impacts from climate change (Fuentes *et al.*, 2012). Therefore, until further information on the effectiveness and potential risks of these strategies is obtained, we should prioritize attempts to predict the impacts of climate change, and thus estimate how

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resilient populations or species could be under future scenarios (Hays *et al*., 2003; Hawkes *et al*., 2009; Fuentes *et al*., 2012).

Resilience is the ability of an ecosystem or species to maintain key functions and processes in the face of stresses or pressures, either by resisting or adapting to change (Holling, 1973; Nyström & Folke, 2001). In the case of biodiversity and climate change, this relates to the ability of a species to adjust to and self-organize in response to environmental change (Moore & Huntington, 2008; Heller & Zavaleta, 2009). Building biodiversity resilience, to date, has focused on reducing non climatic threats under the rationale that large, healthy and stable populations will help maintain the following: 1) genetic diversity, which can facilitate adaptation to variable conditions; 2) a wide geographic distribution, which can minimize the overall impacts of area-specific threats; and 3) a large breeding population, which can help absorb disturbance through an increased ability to recover from population perturbations (Purvis *et al*., 2000; Isaac *et al*., 2009; Sgrò *et al*., 2011). However, to actively manage for resilience in a changing climate, we need to understand the factors that determine species resilience, their relative importance in shaping the ability of species to adjust to climate change, and the 'amount' of resilience that a species has, as defined by the above rationale. However, this is an extremely challenging task because of difficulties associated with how to comprehensively quantify resilience (Carpenter *et al*., 2001).

We explored the resilience of marine turtle regional management units (RMUs, Wallace *et al*., 2010) to climate change to provide guidance on future management activities, highlight knowledge deficiencies, and focus adaptation research efforts. Marine turtles play important ecological roles in maintaining marine and coastal ecosystems (e.g., maintenance of seagrass and algal ecosystems, nutrient cycling) (Moran & Bjorndal, 2005, 2007), cultural roles in terms of their value to indigenous human societies (Johannes & Macfarlane, 1991), and educational roles through a vibrant tourism industry (Wilson & Tisdell, 2001). Despite worldwide legal protection, marine turtle populations in many regions have declined in abundance in recent decades, due to fisheries bycatch, direct take, and coastal development (Lutcavage *et al*., 1996). These existing threats have spurred concerns that climate change impacts on marine turtle populations will compound challenges to population recovery (Fuentes & Cinner, 2010; Hamann *et al*., 2010). Marine turtles are particularly vulnerable to climate change because their life history, physiology, and behavior are extremely sensitive to environmental temperatures (Poloczanska *et al*., 2007; Hawkes *et al*., 2009; Fuentes *et al*., 2011b; Fossette *et al*., 2012). Arguably, the more detectable impacts of climate change will occur during the terrestrial reproductive phase of marine turtles (i.e., egg laying, egg incubation, and egg hatching success), which is crucial to population persistence (Pike, 2013).This not only reflects the general research bias of sea turtle research toward terrestrial nesting grounds but also the clear and relatively direct effects of increased temperature, sea level rise, and large stochastic disturbances (e.g., cyclonic activity) on nesting habitat and reproductive success (Fish *et al*., 2005; Pike & Stiner, 2007; Witt *et al*., 2010; Fuentes *et al*., 2011a, 2012; Katselidis *et al*., 2012). Nevertheless, climate change may affect turtles in multiple ways and at all life stages, ranging from the loss of nesting beaches due to sea level rise and storms (Fish *et al*., 2005; Baker *et al*., 2006; Fuentes *et al*., 2010), to feminization of turtle populations from elevated nest temperatures (Hawkes *et al*., 2007; Fuentes *et al*., 2009), changes in reproductive periodicity (Weishampel *et al*., 2004, 2010; Pike *et al*., 2006), shifts in latitudinal ranges (Mcmahon & Hays, 2006; Witt *et al*., 2010), and hatchling dispersal and migration (Hamann *et al*., 2011; Van Houtan & Halley, 2011), decreased reproductive success (Hawkes *et al*., 2009; Fuentes *et al*., 2011b), and indirect effects to food availability (Hawkes *et al*., 2009). The information we provide on the perceived resilience of global marine turtle regional management units helps identify which RMUs may be most threatened in a changing climate based on inherent population characteristics and existing threats. This will help refine global priority-setting.

