

UPDATE TO NOAA TECHNICAL MEMORANDUM NMFS-PIFSC-101:
INCORPORATING UNCERTAINTY IN MATURATION AND LATEST FISHERY
TAKES

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EXECUTIVE SUMMARY

This internal report revisits, updates, and modifies the population viability analysis (PVA) of Martin et al. (2020a) and the results of Martin et al. (2020b) for the Hawaii deep-set pelagic longline fishery (DSLL) interactions with western Pacific leatherback sea turtles. The net result of the changes implemented is a small change between the 2020 and current assessments. The new approach results in the population declining to below 50% of current annual nesters 0.53 years faster with take than without take (Table 1) with the difference between no-take and take scenarios increasing over time in both deterministic and stochastic model runs (Figure 1).

Incorporating the most recent 5 years of data on interactions altered the shape of the distribution used to predict the anticipated take level (ATL) as well as the relationship used to predict post-release fishery mortality. The Conway-Maxwell-

Poisson distribution (Figure 2) for the ATL included a higher median but lower mean value (16.5 leatherbacks per year) as compared to Martin et al. (2020b; 17.0 leatherbacks per year), indicating an overall slightly lower anticipated level of leatherback interactions in the fishery (see Table 2 for the parameters changes). Updated data also changed the mean size and release mortality of the individuals with which the fishery interacted. The recorded size of turtles has increased (116.6 cm SCL 2004–2016 compared to 121.1 cm SCL from 2004–2021). The assigned mean post-release fishery mortality following the Ryder et al. (2006) memo has changed (~41% 2004–2016 compared to ~36% 2004–2021), resulting from zero leatherback deaths observed in 2017–2021. This resulted in a change to the multivariate normal model (Figure 3, Table 3) used to predict the *unmeasured* interactions lengths and post-release mortalities. The expected interaction length has increased slightly (113.4 cm SCL 2004–2016 compared to 117.5 cm SCL 2004–2021) while the median model-based post-release mortality has declined 10.7% (64.2% 2004–2016 compared to 53.5% 2004–2021). Note that the proportion of unmeasured interactions has increased in recent years resulting in the model being used to estimate length and mortalities for a higher proportion of the interactions.

An alternative approach to setting maturity was also incorporated into the most recent model. In the previous model, maturity of leatherbacks was set using a case-wise function where individuals became mature at 97.5% of mean asymptotic length (L_{∞}) equal to 139.13 cm straight carapace length (SCL) (Martin et al. 2020b). A new approach that allowed smaller (younger) individuals to be mature was implemented using a probability of maturity function. The case-wise approach produced a higher ANE

than the probability of maturity approach due to the way the nester remigration interval was accounted for. In the original case-wise approach, when a juvenile was interacted with, the remigration interval was applied (to reflect uncertainty about which year within the span of a remigration interval it would nest once it matured) but if an adult was interacted with it was removed from the annual nester population in the year lost (conservatively assuming it would have nested that year). With the adoption of the probability of maturity function, adult and juvenile stages are no longer explicitly defined but instead the probability of maturing is used in a Bernoulli draw (coin-flip) to generate the year in which post-interaction maturity occurs. This difference in generating mature turtles from Martin et al. (2020b) requires accounting for the uncertainty of when the first nesting will occur after maturation and, thus, the remigration interval was applied to all turtles. The remigration interval accounting for the probability of maturity approach applied to all turtles is equivalent to the Martin et al. (2020a,b) approach applied to juveniles. Importantly, it is also necessary to apply the remigration interval to the take to convert the take to the currency of the PVA, which is annual nesters.

SIMULATION COMPARISON BETWEEN THE TWO MATURITY APPROACHES

The case-wise maturity PVA reaches the 50%, 25%, and 12.5% population thresholds in 1.1, 3.39, and 6.98 years sooner with take compared to a no-take scenario while the same benchmarks are 0.53, 2.11, and 4.59 years sooner for the probability of maturity model (Table 1). The new maturity approach results in a less pessimistic comparison between take and no take scenarios. The probability of the projected 2021 nester population reaching the 12.5% threshold is 0%, 0%, 27.7%, 96.3% and 100% at the 5-, 10-, 25-, 50- and 100-year benchmarks without the fishery for the case-wise

approach and, for the same benchmarks, 0%, 0%, 32.4%, 97.6%, and 100% for the probability of maturity approach. Adding in the impacts of the DSLL using the case-wise maturity PVA increases these probabilities by 0%, 0.5%, 32.1%, 3.5%, and 0% at the 5-, 10-, 25-, 50-, and 100-year benchmarks (Table 4). The alternative probability at maturity PVA increases these probabilities by 0%, 0.1%, 19.6%, 2.1%, and 0% at the 5-, 10-, 25-, 50-, and 100-year benchmarks, respectively (Table 5). Here again, the new maturity approach results in a less pessimistic comparison between take and no-take scenarios.

Using the updated ATL, the median yearly ANE in the case-wise maturity PVA was 0.9 ANE/yr while the probability of maturity PVA was 0.37 ANE/yr. These values are slightly lower than what would be found using the Martin et al. (2020b) ATL, where the case-wise maturity PVA produced 0.91 ANE/yr and the probability of maturity PVA would have produced 0.38 ANE/yr (see Figure 4 for cross-model comparison). Relative to the case-wise maturity PVA, the distribution of yearly ANE for the probability of maturity PVA is less likely to project a yearly ANE over 2 (Figure 5). Controlling for new data, the discrepancies between these two maturity approaches is largely due to the incorporation of the remigration interval but also the way the maturity function interacts with survivorship to first nesting.

Updating ATL to reflect the most recent 5 years of DSLL leatherback interaction data was an important part of this analysis. Differences between the Martin et al. (2020b) results and those presented here are based on the updated mortality estimates and sizes from the DSLL leatherback interaction data set, as well as the incorporation of the probability of maturity for smaller turtles. These changes resulted in slight

differences between this most recent approach and the approach taken in 2020.

Although the probability of maturity approach does increase the chance of maturing at smaller sizes and does increase the survival to first nesting, the implementation of this approach, actually resulted in a lower ANE. Together, adding 5 more years of DSLL interaction data, updating the anticipated take distribution, using the probability of maturity approach, projecting the declining leatherback population five more years, and adjusting the population benchmarks to reflect the 2021 population status produced an expected mortality of 0.37 annual nesters per year into the future assuming the anticipated take level is realized each year.

Table 1. Hawaii-based deep-set longline (DSLL) fishery—for western Pacific leatherbacks, using the *probability of maturity ANE calculation* with a 99% L_∞ fully mature cutoff on the *median population status* the probability of the population being above or below ($p > \theta$ or $p < \theta$, respectively) abundance thresholds ($\theta = 50\%, 25\%, 12.5\%$ of current Annual Nesters) within the 100- year simulation time frame, and the number of years (mean, median, & 95% credible interval [CI]) to reach each threshold for all runs that fall below them. Results are from the stochastic take model, both with and without take, and with historical ANEs added back into the population; results from the deterministic model were not notably different. $\Delta(NT - T)$ shows the difference between the take and no take projection scenarios. Note the 100-year simulation is based on the years where only the projected anticipated take is included.

