TITLE: Assessing the impact of fishery actions to marine turtle populations in the North Pacific using classical and climate-based models

AUTHOR: Kyle S. Van Houtan

AFFILIATIONS: Marine Turtle Assessment Program, National Marine Fisheries Service, Pacific Islands Fisheries Science Center, 1601 Kapiolani Blvd, Suite 1000, Honolulu, HI 96814

Correspondence: kyle.vanhoutan@noaa.gov

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INTRODUCTION

The Protected Resources Division of the Pacific Islands Regional Office (PIRO) of the National Marine Fisheries Service (NMFS) requested a modeling exercise from the Pacific Islands Fisheries Science Center (PIFSC) to assess the population impacts of a proposed action in the Hawaii shallow-set longline fishery. The proposed action is for the fishery to have 23 interactions and incur 6 mortalities for leatherback sea turtles (*Dermochelys coriacea*) and 35 interactions and 7 mortalities for loggerhead sea turtles (*Caretta caretta*), annually in the foreseeable future. Under the U. S. Endangered Species Act, leatherbacks have a globally "endangered" status, and the North Pacific loggerhead population is "endangered."

Here, I model these proposed actions using two approaches to population viability assessment (PVA). In the first approach I use a classical PVA that calculates population growth and its variability from time series of nest counts. From these parameters I employ Monte Carlo techniques in a stochastic exponential growth (SEG) model to assess extinction probability over the next three generations. In the second approach, I use a climate-based PVA that considers bottom-up climatic forcing at two key life stages – neonates and breeding females. I fit models to the empirical nest time series and forecast forward approximately one generation using available and surrogate climate data. Each model produces clear results, but the approaches disagree in their conclusions for each population. I recommend considering the climate-based PVA for the first generation forecast, and using the classical PVA to evaluate the proposed actions after. However, the latter model in the later forecast years will have greater uncertainty and therefore greater decision-making risk.

METHODS

Determining Adult and Nester Equivalents

As population monitoring data is at nesting beaches, we must first convert anticipated mortalities into nester equivalents. To understand the population demographics of bycatch in the Hawaii shallow-set fishery, I obtained interaction data from 1994-2011 from the PIRO observer program. Before 2001, there was no nominal distinction between the shallow- and deep-set fisheries. After consulting with fishery experts, I considered all turtle interactions from sets with < 10 hooks per float to be interactions from what we today consider the shallow-set fishery.[1] This provided us with more data from the years 1994-2001 from which to understand the demographics of the turtle interactions for each species. From these interaction data, I fit probability models to length distributions for loggerheads (n = 223) and leatherbacks (n = 27). Since the fishery interacts mostly with juvenile loggerheads, I convert juveniles into adults using morphometric models[2] and discounting for annual mortality.[3] I then determine nesters assuming a 50/50 sex ratio for Japan loggerheads[4] and 65/35 female to male ratio in Indonesian leatherbacks[5] (the latter determined from averages in the scientific literature).

Classical Approach to Population Viability

Following Snover's work[4-6] I use a stochastic exponential growth model to describe observed population changes, where constant linear rate of increase yields exponential changes in population time series.[7,8] This model has the basic forms:

$$f(x) = rx \tag{1}$$

$$N(t+1) = N(t) + r \tag{2}$$

where x is the population size in year t, f(x) is the population size in the year t+1, and r is the rate of change. Consistent with the observed pattern of variability of wild populations,[8,9] I use ln-transformed population counts, as per previous turtle modeling exercises for NOAA Fisheries.[4,6] Equation (2) follows this method, where $N(t)$ is the ln-transformed annual nest counts in the year t, $N(t+1)$ is the ln-transformed annual nest counts in the year t+1, and r as previously is the annual growth. I use the running-sum method[5,10] that linearly accumulates data from contiguous years and I convert nest counts from Japan[11] and Indonesia (Tapilatu unpub. data) to nesters. (Recent evidence[12] shows that leatherbacks nesting at Jamursba-Medi are the primary source for interactions with the Hawaii shallow-set fishery and therefore this nesting beach is the appropriate data series for analysis.) The Indonesia survey series I use accumulates nest counts during April-October annually, representing the peak nesting season.[13] For loggerheads I use a three year run-sum and assume each nester produces four nests.[4,5] For leatherbacks I use a run sum that accumulates data from four adjacent years, and I assume an average clutch size of 6.1 nests.[14]

This method focuses on the empirical probability distribution of r, and yields a mean (μ) and standard deviation (σ). If μ is positive and σ approximates zero, then future projections will indicate unambiguous population growth and suggest low extinction risk. Conversely, if μ is negative, or if σ is large, future projections may indicate population declines or ambiguous results and therefore suggest significant extinction risk. Importantly, this method assumes: (i) demographic forces are the primary factor driving population dynamics, and (ii) that the factors that regulate population dynamics remain constant through time. Neither of these assumptions may be warranted, however.[15] In making future projections of population changes, I employ Monte Carlo methods to randomly select r from its fitted distribution, in other words, an empirically-derived stochastic exponential growth (SEG) model. I chose this procedure over the diffusion approximation[6,7] (DA) as Kendall[16] showed the DA systematically overestimates extinction risk, especially for species with life history patterns like sea turtles.

I begin model runs of future population changes with N_0, the current nester cohort, which is the most recent run-sum of nesters. I calculate growth using Eq. (2) and then annually discount for a variety of mortalities under the proposed action. I run the models forward 3 generations, which I calculate for loggerheads to be 95 years and for leatherbacks to be 68 years. As in previous studies,[5] I determine these numbers considering the age at first breeding (AFR) and using 90% annual adult survival. For Japan loggerheads I use an AFR of 25 years[15] and for Indonesia leatherbacks I assume they first breed at 22 (see below). I then make 10,000 replicates of each model run for each population. I consider the average of these 10,000 runs the model average for each model year which is the most likely forecast scenario under these conditions. I rank the runs from each model year and consider the 250th and 9750th values my 95% credible interval. I consider $N_0/2$ to be the quasi-extinction threshold (QET) and I calculate the proportion of all model runs that end below that value. This proportion is analogous to a susceptibility to quasi-extinction (SQE) and is the main determinant of extinction risk in this modeling framework.