Materials and methods

Resilience index (RI)

Several traits are crucial for species resilience to environmental change, including the size and trend of populations, threats, and biological and genetic diversity (Peterson *et al*., 1998; Elmqvist *et al*., 2003; Folke *et al*., 2004; Chambers *et al*., 2005; Sgrò *et al*., 2011). Subsets of these species-specific traits have been used to assess the resilience of a wide range of species to climate change {e.g.,[Isaac *et al*., 2009; Moore & Huntington, 2008]. Here we use two sets of traits to determine the resilience of marine turtle RMUs to climate change. The first set of traits assessed population characteristics that influence risk of decline or loss of genetic diversity [defined as a 'risk matrix' in Wallace *et al*. (2011)]: 1} population size – the average estimated annual number of nesting females in each RMU; 2) recent nesting population trend – based on the past 10 years of available nesting data (because longer term trends for many RMUs are unavailable); 3) long-term nesting population trend – based on a minimum time span of one generation (generation length is the average age of parents of the current cohort, as per IUCN Red List criteria;); 4) rookery vulnerability – the likelihood of functional rookeries (those that successfully produce hatchling turtles) becoming extirpated, which would limit species recovery based on the number and geographic distribution of rookeries within an RMU; and 5) genetic diversity – the number of known or inferred genetic stocks (from species-specific patterns of genetic distinctiveness among rookeries based on haplotype) within an RMU.

The second set of traits assessed relative population-level impacts from non climatic threats. We based this on the 'hazards to marine turtles' established during the Burning Issues Assessment conducted by the Marine Turtle Specialist Group (MTSG-B3) (Mast *et al.*, 2005): 1) fisheries bycatch; 2) take – harvest of turtle eggs, meat, or shells for human use; 3) coastal development of nesting beaches – human-induced alteration of coastal nesting areas due to construction, dredging, or beach modification; and 4) pollution and pathogens – marine pollution and debris that affect marine turtles (i.e., through ingestion or entanglement which can cause injury or mortality, disorientation caused by artificial lighting, etc.), as well as impacts of pervasive pathogens (e.g., fibropapilloma virus). Climate change was the fifth key hazard listed by the MTSG-B3, however, climate change was not incorporated here because of an excessive number of data deficient scores for many RMUs (see Wallace *et al.*, 2011).

Values for the risk and nonclimate threats criteria for each of the 58 marine turtle RMUs, which were used here (as defined by (Wallace *et al.*, 2010), were obtained from Wallace *et al.* (2011), which is the single most thorough conservation status assessment for all populations of marine turtles to date. Information on long-term and recent population trends for some RMUs was unavailable (for detailed information see the supporting datasets in Wallace *et al.*, 2011) and therefore we were unable to score these risk criteria for all RMUs. To account for this data deficiency, we excluded these variables from the Resilience Index.

The relative influence of each of these criteria to the resilience of each RMU was then weighted (w). Because the relative influence of each of these criteria has not been previously quantified for each RMU, we used expert opinion to obtain weights for our resilience criteria. The use of expert knowledge to quantify the relative influence or impact of similar variables on populations has been widely used in other studies (e.g., (Donlan *et al.*, 2010; Fuentes *et al.*, 2011b; Halpern *et al.*, 2007; Sala *et al.*, 2000). We solicited expert opinion from the foremost global authorities on marine turtle research and conservation, the IUCN-SSC Marine Turtle Specialist Group (MTSG), which includes ~220 experts from dozens of countries. We are confident excluding long-term and recent population trends, in this study, as expert respondents evaluated population trend as having the lowest influence on marine turtle RMU resilience to climate change (see Results; Table 1). Consequently, the RI for each marine turtle RMU is described as:

$$\begin{aligned} \mathit{Resilience\ Index}(RI) &= \underbrace{(PS * w) + (RV * w) + (D * w)}_{\text{Risk(R)}} \\ &+ \underbrace{[(F + T + CD + P)/4 * w]}_{\text{NonClimatethreat(NT)}} \end{aligned} \tag{1}$$

where: PS = Population size, RV = Rookery vulnerability, D = Diversity, R = Risk, F = Fisheries, T = Take, CD = coastal development, P = pollution and pathogens, NT = Non climate-related threat, and w = weight.

MTSG respondents had 1 month to answer the survey questions, which are available in the Supporting Information S1. Prior to sending out surveys, we used colleagues to help revise our questions, and we were available during the survey period to answer any questions that respondents had. The survey included a description of the project, references to support the project's background as well as a series of background questions to determine the respondents' experience and expertise with regard to each RMU.

