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Supplementary Material:

S1. Management Unit Maps

S2. Management Unit results profiles and background narratives

S3. Exposure Maps from ESRL

S4. Vulnerability Score Summary Table

S5. Exposure Score Summary Table

S6. Sensitivity Score Summary Table

S7. Sensitivity Attribute Mean Scores Summarized by Species

D1. Dataset

Abstract

Climate change presents challenges to the conservation of sea turtle populations that are already experiencing multiple cumulative anthropogenic stressors including persistent stressors such as harvest, bycatch, and habitat destruction. To inform management and conservation decision-making, we applied a climate vulnerability assessment (CVA) using expert elicitation to provide a qualitative assessment of vulnerability, exposure, and sensitivity to climate change of 49 sea turtle management units (i.e., Regional Management Units and Distinct Population Segments). Eighteen sea turtle experts scored climate exposure (projected changes in climate and ocean conditions within the current population distribution compared with historical conditions) and climate sensitivity (using life history traits as proxies). Results indicate that all management units have either very high (88% of units) or high (12% of units) exposure to climate change, with the most influential factors across all regions being temperature, ocean acidification, dissolved oxygen, and sea level rise. Forty-three percent of the management units have very high sensitivity to climate change, 49% have high sensitivity, and 8% moderate sensitivity. Key factors for sensitivity included nest/egg sensitivity to temperature, in-water habitat specificity, abundance, and trend in population abundance, although primary drivers varied by species and region. The resulting climate vulnerability score was very high for 88% of the management units, high for 10%, and moderate for 2%. This assessment quantified the vulnerability of individual sea turtle management units to climate change, identified data gaps to help guide research, and established a baseline for comparison with future sea turtle assessment efforts.

Introduction

The seven extant species of sea turtles have been, and are expected to continue to be, affected by changing environmental conditions due to temperature-dependent sex determination, reliance on vulnerable beach habitat for nesting, and complex life history, among other considerations (Allen et al., 2015; Butler, 2019; Fuentes and Saba, 2016; Hamann et al., 2013; Hawkes et al., 2009; Jensen et al., 2018; Maurer et al., 2021; Patrício et al., 2021; Poloczanska et al., 2009; Simantiris, 2024). In the coastal and oceanic ecosystems where sea turtles live, physical and environmental conditions that support those systems are changing and are projected to continue to change (Cooley et al., 2022; Doney et al., 2012; Hoegh-Guldberg and Bruno, 2010; USGCRP, 2023; Weiskopf et al., 2020). Studies have projected and predicted the potential impacts of climate change on sea turtles, which include shifting nesting phenology and distribution (Almpanidou et al., 2016; Carreras et al., 2018; Fish et al., 2005; Fuentes et al., 2011, 2024; Monsinjon et al., 2019; Patel et al., 2016), declining abundance (Saba et al., 2012), altered reproductive strategies and success (Montero et al., 2018), shifted hatchling and foraging ground sex-ratios (Hawkes et al., 2007b, 2009; Jensen et al., 2018; Wyneken and Lolavar, 2015), changing foraging distribution and success (Patel et al., 2016; Willis-Norton et al., 2015), and increased cold-stunning (Griffin et al., 2019). Some sea turtle populations have already shown evidence of responding to changing climate conditions through observed changes in distribution (Hamann et al., 2007; Hays et al., 2001; Maffucci et al., 2016), nesting phenology (Lamont and Fujisaki, 2014; Neeman et al., 2015; Pike, 2009; Pike et al., 2006; Weishampel et al., 2004, 2010), sex ratio (Allen et al., 2015; Jensen et al., 2018), and reproductive rates (Stokes, 2014).

Sea turtles are protected under multiple international frameworks such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and the Inter-American Convention for the Protection and Conservation of Sea Turtles (IAC). Regular status reviews (e.g., abundance, trends, threats) are required under the International Union for Conservation of Nature (IUCN) Red List assessments (IUCN, 2016) and in the United States under the Endangered Species Act (ESA). The impacts of climate change are important to consider when assessing the effects of natural and anthropogenic stressors on population viability, especially under the ESA (McClure et al., 2013; NMFS, 2016). An improved understanding of sea turtle responses to changing climate and ocean conditions will help support climate-informed management and conservation efforts.

Approaches such as habitat suitability models (e.g., Butt et al., 2016), scenario planning (Borggaard et al., 2019, 2020; Catano et al., 2015; Haward et al., 2013), and climate vulnerability assessments (CVAs; Foden et al., 2018; Pacifici et al., 2015) characterize climate impacts on living marine resources. Typically, CVAs follow a framework that combines exposure, sensitivity, and adaptive capacity to identify populations that may be most vulnerable to climate change and highlight climate and non-climate factors contributing to their vulnerability (Foden and Young, 2016; Foden et al., 2018; Glick et al., 2011). CVAs can play an important role in planning for climate change impacts to species (Glick et al., 2011).

CVAs for living marine resources include fish (Chin et al., 2010; Foden et al., 2013; Hare et al., 2016; Johnson and Welch, 2010; Pecl et al., 2014), corals (Brainard et al., 2011), sea birds (de los Rios et al., 2018; Gardali et al., 2012; Pacifici et al., 2015), and marine mammals (Albouy et al., 2020; Laidre et al., 2008; Lettrich et al., 2019, 2023; Sousa et al., 2019). CVAs for sea turtles have focused on specific regions (e.g., Abella Perez et al., 2016; Fuentes et al., 2011; Hamann et al., 2007) or specific climate drivers (e.g., Fuentes et al., 2024; Patrício et al., 2018, 2021). Similar to CVAs, Fuentes et al. (2013) assessed the resilience of sea turtle populations by evaluating qualitative characteristics and non-climate threats, though exposure was not explicitly considered. To date, a global sea turtle CVA has not been completed for all species across a variety of climate drivers.

Here, we provide a qualitative assessment of potential climate-associated threats based upon assessments of sea turtle traits. We present a categorization of populations by climate vulnerability score, assess the confidence in those scores, and identify the sensitivity, adaptive capacity, and exposure factors driving climate vulnerability. Additionally, we present population-specific results and background information narratives. Recognizing that climate will continue to change and resulting impacts will manifest in various ways, this effort is intended to serve as a baseline to compare with similar future efforts to assess global sea turtle populations. Results can be used by managers and coordinating bodies to plan and implement conservation measures and promote robust management at regional and/or global scales.

Methods

Overview

We followed the approach outlined for the National Oceanic and Atmospheric Administration (NOAA) Fisheries Sea Turtle Climate Vulnerability Assessment (STCVA) methodology (Lettrich et al., 2020), adapted from the NOAA Fisheries Marine Fish and Invertebrate Climate Vulnerability Assessment (FCVA; Hare et al., 2016; Morrison et al., 2015) and the NOAA Fisheries Marine Mammal Climate Vulnerability Assessment (MMCVA; Lettrich et al., 2019, 2023). The STCVA is a modified Delphi approach (Linstone and Turoff, 1975) that uses expert elicitation and existing information to score two separate components: (1) exposure to climate change; and (2) combined adaptive capacity and sensitivity to climate change. We used prior syntheses of climate impacts on sea turtles (e.g., Hamann et al., 2007; Hawkes et al., 2009; Poloczanska et al., 2009) to establish elements of the two components of the assessment.

We conducted this assessment for the seven species of sea turtles: loggerhead (*Caretta caretta*), green turtle (*Chelonia mydas*), leatherback (*Dermochelys coriacea*), hawksbill (*Eretmochelys imbricata*), Kemp's ridley (*Lepidochelys kempii*), olive ridley (*Lepidochelys olivacea*), and flatback (*Natator depressus*). We assessed these species using 49 subunits (Table 1; Supp. Info. 1) — Regional Management Units defined in 2010 and modified in 2023 (RMUs; Wallace et al., 2010, 2023) and Distinct Population Segments (DPSs, defined under the ESA; US 50 CFR § 223.102, US 50 CFR § 224.101). Although RMUs and DPSs are delineated using different criteria and do not perfectly align, RMUs generally correlate to DPSs for most sea turtle species and the two designations can be roughly cross-walked (as indicated in Table 1). In cases where RMUs and DPSs overlap, we used DPSs. In 2023, after we completed our scoring and analysis, RMU definitions were updated (Wallace et al., 2023). Olive ridley RMUs were consolidated in both the East Pacific Ocean and North Indian Ocean, effectively combining the arribada (mass aggregations of turtles nesting at the same time and location) nesting RMU with the solitary nesting RMU in both regions. Our assessment was initially conducted using the original 2010 delineations, and reanalyzed following the 2023 RMU update to use the 2010 olive ridley East

Pacific and Indian Ocean arribada RMUs as representative of the updated 2023 olive ridley East Pacific and Northeast Indian RMUs and the 2010 olive ridley East Pacific and Northeast Indian RMUs were removed from the assessment (Wallace et al., 2010, 2023). The RMUs and DPSs assessed are hereafter referred to as "units". Our assessment considered the entire life cycle and included the entirety of the known geographic ranges of each unit. At least three experts scored each unit.