Climate-based Approach to Population Viability

I develop a second assessment of population viability considering that the long-term dynamics of sea turtles observes strong climate forcing,[15] or has an apparent dominant influence from environmental conditions. Several studies across a variety of ocean settings and with several species of sea turtles have indicated that ocean conditions matter for nesters,[17-19] I extend that concept to the hatch year based on an extensive empirical demonstrations of its significance for juvenile recruitment in marine organisms from a variety of taxa[20-25] and based on my recent demonstration of its significance for loggerhead turtles in the North Pacific and Northwest Atlantic populations.[15]

Central to developing this modeling framework is the spatiotemporal structure of the populations. For loggerheads, we understand neonates disperse from Japanese beaches to the Kuroshio Current , eventually making it into the Kuroshio Bifurcation Extension Region,[26] and that inter-nesting females reside in the East China Sea.[15,17] For leatherbacks we have less information about neonate habitat, but both physiological estimates[27,28] and location coordinates from the PIRO Observer Program database indicate juvenile leatherbacks concentrate in ocean region south of the Hawaiian Islands. (This location was also recently and independently identified as a key leatherback habitat based on biotelemetry.[12]) The western coast of North America, and in particular the California Current upwelling system, is known to be an important congregating area for foraging nesters before migrating to Indonesia.[12,29]

I use a variety of climate series to capture the oceanographic dynamics for these areas. For loggerheads, I use the Pacific Decadal Oscillation (PDO) to provide insights into neonate survival as the index is positive when circulation is most active in the Kuroshio region.[15,25] The PDO series is the calendar year average of the monthly index values, supplied by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO). To capture ocean dynamics for nesters, I average SST from 8-28°N, 120-128°E during the November-January before the nesting season.[15] SST data are the 2°x2° cell ERSSTv3b series from 1950-1981 and 1°x1° cell OIv2 series from 1981-present, provided by NOAA's National Climatic Data Center (NCDC). For leatherbacks, I also use the PDO to provide insights into neonate survival but in an opposite from loggerheads. Because of its dipole behavior,[25] the PDO index is negative when circulation is most active in the region south of Hawaii discussed above. Therefore I propose neonate survival of leatherbacks will increase when the PDO is in a negative phase. (Thus, to some extent, this predicts that population trajectories of North Pacific loggerheads and Western Pacific leatherbacks may be inherently out-of-phase.) To capture climate dynamics most influential to inter-nesting leatherbacks, I use the ocean coastal upwelling index that describes the California Current dynamics, [30] and is provided by the NOAA's Environmental Research Division (ERD) at the Southwest Fisheries Science Center (SWFSC).

I estimate nest counts using the following generalized linear models:

$$N_1(t \mid \varphi) = \beta_0 + \beta_1 x(t \mid \varphi) \qquad (3)$$

$$N_2(t \mid \varphi) = \beta_0 + \beta_1 x(t \mid \varphi) + \beta_2 z(t) \tag{4}$$

$$N_3(t \mid \varphi) = \beta_0 + \beta_1 x(t \mid \varphi) + \beta_2 x^2(t \mid \varphi) + \beta_3 z(t) \tag{5}$$

Where N_i is the annual nesting activity predicted by the i^{th} model, $x(t|\varphi)$ is the PDO index in year t lagged by φ years and $z(t)$ represents the nester climate series. For loggerheads, $z(t)$ is the SST from the previous winter[15] and for leatherbacks, $z(t)$ is the California Current upwelling index[30] from the previous summer. The numbers β_0, β_1, β_2, β_3, are the fitted model parameters. The squared term in Eq. (5) produces a power law relationship between the lagged PDO and the nesting data; relationships common in ecological studies.[31-33]

I lag the effect of x on N as the variability of x influences juvenile turtles, only a portion of which breed φ years later and are observed nesting. Though I fix this value at 25 years for the loggerhead population,[15] we have no *a priori* estimates for the Indonesia leatherback population. Recent studies, however, estimate age at first breeding in leatherbacks globally is roughly 17-21 years.[27,34] As one may expect φ to vary by population, I fit Eq. (3) to the observed data for the Jamursba-Medi nest series when $9 < \varphi < 31$ years and optimize φ by model performance. With a variety of spatiotemporal options for the California Current upwelling index, I select 14 different periods from June-November at six different offshore locations ranging from San Clemente Island, California, USA up to Vancouver Island, Canada. This provides 84 different scenarios that are used as $z(t)$ in Eq. (4-5).

To rank model performance, I use the corrected Akaike Information Criterion (AIC_c) for small samples, where:

$$AIC_c = n \cdot \left[2\ln(D) + \frac{1 + (k-1)/n}{1 - (k+1)/n} \right] \tag{6}$$

where k is the number of model parameters, n is the series length and D is the mean square deviation between the data and the model.[32,35] Other things being equal, this reduces to simple interpolation of D.

I estimate population forecasts in each series using the highest-ranked relationships from the fitted models. Because of the lagged influence of the oceanographic indices, we already possess real climate data that has yet to manifest itself in nesting females, N. Therefore we forecast nest surveys from 2010 forward, for a period equal to the optimum lag, φ, using existing PDO indices. (This period is less than, but approximates the length of one full generation.) However, we must project values for the nester climate series, winter SST for loggerheads and upwelling index for leatherbacks. To model the uncertainty in the forecast for both nester climate series, I estimated the power spectrum of noise from the empirical series.[36] For the loggerhead winter SST series, I incorporated the A2 emissions scenario from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report[37] to account for noise as well as anthropogenic climatic change.[15] I applied the spectral noise pattern to the IPCC projected SST trends and generated 100 surrogate SST forecasts. I generated 100 additional series by applying the spectral noise pattern from the empirical series to the linear trend extracted from the 1950-2010 merged ERSST series. For the leatherback upwelling index, I generated 1000 surrogate series for the upwelling index based on the spectral noise pattern of the monthly upwelling index from 1946-2011.

Until now, this approach has focused strictly on bottom-up oceanographic forcing and not incorporated any demographic information or harvest. To incorporate the proposed fishery action into this climate-based modeling framework I use the following:

$$N(t \mid \varphi, M) = \ln(e^{N_i(t \mid \varphi)} - \sum_{t=0}^{\varphi} M e^{rt}) \qquad (7)$$

which is based from Eq. (3-5) but adds *M*, the annual anticipated nester mortality, and *r* which is an intrinsic rate of annual growth. When $r = 0$ the proposed fishery action is a simple linear subtraction from the climate model of Eq. (3-5). But to account for potential demographic influences I run growth projections for $r = 0.01$, 0.03, and 0.05, to assess not only simple arithmetic harvest, but the compound interest of their reproductive loss through time. Eq. (2) inherently accounts for this in the SEG model, Eq. (7) incorporates this concept within the climate-driver framework. I replicate each model run 1000 times, I consider the average from each model year the model average and the most likely forecast scenario under these conditions. I rank the runs from each model year and consider the 25th and 975th values my 95% credible interval. Because I do not use the running-sum procedure, I average the last several years nester estimates (three years for loggerheads, four years for leatherbacks) and consider that my N_0, and set $N_0/2$ to be the QET. I calculate the proportion of all model runs that end below the QET, and use this as the main determinant of extinction risk for this modeling approach.