Our questions were structured as pair-wise comparison matrices, whereby respondents indicated their perception of the relative importance of one criterion when compared with another (Supporting Information S1). Respondents could assign one of seven scores to each comparison, ranging from one criteria being 'extremely more important' than another to both criteria having 'equal importance.' Weights (w) for the resilience criteria were calculated from scores given in the pair-wise matrices using Analytical Hierarchy Process (AHP) software (Saaty, 1980; available at http://www.isc.senshu-u.ac.jp/~thc0456/EAHP/AHPweb.html). Analytical Hierarchy Process is a multi-criteria decision-making method that derives weights from paired comparisons using principal Eigen vectors (Saaty, 1980). Weights from all experts were averaged to calculate an overall weighting (w) for each criterion (as per Fuentes & Cinner, 2010; Fuentes *et al.*, 2011b; Mcclanahan *et al.*, 2008) (see Table 1). The overall weight was then multiplied by the corresponding criterion value (which was obtained from Wallace *et al.*, 2011) to obtain the overall Resilience Index (RI) value using Eqn (1). This index varied from 0.76 to 2.28, with the lowest number representing the most resilient RMUs. We divided this index into three resilience categories for analysis, using terciles: high resilience (0.76–1.25), medium resilience (1.26–1.76), and low resilience (1.77–2.28). Information on population characteristics of the Northeast Indian green turtle RMU was unavailable, and therefore this RMU was excluded from analysis (see Wallace *et al.*, 2011).

Results

Respondents

A total of 33 experts answered the survey; 25 experts (75.8%) self-identified as researchers, four experts

Table 1 Relative weights and standard deviations for our six resilience criteria

Resilience variable	Mean weight (w)	Standard Deviation
Rookery Vulnerability	0.24	0.11
Non climate-related threat	0.20	0.13
Population size	0.17	0.12
Diversity	0.15	0.13
Recent trend	0.12	0.09
Long-term trend	0.12	0.08

(12.1%) as managers, and four experts (12.1%) as educators (see Supporting Information S2). Survey participants had expertise in all 58 marine turtle RMUs, with most respondents having experience working with loggerhead turtles (*Caretta caretta*) in the Mediterranean Sea ($n = 9$) and Northwest Atlantic Ocean ($n = 8$), green turtles (*Chelonia mydas*) in the South Caribbean ($n = 8$) and Northwest Atlantic Oceans ($n = 7$), and olive ridley turtles (*Lepidochelys olivacea*) in the East Pacific Ocean ($n = 7$). Some RMUs were represented by the experience of only a single respondent; these included loggerhead turtles in the Northeast Indian Ocean, green turtles in the West Central Pacific Ocean, and Southeast Indian Ocean, leatherback turtles in the Northeast and Southwest Indian Oceans and Southeast Atlantic Ocean, hawksbill turtles in the East Atlantic Ocean, in the Southeast Indian Ocean and West and North Central Pacific Oceans, and olive ridley turtles in the Northeast Indian Ocean (arribadas) West Pacific Ocean and East Atlantic Ocean (see Supporting Information S2).

Relative importance of resilience variables

The variables perceived to be most important to the resilience of RMUs to climate change were rookery vulnerability (35% of respondents) and nonclimate threats (25% of respondents). These variables also had the highest average weights (0.24 and 0.20, respectively; Table 1), with recent and long-term trends having the lowest weights (0.12; Table 1).

Resilience of regional management units to climate change

The RMU resilience index (RI) values ranged from a low of 0.89 (most resilient, northwest Atlantic leatherback) to a high of 2.08 (least resilient, southwest Atlantic leatherback) (Table 2). At the ocean basin scale, the Indian Ocean had the highest proportion of RMUs that were ranked as least resilient (29.4% of the 18 RMUs in the basin) (Table 2, Fig. 1). The Indian and Atlantic Oceans also presented the highest proportion of RMUs with high resilience (41.2% of 18 and 17 RMUs in the basin, respectively) (Table 2, Fig. 1). However, there was little variation among the mean RI scores for all RMUs within each basin (mean RIs: Indian Ocean = 1.46, Atlantic Ocean = 1.44, Pacific Ocean = 1.43 and Mediterranean Sea = 1.37). The highest proportion of hawksbill and loggerhead RMUs were ranked as being least resilient to climate change (30.8% and 30.0% of 13 and 10 RMUs, respectively) and a high proportion of green and leatherback RMUs were ranked as being the most resilient to climate change (50.3% and 42.9% of 17 and 7 RMUs, respectively) (Table 2, Fig. 1).

Discussion

Managing for resilience is critical for coping with uncertainty caused by stresses or pressures on ecological systems, such as those related to changing environmental conditions (Folke *et al.*, 2002). To manage effectively, we need to understand what factors determine species resilience and their relative importance in affecting the ability of species to adjust to climate change. Here, we explored the factors that influence the resilience of marine turtles to climate change and their relative importance. Our expert panel perceived rookery vulnerability and nonclimate-related threats as those factors most likely to influence the resilience of RMUs to climate change.