Threshold	Scenario	$p > \theta$	$p < \theta$	Mean yr	Median yr	L95% yr	U95% yr
50%	No Take	0	1	7.85	7	1	21
	Take	0	1	7.33	6	1	19
	$\Delta(NT - T)$	0	0	0.53	1	0	2
25%	No Take	0	1	19.24	18	9	36
	Take	0	1	17.14	16	8	32
	$\Delta(NT - T)$	0	0	2.11	2	1	4
12.5%	No Take	0	1	30.48	29	17	50
	Take	0	1	25.87	25	15	42
	$\Delta(NT - T)$	0	0	4.59	4	2	8

Table 2. Comparison of the location (μ), scale (ν), and expectation ($E[x]$) of the Conway-Maxwell-Poisson distribution between Martin et al. (2020b) and the updated parameter values used in this report.

Parameter	Martin et al. (2020b)	This report
μ	7.38694	8.284754
ν	0.04967579	0.05725318
$E[x]^*$	16.95221	16.51789

$$*E[x] = \mu + \frac{1}{2\nu} - \frac{1}{2}$$

Table 3. Summary of the median parameter estimates for the multivariate normal model of lengths and interaction mortalities of leatherback sea turtles interacting with the DSLL fishery.

Parameter	2004-2016 Median	2004-2021 Median	Description	
μ_D	0.643	0.535	interaction mortality intercept	
μ_L	113.4	117.5 cm SCL	mean interaction length	
β_0	106.4	108.8 cm SCL	interaction length intercept	
β_1	0.00519	0.00618	interaction length slope	
σ_D	4.231	3.783	std. dev. in log(SCL)	
σ_L	0.372	0.338	std. dev. in logit(D)	
ρ	-0.57	-0.51	correlation coefficient	

Table 4. Hawaii-based deep-set longline (DSLL) fishery—for western Pacific leatherbacks, using the case-wise maturity ANE calculation on the median population status from Martin et al. (2020a,b), the probability (median with 95% credible intervals [CI]) of the population reaching abundance thresholds at 5, 10, 25, 50, and 100 years from final data year (2021). Results are from the stochastic version of the take model with historical takes accounted for by adding the ANEs back into the population. Scenarios with and without take are provided, with $\Delta(NT - T)$ showing the difference between the two scenarios.

		Pop. Status	Scenario	5yr	10yr	25yr	50yr	100yr
50%	Median	No Take	0.341	0.725	0.989	1	1	
		Take	0.403	0.807	0.995	1	1	
		$\Delta(NT - T)$	-0.062	-0.082	-0.006	0	0	
L95%		No Take	0.331	0.716	0.988	1	1	
		Take	0.393	0.799	0.994	1	1	
		$\Delta(NT - T)$	-0.062	-0.083	-0.007	0	0	
U95%	Median	No Take	0.35	0.734	0.992	1	1	
		Take	0.413	0.816	0.997	1	1	
		$\Delta(NT - T)$	-0.063	-0.081	-0.004	0	0	
25%	Median	No Take	0.001	0.068	0.799	0.997	1	
		Take	0.003	0.13	0.909	1	1	

Pop.	Scenario	5yr	10yr	25yr	50yr	100yr
		$\Delta(\text{NT-T})$	-0.002	-0.062	-0.11	-0.003
L95%	No Take	0	0.062	0.791	0.997	1
	Take	0.001	0.122	0.904	1	1
		$\Delta(\text{NT-T})$	-0.001	-0.06	-0.112	-0.003
U95%	No Take	0.001	0.072	0.808	0.998	1
	Take	0.003	0.137	0.916	1	1
		$\Delta(\text{NT-T})$	-0.002	-0.064	-0.108	-0.002
12.5%	Median	No Take	0	0	0.277	0.963
		Take	0	0.005	0.598	0.998
			$\Delta(\text{NT-T})$	0	-0.005	-0.321
L95%	No Take	0	0	0.268	0.96	1
	Take	0	0.003	0.588	0.998	1
			$\Delta(\text{NT-T})$	0	-0.003	-0.32
U95%	No Take	0	0	0.286	0.968	1
	Take	0	0.006	0.608	0.999	1
			$\Delta(\text{NT-T})$	0	-0.006	-0.322
					-0.031	0

Table 5. Hawaii-based deep-set longline (DSLL) fishery—for western Pacific leatherbacks, using the probability of maturity ANE calculation on the median population status from Martin et al. (2020a,b), the probability (median with 95% credible intervals [CI]) of the population reaching abundance thresholds at 5, 10, 25, 50, and 100 years from final data year (2021). Results are from the stochastic version of the take model with historical takes accounted for by adding the ANEs back into the population. Scenarios with and without take are provided, with $\Delta(NT - T)$ showing the difference between the two scenarios.

		Pop. Status	Scenario	5yr	10yr	25yr	50yr	100yr
50%	Median	No Take	0.388	0.758	0.995	1	1	
		Take	0.412	0.787	0.997	1	1	
		$\Delta(NT - T)$	-0.024	-0.029	-0.002	0	0	
L95%		No Take	0.378	0.75	0.994	1	1	
		Take	0.401	0.779	0.997	1	1	
		$\Delta(NT - T)$	-0.023	-0.029	-0.002	0	0	
U95%	Median	No Take	0.398	0.767	0.997	1	1	
		Take	0.422	0.796	0.999	1	1	
		$\Delta(NT - T)$	-0.024	-0.029	-0.002	0	0	
25%	Median	No Take	0	0.081	0.815	1	1	
		Take	0	0.12	0.9	1	1	
		$\Delta(NT - T)$	0	-0.039	-0.085	0	0	
L95%		No Take	0	0.076	0.808	1	1	
		Take	0	0.113	0.894	1	1	
		$\Delta(NT - T)$	0	-0.038	-0.082	0	0	
U95%	Median	No Take	0	0.087	0.824	1	1	
		Take	0	0.127	0.907	1	1	
		$\Delta(NT - T)$	0	-0.04	-0.082	0	0	
12.5%	Median	No Take	0	0	0.324	0.976	1	

Pop. Status	Scenario	5yr	10yr	25yr	50yr	100yr
	Take	0	0.001	0.52	0.997	1
	$\Delta(\text{NT-T})$	0	-0.001	-0.196	-0.021	0
L95%	No Take	0	0	0.313	0.973	1
	Take	0	0	0.509	0.997	1
	$\Delta(\text{NT-T})$	0	0	-0.196	-0.023	0
U95%	No Take	0	0	0.333	0.979	1
	Take	0	0.001	0.531	0.998	1
	$\Delta(\text{NT-T})$	0	-0.001	-0.198	-0.019	0