RESULTS

Figure 1 plots the sizes of the shallow-set fishery turtle interactions for (a) loggerheads and (b) leatherbacks. For loggerheads, the fishery overwhelmingly interacts with juveniles (Fig. 1a). According to the best-fit model, loggerhead sizes are consistent with a gamma distribution ($\alpha = 29.99$, $\beta = 1.93$) with 50% of the observations falling below 57.3 cm straight carapace length (SCL). From the empirical data, 96% (214/223) of the total loggerhead interactions are with juveniles (i.e., <80 cm SCL)[3]. For leatherbacks, the fishery overwhelmingly interacts with adults (Fig. 1b). According to the best-fit model, leatherback sizes are consistent with a gamma distribution ($\alpha = 34.39$, $\beta = 4.25$) with 50% of the observations falling below 144.8 cm SCL. From the empirical data, 93% (26/28) of the total interactions are with adults (i.e., >120 cm SCL)[27,34]. This statistic is likely significantly higher, as adult leatherbacks are difficult for NMFS observers to land and measure and therefore larger leatherbacks are often released without length being estimated. Figure 1c plots the most commonly interacted loggerhead size on a recent modeled estimate[2] of loggerhead growth indicating these turtles are in their 13th year. Figure 1d discounts mortality[3] from this age until the AFR estimate of 25 years, the time when this population likely first breeds.[15] Each of the proposed fishery actions from 1-7 mortalities, results in <1 adult equivalent, and does not appear to be sensitive to realistic perturbations of *S*.

The population growth parameters under exponential growth are shown in Figure 2. The leatherback nesting trend in Jamursba-Medi, Papua Province, Indonesia has been declining since records have been first kept, resulting in most of the annual changes being population losses, and a negative overall population growth rate ($\mu = -0.066$, $\sigma = 0.017$). The loggerhead nesting trend in Japan, provided by the Sea Turtle Association of Japan (STAJ) as a cumulative account of all nests in the Japanese archipelago, declined from the beginning of the study and then apparently rebounded after 2000. This has resulted in a slight population growth ($\mu = 0.023$, $\sigma = 0.034$) during the overall period. Plotted series for both populations apply the running-sum.[10]

Figure 3 plots the population projections under the classical PVA that relies on the SEG model and observed population growth parameters. The default forecast with no fishery mortality for leatherbacks shows a statistically significant decline over three future generations. Beginning with an N_0 = 1233, essentially all SEG model runs fall below, and the 95% interval is entirely below, the QET. The proposed action of six annual mortalities exacerbates this trend even further, reducing the final run value 87% from the default trend – from 16 to 2 nesters. This analysis suggests that this population will very likely be completely extirpated by the year 2080. The default loggerhead forecast with no fishery mortality shows a statistically significant increase. Beginning with an N_0 = 7138, never fewer than 94% of the model runs remain above, but the 95% interval contains the QET. The proposed action amounting to a single annual mortality is not immediately apparent, but reduces the final run value 2% from the default trend. However, this analysis suggests the loggerhead population in Japan, given population dynamics and controlling factors remains constant, may increase nearly nine-fold by 2110.

Figure 4 maps the spatiotemporal structure of the North Pacific loggerhead and Western Pacific leatherback populations to identify key habitats and climates that may be influential for long-term population dynamics. These areas are selected as a combination of empirical observations, physiological models, and climate model optimizations. Figure 5 plots the residual error from the climate forcing models across a range of plausible estimates for AFR. The models, and their average, all agree on 22 years as the appropriate lag length, φ, for the PDO amounting to a climate-based estimate of AFR. (Previously,[15] I achieved similar model agreement on φ for the North Pacific loggerhead population at 25, which corresponded to empirical data.[38]) Though the optimum of φ = 22 is slightly larger than estimates of a global average, Indonesian nesters are physically larger when compared to other locations.[29] Other things being equal, larger is older,[2,3,27] and therefore the climate-based result of 22 is consistent with observed morphometrics.

The results of 84 model correlations comparing upwelling index series from the California Current to the residuals from the simple climate forcing model (Fig. 5) are seen in Figure 6. This effort is to establish exactly which series to use from the California Current that is meaningful for females foraging there and nesting in Indonesia the following year. In general, a distinct environmental gradient is visible that patterns almost identically[12] to observations of tagged leatherbacks in the same region. The highest-ranked model in this analysis is the August-October upwelling index for the area proximate 36° N, 122° W, just offshore Monterey, California, USA. These results confirm the climate forcing approach, and this particular index, are both meaningful for describing nesting time series of Western Pacific leatherbacks.

Figure 7 establishes the climate forcing relationships over the observed record of nesting. For both populations the prevailing empirical trends are consistent with climate oscillations indicating that environmental conditions may likely drive long-term population dynamics and be largely responsible for the observed time series patterns. For loggerheads in Japan, this includes the historical decline from 1960-2000[15,17] and the more recent increases. Importantly, this climate-based approach captures the 300% (linear scale) increase observed from 2007-8. For leatherbacks in Jamursba-Medi, Indonesia, this indicates that the overall observed decline, as well as the 77% (linear scale) drop between 2004-5 may also have a climatic origin. Unlike the classical PVA, the climate-based approach does not use the running-sum, and therefore incorporates annual changes to be real and meaningful information. Importantly, the climate-based modeling approach describes the empirical record well, and captures extreme (sometimes annual) population shifts that demographic models are challenged to explain.

Figure 8 plots the climate-based PVA projections based on the empirically-fitted model relationships and considering the proposed actions. After enduring several decades of declines, the climate models suggest Western Pacific leatherbacks are poised for a rebound and will increase significantly by 2035. This has mostly to do with decadal oscillations in the North Pacific Ocean as captured in the PDO index and its influence of juvenile leatherback recruitment. The spread in the forecast trends is due to the uncertainty of the upwelling index forecast as captured in the noise spectra of that empirical series. Based on a variety of harvest scenarios (see Table 3) the range of expected increase in the population during the forecast period is 27-82%. This approach suggests low extinction risk with high confidence in those model projections. None of the leatherback climate model runs end below the QET. Somewhat conversely, after several years of impressive nesting increases, the Japanese loggerhead population appears headed for a significant decline, based largely on the modeled impacts from changes in the PDO and its anticipated influence of juvenile recruitment in the North Pacific. Because the proposed action is calculated to be at one nester per year, the differences between the default trend and that of the proposed action only vary slightly. Virtually all the loggerhead climate model runs fall below the QET indicating high extinction risk with high model confidence.