Expert Scorers

A total of 18 sea turtle experts scored units. These subject matter experts were highly familiar with multiple species and populations through laboratory, field, or other research experience. The ability of experts to score multiple units allowed for more robust comparisons across units. Expert scorers included staff from U.S. Federal agencies (i.e., NOAA Fisheries and U.S. Fish and Wildlife Service), U.S. and international academic institutions, and international non-governmental organizations. All expert scorers are co-authors, but not all co-authors served as expert scorers.

Scoring

Experts individually scored sensitivity attributes, exposure factors, and data quality of assigned units through a modified Delphi approach that included a preliminary scoring round, a discussion period, and a final scoring round (Linstone and Turoff, 1975). Each exposure factor and sensitivity attribute were scored individually by experts for a given unit by allocating five points across four scoring bins (Hare et al., 2016; Lettrich et al., 2020). Scoring bins were delineated by criteria specific to that factor or attribute (Tables 2 and 3). Prior to the assessment, we assembled information about each unit's life history attributes, distribution, and studies about the unit relating to climate change. This information was derived from a variety of sources, including population assessments (e.g., IUCN, ESA), peer-reviewed literature, and gray literature. We organized this information into background narratives (Supp. Info. 2), similar to other CVAs (e.g., Chin et al., 2010; Hare et al., 2016; Lettrich et al., 2023; Pecl et al., 2014). For poorly studied units, we considered related units' life history information.

During training webinars, we briefed expert scorers on the scoring process, scoring criteria, and potential sources of bias. We initiated the scoring process with the preliminary scoring round (February 2019 – April 2019). In May 2019, we held a full group webinar to discuss major trends in scoring, clarified questions about the scoring criteria, and provided guidance to ensure a consistent scoring process. Experts discussed scoring differences for each unit using Google Docs as a collaboration platform and revised and updated individual scores during the final scoring round (June 2019 – September 2019). Of the 49 sea turtle units scored, nine (18%) had three scorers, 30 (61%) had four scorers, and 10 (20%) had five scorers. The number of scorers varied by unit as a result of variations in the number of experts knowledgeable in a given unit. To provide consistency across regions, some experts were asked to score units in which they were familiar at the species-level or with the region and scored using a greater reliance on background literature.

Climate exposure was defined as the magnitude of climate change a unit is expected to experience at mid-century (defined by projections within the 2006–2055 period) relative to recent historical conditions (1956–2005 period) within its current distribution (Hare et al., 2016; Lettrich et al., 2020, 2023; Solomon et al., 2011). Projections for the year 2055 provided a timeframe that captured climate trends and decadal variability during the 2006–2055 period, but were still near-term enough to inform management actions (Hare et al., 2016; Lettrich et al., 2019, 2020; Solomon et al., 2011). Climate exposure was scored using eight exposure factors, consisting of abiotic factors expected to affect sea turtles, their prey, and/or their habitat (Table 2; Lettrich et al., 2020). Sea turtle distributions at-sea have been correlated with sea surface temperature (SST; e.g., Hawkes et al., 2007a; McMahon and Hays, 2006; Polovina et al., 2004) and prey abundance and distribution have been shown to track SST (Pinsky et al., 2013; Schuetz et al., 2018). Water temperature has been shown to affect physiological processes and has implications for survival at both warm and cold extremes (Bjorndal et al., 2017; Griffin et al., 2019; Schwartz, 1978; Witherington and Ehrhart, 1989). Near-surface air temperature (hereafter "air temperature") has been shown to have physiological impacts on sea turtles (Dudley et al., 2016; Sato, 2014), particularly when nesting or basking (Swimmer, 1997; Whittow and Balazs, 1982). Air temperature has been correlated with sand temperature, which affects the viability, sex ratio, and survival of sea turtle nests and eggs (Esteban et al., 2016; Hays et al., 2003; Jensen et al., 2018; Laloë et al., 2014). Precipitation has been shown to be a mediating factor in nest temperature (e.g., Lolavar and Wyneken 2015, Wyneken and Lolavar 2015) and also serves as a delivery mechanism for pollutants. Other exposure factors, like pH and dissolved oxygen, have not been documented directly affecting sea turtle physiology, but both have been shown to impact habitats (e.g., coral reefs) as well as prey and forage (Craig et al., 2001; Fabry et al., 2008; Fuentes et al., 2010a; Langdon and Atkinson, 2005). Sea level rise is expected to reduce available nesting habitat (Dimitriadis et al., 2022; Fish et al., 2005; Fuentes et al., 2010a, b; Pike et al., 2015; Rivas et al., 2023; Sönmez et al., 2021; Veelenturf et al., 2020). Studies have shown circulation to affect multiple life stages, with much of the focus on the Gulf Stream and the western Atlantic (e.g., Arendt et al., 2023; Putman et al., 2013). While circulation has been shown to contribute to dispersal (Briscoe et al., 2016; Chambault, 2017; Hays et al., 2010; Mansfield and Putman, 2013; Putman et al., 2010, 2012, 2013), migration (Luschi et al., 2003; Wolanski, 2017), recruitment (Ascani et al., 2016), and prey aggregation (Chivers et al., 2017; Hays et al., 2005; Scales et al. 2014, 2015), questions remain about how changes in the direction, magnitude, and presence of different circulation patterns may affect sea turtle populations in the future.

Future climate projections were based on the representative concentration pathway (RCP) 8.5, which assumes the fewest greenhouse gas mitigation measures will be implemented (Moss et al., 2010; Riahi et al., 2011; van Vuuren et al., 2011). RCP 8.5 was used to maximize utility for management as, for example, using RCP 8.5 was the benchmark scenario in the USA under NOAA Fisheries policy guidance for considering the treatment of climate change in ESA actions at the time of the assessment (NMFS, 2016) and used in several other NOAA Fisheries CVAs (e.g., Crozier et al., 2019; Farr et al., 2021; Hare et al., 2016; Lettrich et al., 2023). RCP 8.5 was initially considered a "business-as-usual" emission scenario, but has recently been considered more implausible at the 2100 timeframe (Burgess et al., 2023; Hausfather and Peters 2020a, b; Pielke et al. 2022). However, the climate impacts from the RCP 8.5 scenario remain plausible at the mid-century time frame assessed in this study (Hansen et al., 2023; Schwalm et al., 2020).

Six of the exposure factors (SST, air temperature, precipitation, salinity, ocean acidification, and dissolved oxygen) were obtained from the NOAA Climate Change Web Portal (Scott et al., 2016) and scored using two metrics: projected change in mean (calculated as standard anomaly; difference between future and recent historical mean divided by recent historical standard deviation) and projected change in variability (calculated as an F-ratio; future variance divided by recent historical variance; Supp. Info. 3).

Using range maps of each unit and projected exposure maps for each factor, experts scored each exposure factor by placing five points across four exposure scoring bins according to the magnitude of exposure projected across the entirety of the unit's current distribution (Lettrich et al., 2020). Experts considered variable spatial density and habitat use patterns across the distribution when scoring exposure. Sea level rise and circulation projections were not available through the NOAA Climate Change Web Portal and were scored using separate criteria described below.

Sea level rise was scored using projected relative sea level change by the year 2060 (Jackson and Jevrejeva, 2016; Sweet et al., 2017), which was the nearest available timeframe to the 2055 timeframe used for the other exposure factors. Bin breaks were established by approximating rates of relative sea level rise that correlated to varying amounts of habitat loss across multiple studies (e.g., Baker et al., 2006; Daniels et al., 1993; Fish et al., 2005, 2008; Fuentes et al. 2010b; Garcia et al., 2015; Reece et al., 2013). Circulation was scored qualitatively by evaluating the types of circulation (e.g., wind-driven, tidal) with which the unit interacts. Experts overlaid knowledge of local projections for each of the units they scored.