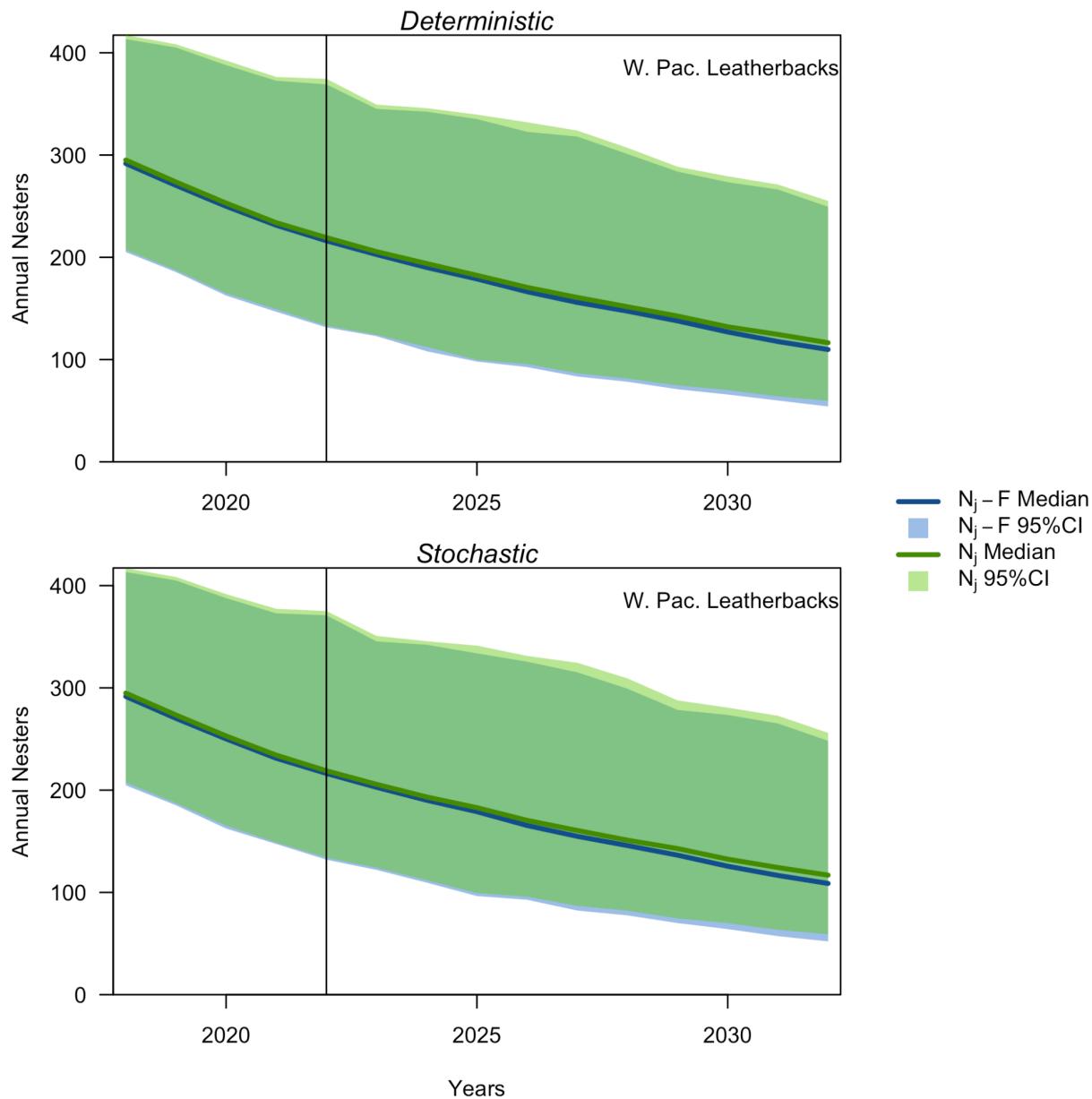


Figure 1. Projection of the western Pacific leatherback population without future fishery interactions (green) and with future fishery interactions (blue) over 10 projected years using the probability of maturity ANE calculation with a 99% L_∞ fully mature cutoff. Years to the left of the vertical black line indicate a forward projection of the leatherback population trend including the historic interactions while years to the right indicate forward projection with projected anticipated take levels. The initial population size and trend parameters are from the median population status from the imputation conducted in Martin et al. (2020a).

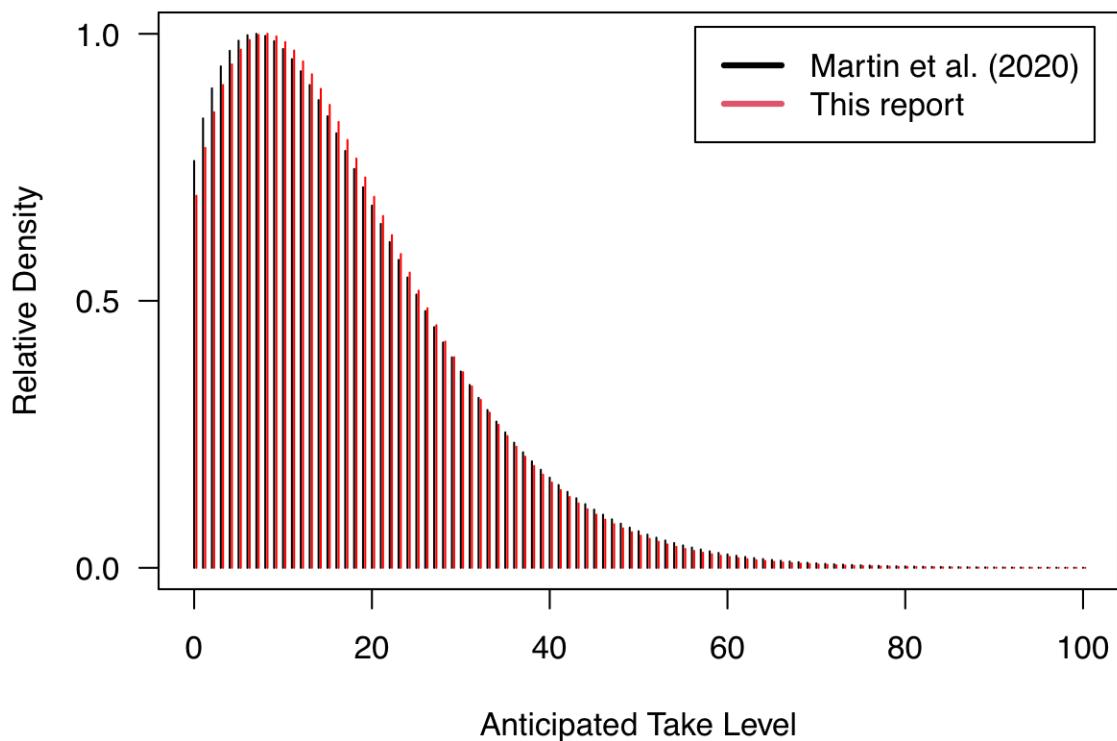


Figure 2. Relative density of anticipated take levels using the location and scale parameters of the Conway-Maxwell-Poisson distribution used in the Martin et al. (2020b) estimated impacts and the updated values used in this report's estimated impacts.