DISCUSSION

The analytical approaches I present here yield differing conclusions, which deserves explanation and interpretation. To begin, there are important differences in the classical and climate-based PVAs. Both approaches make use of nesting ground monitoring efforts and assume those are reliable indices of population changes over time. The classical approach combines counts from adjacent years (the running-sum), assesses growth on annual changes, and projects forward three generations. This method assumes all (environmental and anthropogenic) pressures will remain constant in the forecast period and it relies on nesting data alone. The climate-based approach also uses nesting data, but does not combine adjacent years, instead using the annual variability as real and important population information. To these data, this method adds qualitative and quantitative life history insights into AFR, empirical data on spatiotemporal population structure, and multiple climate data series. Together, these data streams describe the observed nesting trends, in terms of both annual and long-term variability. The climate-based approach also only projects forward approximately one generation, mainly due to difficulties in predicting the PDO.[15]

So why would the approaches obtain such different results? The answer is fairly simple in that the classical approach assumes static (though stochastic) growth that is based solely on the empirical nest counts. In other words, the classical approach extends the recent average growth trends into the future. The model averages from this method will always approximate monotonic change and will neither capture empirical periodicity nor project future oscillations. Therefore, if there is a single trend in the empirical observations, the classical PVA will just carry that forward (Fig. 3), irrespective of so-called oceanographic regime shifts or other cyclical factors.[21,23,25] The climate-based approach, however, observes the decadal oscillations of oceanographic conditions and therefore will both empirically capture and project forward population variability in model averages. Unlike the SEG model, the climate approach achieves this variability not from parameter uncertainty, but from underlying environmental oscillations which are considered mechanistic for resources and population recruitment.[15]

Which answer is correct? Each modeling approach entails statistical and ecological assumptions that may be better suited in different contexts. Both modeling approaches are largely based on interpreting nesting beach monitoring data. Though these data may present shortcomings,[39] it is the best data series we currently possess for both of the populations in question. And furthermore, breeding female surveys are what many population studies desire and do not possess. To summarize, the climate-based PVA: (i) takes a mechanistic approach to understanding population drivers, (ii) predicts the observed changes in the empirical record, and (iii) achieves such results when replicated with multiple species and in multiple ocean regions and basins. The climate-based PVA therefore provides a more robust analysis of the likelihoods of extinction over the first forecast generation, beyond that period the classical PVA approach and any extension of the climate based model using IPCC scenarios, for example, are both less reliable. Because the classical approach makes use of essentially a single and brief data series, there is significantly greater risk in using this approach as a decision-making tool, especially out one century from the present observations.

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FIGURE CAPTIONS

Figure 1. Determining adult equivalents of marine turtle interactions in the Hawaii-based shallow set longline fishery. Empirical observations indicate (a) 96% (214/223) of fishery interactions with loggerheads are with juveniles, and for leatherbacks (b) 93% (26/28) of interactions are with breeding adults. The data span 1994-2011 and are provided by the NMFS vessel observer program. Shaded histograms represent the raw data, lines are fitted probability models (see text). Size is represented in straight carapace length (SCL). As we measure fishery impacts to nesting populations, for loggerheads we must calculate adult impacts from juvenile mortality. (c) Empirical relationship between age and size (SCL) for loggerheads in the Western North Atlantic.[2] Assuming similar growth in the North Pacific population, this indicates the fishery interactions are most commonly with loggerheads in their 13th year. Discounted by survival rates, we calculate adult equivalents of 1-7 juvenile mortalities (see text). "*S*" is the survival rate at three distinct life stages. Illustrations throughout by César Landazábal / SWoT Report[40], used with permission.

Figure 2. Representative surveys and calculated growth for nesting leatherback and loggerhead sea turtle populations. Left panels represent time series of nesting leatherbacks at Jamursba-Medi, Indonesia; loggerhead numbers accumulate surveys from the Japanese archipelago. Plotted anomalies are a run-sum of nesting females (see text). Center panels display the contiguous annual changes where the dotted line is equal replacement. Hollow circles represent annual declines, filled circles are annual growth. Right panels show the probability distribution of annual growth rates, determined from a stochastic exponential growth (SEG) model. Shaded bars are the observed empirical rates, line is fitted normal distribution. Here, leatherbacks have μ = -0.066 and σ = 0.017 and loggerheads have μ = 0.023 and σ = 0.034. The axes are conserved unless otherwise noted.

Figure 3. Classical population viability forecasts for leatherbacks and loggerheads considering the proposed action. Left panels are the default forecast trend assuming observed population growth parameters (see Fig. 2). Solid, colored line is the average result of 10,000 model runs, shaded area is the 95% credible interval. Center panels are the default growth trend, annually discounted for the proposed mortalities (leatherbacks = 6, loggerheads = 1), with the dotted lines being the model averages. Right panels display the deviation between the default trends and the proposed actions. Grey line is the quasi-extinction threshold (QET) or 50% decline from the current population size. Tables 1-2 present the full results.

Figure 4. Spatiotemporal population structure for loggerheads and leatherbacks in the North Pacific. North Pacific loggerhead (orange) and Western Pacific leatherback populations (purple) occupy different ocean locations at different life stages. Arrows indicate presumed pelagic habitat locations for hatch-year and juvenile turtles. Both of these regions are described to various extents by the Pacific Decadal Oscillation (PDO). Inter-nesting habitats for breeding adult populations indicated by "+".

Figure 5. Estimating age at first breeding in western Pacific leatherbacks. Using a previous method,[15] I report residual mean square values for each model at each lag length of the Pacific Decadal Oscillation (PDO). Green lines are two linear models, red lines are two curvilinear models, black line is the average of all models (see text). Blue rectangle identifies the optimum lag length according to the data. All models agree on a 22 year optima, suggesting a maturity consistent with recent estimates.[27]

Figure 6. Identifying climate series influential for leatherback nesters. Heat maps showing correlations between leatherback nesting in Indonesia and coastal upwelling off Western North America.[30] Correlations are with the residuals from the PDO-based model that captures juvenile environmental

dynamics. Highest-ranked model identifies Aug-Oct (inclusive) upwelling index offshore of Monterey, California (122W, 36N) as a key location in determining nesting the subsequent year in Jamursba-Medi, Papua, Indonesia. This area has been independently confirmed through aerial surveys as critical habitat for leatherbacks.[12,29] Inset tables represent time periods modeled for six upwelling locations (pink circles). Model rank increases with color saturation. Upwelling indices calculated by NOAA's Pacific Fisheries Environmental Laboratory.

Figure 7. Establishing climatic forcing of nesting populations over the empirical record. Nest observations (columns) are plotted against lagged ocean oscillations (dotted line) and forcing model (black line). Highest-ranked forcing model incorporates the decadal series including the juvenile (PDO) and adult (California Current upwelling) climate indices. Models for both nesting series perform well, suggesting that climatic conditions contribute significantly to the long-term population dynamics of loggerheads and leatherbacks in the North Pacific. Available and modeled climate data therefore may be important for forecasting the next several decades of population changes.