We defined sensitivity as the degree to which a unit is likely to be affected by climate-driven changes in environmental conditions to which it is exposed and adaptive capacity as the ability of a unit to modify intrinsic characteristics (e.g., behavior, physiology, habitat use) to cope with climate-driven changes in environmental conditions (Glick et al., 2011; Hare et al., 2016; Lettrich et al., 2020, 2023). Because sensitivity and adaptive capacity exist along a similar spectrum, we considered them in a single component (Hare et al., 2016; Lettrich et al., 2020, 2023; Williams et al., 2008), hereafter referred to as the "sensitivity component," with the attributes within it referred to as "sensitivity attributes." For example, we considered habitat specificity a sensitivity attribute, with greater specificity correlating to greater sensitivity. Fourteen sensitivity attributes and scoring criteria were identified prior to the assessment (Table 3; Lettrich et al., 2020).

Sensitivity attributes included elements of foraging ecology, habitat use, reproduction, and cumulative non-climate stressors. Prey/diet specificity and habitat specificity were selected as generalists, which are considered to be resilient and adaptive to changes in prey and habitat (Beever et al., 2016; Clavel and Julliard, 2011; Young et al., 2015) and the underlying vulnerability to climate change of that prey and habitat (e.g., Chin et al., 2010; Farr et al., 2021; Okey et al., 2015). Elements of nesting ecology (beach type, geographic extent, site fidelity, nesting season length) were selected to assess sensitivity to changes in the beach and nearshore environments (Fuentes et al., 2011; Hawkes et al., 2009; Pike and Stiner, 2007; Poloczanska et al., 2009; Witt et al., 2010). The lifetime reproductive potential, population abundance, and trend in population abundance attributes were included to capture replacement potential and recruitment, and serve as a proxy for genetic adaptation (Hagger et al. 2013; Morrison et al., 2015; Purvis et al., 2000; ZSL 2010). Physiological sensitivity to temperatures is an important consideration across life stages. Temperature plays a major role in the sex-ratio of sea turtle eggs through temperature-dependent sex determination (Ackerman, 1997; Hawkes et al., 2009; Mrosovsky, 1994). Having many nests consistently cooler or consistently warmer than a central pivotal temperature (the temperature at which the number of eggs resulting in female hatchlings is equal to the number of eggs resulting in male hatchlings [Mrosovsky and Pieau 1991]) can have lasting impacts on the population structure and viability of the population (Jensen et al., 2018; Saba et al., 2012; Santidrián Tomillo et al., 2014). Meanwhile, adults may be affected by temperature while nesting, foraging, and basking (Dudley et al., 2016; Hayden and Harrison, 2007; Madrak et al., 2016). Elements of spatial ecology (migration and home range) were selected to assess potential to find and utilize additional habitat (Witt et al., 2010; ZSL 2010). Units that experience stress from non-climate sources likely have reduced fitness and therefore reduced capacity to cope with and adapt to climate change (Fuentes et al., 2013, 2020; Morrison et al., 2015). The pressure a particular stressor places on a unit depends on the intensity, duration, and frequency of the stressor and the adaptive capacity of the unit (Klein et al., 2017; Milton and Lutz, 2003). We did not attempt to project the future magnitude of non-climate stressors but note that responses to climate change from other sectors and actors will be dynamic and likely difficult to predict in space and time.

Experts scored the data quality of each attribute and factor using the approach outlined by Hare et al. (2016; Table 4). Exposure factor data quality was scored based on the underlying data used to establish the unit's geographic range. Well documented geographic ranges were scored as "high" while geographic ranges based on few or older studies were scored "low." Uncertainty associated with model projections was characterized within the portal (Hare et al., 2016; Scott et al., 2016) and the climate data were considered to be high quality for the purposes of the assessment. Sensitivity attributes described in recent, published studies were scored "high" while sensitivity attributes described in older studies or studies from related units were scored "low."

Analyses

To calculate vulnerability scores for each unit, we followed a process similar to Hare et al. (2016) and outlined by Lettrich et al. (2020). First, we calculated attribute and factor mean scores for each exposure factor and sensitivity attribute using the scores from all experts for each unit/attribute combination and the following equation:

$$Factor\ or\ Attribute\ Weighted\ Mean = \frac{((B_1 * 1) + (B_2 * 2) + (B_3 * 3) + (B_4 * 4))}{(B_1 + B_2 + B_3 + B_4)}$$

where B_1–B_4 are the number of points within each bin and the multipliers in the numerator are the weighting value for each bin. For the climate exposure factors that included both change in variability and change in mean (i.e., all factors except circulation and sea level rise), we used the greater of the two calculated factor weighted means as the score for that factor. For example, if the weighted mean score for change in mean SST conditions was 3.0 and the weighted mean score for change in variability of SST was 2.5, we used 3.0 as the score for SST.

We determined exposure and sensitivity component scores using a logic model (Hare et al., 2016; Table 5). The logic model allowed us to avoid discounting situations in which most factors or attributes scored low, but a few factors or attributes scored high and would have a disproportionate effect on the unit's exposure or sensitivity (Lettrich et al., 2020). For example, if SST and air temperature both scored 3.0 ("high") and all other factors scored less than 3.0 ("moderate" or "low"), the exposure component score would be 3 ("high"; Table 5).

We determined overall vulnerability for a unit by multiplying exposure component scores and sensitivity component scores to generate a vulnerability score using a cross-referenced vulnerability matrix derived from Hare et al. (2016). For a full scoring example, see Appendix C in Lettrich et al. (2020).

To estimate the certainty of the climate vulnerability scores, we conducted a bootstrap analysis using R (R Core Team, 2022) by sampling with replacement the points of all experts for each sensitivity attribute and each exposure factor for each unit. We recalculated the sensitivity score, exposure score, and vulnerability score for each of 10,000 iterations and reported certainty as the proportion of those 10,000 iterations that scored in each bin.

Abundance, Distribution, and Phenology Responses

We used subsets of sensitivity attributes to assess a unit's potential response in abundance, geographic distribution, and/or phenology (Table 6; see Appendix B in Lettrich et al., 2020). Some attributes were factored into all three response category scores, while other attributes were factored into only one or two response category scores. Response scores (abundance, distribution, phenology) were calculated using the same logic model used for the sensitivity component. The three response categories were calculated independently of one another and were supplemental to the sensitivity component score.

Attribute and Expert Effect on Scores: Leave-One-Out Analysis

To determine the influence of each exposure factor or sensitivity attribute we calculated exposure, sensitivity and vulnerability scores for each unit by sequentially omitting each exposure factor and sensitivity attribute, and then recalculating scores. We examined changes in exposure score, sensitivity score, and vulnerability score that resulted from omitting each exposure factor and sensitivity attribute. We conducted a similar leave-one-out analysis to determine the influence of each scorer by sequentially removing the scores of each scorer and recalculating exposure, sensitivity, and vulnerability scores.

Results

Overall Vulnerability

Of the 49 sea turtle units, 43 (88%) scored very high vulnerability to climate change, five (10%) high vulnerability, and one (2%) moderate vulnerability (Fig. 1, Fig. 2, Supp. Info. 4). The majority of units (n = 46, 94%) scored very high exposure while three (6%) scored high exposure (Fig. 1, Fig. 2, Supp. Info. 4). Twenty-one (43%) units scored very high sensitivity, 24 (49%) high sensitivity, and four (8%) moderate sensitivity (Fig. 1, Fig. 2, Supp. Info. 4).

Exposure Factors

Dissolved oxygen (change in mean), ocean pH (change in mean), air temperature (change in mean), and SST (change in mean) had the highest median weighted average scores with 4.00, 3.95, 3.95, and 3.85, respectively, while air temperature (change in variability) had the lowest median weighted average scores (1.00) (Fig. 7). Generally, change in mean condition had greater influence on exposure component scores than change in variability (Supp. Info. 5). Leave-one-out sensitivity analysis indicated that air temperature (change in mean) had the greatest ability to shift vulnerability scores (Fig. 8), and omitting it would have shifted four units (flatback Southwest Pacific RMU, green turtle South Pacific DPS, Kemp's ridley Northwest Atlantic RMU, and olive ridley West Pacific RMU) to a lower vulnerability score. Removing dissolved oxygen (change in mean) or ocean pH (change in mean) would have each resulted in three units shifting to a lower vulnerability score (flatback Southwest Pacific RMU, green turtle South Pacific DPS, and olive ridley West Pacific RMU for dissolved oxygen and Kemp's ridley Northwest Atlantic RMU, and olive ridley West Pacific RMU for ocean pH).