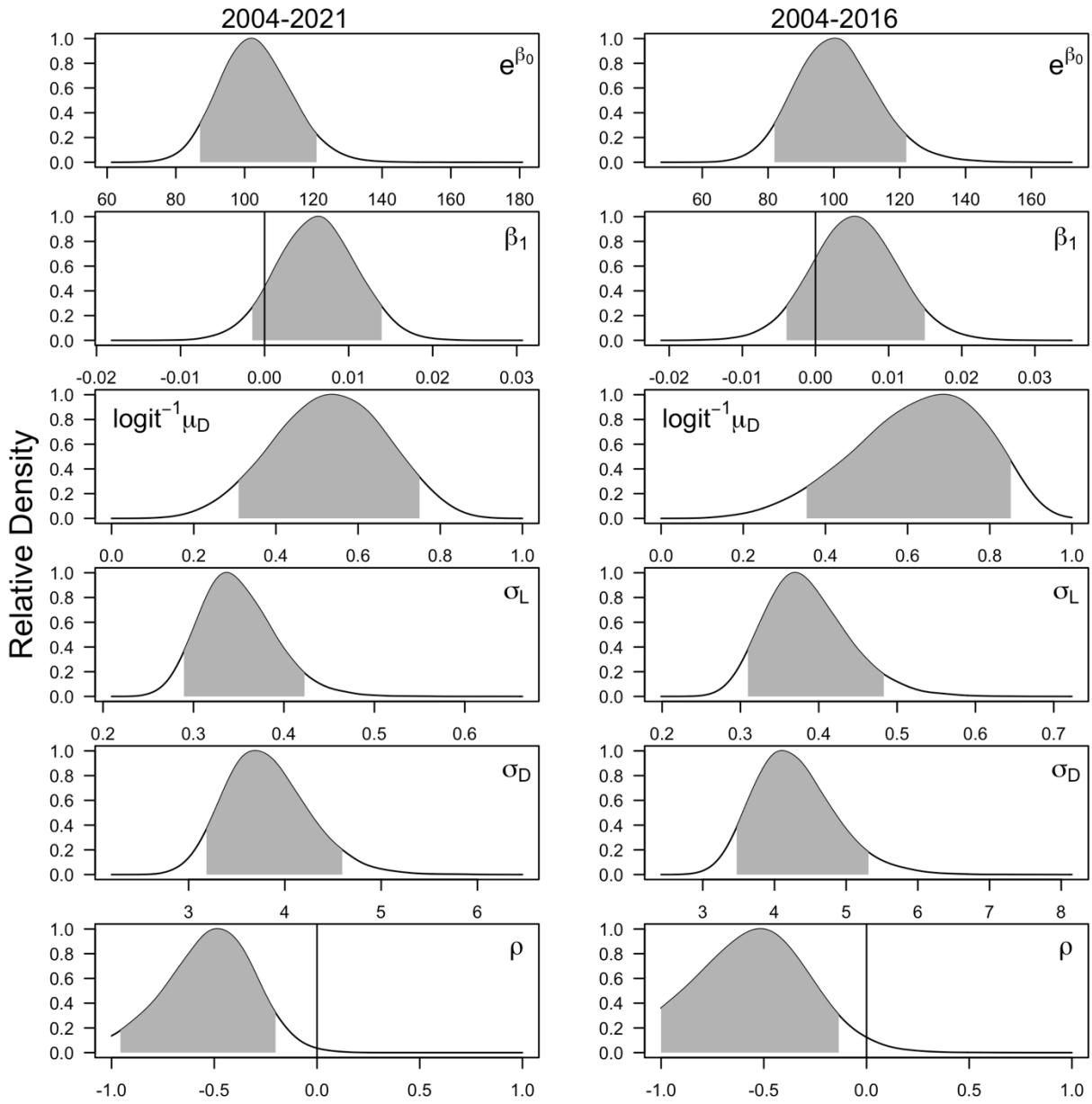


Figure 3. Distribution of the key parameters of the multivariate normal model describing the historical leatherback interactions length (in cm of SCL) and interaction mortalities. e^{β_0} describes the expected interaction length, β_1 describes the change in interaction length as a function of cohort strength, $\text{logit}^{-1} \mu_D$ describes the interaction mortality, σ_L is the standard deviation of the log-transformed lengths, σ_D is the standard deviation of the logistic-transformed interaction mortality, and ρ is correlation coefficient between the log-transformed lengths and logistic-transformed interaction mortality.

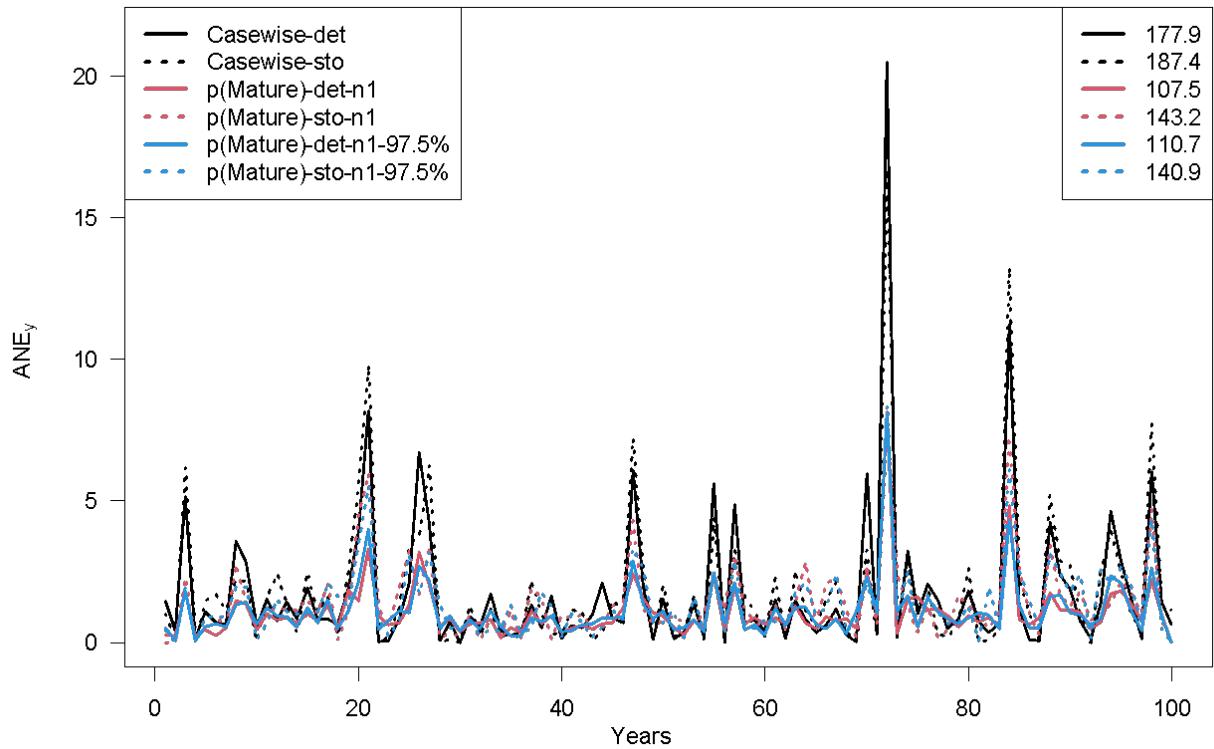


Figure 4. Comparison between ANE calculations for the deterministic (det; solid lines) and stochastic (sto; dashed lines) runs. Different ANE calculations were the case-wise ANE calculation in Martin et al. (2020 a,b), the probability of maturity ANE calculation presented here using 99% of L_∞ (p(Mature)) and using 97.5% of L_∞ (p(Mature)-97.5%) as fully mature cutoffs. Legend in upper right indicates the total ANE for each ANE calculation and run type over the 100 years. Note these totals are random variables and are provided for illustrative purposes here.