Figure 8. Climate-based population forecasts considering the proposed action. Forecasts are based on fitted model relationships during the observed record, using available PDO series and modeled surrogates for the nester climate indices (see text). Left panels show default trend with no fishery action. QET is 50% of N_0, defined here as the average estimated annual nester abundance during the final four years in the observed record. These forecasts predict an oscillating increase for leatherbacks, but a substantial decline for loggerheads – opposite the results from the classical PVA. Colored lines are the model average, shaded areas the 95% credible interval. Center panels report the default climate-based forecast, discounted for the proposed fishery actions, where $r_m = 0.05$. Right panels report the model averages of the two approaches and report the deviation between the default climate trend and additional influence from the proposed action. Though these forecasts are a shorter time horizon than the classical approach (Fig. 3) they incorporate bottom-up oceanographic mechanisms known to be significant for many marine organisms. Tables 3-4 present the full results.

TABLE CAPTIONS

Table 1. Classical PVA model inputs and results for leatherbacks. As the shallow set fishery overwhelmingly interacts with adult leatherbacks, the proposed mortality and adult equivalents are equal. Nester equivalents are calculated assuming the population is 65% female. Runs below QET is the percentage of model runs where the final value is less than half of the current value—analogous to a probability of quasi-extinction. N_{68}/N_0 is the model average final value divided by the current value (95% interval in parentheses). Years to QET is the number of years until the model average reaches 50% of the current value (95% interval in parentheses). Extinction risk and Model confidence are either "high", "medium," or "low." Extinction risk is high as ~100% of the model runs fall below the QET. Model confidence is high as the QET lies above the 95% credible interval for each scenario.

Table 2. Classical PVA model inputs and results for loggerheads. As the shallow set fishery overwhelmingly interacts with juvenile loggerheads, adult equivalents are discounted from proposed mortalities (Fig.1b-c). Nester equivalents are calculated assuming the population is 50% female. "Runs below QET" is the percentage of model runs where the final value is less than half of the current value—analogous to a probability of quasi-extinction. N_{95}/N_0 is the model average final value divided by the current value (95% interval in parentheses). Years to QET is the number of years until the model average reaches 50% of the current value (95% interval in parentheses). Extinction risk is low as the population is increasing and > 94% of model runs end above the QET. Model confidence is medium as the QET is within the 95% credible interval in all scenarios.

Table 3. Climate-based PVA model inputs and results for leatherbacks. Future forecasts from the climate models considering various fishery scenarios. As the PDO is not predictable, we only forecast forward the length of the lag (φ) which is a climate-based estimate of age at first reproduction (AFR). Here, model runs optimized to be 22 years for leatherbacks nesting at Jamursba-Medi. The added demographic increase ranges from 0.0-0.05 is "r_m". As previously, "Runs below QET" is the percentage of model runs where the final value is less than half of the current value – analogous to a probability of quasi-extinction. N_φ/N_0 is the model average final value divided by the current value (95% interval in parentheses). Default deviation is the proportional population change between the default climate scenario and the proposed action. Extinction risk for all scenarios is low as the runs show a population increase over the forecast period and ~0% of the runs fall below the QET. Model confidence is high as the entire 95% interval is outside the QET. These models consider a range of nester mortalities from 0-4 per annum, based on 0-6 fishery mortalities per annum (Table 1).

Table 4. Climate-based PVA model inputs and results for loggerheads. Future forecasts from the climate models considering a single nester mortality per annum, based on 0-7 fishery mortalities per annum (Table 2). As the PDO is not predictable, we only forecast forward the length of the lag (φ) which is a climate-based estimate of age at first reproduction (AFR). Here, model runs optimized to be 25 years for loggerheads nesting in Japan.[15] The added demographic increase ranges from 0.0-0.05 is "r_m". As previously, "Runs below QET" is the percentage of model runs where the final value is less than half of the current value – analogous to a probability of quasi-extinction. N_φ/N_0 is the model average final value divided by the current value (95% interval in parentheses). Default deviation is the proportional population change between the default climate scenario and the proposed action. Extinction risk for all scenarios is high as the runs show a population decrease over the forecast period and ~100% of the runs fall below the QET. Model confidence is high as the entire 95% interval is outside the QET.

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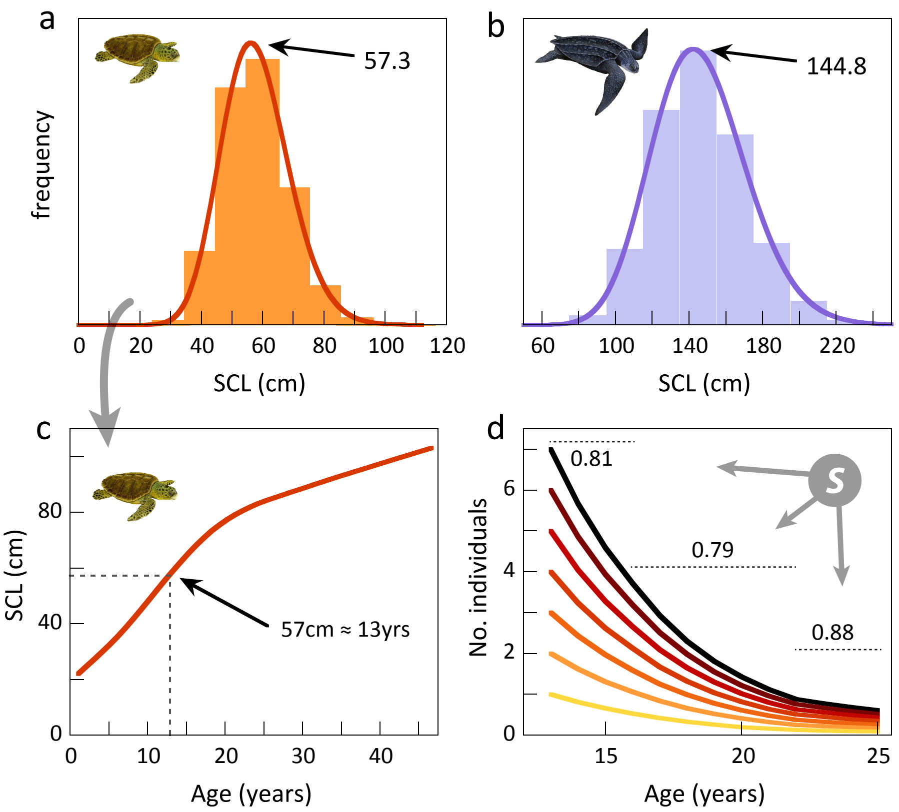
a
frequency
57.3
0
20
40
60
80
100
120
SCL (cm)
b
144.8
60
100
140
180
220
SCL (cm)
c
SCL (cm)
80
40
0
57cm ≈ 13yrs
0
10
20
30
40
Age (years)
d
No. individuals
6
4
2
0
0.81
0.79
0.88
S
15
20
25
Age (years)