Rookery vulnerability relates to the likelihood of extirpation of functional rookeries that would prevent recovery based on the number and distribution of rookeries within an RMU. This can be used as an indicator of persistence of viable nesting in an RMU, given various threats and potential for range shifts over time (Wallace *et al.*, 2011). The importance of rookery persistence relates to the need for optimal nesting areas necessary for reproduction and thus recruitment entry into the population, and buffer areas that will encompass any need for marine turtles to redistribute the geographic locations of nesting grounds as an adaptive response to deal with environmental or land-use changes (Pike, 2013). Marine turtles have persisted through dramatic changes in past climates (Hamann *et al.*, 2007; Hawkes *et al.*, 2009) and are thought to have adapted by redistributing their nesting sites (Hamann *et al.*, 2007). Such behavioral flexibility may offer one of the most promising avenues for adaptation in marine turtles (Hawkes *et al.*, 2009; Schofield *et al.*, 2009). However, a necessary requirement for behavioral flexibility to ameliorate the negative impacts of climate change is that novel geographic areas that are conducive to egg incubation must exist (Katselidis *et al.*, 2012; Pike, 2013). This highlights the need to maintain and protect important regional nesting beaches and to identify and legally protect areas that will maintain suitable nesting environments in the future (Fuentes *et al.*, 2012). This will be particularly difficult in areas where coastal development and beach alteration is widespread and continually expanding, such as in the Caribbean and southeastern United States, where important populations of marine turtles nest. Indeed, 11 of the RMUs identified as least resilient to climate change in our study (Table 2) have previously been identified as having a high likelihood of complete loss of nesting

Table 2 The most and least resilient marine turtle regional management units, presented by species, as assessed by 33 experts in the field

Most resilient (0.76 ≤ RI ≤ 1.26)				Least resilient (1.77 ≤ RI ≤ 2.28)			
Species	Ocean Basin	Region	RI	Species	Ocean Basin	Region	RI
Loggerhead	Atlantic	Northwest	0.96	Loggerhead	Pacific	North	1.80
Loggerhead	Indian	Northwest	1.10	Loggerhead	Indian	Southwest	1.90
Loggerhead	Mediterranean	Mediterranean	1.26	Loggerhead	Indian	Northeast	1.90
Green	Indian	Northwest	0.96	Green	Pacific	North Central	1.80
Green	Atlantic	Northwest	0.99	Leatherback	Atlantic	Southwest	2.08
Green	Pacific	Southwest	1.03	Leatherback	Indian	Southwest	1.95
Green	Indian	Southwest	1.03	Hawksbill	Pacific	East	1.91
Green	Indian	Southeast	1.06	Hawksbill	Atlantic	East	1.90
Green	Pacific	South Central	1.12	Hawksbill	Pacific	North Central	1.88
Green	Pacific	West Pacific	1.18	Hawksbill	Atlantic	Southwest	1.85
Green	Pacific	West Central	1.18	Olive Ridley	Indian	West	1.96
Green	Atlantic	Southwest	1.21	Olive Ridley	Indian	Northeast (arribadas)	1.87
Leatherback	Atlantic	Northwest	0.89	Kemps Ridley	Atlantic	Northwest	1.84
Leatherback	Atlantic	Southeast	1.19				
Hawksbill	Pacific	Southwest	0.98				
Hawksbill	Indian	Southwest	1.10				
Hawksbill	Indian	Northwest	1.13				
Hawksbill	Indian	Southeast	1.15				
Hawksbill	Atlantic	West	1.23				
Olive Ridley	Pacific	East (arribadas)	1.07				
Olive Ridley	Atlantic	East	1.20				

RI = Resilience Index

rookeries (Wallace *et al.*, 2011). The other two RMUs, loggerheads in the North Pacific Ocean and olive ridleys in the West Indian Ocean, present ‘medium’ values of rookery vulnerability (Wallace *et al.*, 2011).

Our expert panel also perceived non climate-related threats to be a key factor influencing marine turtle resilience to climate change. This follows the rationale that a vulnerable and depleted population will be less likely to absorb disturbance. The main nonclimate-related threats to the RMUs least resilient to climate change (Table 2) include fishery bycatch and coastal development, where 53.8% and 38.5% of the least resilient RMUs experience high levels of fisheries bycatch and coastal development, respectively (Wallace *et al.*, 2011).