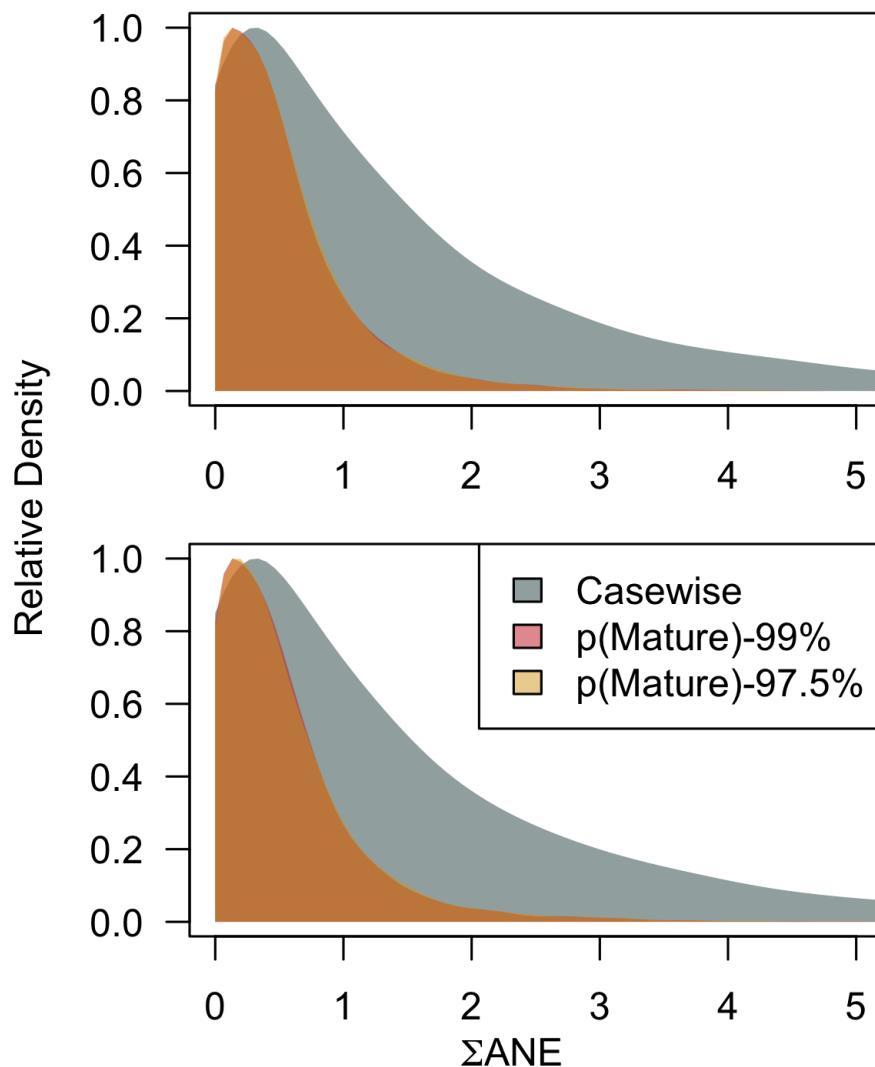


Figure 5. Distribution of the adult nester equivalency for 1,000 simulations of 10 years of projected take using the case-wise ANE calculation in Martin et al. (2020 a,b), the probability of maturity ANE calculation presented here using 99% of L_∞ and using 97.5% of L_∞ as fully mature cutoffs. Note that all distributions shown here used the updated Conway-Maxwell-Poisson parameters in Table 1 to draw anticipated take levels for the top panel and the Martin et al. (2020a,b) parameters in the bottom panel.

TECHNICAL APPENDIX TO:
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OVERVIEW

Martin et al. (2020b) presented estimates of the impacts of fishery interactions with Leatherback sea turtles (*Dermochelys coriacea*) by the Hawai'i-based deep-set longline fishery (DSLL). A key feature of this analysis was the conversion of past and future interactions into adult nester equivalents (ANE). This conversion used the size of turtles incidentally caught in the fishery to estimate the maturation stage based on the length at maturity and, for juveniles, calculated the number of years to the first year of nesting. The survival to first nesting was used to convert a juvenile into an adult nester equivalent (Equation 1):

$$ANE = \begin{cases} \frac{\varphi^Y}{RI} \times P_{SEX} \times D & \text{if Juvenile} \\ 1 \times P_{SEX} \times D & \text{if Adult} \end{cases} \quad \text{Eq. 1}$$

where φ is the juvenile survival rate, Y is the years to first nesting, RI is the remigration interval, P_{SEX} is the probability of being female, and D is the interaction mortality rate.

In this technical appendix, we provide additional information on the updates and modifications we made to the Martin et al. (2020b) analysis to reflect the latest fishery interactions since its publication as well as modify the implementation of maturity in the analysis. We detail the modifications made to the maturation schedule and discuss how these change the calculation of the adult nester equivalency. We then compare the maturity implementation from Martin et al. (2020a b) to the modified version presented here.

STRUCTURAL CHANGES TO MARTIN ET AL. (2020 A, B) ANALYSIS

Important functional relationships were updated with new data. The Conway-Maxwell-Poisson distribution was updated to include the most recent information on interactions (see parameter values Table 2). The relationship between leatherback sea

turtle length and interaction mortality was also updated with the most recent information (Table 3) and the parameterization for estimating the covariance between length and interaction mortality was also updated.

Martin et al. (2020b) used data from the years 2004–2016 and the updated data set added information from 2017–2021 (Figure 6). Interactions in 2022 were not included in the analysis as the 2022 fishing season had not yet concluded. The 2017–2021 observed interactions were, in order, zero, two, three, four, and one while the estimated number of interactions were, in order, 0, 12, 14, 31, and 8.