Figure 1

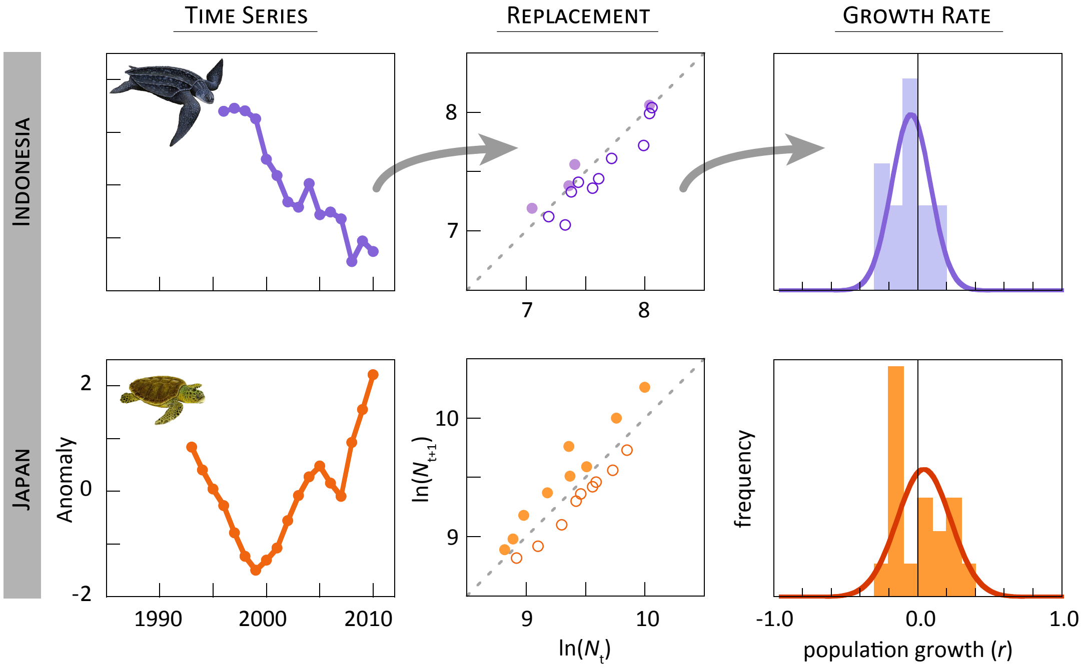
TIME SERIES
REPLACEMENT
GROWTH RATE
INDONESIA
JAPAN
Anomaly
2
0
-2
1990
2000
2010
8
7
7
8
10
9
9
10
$\ln(N_{t+1})$
$\ln(N_t)$
frequency
-1.0
0.0
1.0
population growth (r)

Figure 2

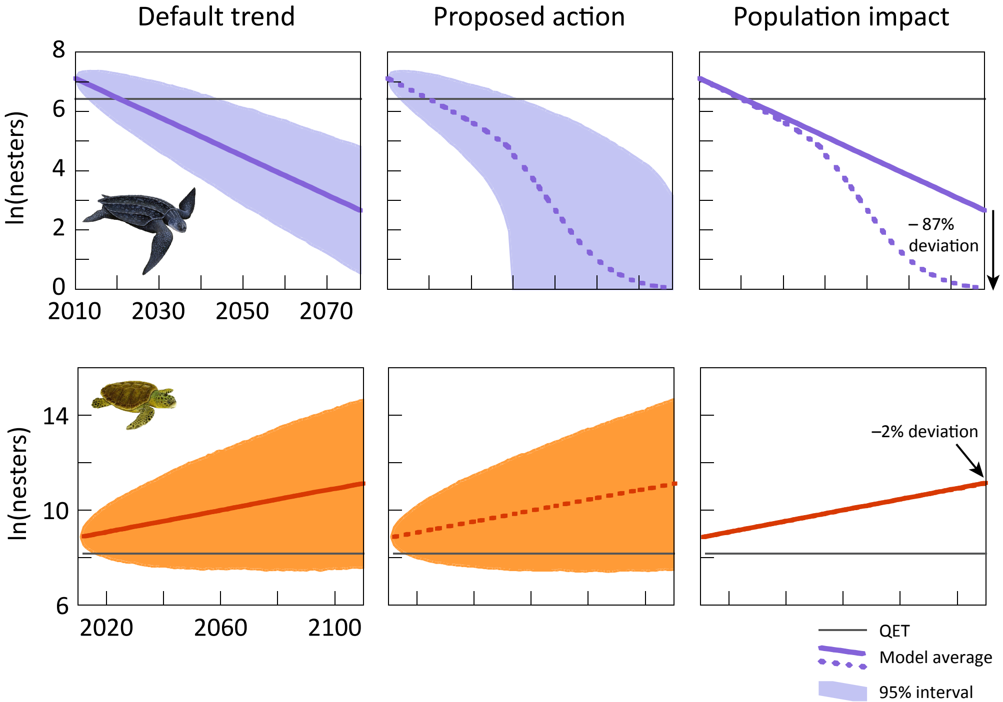
Default trend
Proposed action
Population impact
ln(nesters)
8
6
4
2
0
2010
2030
2050
2070
− 87% deviation
ln(nesters)
14
10
6
2020
2060
2100
−2% deviation
QET
Model average
95% interval

Figure 3

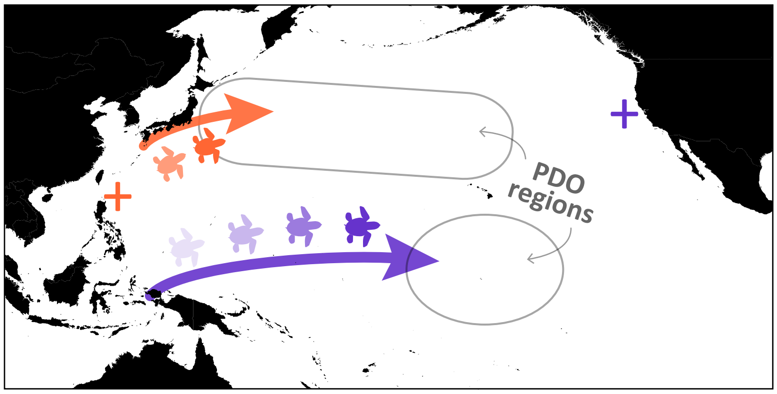

Figure 4

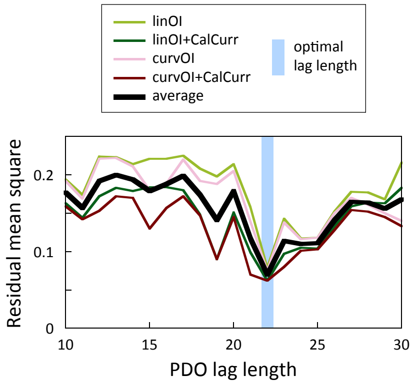
linOI
linOI+CalCurr
curvOI
curvOI+CalCurr
average
optimal lag length
Residual mean square
0
0.1
0.2
10
15
20
25
30
PDO lag length