Sensitivity Attributes

Nest/egg sensitivity to temperature had the highest median weighted average score (3.45) among the populations while migration had the lowest median weighted average score (1.64; Fig. 9). Scores within attributes were more variable among units for most sensitivity attributes compared to exposure factors (Fig. 7, Fig. 9, Supp. Info. 6). Nest/egg sensitivity to temperature was the only attribute with median weighted average scores greater than 3.0 when grouped by species (Supp. Info. 7). Some attributes showed high within-species variability (e.g., population abundance and trend in population abundance) while others showed high between-species variability (e.g., foraging home range and prey/diet specificity; Supp. Info. 7). A leave-one-out sensitivity analysis showed that nest/egg sensitivity to temperature had the greatest tendency to shift vulnerability scores (Fig. 11). Without the nest/egg sensitivity to temperature attribute, three units (flatback Southeast Indian RMU, green turtle East Pacific DPS, and green turtle South Atlantic DPS) would have shifted to a lower vulnerability score. Two units each would have moved to a lower vulnerability score by removing cumulative stressors (flatback Southeast Indian RMU and green turtle East Pacific DPS), geographic extent of nesting (loggerhead North Indian DPS and loggerhead Northeast Atlantic DPS), or nesting site fidelity (green turtle South Atlantic DPS and loggerhead Northeast Atlantic DPS). Removing the trend in population abundance attribute would have resulted in one unit (loggerhead North Indian DPS) shifting to a lower vulnerability score.

Species-specific Vulnerability

Green turtle, loggerhead, and olive ridley turtles were the only species with units that scored less than very high vulnerability (Fig. 3, Fig. 4, Fig 5). For green turtles, the East Pacific DPS and North Atlantic DPS scored high vulnerability. For loggerhead turtles, the Northwest Atlantic DPS and Southwest Indian DPS scored high vulnerability. For olive ridley turtles, the East Atlantic RMU scored high vulnerability, and the modified East Pacific RMU which includes arribada and individual nesting scored moderate vulnerability. Only three units scored below very high exposure: the green turtle East Pacific DPS and North Atlantic DPS and the modified East Pacific RMU scored high exposure (Fig. 5). All leatherback units scored very high sensitivity while other multi-unit species showed a variety of sensitivity scores (Fig. 5).

Regional Vulnerability

The Pacific Ocean was the only basin with units that scored moderate vulnerability to climate change (olive ridley modified East Pacific RMU). The majority of units in each basin scored very high vulnerability to climate change — 11 (79%) in the Atlantic Ocean, 15 (93%) in the Indian Ocean, two (100%) in the Mediterranean Sea, and 16 (89%) in the Pacific Ocean (Fig. 4, Fig. 6).

Distribution, Abundance and Phenology

Sixteen units (33%) were characterized as having a very high potential to decline in abundance, 26 (53%) as high, and seven (14%) as moderate. One unit (2%) was characterized as having a very high potential to shift phenology, 17 (35%) as high, 17 (35%) as moderate, and 14 (29%) as low. Seventeen units (35%) were characterized as having a very high potential to shift distribution, 25 (51%) as high, and seven (14%) as moderate (Table 6).

Assessment Performance

Data Quality

In total, 34 (69%) units had high data quality as indicated by 80% or more of sensitivity attributes with a data quality score of two or higher, 12 (24%) units had moderate data quality as indicated by 50–79% of sensitivity attributes with a score of two or higher, three (6%) units had poor data quality as indicated by fewer than 50% of sensitivity attributes with a score of two or higher (Supp. Info. 2). Across all units, SST (change in variability), SST (change in mean), ocean pH (change in mean), air temperature (change in variability), and air temperature (change in mean) factors had the highest median data quality while the circulation factor had the lowest median data quality score (Fig. 12). The geographic extent of nesting, abundance, length of nesting season, and adult physiological sensitivity to temperature attributes had the highest median data quality score while the lifetime reproductive potential, nest/egg sensitivity to temperature, and nesting site fidelity attributes had the lowest data quality (Fig. 13).

Bootstrap Analysis

Bootstrap analysis showed that 39 (80%) units scored ≥ 90% certainty, seven (14%) had certainty scores 66–89% and three (6%) had certainty scores < 66%. The original vulnerability score matched the score with the greatest proportion of iterations in all units. All units maintained the same vulnerability score in the bootstrap analysis relative to their initial score. Sensitivity scores changed from high to very high in the bootstrap analysis for two units (hawksbill Southeast Indian RMU and loggerhead Southeast Indian DPS).

Exposure scores remained consistent through bootstrap analysis. Bootstrapped exposure scores matched exposure scores calculated directly from expert scores for all units, suggesting exposure scores calculated directly from expert scores sufficiently accounted for expert variability. In the western North Atlantic, bootstrap simulations showed lower consistency for leatherback Northwest Atlantic RMU (38% high; 62% very high) than green turtle North Atlantic DPS (96% high; 4% very high), loggerhead Northwest Atlantic DPS (6% high; 94% very high), and Kemp's ridley Northwest Atlantic DPS (5% high; 95% very high). The extended range of the green turtle North Atlantic DPS and leatherback Northwest Atlantic RMU relative to the loggerhead Northwest Atlantic DPS and Kemp's ridley Northwest Atlantic RMU was a contributing factor to the differences in score and consistency. In the eastern Pacific, hawksbill East Pacific RMU (100% very high) and leatherback East Pacific RMU (7% high; 93% very high) both showed high consistency between bootstrap and calculated scores. Similar to the western North Atlantic, differences in exposure scores and bootstrap consistency were likely affected by overall unit range.

Expert Effect

The combination of units and scoring assignments set up 197 scenarios for expert leave-one-out analysis. The effect of removing an individual expert's scores resulted in no change in vulnerability score in 94% (n=185) of scenarios and a change in vulnerability score of one category (i.e., moving to an adjacent category) in 6% (n=12) of cases. Six leave-one-expert-out scenarios resulted in a decrease in vulnerability category and six scenarios resulted in an increase in vulnerability category. Thus we concluded that the makeup of the pool of experts for each unit had negligible effect on our overall results and included all experts in our analysis.

Discussion

This assessment shows that most sea turtle units assessed are considered to be highly or very highly vulnerable to climate change. Almost all units scored as very highly exposed to climate change, with similar drivers of exposure. Most units scored as highly or very highly sensitive to climate change, with different drivers of sensitivity among different species and units. Relative to CVAs conducted for other taxonomic groups (e.g., Brainard et al., 2011; Hare et al. 2016; Lettrich et al., 2023), a large proportion of units in this assessment scored very high vulnerability to climate change, which underscores the need to examine scores at the unit level to understand and compare the underlying drivers of vulnerability. Individual unit results and background information narratives are presented in Supplementary Information (Supp. Info. 2).

Exposure

The most influential exposure factors in our assessment included air temperature, SST, ocean acidification, and dissolved oxygen. Temperature, both sea surface and air, was an influential factor in the exposure scores of most units. Exposure scores for SST (change in mean) were high or very high for all units, showing that, globally, sea turtles are expected to experience meaningful differences in water temperatures in the future relative to the recent past. Notably, some units in waters of the equatorial East Pacific and western North Atlantic scored high rather than very high for this exposure factor. Part of the reason for this lower score is that exposure was scored using standard anomaly to gauge projected future change relative to recent historical variability. Although these areas show rapid warming, they are also areas of high historical variability (Scott et al., 2016). Generally, units that experienced greater variability in conditions in the past could be expected to be less sensitive and more adaptive to changes in those conditions in the future.

Similar to SST, some units associated with the tropical East Pacific had lower air temperature scores than units in other regions due to a narrow band of relatively lower air temperature exposure along parts of the East Pacific coastline. This is an area of high historical variability (Scott et al., 2016), resulting in lower standard anomaly values. However, an expectation of reduced sensitivity and increased adaptivity to changes in near-surface air temperature may not be realistic considering the link between air and sand temperatures and thresholds associated with temperature-dependent sex determination (TSD; Ackerman, 1997; Hawkes et al., 2009; Lockley and Eizaguirre, 2021; Mrosovsky, 1994; Mrosovsky and Pieau, 1991).