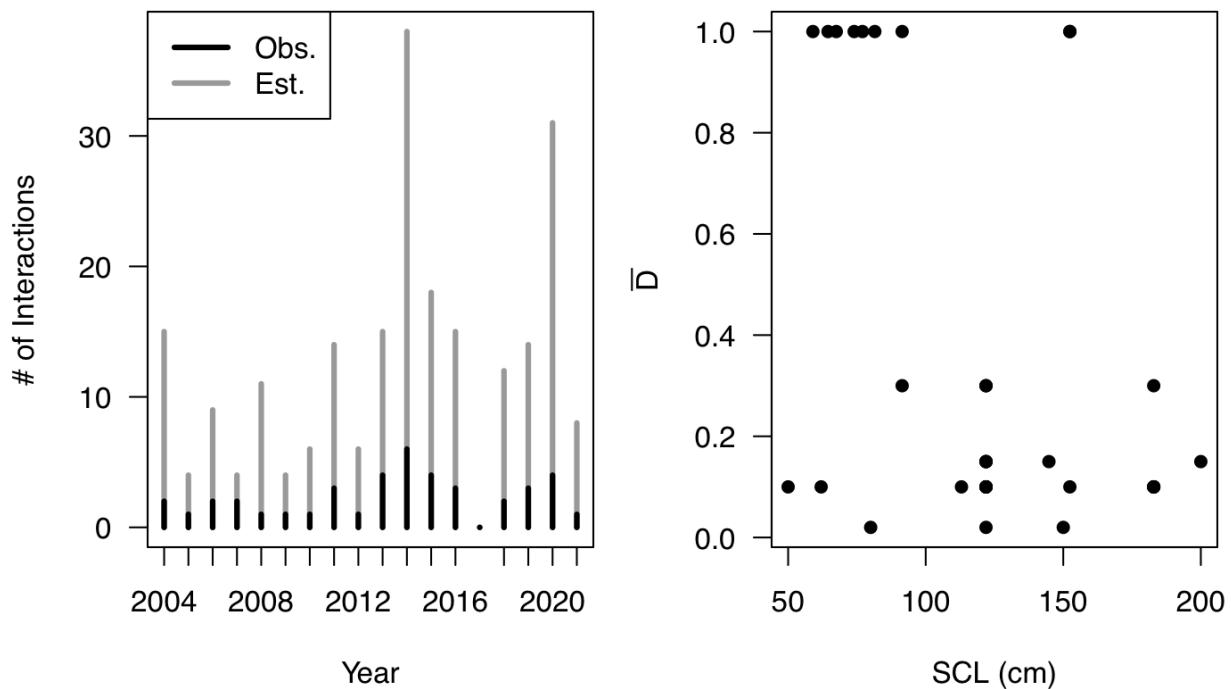


Figure 6. Summary of the historic leatherback take. (left) Number of observed (black line) and estimated (gray line) leatherback interactions per year with the DSLL fishery. **(right)** Mean interaction mortality (\bar{D}) as a function of curved carapace length of leatherback turtles in observed interactions.

Changes to length and fishery interaction mortality model estimation

Cholesky decomposition for covariance matrix estimation

In Martin et al. (2020a b), the length and interaction mortality were estimated in a multivariate normal model to jointly estimate the distribution of lengths and interaction mortalities (Equation 2). For the lengths, the influence of cohorts on the size of turtles was estimated by including the observed number of interactions per year as a linear effect on length. For the interaction mortality, the influence of a turtle's length on its interaction mortality was estimated by estimating the correlation between length and mortality.

$$\begin{bmatrix} L_i \\ D_i \end{bmatrix} \sim MVN \left(\begin{bmatrix} \beta_0 + \beta_1 X_c \\ \mu_D \end{bmatrix}, \Sigma \right) \quad \text{Eq.2}$$

where $[L_i, D_i]$ is the set of curved carapace length (L_i) and interaction mortality (D_i) for each individual observed interaction i that is described by a multivariate normal distribution with two means. The first mean is the mean interaction length described by a linear model with intercept β_0 and slope β_1 as function of cohort strength X_c in terms of numbers of observed interactions. The second mean is the mean interaction mortality, μ_D . The covariance matrix Σ describes how the lengths and interaction mortalities covary and how correlated they are.

This covariance matrix can be challenging to directly estimate (as Martin et al. 2020b did) so an inconsequential modification is to decompose the covariance matrix to the variance ($diag(\sigma)$) and the correlation matrix Ω (Equation 3) and to further decompose the correlation matrix to its Cholesky factorization (Equation 4).

$$\Sigma = diag(\sigma) \Omega diag(\sigma) \quad \text{Eq.3}$$

$$\Omega = LL' \quad \text{Eq.4}$$

Adjustment of the influence of cohorts

In Martin et al. (2020a b), the cohort strength used in the multivariate normal model presented above used the observed number of interactions to set the scale of the β_1 , the slope of the change in interaction length as a function of cohort strength. This was used to predict the length and discard mortalities of the unobserved historical interactions with the DSLL fishery. In this prediction, the difference in the observed and estimated total interactions was used as the cohort strength index. We have subsequently changed the cohort strength index used in the multivariate normal model to the total estimated number of interactions for both the estimation of the model parameters and the prediction of the expected lengths and discard mortalities of the historical take. This change is intended to keep parity between the observed and predicted lengths based on the total number of interactions.

Updated length and fishery interaction mortality relationship

The updated multivariate normal model of the historical interaction lengths and fishery interaction mortalities converged (Figure 3). The median discard mortality underwent a marked shift to lower interaction mortalities from the 2004-2016 value ($\mu_D = 0.643$) used in Martin et al. (2020b) with the addition of the 2017-2021 data (Table 3). This is entirely due to zero interaction mortalities in 2017-2021 despite 10 additional interactions. In the 2004-2016 time period, there were 9 deaths representing 29% of all observed interactions in this time frame. Also of note is the low rate at which interaction length changes as a function of cohort strength (Figure 3). For both the 2004-2016 analysis in Martin et al. (2020b) and this analysis on the 2004-2021 data set, there is no real apparent relationship between a turtle's size and the estimated total number of interactions (Figure 7) which is reflected in the slope values (β_1) being close to zero (or the credible interval overlapping zero).

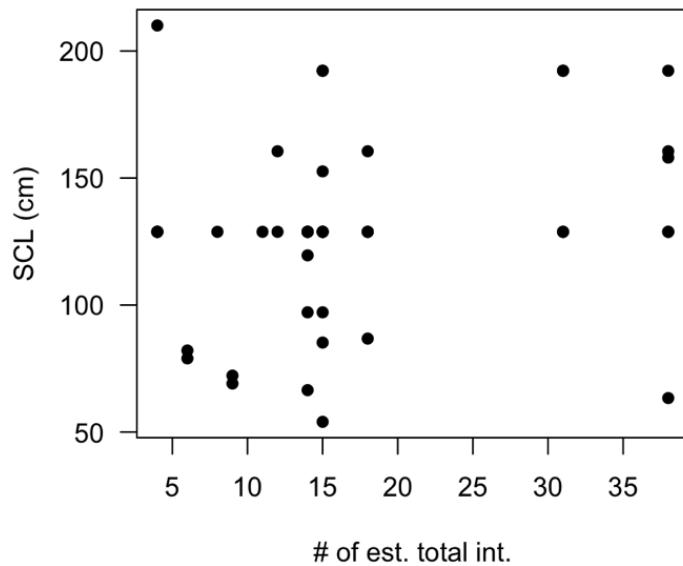


Figure 7. The length of observed leatherback turtles interacting with the DSLL fishery as a function of the estimated total number of interactions per year.

Comparison of historical unobserved interaction lengths and mortality

To facilitate comparison between the Martin et al. (2020b) analysis and the updated analysis¹, we produced a comparison between the distribution of unobserved interactions lengths and interaction mortalities using different data sets (2004-2016 vs. 2004-2021) and different cohort strength indices (observed/unobserved interactions vs. total interactions). These cohort strength indices impact the analysis in the multivariate normal model and in the projection of unobserved historical interactions. In the former, either the *observed* number of interactions was used as the index or the *total* number of interactions was used. For the latter, either the *unobserved* number of interactions was used as the index or the *total* number of interactions was used. The result of this comparison is a slightly lower chance of drawing a larger-sized individual using the total

¹ This comparison was limited and focused only on understanding the effects of specific changes.

index method. For mortality the observed/unobserved index resulted in higher chance of high interaction mortalities than the total index method. With the 2004-2021 data set and the total index, the difference between the chance of getting a low and high interaction mortality was the smallest among the comparisons.