Figure 5

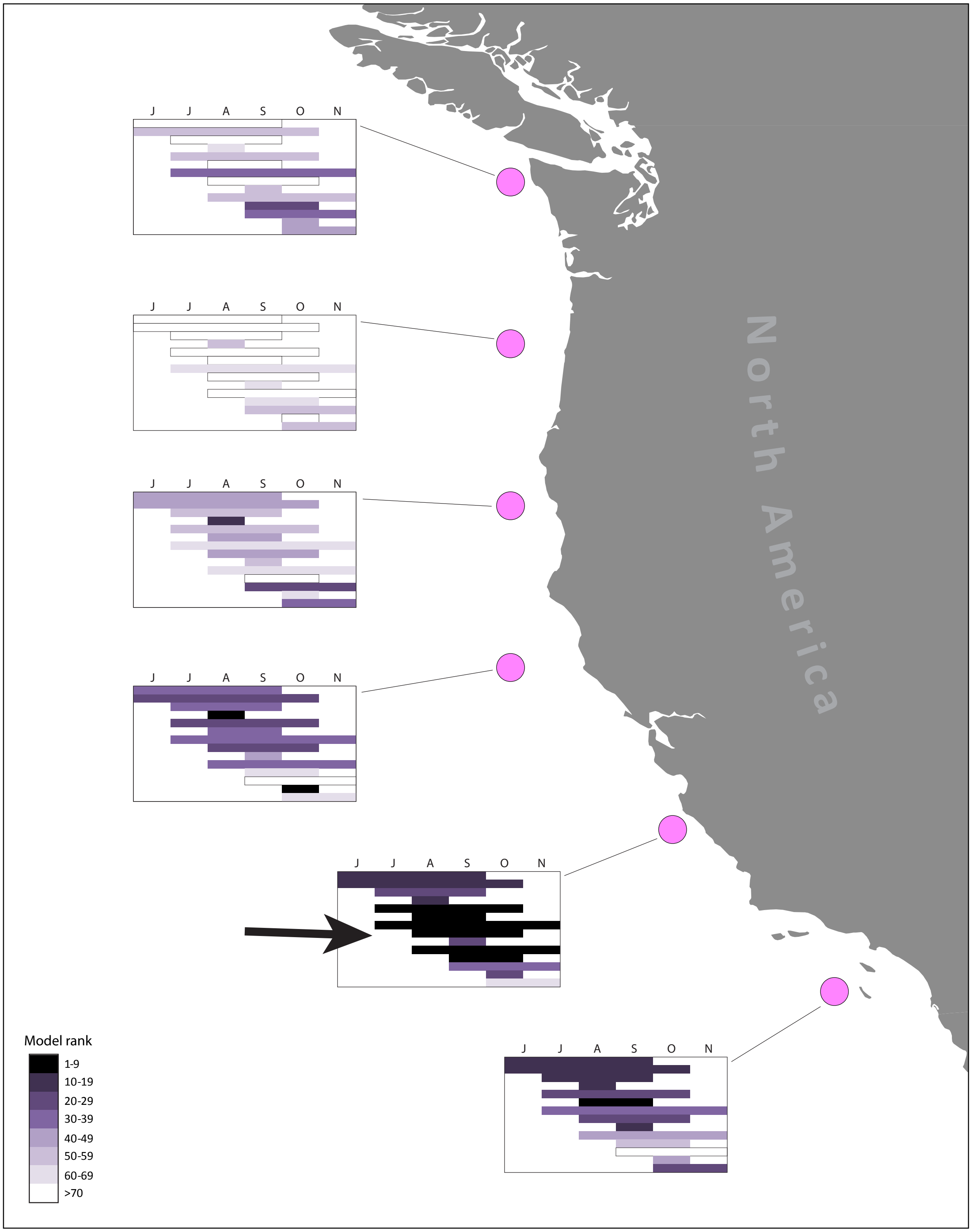
North America
J J A S O N
Model rank
1-9
10-19
20-29
30-39
40-49
50-59
60-69
>70

Figure 6

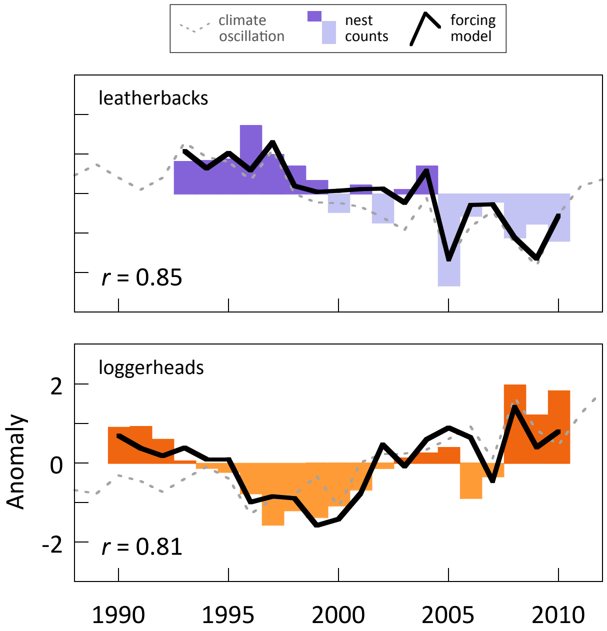
climate oscillation
nest counts
forcing model
leatherbacks
r = 0.85
loggerheads
r = 0.81
Anomaly
2
0
-2
1990
1995
2000
2005
2010