The sea level rise exposure factor had the fifth greatest median score and was highly variable between populations (Fig. 7). That variability is not surprising because the relative sea level rise rate varies widely by geography (Jackson and Jevrejeva, 2016; Sweet et al., 2017). For nesting and basking sites, sea level rise only captures the seaward limit of available habitat and does not account for the upland limit of the habitat. The upland limit is partially accounted for in the "nesting beach type" sensitivity attribute, but some low-lying islands (e.g., Lalo/French Frigate Shoals in the Northwest Hawaiian Islands) and beaches with no ability to retreat (e.g., beaches with coastal development) are already approaching critical thresholds that can be exceeded by sea level rise (e.g., Baker et al., 2020; Fuentes et al., 2020; Reynolds et al., 2012). Multiple studies have examined coastal squeeze at local and sub-regional scales (e.g., Fish et al., 2005; Fuentes et al., 2011, 2020; Lyons et al., 2020; Varela et al., 2019), but many of those studies have been conducted at geographic extents that are considerably smaller than the units that we scored. Future iterations of this approach should consider novel ways to assess sea level rise with regard to coastal squeeze and other thresholds at regional scales.

The circulation exposure factor had the lowest median data quality score and the greatest inter-unit variability. Low data quality scores reflect both the challenge of projecting fine-scale circulation processes under changing climate conditions (Fox-Kemper et al., 2021) and the recognition that the published literature on the effects of circulation on sea turtles is relatively sparse compared to the effects of other climate factors (Patricio et al., 2021). Improved climate models and projections would improve the circulation data quality score.

The exposure scoring was conducted using future conditions projected under RCP8.5. There is ongoing debate about the appropriateness of using higher-end emissions scenarios in conservation science (e.g., Burgess et al. 2023; Hansen et al., 2023; Hausfather and Peters et al. 2020a, b; Pielke et al., 2022; Riahi et al., 2022; Schwalm et al., 2020) and future iterations of this assessment should carefully monitor that debate and consider selecting multiple scenarios from the latest emissions projections to account for a range of future conditions.

Sensitivity

Sensitivity attribute scores that drove vulnerability differed among and within species; however, the most common influential sensitivity attributes included nest/egg sensitivity to temperature, in-water habitat specificity, population abundance, and trend in population abundance.

The nest/egg sensitivity to temperature attribute, which highlights how TSD affects sex ratios, generally scored high across species (Supp. Info. 5). Populations (and their associated scores) in the green turtle Southwest Pacific DPS (Jensen et al., 2018; 4.0), hawksbill Northwest Indian RMU (Chatting et al., 2021; 3.5), hawksbill West Atlantic RMU (Flores-Aguire et al., 2020; 3.5), loggerhead Mediterranean DPS (Monsinjon et al. 2019; 3.5), loggerhead Northeast Atlantic DPS (Tanner et al., 2019; 2.9), loggerhead Northwest Atlantic DPS (Monsinjon et al. 2019; 3.0), loggerhead South Atlantic DPS (Monsinjon et al. 2019; 3.9), and loggerhead Southwest Indian DPS (Monsinjon et al. 2019; 2.9) units have been observed with hatchling ratios skewing highly female and studies have connected sex ratios to current or future climate change. Of those seven units, only the loggerhead Northeast Atlantic DPS and loggerhead Southwest Indian DPS scored below 3 for nest/egg sensitivity to temperature (both scored 2.9). Sea turtle populations have been hypothesized to be able to shift phenology to adapt to increasing nest temperatures and avoid feminization of the population (Almpanidou et al., 2018; Dalleau et al., 2012; Fuentes et al, 2023; Patrício et al. 2018; Pike et al., 2006; Weishampel et al., 2004). However, recent studies suggest populations do not have capacity to adapt nesting phenology at a rate sufficient to meet the rate of climate change (Fuentes et al., 2023; Laloë and Hays, 2023; Monsinjon et al., 2019).

The nest/egg sensitivity to temperature attribute also considers reproductive processes and metrics beyond TSD and sex ratios, such as egg development and hatchling output, with elevated temperatures accelerating developmental rates, reducing hatching success and emergence rates, and potentially affecting hatchling fitness (Burgess et al., 2006; Hewavisenthi and Parmenter, 2001; Howard et al., 2014; Jensen et al., 2018; Kobayashi et al., 2017; Poloczanska et al., 2009; Saba et al., 2012; Santidrián Tomillo et al., 2012, 2014; Santidrián Tomillo and Swiggs, 2015). Nest incubation temperatures are not only affected by air temperature, and may be mediated or exacerbated by other natural components of the nesting beach (e.g., precipitation, sand color, groundwater influences, beach orientation; Lolavar and Wyneken, 2015, 2017; Santidrián Tomillo et al., 2014; Tapilatu and Tiwari, 2007). In this assessment, we did not separately consider each of those mediating and/or exacerbating components but instead considered the net effect of all of those factors on the temperature of a nest. We also did not include in our scoring the potential use of conservation and management actions (e.g., nest shading, irrigating) to alleviate the effects of temperature on nests.

Inherent or implicit elements of adaptive capacity exist in other sensitivity attributes as well. For example, the prey and diet specificity attribute includes elements of the ability to switch prey based on availability. Likewise, in-water habitat specificity includes an element of capacity to adapt to changing habitat conditions. Future iterations of this assessment should emphasize more explicitly integrating adaptive capacity into the scoring system (Beever et al., 2016; Mainwaring et al., 2017; Ofori et al., 2017; Wade et al., 2017).

Non-climate stressors will respond to climate change in different ways, and some may result in novel interactions between turtles and non-climate threats (Crain et al., 2008; Fuentes et al., 2023; Orr et al., 2020; Piggot et al., 2015). For example, changes in fishing activity (e.g., effort, gear, target species, target areas) as fish distributions shift may result in increased sea turtle bycatch (Patel et al., 2021) and responses in coastal development and usage to changing coastal conditions (e.g., sea level rise) may result in reduced nesting habitat (Fish et al., 2005; Fuentes et al., 2020). In the absence of other climate adaptation strategies, reducing non-climate stressors and conserving habitat may be the only options currently available to managers (Dutra et al., 2021).

Sensitivity and resilience can be considered opposite ends of a similar spectrum (although resilience does not necessarily equate to adaptive capacity). Fuentes et al. (2013) considered a similar set of traits in their assessment of climate resilience for sea turtle populations. Abundance, trends in population size, and non-climate threats were evaluated in both assessments. Elements of our nesting beach type, geographic extent of nesting, nesting site fidelity, nest/egg sensitivity to temperature, and length of nesting season are all components of the rookery vulnerability trait assessed in Fuentes et al. (2013). Fuentes et al. (2013)

included a trait for genetic diversity that was not included in the current assessment, while our approach included additional attributes related to in-water habitat, prey and diet specificity, migratory behavior, reproductive potential, and adult sensitivity to temperature. Fuentes et al. (2013) used values from the published literature to score two components (“risk of decline or loss of genetic diversity” and “relative population-level impacts from non-climatic threats”) and then used expert opinion to weight the relative importance of each trait. Our assessment used a combination of expert opinion and existing literature to score attributes against a well-defined rubric, which allowed for scores to be based on values from the literature where available and based on expert opinion where published values were unavailable. This also had the effect of limiting the use of expert judgment to likely ranges of an attribute’s value for a given unit, rather than an interpreted relative importance. Future iterations of this approach could explore including a weighting component similar to the Fuentes et al. (2013) approach.