UPDATES TO ADULT NESTER EQUIVALENCY

Updates to maturity relationships

We modified the method for how adult nester equivalency was estimated by altering the way that maturity interacts with the survival rates to first nesting. In Martin et al. (2020a, b), maturity was calculated based on a case function where turtles with a length converted age less than the age at maturity were considered juveniles and those equal to or greater than the age at maturity were considered adults (Equation 5).

$$\text{Stage} = \begin{cases} \text{Juvenile} & \text{if } A_i < A_{mat} \\ \text{Adult} & \text{if } A_i \geq A_{mat} \end{cases} \quad \text{Eq. 5}$$

where A_i and A_{mat} are determined by doing the back-calculation of the von Bertalanffy growth model from either the interaction length or using the length at maturity ($L_{mat} = 0.975 * L_{\infty}$), respectively. The von Bertalanffy parameters were obtained from Jones et al. (2011) along with the 97.5% of L_{∞} definition of L_{mat} .

$$A_i = \left(\frac{1}{-k} \right) \log \left(\frac{L_i - L_{\infty}}{-L_{\infty}} \right) + t_0 = \left(\frac{1}{k} \right) \log \left(\frac{L_{\infty} - L_0}{L_{\infty} - L_i} \right) \quad \text{Eq. 6}$$

Martin et al. (2020a b) identified that a proportion mature relationship could be used to replace this case function. However, the Jones et al. (2011) study did not estimate a length at maturity relationship directly which prevented the estimation of r , the logistic scale. The logistic function can be parameterized many ways but one common parameterization for length at maturity in fisheries is:

$$p(\text{Mature}) = \frac{1}{1+e^{-\frac{L_i-L_{mat}}{r}}} \quad \text{Eq. 7}$$

To estimate a logistic scale, we built an optimization algorithm minimizing the sum of square differences between a 1% chance of maturity for the smallest known nesting female of 110 cm (Lontoh 2014) and the logistic model estimated probability of maturity. The estimated logistic scale was 6.34. However, this parametrization of the maturity ogive is symmetric and results in an undesirably low chance of being mature for turtles greater than L_∞ . We therefore set the final new maturity function as a case function using the probability of maturity defined by the logistic function for turtles less than 99.9% of L_∞ and set as 100% chance greater than 99.9% of L_∞ (Equation 8).

$$p(\text{Mature}) = \begin{cases} 1 & \text{if } L_i \geq 0.99 * L_\infty \\ \frac{1}{1+e^{-\frac{L_i-L_{mat}}{r}}} & \text{if } L_i < 0.99 * L_\infty \end{cases} \quad \text{Eq. 8}$$

It is important to note that this is not really a measure of maturity but really a metric of the first nesting event that is likely to occur at some time after maturation. Depending on when maturation occurs in the migration cycle of a western Pacific leatherback, the first nesting could be imminent or several years later. The resulting maturity ogive from this case function (Equation 8) is shown in Figure 8.

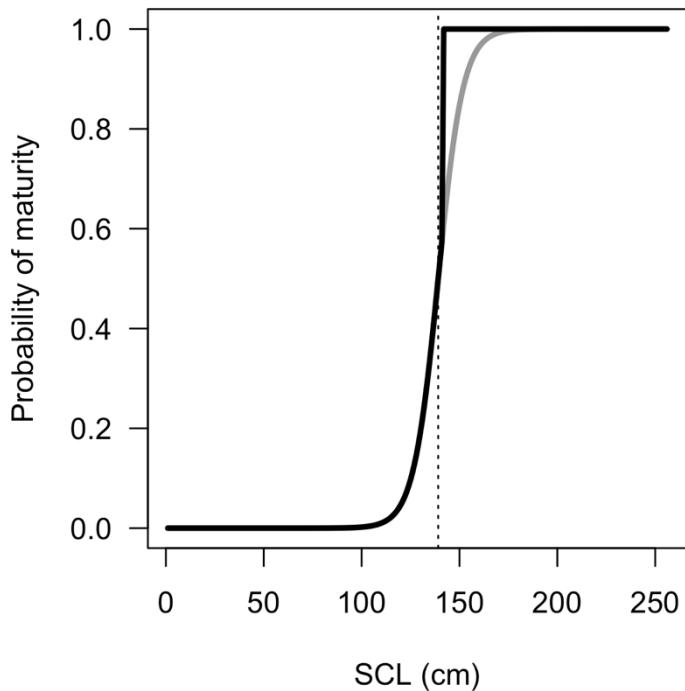


Figure 8. Maturity ogive for western Pacific leatherback sea turtles based on Jones et al. (2011) von Bertalanffy growth parameters and a 1% probability of maturity for the smallest known nesting female at 110 cm SCL. The solid gray line is the maturity ogive while the solid black line is the maturity ogive with an assumed 100% probability of maturity if the length is greater than 0.99 * L_{∞} =141.27 cm SCL. The vertical dashed line is the length at 50% maturity which was set equal to 0.975 * L_{∞} =139.13 cm SCL.

Updates to survival calculations

Martin et al. (2020a b) used the probability of maturity to calculate the number of years until maturity (again, referring to the first nesting event as maturity). This number of years was then used to calculate survival to the first nesting event (Equation 9).

$$p(\text{First nesting}) = \begin{cases} 1 & \text{if } L_i \geq L_{mat} \\ \varphi_j^{Y_i} & \text{if } L_i < L_{mat} \end{cases} \quad \text{Eq. 9}$$

Where φ_j is the juvenile survival rate and Y_i is the years until first nesting ($Y_i = A_i - A_{mat}$). With the update to maturity, both the survival rate and the years until

first nesting are changed. For the survival rate, the probability of maturity is used to create a mixture of the juvenile and adult survival rates (Equation 10).

$$\varphi_y = (1 - p(Mature)_y)\varphi_j + p(Mature)_y\varphi_a \quad \text{Eq. 10}$$

where φ_y is the survival rate in a given year after capture resulting from the mixture of juvenile (φ_j) and adult survival rates (φ_a) with the mixture being dictated by the $p(Mature)_y$, the probability of being mature in a given year after capture.

The result in the difference between the case-wise maturity function (Eq. 5) and the probability of maturity function (Eq. 8) is that the definition of 100% probability of maturity is different; the former is set at L_{mat} and the latter is set at $0.99 * L_\infty$. As the probability of maturity survival mixes with the higher rate of adult survival to earlier ages, the survival to full maturity at any given age of capture is higher than the case-wise function. However, when set to the same number of years to “fully mature”, such as L_{mat} or $0.99 * L_\infty$, the probability of maturity function results in slightly higher survivorship for turtles less than “fully mature” than the case-wise function survivorship.