Figure 7

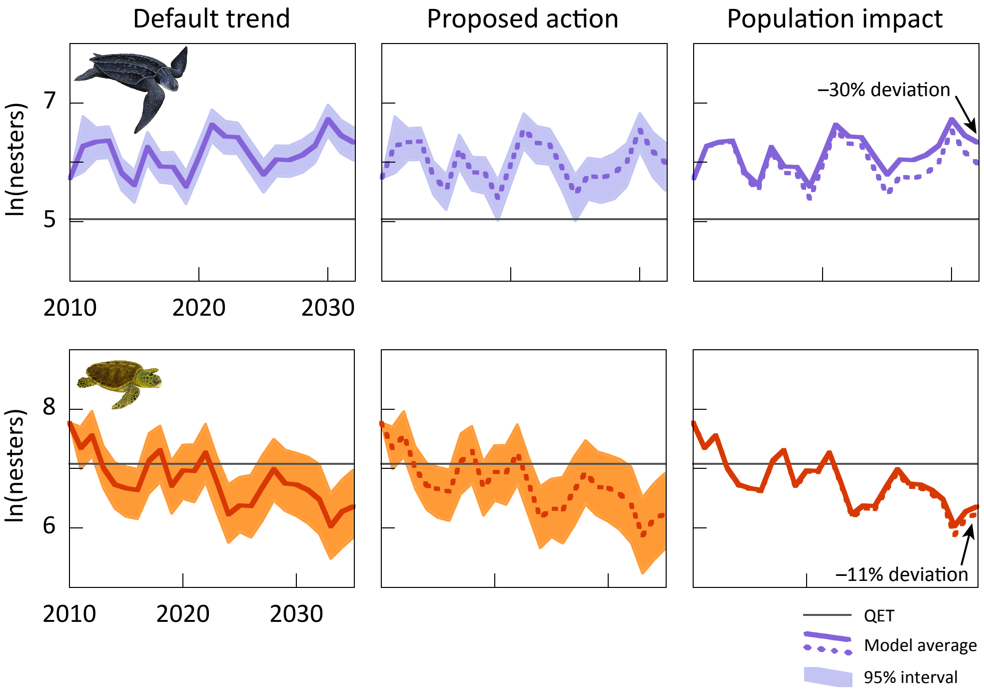
Default trend
Proposed action
Population impact
ln(nesters)
7
5
2010
2020
2030
−30% deviation
ln(nesters)
8
6
2010
2020
2030
−11% deviation
QET
Model average
95% interval

Figure 8

TABLE 1. Classical PVA model inputs and results for leatherbacks

Fishery Mortality	Adult Equiv.	Nesters yr^{-1} Equiv.	Nests yr^{-1} Equiv.	Runs below QET	N_{68} / N_0	Default Devation	Years to QET	Extinction risk	Model confidence
0	0	0	0	99.97%	0.01 (0-0.1)	0.0%	11 (4-34)	high	high
1	1	1	7	99.95%	0 (0-0.07)	-80.0%	10 (3-32)	high	high
2	2	2	13	99.98%	0 (0-0.05)	-86.7%	10 (3-31)	high	high
3	3	2	13	99.98%	0 (0-0.05)	-86.7%	10 (3-31)	high	high
4	4	3	19	100.00%	0 (0-0.03)	-86.7%	9 (3-29)	high	high
5	5	4	25	99.99%	0 (0-0.02)	-86.7%	9 (3-30)	high	high
6	6	4	25	99.99%	0 (0-0.02)	-86.7%	9 (3-30)	high	high

TABLE 2. Classical PVA model inputs and results for loggerheads

Fishery Mortality	Adult Equiv.	Nesters yr^{-1} Equiv.	Nests yr^{-1} Equiv.	Runs below QET	N_{95} / N_0	Default Devation	Years to QET	Extinction risk	Model confidence
0	0	0	0	4.90%	9 (0.28-288)	0.0%	n/a (6-n/a)	low	medium
1	0.09	1	4	5.72%	8.7 (0.25-275)	-2.4%	n/a (6-n/a)	low	medium
2	0.17	1	4	5.72%	8.7 (0.25-275)	-2.4%	n/a (6-n/a)	low	medium
3	0.26	1	4	5.72%	8.7 (0.25-275)	-2.4%	n/a (6-n/a)	low	medium
4	0.35	1	4	5.72%	8.7 (0.25-275)	-2.4%	n/a (6-n/a)	low	medium
5	0.43	1	4	5.72%	8.7 (0.25-275)	-2.4%	n/a (6-n/a)	low	medium
6	0.52	1	4	5.72%	8.7 (0.25-275)	-2.4%	n/a (6-n/a)	low	medium
7	0.61	1	4	5.72%	8.7 (0.25-275)	-2.4%	n/a (6-n/a)	low	medium

TABLE 3. Climate-based PVA model inputs and results for leatherbacks

Nesters yr^{-1} Mortality	AFR (φ)	r_M	Runs below QET	N_{φ} / N_0	Default Devation	Extinction risk	Model confidence
0	22	n/a	0.0%	1.82 (1.3-2.3)	0.0%	low	high
1	22	0	0.0%	1.75 (1.2-2.2)	-3.9%	low	high
1	22	0.01	0.0%	1.68 (1.2-2.2)	-7.8%	low	high
1	22	0.03	0.0%	1.68 (1.2-2.2)	-7.8%	low	high
1	22	0.05	0.0%	1.65 (1.1-2.2)	-9.1%	low	high
2	22	0	0.0%	1.67 (1.2-2.2)	-8.0%	low	high
2	22	0.01	0.0%	1.61 (1.1-2.1)	-11.7%	low	high
2	22	0.03	0.0%	1.58 (1.1-2.1)	-13.2%	low	high
2	22	0.05	0.0%	1.53 (1-2)	-15.8%	low	high
3	22	0	0.0%	1.6 (1.1-2.1)	-11.9%	low	high
3	22	0.01	0.0%	1.53 (1-2)	-15.7%	low	high
3	22	0.03	0.0%	1.48 (1-2)	-18.7%	low	high
3	22	0.05	0.0%	1.4 (0.9-1.9)	-22.8%	low	high
4	22	0	0.0%	1.53 (1-2)	-15.8%	low	high
4	22	0.01	0.0%	1.46 (0.9-2)	-19.8%	low	high
4	22	0.03	0.0%	1.38 (0.9-1.9)	-24.2%	low	high
4	22	0.05	0.0%	1.27 (0.8-1.8)	-29.9%	low	high

TABLE 4. Climate-based PVA model inputs and results for loggerheads

Nesters yr^{-1} Mortality	AFR (φ)	r_M	Runs below QET	N_{φ} / N_0	Default Devation	Extinction risk	Model confidence
0	25	n/a	99.5%	0.24 (0.1-0.4)	0.0%	high	high
1	25	0	99.5%	0.23 (0.1-0.4)	-4.5%	high	high
1	25	0.01	100%	0.22 (0.1-0.4)	-8.8%	high	high
1	25	0.03	100%	0.22 (0.1-0.4)	-9.0%	high	high
1	25	0.05	100%	0.22 (0.1-0.4)	-11.0%	high	high