Of the 13 units Fuentes et al. (2013) identified as the least resilient to climate change, our study found all except the loggerhead Southwest Indian DPS to be highly or very highly sensitive to climate change. The nest/egg sensitivity to temperature, length of nesting season, population abundance, and lifetime reproductive potential attributes scored highest for this unit, but none scored high enough to move the unit into the high sensitivity category. Of the 21 units Fuentes et al. (2013) identified as the most resilient to climate change, our study found three units scored moderate sensitivity, 12 scored high sensitivity, and five scored very high sensitivity. The loggerhead North Indian DPS scored in this assessment covered the geographic range associated with both the Northeast Indian (part of least resilient group) and Northwest Indian (part of most resilient group) in the Fuentes et al. (2013) assessment, complicating comparisons. The leatherback Northwest Atlantic RMU scored the most resilient to climate change in the Fuentes et al. (2013) study, but scored very high sensitivity to climate change in this assessment. Primary drivers of sensitivity in this assessment included three attributes not explicitly considered in Fuentes et al. (2013; prey/diet specificity, adult sensitivity to temperature, and in-water habitat specificity) and the nest/egg sensitivity to temperature attribute that was likely captured within the rookery vulnerability component of Fuentes et al. (2013). The leatherback Northwest Atlantic RMU has shown substantial declines in nesting abundance through the 2010s, with potential causes of the decline including anthropogenic sources of mortality on and near nesting beaches and at foraging areas, nesting habitat loss, and changes in life history parameters (Eckert and Hart, 2021; Northwest Atlantic Leatherback Working Group, 2018, 2019). The rate at which nesting abundance of this unit has changed highlights the importance of revisiting assessments as conditions change and more information becomes available.

Assessment Design

Variability and uncertainty are features that must be characterized in trait-based CVAs (Huntley et al., 2016). Similar to other related CVA approaches (e.g., Farr et al., 2021; Hare et al., 2016; Lettrich et al., 2023), inter-scorer interpretation of life history information and differing levels of each expert’s underlying experience and knowledge were sources of variability in this study. Variability resulting from these sources was characterized using the bootstrap analysis and leave-one-out analyses. Lettrich et al. (2023) suggested replicating an assessment with a separate set of scorers to test the variability in scores, but doing so is personnel-intensive and would have required effectively doubling the number of experts involved. We are unaware of any CVAs that have published a replication study. Sources of uncertainty for this type of CVA included data (e.g., the availability and quality of underlying published literature) and methodological decisions such as scoring criteria thresholds and logic model thresholds (e.g., Farr et al., 2021; Hare et al., 2016; Lettrich et al., 2023). The data quality score was used to account for uncertainty in the availability and quality of underlying data, such as that in published reports and peer-reviewed literature. Although the data quality score was not a factor in the final vulnerability score, it provides context about the level of confidence associated with each score. Data gaps were indicated by low data quality score and also evident where information was not found in the published literature (see Supp. Info. 2). Targeted research to fill those data gaps could increase data quality scores, reduce assessment uncertainty, and enhance the potential to understand underlying drivers of vulnerability.

As mentioned earlier, RMU delineations were updated after we completed our scoring (Wallace et al., 2010, 2023). The RMUs in our assessment most affected by this realignment are the olive ridley RMUs in the North Indian Ocean and East Pacific Ocean. In the Indian Ocean, the 2010 olive ridley arribadas and solitary nesting RMUs scored the same exposure, sensitivity, and vulnerability (very high, high, and very high, respectively). Therefore, the modified 2023 Northeast Indian RMU that included both arribadas and individual nesting had the same exposure, sensitivity, and vulnerability scores. In the East Pacific Ocean, the 2010 olive ridley arribadas and solitary nesting RMUs both scored high exposure but differed in sensitivity and vulnerability, with the arribadas RMU scoring moderate sensitivity and vulnerability and the solitary nesting RMU scoring low sensitivity and vulnerability. The number of turtles in this RMU nesting in arribadas (over one million) far exceeds those nesting individually (hundreds to thousands) and the updated 2023 East Pacific RMU most closely aligned with the 2010 arribadas RMU. Future iterations of the assessment should closely monitor evolving management unit definitions and also consider conducting the assessment using smaller taxonomic units (e.g., genetic stocks).

We used climate projections that had a spatial resolution of 1 degree latitude by 1 degree longitude. We chose to use these projections for this assessment so that all of the units were assessed using the same projections, rather than a patchwork of downscaled or regional climate models that may have resulted in a variety of spatial resolutions and underlying projections across the assessment. Many of those downscaled and regional climate models have greater capability to resolve fine-scale features that are poorly resolved by the global climate models, as can be seen in areas like the Gulf of Maine off the U.S. Atlantic coast (Saba et al., 2016) or the Great Barrier Reef region in Australia (e.g., in eReefs; Steven et al., 2019) and could reduce uncertainty associated with exposure scores. Future iterations of this assessment are encouraged to explore the use of these finer-scale projections. As reliable downscaled and regional climate models become available, it will be possible to conduct CVAs using finer-scale biological units, such as genetically-defined populations or units delineated by important habitats.

Exposure scores were determined on the basis of unit ranges and the climate changes within those ranges drove geographic differences in exposure scores. Units that share significant overlap of ranges are expected to experience similar changes in climate conditions and therefore share similar exposure scores. Differences in scores between populations with similar ranges (e.g., green turtle North Atlantic DPS and loggerhead Northwest Atlantic DPS) may result from spatial density differences or differences in habitat use within the broader distribution. Unit distributions limited by historical or current human activity may affect the exposure scoring by mischaracterizing the unit's true geographic extent (Faurby and Araujo, 2018).

Our assessment scored exposure as the anticipated environmental change relative to recent historical variability to account for the units' historical experience with variable conditions. However, doing so may miss critical thresholds (e.g., thermal thresholds for egg/hatchling survival, sex ratios) that may be crossed (Hare et al., 2016; Lettrich et al., 2020). There is evidence that some of these thresholds may already be reached or exceeded (Jensen et al., 2018; see discussion in "Sensitivity"). Future iterations of this assessment may include explicit consideration for known or assumed thresholds related to environmental parameters.

Recommendations and Conclusions

Our assessment found the majority of sea turtle management units to have very high vulnerability to climate change. This vulnerability was driven by very high (88% of units) or high (12%) exposure to climate change and very high (43%), high (49%), or moderate (8%) sensitivity to climate change. Sea surface and air temperatures, ocean acidification, dissolved oxygen, and sea level rise were consistently influential exposure factors across all regions while influential sensitivity attributes varied by species and region.

This climate-related information can help inform management and monitoring activities (e.g., under national legislation and policy and other international analogs), and CVAs can provide important information for consideration when assessing development applications, prioritizing recovery plan implementation, managing regional threats, and designing and managing marine protected areas. CVAs are a foundational tool within the Climate-Smart Conservation Cycle (Stein et al., 2014), where they serve as an input for scenario planning exercises (e.g., Borggaard et al., 2019, 2020) and provide a systemic approach for reducing and characterizing uncertainty (Wilkening et al., 2022). Beyond population- and species-specific management, results can inform place-based management and science activities such as vulnerability assessments and management plans for marine protected areas (e.g., Shein et al., 2019). As CVAs become more common for marine species, we encourage future iterations to use results from other related CVAs (e.g., prey, predators, habitat) to inform sensitivity scoring.

Our assessment identified the sea turtle management units most vulnerable to climate change and the life history attributes that most contribute to that vulnerability. These results can support decision-making for prioritizing sea turtle management units for additional monitoring, targeted research, or advanced modeling to predict and detect climate-driven changes in distribution, abundance, and phenology at all sea turtle life stages. For example, exposure factors or sensitivity attributes that contributed significantly to a management unit's vulnerability may warrant specific study to further explore the implications of those factors or attributes in the unit's response to climate change. The assessment can be repeated at regular intervals to incorporate updated climate projections from new IPCC reports and new unit-specific biological information, particularly that which fills the data gaps identified within the assessment. The results of this assessment improved our understanding of the climate vulnerability of sea turtle populations, which will help inform actions and activities that support the conservation, management, and recovery of these protected species.

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Tables and Figures

Table 1. List of units scored in this assessment. Where available, Endangered Species Act (ESA) Distinct Population Segments (DPS) were used. In all other cases, Regional Management Units (RMU) were used (Wallace et al., 2010, 2023).