Our assessment allowed us to identify the top 13 marine turtle RMUs that are predicted to be the least resilient to climate change, which encompassed six of the world’s seven species and all three major ocean basins. Six out of the 13 least resilient RMUs to climate change (olive ridley, West Indian Ocean and Northeast Indian Ocean; loggerhead, Northeast Indian Ocean and North Pacific Ocean; and hawksbill, East Atlantic Ocean and East Pacific Ocean) were also identified within the world’s 11 most endangered RMUs (as per Wallace *et al.*, 2011). A common pattern among these six RMUs is the high threat level from fisheries bycatch (Wallace *et al.*, 2011). This highlights the urgent need to reduce threats and enhance monitoring of those RMUs for which crucial data on fisheries impact are lacking, to obtain valuable information about their population demography and an understanding of current and future threats. Further insights into the vulnerability of nesting grounds to climate change will require a better understanding of the threat that climate change poses to each RMU. Unfortunately, limited information exists on threats of climate change to RMUs; Wallace *et al.* (2011) reported that 66% of RMUs were scored as data deficient in terms of climate change threats. Indeed, of the 13 least resilient RMUs, only four had sufficient information to obtain climate change threat scores in that study, and of those, one RMU presents high threat from climate change (hawksbill, Southwest Atlantic Ocean), two RMUs were assigned medium threat level (loggerhead, North Central Pacific Ocean and Kemp’s ridley, Northwest Atlantic Ocean) and the other RMU (leatherback, Southwest Indian Ocean) has a low level threat from climate change (after Wallace *et al.*, 2011). This lack of information and/or agreement between study results clearly highlights the need to enhance investigation of the potential impact of climate change on marine turtles, which will improve our understanding of marine turtle vulnerability to climate change and help improve future conservation status assessments (Hamann *et al.*, 2010).

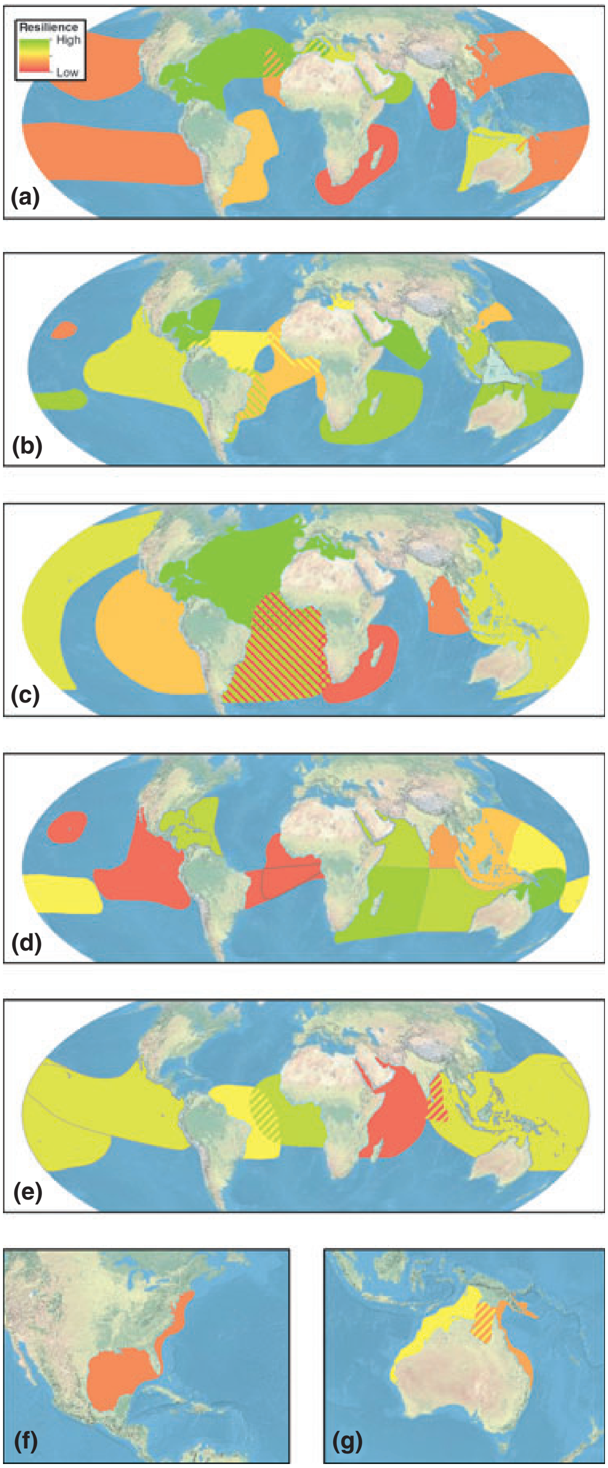

Fig. 1 Resilience for each marine turtle regional management unit (RMU) by species. (a) loggerheads (*Caretta caretta*), (b) green turtles (*Chelonia mydas*), (c) leatherbacks (*Dermochelys coriacea*), (d) hawksbills (*Eretmochelys imbricata*), (e) olive ridleys (*Lepidochelys olivacea*), (f) Kemp's ridleys (*Lepidochelys kempii*), and (g) flatbacks (*Natator depressus*).

