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Monte Carlo simulation modelling of possible measures to reduce impacts of
longlining on oceanic whitetip and silky sharks

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Revision 2: 30 July 2015

In Rev 1 the result plot for the additional scenario had been included for oceanic whitetip shark, but not silky shark. It has been included here now (Figure 6).

Revision 1: 29 July 2015

In response to a comment on the initial version of this paper we have added an additional scenario (prohibiting both wire traces and shark lines) to assist with consideration of the current shark CMM, in particular the consequences of allowing CCMs to choose which measure to apply (shark line or wire trace restrictions).

This scenario has been added to the text, figures, and tables as appropriate.

Executive Summary

The paper develops and applies a model for how oceanic whitetip shark and silky shark might interact with longline gear; using it to quantify potential sources of fishing-related mortality. It integrates available information of gear characteristics, spatial differences in the density of the two species, and the results of previous studies on catchability and survival. With this model we evaluate four simple potential management measures: (1) removal of shallow hooks; (2) removal of shark lines; (3) requirement for circle hooks; and (4) requirement for monofilament leaders.

The analyses, and measures considered, represent an example of what can be undertaken with the simulation model developed and we anticipate examining other scenarios at the request of SC11 or CCMs.

The key conclusions of the analyses are:

1. There are still critical gaps in our knowledge of longline gear configurations – with respect to the key variables important to sharks – for almost all Distant Water longline fleets due to the paucity or absence of observer data;
2. Collection of data on hook location (i.e., whether the hook was swallowed, or the shark was hooked in the lip), and how oceanic whitetip shark and silky shark are released (e.g., cut-off on the line in water or brought on-board and hook retrieved) will be critical for better understanding the potential fishing-related mortality and the effectiveness of the current Conservation and Management Measures (CMMs). We recommend that collection of these data by observers be considered;
3. There are few relevant scientific studies of likely rates of release mortality for oceanic whitetip shark and silky shark caught and released under commercial fishing conditions. This should be a priority for field studies, but the design of such studies should consider information under (2) above, particularly how sharks are released; and
4. Given available data and assumptions made in the analyses - the following results were obtained from application of the model through Monte Carlo simulation testing:
 - The initial interaction of silky shark and oceanic whitetip shark with longline gear can be reduced by both the banning of shark lines or the removal of “shallow-hooks”, which we defined as the three hooks closest to the start/end of the basket;
 - Banning shark lines has the potential to reduce fishing mortality by 14.7% and 23.3% for silky shark and oceanic whitetip shark respectively, and removing shallow hooks has the potential to reduce fishing mortality by 11.7% and 6.7% respectively;
 - Banning wire trace – while unlikely to influence initial interaction – lead to increased bite-offs which resulted in the greatest reductions in fishing mortality of the measures

considered – 17.6% and 23.3% for silky shark and oceanic whitetip shark respectively;

- Prohibiting both shark lines and wire trace is predicted to reduce mortality by 29.4% and 40% for silky shark and oceanic whitetip shark respectively.
- The tendency for greater lip-hooking with circle hooks and therefore fewer bite-offs meant little predicted benefit from requiring circle hooks; and
- Given the high levels of fishing mortality experienced by these two species, it is unlikely that the options under the shark CMM (2014-05) of **either** banning shark lines **or** wire traces will result in sufficient reductions in fishing mortality. Strengthening this measure may be necessary.

We invite SC11 to consider the specific recommendations of this work and the preliminary results from the model. We particularly invite comments on the model assumptions, potential sources of information to better support the model, and potential mitigation measures that could be examined.