Species Common Name	Scientific Name	Unit	Notes
Flatback	*Natator depressus*	Southeast Indian RMU	
Flatback	*Natator depressus*	Southwest Pacific RMU	
Green turtle	*Chelonia mydas*	Mediterranean DPS	Corresponds to Mediterranean RMU
Green turtle	*Chelonia mydas*	East Indian DPS	Corresponds to East Indian and Southeast Asia RMUs
Green turtle	*Chelonia mydas*	East Pacific DPS	Corresponds to East Pacific RMU
Green turtle	*Chelonia mydas*	North Atlantic DPS	Corresponds to North Atlantic RMU
Green turtle	*Chelonia mydas*	North Indian DPS	Corresponds to Northwest Indian RMU
Green turtle	*Chelonia mydas*	North Pacific DPS	Corresponds to North Central Pacific RMU
Green turtle	*Chelonia mydas*	South Atlantic DPS	Corresponds to and South Atlantic RMUs
Green turtle	*Chelonia mydas*	South Pacific DPS	Corresponds to South Central Pacific and Southwest RMU
Green turtle	*Chelonia mydas*	Southwest Indian DPS	Corresponds to Southwest Indian RMU
Green turtle	*Chelonia mydas*	Southwest Pacific DPS	Corresponds to Southwest Pacific RMU
Green turtle	*Chelonia mydas*	West Pacific DPS	Corresponds to West Central Pacific RMUs
Hawksbill	*Eretmochelys imbricata*	East Atlantic RMU	
Hawksbill	*Eretmochelys imbricata*	East Pacific RMU	
Hawksbill	*Eretmochelys imbricata*	North Pacific RMU	
Hawksbill	*Eretmochelys imbricata*	Northeast Indian RMU	
Hawksbill	*Eretmochelys imbricata*	Northwest Indian RMU	
Hawksbill	*Eretmochelys imbricata*	South Pacific RMU	
Hawksbill	*Eretmochelys imbricata*	Southeast Indian RMU	
Hawksbill	*Eretmochelys imbricata*	Southwest Atlantic RMU	
Hawksbill	*Eretmochelys imbricata*	Southwest Indian RMU	
Hawksbill	*Eretmochelys imbricata*	Southwest Pacific RMU	
Hawksbill	*Eretmochelys imbricata*	West Atlantic RMU	
Hawksbill	*Eretmochelys imbricata*	West Pacific RMU	
Hawksbill	*Eretmochelys imbricata*	West Pacific SE Asia RMU	
Kemp's ridley	*Lepidochelys kempii*	Northwest Atlantic RMU	

Leatherback	*Dermochelys coriacea*	East Pacific RMU	
Leatherback	*Dermochelys coriacea*	Northeast Indian RMU	
Leatherback	*Dermochelys coriacea*	Northwest Atlantic RMU	
Leatherback	*Dermochelys coriacea*	Southeast Atlantic RMU	
Leatherback	*Dermochelys coriacea*	Southwest Atlantic RMU	
Leatherback	*Dermochelys coriacea*	Southwest Indian RMU	
Leatherback	*Dermochelys coriacea*	West Pacific RMU	
Loggerhead	*Caretta caretta*	Mediterranean DPS	Corresponds to Mediterranean RMU
Loggerhead	*Caretta caretta*	North Indian DPS	Corresponds to Northwest Indian RMU
Loggerhead	*Caretta caretta*	North Pacific DPS	Corresponds to North Pacific RMU
Loggerhead	*Caretta caretta*	Northeast Atlantic DPS	Corresponds to Northeast Atlantic RMU
Loggerhead	*Caretta caretta*	Northwest Atlantic DPS	Corresponds to Northwest Atlantic RMU
Loggerhead	*Caretta caretta*	South Atlantic DPS	Corresponds to Southwest Atlantic RMU
Loggerhead	*Caretta caretta*	South Pacific DPS	Corresponds to South Pacific RMU
Loggerhead	*Caretta caretta*	Southeast Indian DPS	Corresponds to Southeast Indian RMU
Loggerhead	*Caretta caretta*	Southwest Indian DPS	Corresponds to Southwest Indian RMU
Olive ridley	*Lepidochelys olivacea*	East Atlantic RMU	
Olive ridley	*Lepidochelys olivacea*	East Pacific RMU	In 2023, this RMU was consolidated with the Arribadas Pacific RMU and the new RMU retained the name East Pacific RMU
Olive ridley	*Lepidochelys olivacea*	Northeast Indian RMU	In 2023, this RMU was consolidated with the Arribadas Indian RMU and the new RMU retained the name Northeast Indian RMU
Olive ridley	*Lepidochelys olivacea*	West Atlantic RMU	
Olive ridley	*Lepidochelys olivacea*	West Indian RMU	
Olive ridley	*Lepidochelys olivacea*	West Pacific RMU	

Table 2. Exposure factors and scoring criteria.

		Scoring Criteria			
Exposure Factor	**Metric**	**Low Exposure**	**Moderate Exposure**	**High Exposure**	**Very High Exposure**
Sea Surface Temperature	Change in mean	|x| < 0.5 std dev	0.5 std dev ≤ |x| < 1.5 std dev	1.5 std dev ≤ |x| < 2.0 std dev	|x| ≥ 2.0 std dev
	Change in variability	F ratio <1.15	1.15 ≤ F ratio <1.54	1.54 ≤ F ratio < 1.78	F ratio ≥ 1.78
Air Temperature	Change in mean	|x| < 0.5 std dev	0.5 std dev ≤ |x| < 1.5 std dev	1.5 std dev ≤ |x| < 2.0 std dev	|x| ≥ 2.0 std dev
	Change in variability	F ratio <1.15	1.15 ≤ F ratio <1.54	1.54 ≤ F ratio < 1.78	F ratio ≥ 1.78
Precipitation	Change in mean	|x| < 0.5 std dev	0.5 std dev ≤ |x| < 1.5 std dev	1.5 std dev ≤ |x| < 2.0 std dev	|x| ≥ 2.0 std dev
	Change in variability	F ratio <1.15	1.15 ≤ F ratio <1.54	1.54 ≤ F ratio < 1.78	F ratio ≥ 1.78
Salinity	Change in mean	|x| < 0.5 std dev	0.5 std dev ≤ |x| < 1.5 std dev	1.5 std dev ≤ |x| < 2.0 std dev	|x| ≥ 2.0 std dev
	Change in variability	F ratio <1.15	1.15 ≤ F ratio <1.54	1.54 ≤ F ratio < 1.78	F ratio ≥ 1.78
Ocean Acidification	Change in mean	|x| < 0.5 std dev	0.5 std dev ≤ |x| < 1.5 std dev	1.5 std dev ≤ |x| < 2.0 std dev	|x| ≥ 2.0 std dev
	Change in variability	F ratio <1.15	1.15 ≤ F ratio <1.54	1.54 ≤ F ratio < 1.78	F ratio ≥ 1.78
Dissolved Oxygen	Change in mean	|x| < 0.5 std dev	0.5 std dev ≤ |x| < 1.5 std dev	1.5 std dev ≤ |x| < 2.0 std dev	|x| ≥ 2.0 std dev
	Change in variability	F ratio <1.15	1.15 ≤ F ratio <1.54	1.54 ≤ F ratio < 1.78	F ratio ≥ 1.78
Circulation	Qualitative	Distribution overlaps almost exclusively with large boundary currents or tidal currents	Much of distribution overlaps with large boundary currents or tidal currents.	Much of distribution overlaps with currents that are expected to have a high magnitude of change such as estuarine circulation, and/or nearshore density- and wind-driven currents	Distribution overlaps almost exclusively with currents that are expected to have a high magnitude of change such as estuarine circulation, and/or nearshore density- and wind-driven currents
Sea Level Rise	Qualitative	Relative sea level within nesting habitat is expected to increase less than 10 cm by mid-century	Relative sea level within nesting habitat is expected to increase 10–20 cm by mid-century	Relative sea level within nesting habitat is expected to increase 20–45 cm by mid-century	Relative sea level within nesting habitat is expected to increase more than 45 cm by mid-century.

Table 3. Sensitivity attributes and scoring criteria.