Our results provide important insights into the relative resilience of marine turtle RMUs. However, this should be interpreted with caution because our results are constrained by the perception of experts at the time of our survey (Fuentes & Cinner, 2010), the data and expertise bias toward some RMUs with little information gathered from others (which reflects the overall global bias of sea turtle research; for further information on data availability for each RMU see the Supporting Information in Wallace *et al.* (2011) and for information on variation in expert response for this study see the provided Supplementary Information S2), and the low response rates that we obtained relative to other studies [$n = 33$ respondents to our survey, a 15% response rate, as compared to an average response rate of 36.0% ± 15.6% for other online surveys; (Cook *et al.*, 2000)]. Respondents indicated that they have worked in all RMUs; however, some RMUs were represented by the experience of only a single respondent (Supplementary Table S2), which could result in biased information for those RMUs. Therefore, future surveys should target experts involved with underrepresented RMUs. Similarly, it will also be important to revisit future responses and consequent results, as more information on resilience and climate change threats become available.

Data deficiencies presented a challenge to calculation of the Resilience Index. As a result of the lack of information on both recent- and long-term nesting population trends for several RMUs, as discussed in the Methods sections we did not incorporate these variables into the overall resilience scores. Similarly, the green turtle Northeast Indian Ocean RMU was not included in our analysis because only very limited information exists for this RMU (Wallace *et al.*, 2011). As more information becomes available on these variables in the future, we can easily incorporate those data into our model, which will improve the reliability of our results.

Despite the caution necessary to interpret our results, our methodology provides a tool to begin exploring the relative resilience of marine turtle RMUs to climate change, which is a topic rarely addressed. 'Resilience' has become a common objective of climate change adaptation (Heller & Zavaleta, 2009; Morecroft, 2012). However, to effectively increase resilience it is necessary to understand the factors that influence the ability of an ecosystem or species to maintain key functions and processes. This will allow efforts to be prioritized and the most efficient and effective way to increase resilience to be determined (Morecroft, 2012). Thus, our study sheds light on the topic of resilience in globally distributed taxa and highlights the need for metrics that attempt to measure or estimate resilience. Future studies should investigate other potential variables (e.g., primary and secondary sex ratios, survival rates, responses to changes in food availability, physiological plasticity, etc.) that can also influence the resilience of marine turtles RMUs to climate change.

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References

Baker JD, Littnan CL, Johnston DW (2006) Potential effects of se level rise on the terrestrial habitats of endangered and endemic megafauna on the northwestern hawaiian islands. *Endangered Species Research*, **4**, 1–10.

Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. *Ecology Letters*, **15**, 365–377.

Carpenter S, Walker B, Anderies JM, Abel N (2001) From metaphor to measurement: resilience of what to what? *Ecosystems*, **4**, 765–781.

Chambers LE, Hughes L, Weston MA (2005) Climate change and its impact on australia's avifauna. *Emu*, **105**, 1–20.

Cook C, Heath F, Thompson RL (2000) A meta-analysis of response rates in web- or internet-based surveys. *Educational and Psychological Measurement*, **60**, 821–836.

Donlan CJ, Wingfield DK, Crowder LB, Wilcox C (2010) Using expert opinion surveys to rank threats to endangered species: a case study with sea turtles. *Conservation Biology*, **24**, 1586–1595.

Elmqvist T, Folke C, Nyström M, Peterson G, Bengtsson J, Walker B, Norberg J (2003) Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment*, **1**, 488–494.

Fish MR, Cote IM, Gill JA, Jones AP, Renshoff S, Watkinson AR (2005) Predicting the impact of sea-level rise on caribbean sea turtle nesting habitat. *Conservation Biology*, **19**, 482–491.

Folke C, Carpenter S, Elmqvist T, Gunderson L, Holling CS, Walker B (2002) Resilience and sustainable development: building adaptive capacity in a world of transformations. *AMBIO: A Journal of the Human Environment*, **31**, 437–440.

Folke C, Carpenter S, Walker B, Scheffer M, Elmqvist T, Gunderson L, Holling CS (2004) Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics*, **35**, 557–581.

Fossette S, Schofield G, Lilley MKS, Gleiss AC, Hays GC (2012) Acceleration data reveal the energy management strategy of a marine ectotherm during reproduction. *Functional Ecology*, **26**, 324–333.

Fuentes MMPB, Cinner JE (2010) Using expert opinion to prioritize impacts of climate change on sea turtles' nesting grounds. *Journal of Environmental Management*, **91**, 2511–2518.