1 Introduction

MSY-based reference points from stock assessments for oceanic whitetip shark (Rice and Harley, 2012) and silky shark (Rice and Harley, 2013) indicated that the stocks were experiencing overfishing ($F_{current}/F_{MSY} > 1$) and in an overfished state ($SB_{current}/SB_{MSY} < 1$). As a consequence the Western and Central Pacific Fisheries Commission (WCPFC) prohibited the retention of these species (WCPFC, 2011, 2013), and initiated analytical work of existing longline observer data to determine factor relating to the capture and life status of these species. Following the analyses provided in Bromhead et al. (2013) and Caneco et al. (2014), the WCPF Commission banned the use of shark lines (WCPFC, 2014) and then requested that we use the results from this work, and other relevant work, to examine the potential impacts of different mitigation measures on total fishing related mortality for oceanic whitetip shark and silky shark.

This paper describes the development of a model of the capture and handling of sharks by longlines, describes how the various model inputs were derived, then describes the results of a set of evaluations where we compare the performance of different potential mitigation measures. This analysis encountered several data issues and data gaps which are then described within the context of suggested recommendations for the SC to consider.

2 Methods

This analysis was comprised of several steps which are briefly outlined below and then expanded on in the follow sections:

1. Development of a process model of how oceanic whitetip shark and silky shark can interact with a longline fishing gear, including the key factors likely to influence life status;
2. Development of a spatial surface of total longline fishing effort in terms of hooks deployed with particular gear configurations;
3. Development of a spatial surface of oceanic whitetip shark and silky shark abundance so that the location of deployment of fishing gear relative to the density of the two shark species can be taken into account, e.g., fishing patterns in areas of highest abundance will be more important to the overall longline impact than fishing in areas of low density;
4. Use information from previous analyses and the literature to parameterise the model in (1) in terms of values (or probability distributions) for catchability and survival etc.;
5. Develop several management intervention scenarios, e.g., a total prohibition on the use of shark lines, wire traces, and shallow hooks etc.; and
6. Evaluate the scenarios with the model and compare key outcomes.

2.1 Development of the process model

The first step in the analysis was to develop a model that describes how the two species encounter longline fishing gear and how different aspects of the way in which the longline gear is configured can impact on encounter rates and subsequent fishing mortality.

In developing the model we considered models developed by others (e.g., [Patterson et al., 2014](#)), reviews of shark mitigation (e.g., [Clarke, 2011](#); [Curran, 2014](#)) and the results of our own previous analyses of the impacts of longline gear characters on catch rates and fate (e.g., [Bromhead et al., 2013](#); [Caneco et al., 2014](#)).

The model was separated into two parts:

The catch component: what were the factors that determined how many sharks would encounter and be at least briefly hooked on the gear ([Figure 1](#)); and

The fate component: what happens to those sharks that are hooked ([Figure 2](#)).

The catch model ([Figure 1](#)) firstly required a determination of effort: a spatial surface where effort was weighted based on the estimated relative abundance at that location (see [Section 2.4](#)). [Caneco et al. \(2014\)](#) showed differential catching efficiency of shark lines, shallow hooks (defined here as the 3 hooks at the start/end of the basket), and deep hooks (the remainder of hooks in the basket), so effort was characterized by these three categories and this was used to predict the catch. We also monitored whether the shark was caught on a wire or monofilament trace. We assumed that leader material did not impact of catchability ([Afonso et al., 2012](#)), but was important to follow for the fate model.

The fate model was more complex and started with a ‘fork’ as to whether the sharks that had been caught on the line were hooked in the mouth area (i.e., lip hooked) or whether they had swallowed the hook (i.e., gut hooked). In our model this break down was dependent on the hook types used, and hooking location determined the likelihood of a shark biting off the line, and subsequent survival probabilities at different stages of the process (i.e., gut-hooked fish are less likely to survive release or escape than lip-hooked fish).

The first step for hooked fish was the ‘bite-off’ where fish potentially escape from the line. We assume that hooking location and leader material influences the probability of biting off, with minimal bite-offs assumed for wire leaders, and higher bite-offs for gut hooked fish as the leader is exposed to contact with their teeth.

For those that remain on the line, we have estimates of the probability that they will be dead once they are retrieved to the side of the boat. For those that are alive at the time of retrieval, they can either be released while in the water, or brought on-board and then returned to the water. Their subsequent mortality depends again on hooking location and where they were released.