Update to adult nester equivalency calculation

Martin et al. (2020a b) chose to assume that adults, defined by Eq. 5, were removed from the population in the year of capture while juveniles, defined by Eq. 5, were first removed in the first year of nesting, defined as $A_{mat} - A_i + Y_c$ where Y_c is the year of capture. To account for the average remigration interval of 3 years, each adult turtle, either at capture or after growing to first nesting, was then assumed to return every three years after the first nesting year. This three-year cycle served to pass on some of the variability in the estimated number of *historical* interactions per year into the total adult nester equivalents interacted with per year by the fishery (Figure 9).

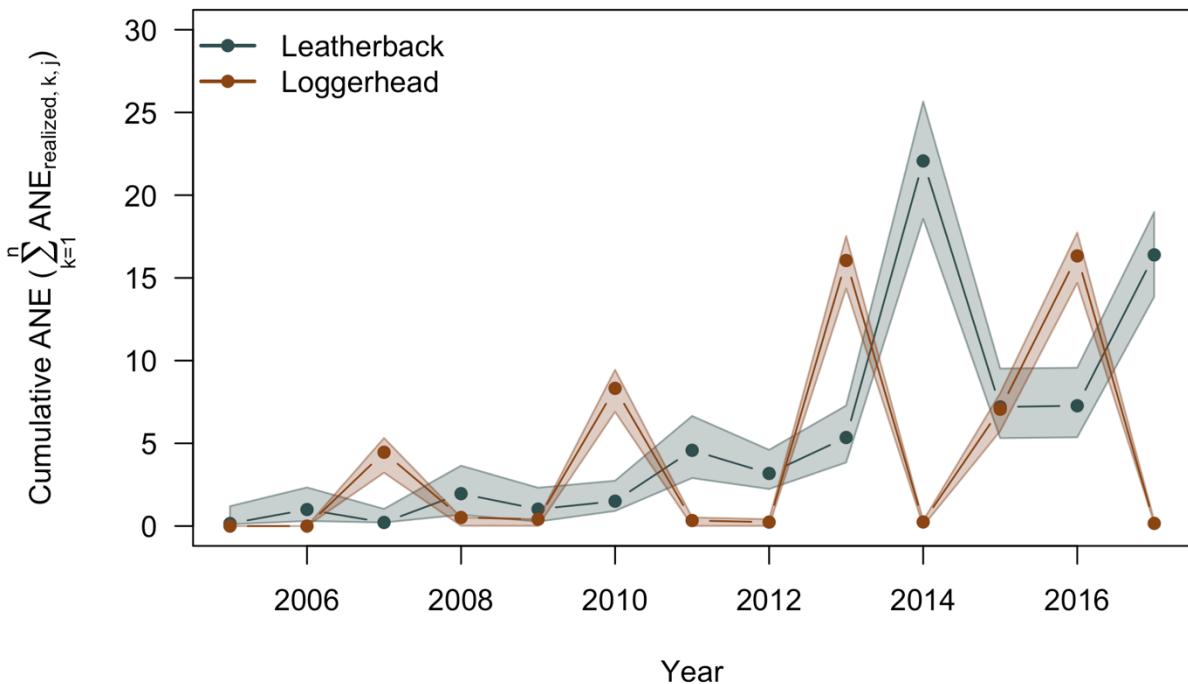


Figure 9. Reprint of Figure 4 in Martin et al. (2020b) of the cumulative adult nester equivalents interacted with by the DSLL fishery demonstrating the variability seen in the observed/estimated annual number of interactions being passed along to the ANE calculation under the Martin et al. (2020a b) calculation method.

The result of the scheme for the adult nester equivalents is:

$$ANE_{i,y} = \begin{cases} \varphi_a^{RI} & y > 1 \\ \varphi_j^{\max\{0, A_i - A_{mat}\}} * p(F) * D_i & y = 1 \end{cases} \quad \text{Eq. 11}$$

where in the first year of nesting, $y = 1$, the juvenile survival rate (φ_j) is raised to the maximum of zero or $A_i - A_{mat}$ (thus, adults have 100% survival) and multiplied by the probability of being female ($p(F)$), and the individual interaction mortality (D_i). In subsequent years after the first nesting, the adult survival rate (φ_a) is applied and raised to the remigration interval, RI . Note this is notation modification from Eq. 22 of Martin et al. (2020a) to reflect the equations herein. Martin et al. (2020 a,b) modified Equation 11 when projecting the future impacts of the fishery:

$$ANE_{i,y} = \begin{cases} 1 * p(F) * D_i & \text{if Adult} \\ \varphi_j^{\max\{0, A_i - A_{mat}\}} * p(F) * D_i * \frac{1}{RI} & y = 1 \end{cases} \quad \text{Eq. 12}$$

assuming that adults nested in the year of capture while juveniles nested at some point after maturing (Eq. 5) and, thus, were divided by the remigration interval. This modification was to account for the historical population abundance needing to be corrected for the loss of a turtle in the past and not returning to the nesting beach in subsequent years. When projecting the population forward this was not necessary as the yearly losses influenced the population size in the future (Equation 13; Equation 24 in Martin et al. (2020a)):

$$N_{y+1} = (N_y - ANE_y) * e^r \quad \text{Eq. 13}$$

where N_y is the population size in a given year, ANE_y is the sum adult nester equivalents interacted with by the fishery, and r is the population growth rate.

In order to calculate the adult nester equivalency using the probability of maturity the remigration cycle scheme used in Martin et al. (2020a b) can no longer be used (Eq. 11-12). Instead, a sequential series of calculations is used to develop the year-specific survival, φ_y , and ultimately the adult nester equivalency of each interaction in a given year.

1. Each turtle's size at capture is determined either by the observer observation or predicted using the MVN model.
2. Then each turtle is grown each year until reaching 99% of L_∞ following a von Bertalanffy growth model using Jones et al. (2011) after which the turtle is assumed to be 99% of L_∞ .
3. Then the year- and size-specific probability of maturity is calculated using Eq. 8

4. A Bernoulli draw is performed based on the year-specific probability of maturity to determine the maturation year.
5. Then the year-specific survival is calculated using Eq. 10 for the years between the year capture and the year of maturation.
6. The product of the year-specific survivals between the year capture and the year of maturation are then calculated and multiplied by the probability of being female, by the one over the remigration interval, and by the individual specific interaction mortality either coming from the Ryder et al. (2006) rubric or predicted from the MVN model to calculate the year- and individual-specific adult nester equivalency (Equation 14).

$$ANE_{y,i} = \prod_{y=1}^{Y_{mat}-Y_c} \varphi_{y,i} * p(F) * \left(\frac{1}{RI}\right) * D_i \quad \text{Eq. 14}$$

where $\prod_{y=1}^{Y_{mat}-Y_c} \varphi_{y,i}$ is the product of the year-specific survivals between the year capture (Y_c) and the year of maturation (Y_{mat}).

Note that the remigration interval is applied to all turtles that are interacted with in these calculations. This is because the stage of a turtle is not explicitly defined (Eq. 5) and, instead, uses the probability of maturity. The stochastic component of when maturation occurs using a Bernoulli draw means that we can relax the conservative assumption of adults nesting in the year of interaction and instead account for the remigration interval for each individual with which the fishery interacts.