Fuentes MMPB, Maynard JA, Guinea M, Bell IP, Werdell PJ, Hamann M (2009) Proxy indicators of sand temperature help project impacts of global warming on sea turtles in northern australia. *Endangered Species Research*, **9**, 33–40.

Fuentes MMPB, Limpus CJ, Hamann M, Dawson J (2010) Potential impacts of projected sea-level rise on sea turtle rookeries. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **20**, 132–139.

Fuentes MMPB, Bateman BL, Hamann M (2011a) Relationship between tropical cyclones and the distribution of sea turtle nesting grounds. *Journal of Biogeography*, **38**, 1886–1896.

Fuentes MMPB, Limpus CJ, Hamann M (2011b) Vulnerability of sea turtle nesting grounds to climate change. *Global Change Biology*, **17**, 140–153.

Fuentes MMPB, Fish M, Maynard J (2012) Management strategies to mitigate the impacts of climate change on sea turtle's terrestrial reproductive phase. *Mitigation and Adaptation Strategies for Global Change*, **17**, 51–63.

Gitay H, Suarez A, Watson R, Dj D (2002) *Climate change and biodiversity. Intergovernmental panel on climate change IPCC Technical Paper V*. Cambridge University Press, Cambridge/New York.

Halpern BS, Selkoe KA, Micheli F, Kappel CV (2007) Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats. *Conservation Biology*, **21**, 1301–1315.

Hamann M, Limpus CJ, Read MA (2007) Vulnerability of marine reptiles in the great barrier reef to climate change. In: *Climate change and the great barrier reef: a vulnerability assessment*, (eds Johnson J, Marshall P), pp. 466–496. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia.

Hamann M, Godfrey M, Seminoff J *et al*. (2010) Global research priorities for sea turtles: informing management and conservation in the 21st century. *Endangered Species Research*, **11**, 245–269.

Hamann M, Grech A, Wolanski E, Lambrechts J (2011) Modelling the fate of marine turtle hatchlings. *Ecological Modelling*, **222**, 1515–1521.

Hannah L, Midgley GF, Lovejoy T *et al*. (2002) Conservation of biodiversity in a changing climate. *Conservation Biology*, **16**, 264–268.

Hawkes LA, Broderick AC, Godfrey MH, Godley BJ (2007) Investigating the potential impacts of climate change on a marine turtle population. *Global Change Biology*, **13**, 923–932.

Hawkes LA, Broderick AC, Godfrey MH, Godley BJ (2009) Climate change and marine turtles. *Endangered Species Research*, **7**, 137–154.

Hays GC, Broderick AC, Glen F, Godley BJ (2003) Climate change and sea turtles: a 150-year reconstruction of incubation temperatures at a major marine turtle rookery. *Global Change Biology*, **9**, 642–646.

Heller NE, Zavaleta ES (2009) Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological Conservation*, **142**, 14–32.

Holling CS (1973) Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, **4**, 1–23.

Isaac JL, Vanderwal J, Johnson CN, Williams SE (2009) Resistance and resilience: quantifying relative extinction risk in a diverse assemblage of australian tropical rainforest vertebrates. *Diversity and Distributions*, **15**, 280–288.

Johannes RE, Macfarlane JW (1991) *Traditional fishing in the torres strait islands*. CSIRO Division of Fisheries, Hobart, Australia, 268 pp

Katselidis KA, Schofield G, Stamou G, Dimopoulos P, Pantis JD (2012) Females first? Past, present and future variability in offspring sex ratio at a temperate sea turtle breeding area. *Animal Conservation*, **15**, 508–518.

Lutcavage M, Plotkin P, Witherington B, Lutz P (1996) Human impacts on sea turtle survival. In: *The biology of sea turtles*, (eds Lutz P, Musick J), pp. 387–409. CRC Press, Boca Raton, FL.

Maclean IMD, Wilson RJ (2011) Recent ecological responses to climate change support predictions of high extinction risk. *Proceedings of the National Academy of Sciences*, **108**, 12337–12342.

Mast RB, Hutchinson BJ, Howgate E, Pilcher NJ (2005) Iucn/ssc marine turtle specialist group hosts the second burning issues assessment workshop. *Marine Turtle Newsletter*, **110**, 13–15.

Mawdsley JR, O'malley R, Ojima DS (2009) A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. *Conservation Biology*, **23**, 1080–1089.

Mcclanahan TR, Cinner JE, Maina J *et al*. (2008) Conservation action in a changing climate. *Conservation Letters*, **1**, 53–59.