Sensitivity Attribute	Low Sensitivity	Moderate Sensitivity	High Sensitivity	Very High Sensitivity
Prey/Diet Specificity	Generalist; feeds on a wide range of prey types and sizes	Generalist; feeds on a limited number of prey types, but a wide variety of species within those types	Specialist; exhibits strong preference for one prey type but is capable of switching when necessary	Specialist; reliant on one prey type and unable to switch to other prey types
Habitat Specificity (in-water)	Population mostly utilizes physical features resilient to climate conditions	Population mostly utilizes biogenic features or physical features vulnerable to climate conditions	Population relies on biogenic features or physical features vulnerable to climate conditions for critical life stages or events	Population relies on biogenic features or physical features vulnerable to climate conditions throughout its entire life
Nesting Beach Type	Species nests primarily on continental beaches without adjacent development	Species nests primarily on one of the following: high islands without adjacent development or continental beaches with adjacent low-density development	Species nests primarily on one of the following: non-isolated low-lying islands without adjacent development, high islands with adjacent development, or continental beaches with adjacent high-density development	Species nests primarily on one of the following: isolated low-lying islands, non-isolated low-lying islands with adjacent development, high islands with adjacent development and in-water development, or continental beaches with adjacent high-density development and in-water development
Geographic Extent of Nesting	Broad distribution of nests/uniform density	Broad distribution of nests/non-uniform density	Narrow distribution of nests/uniform density	Narrow distribution of nests/non-uniform density
Nesting Site Fidelity	Nesting females display a low degree of site fidelity (nests within ~100km in successive nesting seasons)	Nesting females display a moderate degree of site fidelity (nests within ~50km in successive nesting seasons)	Nesting females display a high degree of site fidelity (nests within ~10km in successive nesting seasons)	Nesting females display extreme site fidelity (nests within 1km in successive nesting seasons)
Lifetime Reproductive Potential	High reproductive output and survival to maturity	Closer to high reproductive output and survival to maturity	Closer to low reproductive output and survival to maturity	Low reproductive output and survival to maturity
Length of Nesting Season	Population nests 10–12 months per year	Population nests 7–9 months per year	Population nests 4–6 months per year	Population nests 1–3 months per year
Adult Physiological Sensitivity to Temperature	Average nesting female curved carapace length is less than 80cm	Average nesting female curved carapace length is greater than or	Average nesting female curved carapace length is greater than or equal	Average nesting female curved carapace length is greater than or equal to 150cm

		equal to 80cm but less than 100cm	to 100cm but less than 150cm	
Nest/Egg Sensitivity to Temperature	TRT > 5°C	3.5°C ≤ TRT < 5°C	2°C ≤ TRT < 3.5°C	TRT < 2°C
Migration	Reproductive migration; multiple migratory foraging area destinations	Reproductive migration; few or single foraging area destinations	No reproductive migration; seasonal foraging migration	No migration; local movement only
Foraging Home Range	Individuals' foraging home range are broad, primarily including oceanic pelagic habitat	Individuals transit coastline within continental shelf waters to forage	Individuals typically remain in bays or archipelagos to forage but occasionally travel farther and have the capacity to find other locations	Individuals' foraging ranges are narrow, primarily confined to bays or archipelagos
Population Abundance	>10,000 nesting females	5,000–10,000 nesting females	1,000–5,000 nesting females	< 1,000 nesting females
Trend in Population Abundance	Increasing trend in population abundance over recent period	Stable trend in population abundance over recent period	Declining trend in population abundance over recent period	Rapidly declining trend in population abundance over recent period or deficient data to estimate trend
Cumulative Stressors	Population currently experiences 2 or fewer additional stressors	Population currently experiences 3 or 4 additional stressors	Population currently experiences 5 or 6 additional stressors	Population currently experiences more than 6 additional stressors or has one additional stressor that accounts for more than half of annual mortality

Table 4. Data quality score criteria used for assessing underlying information for exposure factor and sensitivity attribute scoring. Rubric is derived from Hare et al. (2016).

Data Quality Score	Criteria
3	Observed, modeled, or measured data support exposure factor/sensitivity attribute score
2	Observed, modeled, or measured data from similar stocks or species support exposure factor/sensitivity attribute score. Dated or conflicting information complicates the ability to place scores.
1	Expert’s knowledge of and experience with the population is the sole basis for exposure factor/sensitivity attribute score
0	No information is available to support exposure factor/sensitivity attribute score and the expert’s familiarity with the population is insufficient to provide expert judgment.

Table 5. Logic model used to determine exposure and sensitivity component scores (Hare et al., 2016, Lettrich et al., 2020).

Component Score	**Criteria**
Very High (4)	3 or more attribute or factor mean scores ≥ 3.5
High (3)	2 or more attribute or factor mean scores ≥ 3.0, but does not meet threshold for “Very High”
Moderate (2)	2 or more attribute or factor mean scores ≥ 2.5, but does not meet threshold for “High” or “Very High”
Low (1)	Less than 2 attribute or factor mean scores ≥ 2.5

Table 6. Response variable ordination. Direct and inverse refer to the ordination relative to the scoring criteria in Table 2.

Sensitivity Attribute	**Distribution**	**Abundance**	**Phenology**
Prey/Diet Specificity	Direct	Direct	Direct
Habitat Specificity (in-water)	Direct	Direct	Direct
Nesting Beach Type	Direct	Direct	N/A
Geographic Extent of Nesting	Direct	Direct	N/A
Nesting Site Fidelity	Inverse	Direct	N/A
Lifetime Reproductive Potential	N/A	Direct	N/A
Length of Nesting Season	N/A	Direct	Direct
Adult Physiological Sensitivity to Temperature	Direct	Direct	Direct
Nest/Egg Sensitivity to Temperature	Direct	Direct	N/A
Migration	Inverse	N/A	N/A
Foraging Home Range	Direct	Direct	N/A
Population Abundance	Direct	Direct	Direct
Trend in Population Abundance	Direct	Direct	Direct
Cumulative Stressors	Direct	Direct	N/A

Figure 1. The majority of units (86%; n=44) scored “Very High” vulnerability. This was partly driven by units scoring only “High” and “Very High” exposure. Italic values inside parentheses indicate sensitivity, exposure, and vulnerability score (calculated as sensitivity x exposure). Green cells signify “Low” vulnerability, yellow cells signify “Moderate” vulnerability, orange cells signify “High” vulnerability, and red cells signify “Very High” vulnerability.

Figure 2. Distribution of vulnerability, exposure, and sensitivity categories for all sea turtle units assessed.

Figure 3. Unit vulnerability scores. Italic values inside parentheses indicate sensitivity and exposure scores. Green cells signify “Low” vulnerability, yellow cells signify “Moderate” vulnerability, orange cells signify “High” vulnerability, and red cells signify “Very High” vulnerability. RMUs defined by Wallace et al. (2010, 2023); DPSs defined under the ESA (US 50 CFR § 223.102, US 50 CFR § 224.101). Cc = *Caretta caretta*; Cm = *Chelonia mydas*; Dc = *Dermochelys coriacea*; Ei = *Eretmochelys imbricata*; Lk = *Lepidochelys kempii*; Lo = *Lepidochelys olivacea*; Nd = *Natator depressus*. *Wallace et al. (2023) consolidated arribadas and individual nesting RMUs, resulting in one East Pacific RMU and one Northeast Indian RMU; results reflect the combined RMU.

Figure 4. Map of unit vulnerability by species. RMUs defined by Wallace et al. (2010, 2023); DPSs defined under the ESA (US 50 CFR § 223.102, US 50 CFR § 224.101). (a) green turtle(*Chelonia mydas*), (b) loggerhead (*Caretta caretta*), (c) hawksbill (*Eretmochelys imbricata*), (d) leatherback (*Dermochelys coriacea*), (e) olive ridley (*Lepidochelys olivacea*), (f) Kemp’s ridley (*Lepidochelys kempii*), and (g) flatback (*Natator depressus*).

Figure 5. Vulnerability, exposure, and sensitivity scores for each sea turtle unit by species.

Figure 6. Vulnerability, exposure, and sensitivity scores of each sea turtle unit by geographic region.

Figure 7. Exposure factor mean scores for all sea turtle units assessed. The vertical bar represents the median; the box is bounded by the first and third quartiles; whiskers represent 1.5 times the inter-quartile range; points represent all outlying values.

Figure 8. Leave-one-out sensitivity analysis showing how many sea turtle units changed climate vulnerability score when a given exposure factor was omitted.

Figure 9. Sensitivity attribute mean scores for all sea turtle units assessed. The vertical bar represents the median; the box is bounded by the first and third quartiles; whiskers represent 1.5 times the inter-quartile range; points represent all outlying values.

Figure 10. Leave-one-out sensitivity analysis showing how many sea turtle units changed climate vulnerability score when a given sensitivity attribute was omitted.

Figure 11. Mean data quality score for each exposure factor across all sea turtle units assessed. The vertical bar represents the median; the box is bounded by the first and third quartiles; whiskers represent 1.5 times the inter-quartile range; points represent all outlying values.

Figure 12. Mean data quality score for each sensitivity attribute across all sea turtle units assessed. The vertical bar represents the median; the box is bounded by the first and third quartiles; whiskers represent 1.5 times the inter-quartile range; points represent all outlying values.