Mcmahon CR, Hays GC (2006) Thermal niche, large-scale movements and implications of climate change for a critically endangered marine vertebrate. *Global Change Biology*, **12**, 1330–1338.

Moore SE, Huntington HP (2008) Artic marine mammals and climate change: impacts and resilience. *Ecological Applications*, **18**, S157–S165.

Moran K, Bjorndal KA (2005) Simulated green turtle grazing affects structure and productivity of seagrass pastures. *Marine Ecology Progress Series*, **305**, 235–247.

Moran K, Bjorndal KA (2007) Simulated green turtle grazing affects nutrient composition of the seagrass *thalassia testudinum*. *Marine Biology*, **150**, 1083–1092.

Morecroft MD (2012) Adapting conservation to a changing climate. *Journal of Applied Ecology*, **49**, 546–546.

Nyström M, Folke C (2001) Spatial resilience of coral reefs. *Ecosystems*, **4**, 406–417.

Peterson G, De Leo GA, Hellmann JJ *et al*. (1997) Uncertainty, climate change, and adaptive management. *Conservation Ecology*, **1**, 4.

Peterson G, Allen CR, Holling CS (1998) Ecological resilience, biodiversity, and scale. *Ecosystems*, **1**, 6–18.

Pike DA (2013) Climate influences the global distribution of sea turtle nesting. *Global Ecology and Biogeography*, doi:10.1111/geb.12025.

Pike DA, Stiner JC (2007) Sea turtles species vary their susceptibility to tropical cyclones. *Oecologia*, **153**, 1432–1939.

Pike DA, Antworth RL, Stiner JC (2006) Earlier nesting contributes to shorter nesting seasons for the loggerhead seaturtle, caretta caretta. *Journal of Herpetology*, **40**, 91–94.

Poloczanska ES, Babcock RC, Butler A *et al.* (2007) Climate change and australian marine life. *Oceanography and Marine Biology*, **45**, 407–478.

Purvis A, Gittleman JL, Cowlishaw G, Mace GM (2000) Predicting extinction risk in declining species. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, **267**, 1947–1952.

Root T, Price J, Schneider S, Rosenzweig C, Pounds J (2003) Fingerprints of global warming on wild animals and plants. *Nature*, **421**, 57–60.

Saaty T (1980) *The analytic hierarchy process*. T. McGraw-Hill, New York.

Sala OE, Chapin FS, Armesto JJ *et al.* (2000) Global biodiversity scenarios for the year 2100. *Science*, **287**, 1770–1774.

Schofield G, Bishop CM, Katselidis KA, Dimopoulos P, Pantis JD, Hays GC (2009) Microhabitat selection by sea turtles in a dynamic thermal marine environment. *Journal of Animal Ecology*, **78**, 14–21.

Sgrò CM, Lowe AJ, Hoffmann AA (2011) Building evolutionary resilience for conserving biodiversity under climate change. *Evolutionary Applications*, **4**, 326–337.

Van Houtan KS, Halley JM (2011) Long-term climate forcing in loggerhead sea turtle nesting. *PLoS ONE*, **6**, e19043.

Wallace BP, Dimatteo AD, Hurley BJ *et al.* (2010) Regional management units for marine turtles: a novel framework for prioritizing conservation and research across multiple scales. *PLoS ONE*, **5**, e15465.

Wallace BP, Dimatteo AD, Bolten AB *et al.* (2011) Global conservation priorities for marine turtles. *PLoS ONE*, **6**, e24510.

Walther G-R (2010) Community and ecosystem responses to recent climate change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365**, 2019–2024.

Walther GR, Prost E, Convey P *et al.* (2002) Ecological responses to recent climate change. *Nature*, **416**, 389–395.

Weishampel JF, Bagley DA, Ehrhart LM (2004) Earlier nesting by loggerhead sea turtles following sea surface warming. *Global Change Biology*, **10**, 1424–1427.

Weishampel J, Bagley D, Ehrhart L, Weishampe LA (2010) Nesting phenologies of two sympatric sea turtle species related to sea surface temperatures. *Endangered Species Research*, **12**, 41–47.

Wilson C, Tisdell C (2001) Sea turtles as a non-consumptive tourism resource especially in australia. *Tourism Management*, **22**, 279–288.

Witt MJ, Hawkes LA, Godfrey MH, Godley BJ, Broderick AC (2010) Predicting the impacts of climate change on a globally distributed species: the case of the loggerhead turtle. *The Journal of Experimental Biology*, **213**, 901–911.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Supporting Information S1: Survey undertaken with the IUCN-SSC Marine Turtle Specialist Group to obtain weight values for the Resilience Index criteria.
Supporting Information S2: Expertise of each of our survey respondents (n = 33).