2.2 Data

Two data sets were used for this analysis.

The first was raised $5 \times 5^\circ$ longline effort data by vessel-flag for the years 2008–2013 were aggregated over time to give a spatial surface of hooks set by vessel-flag. We excluded effort outside the equatorial region (20° N– 20° S) as the abundance of the two species was generally highest in this area.

The second data set was observer records by vessel-flag again covering 2008–2013 and the same equatorial region. These data were used for two purposes (1) The relative abundance surface described in Section 2.4; and (2) to characterize the gear characteristics for each flag. We were specifically interested in shark line use, and the leader materials, and hook types used. While there is likely some spatial and temporal differences within a fleet in these variables, the data are so sparse that even a description at the flag-level (without including a spatial component) was uncertain for some fleets.

2.3 Effort spatial surface

We applied the flag-specific gear characteristics (probabilities of different gear use) from the observer data³ to the flag-based $5 \times 5^\circ$ longline effort data (Table 1) to give a spatial breakdown on hooks set with different gear configurations. Once this was done for all of the major fleets (we covered

³For Japan we assumed the same gear characteristics as for Korea due to the lack of observer data for Japanese DW vessels and the values for the United States were provided by Dr Keith Bigelow

those fleets comprising 95% of the effort in the region), we then aggregated the data set over flags (i.e., once we had split out the effort into gear configurations, then flag was no longer important) so we had a spatial surface with effort by different gear configurations.

At this stage we then applied the species-specific relative abundance surface so that effort was scaled relative to abundance of the species in the location, e.g., a shark line set in a location with high shark abundance will yield a higher expected catch than a shark line set in an area of low shark abundance.

Once this spatial rescaling had occurred, we then aggregated the effort over space to leave a single vector of the number of effective (correcting for abundance) hooks set with different gear configurations.

2.4 Relative abundance surface

As noted above, if the use of particular gear configurations differs in space (e.g., different flagged vessels go fishing in different areas) and the abundance of the two species is not uniform, then we want to account for the overlap between gear-types and shark abundance. The first part is taken into account in the construction of a spatially explicit layer of effort by gear-configuration, and the second we describe here.

The approach taken is very similar to the construction of a relative weight surface for the MULTIFAN-CL stock assessments (see Tremblay-Boyer et al., 2015). We use all available observer data for the period 2008–2013 for this analysis.

We constructed a simple model of relative abundance where catch in counts were fitted against the absolute value of latitude with an effort offset (in hooks). We used thin-plate splines from the `mgcv` package (Wood, 2006) and assumed a negative binomial error distribution. We then predicted relative abundance for 5-degree latitudinal bands and standardized to have the maximum value equal to 1.

In considering the best spatial model to predict over, there were three models considered: (a) predicting a two-dimensional spatial surface; (b) predicting a latitude surface and assuming abundance was constant across longitude, and (c) predicting an absolute latitude surface where we assume that relative abundance is mirrored north and south of the equator, and constant across longitude. While we considered all three models, in the end we felt that the simplest model (c) was the best to use because the more complex models were biased by the spatial coverage of observer data. Predicted surfaces for oceanic whitetip shark (OCS) and silky shark (FAL) for models (a) and (c) are provided in Figure 3.

2.5 Parameterizing the catch and fate models

Below we describe the inputs to the fate and catch models and the species-specific values are provided in Tables 2 and 3 and Figures 4 and 5.

2.5.1 Catch model

Total numbers of hooks: see Sections 2.3 and 2.4 above.

Basket size: Determined from WCPO longline data underpinning Caneco et al. (2014). Expressed here as an average size, although there are a range of sizes observed.

Hook position: Determined from WCPO long-line data as per Caneco et al. (2014). Three positions considered, Shark lines/shallow hooks/deep hooks, as previously defined. Parameterised as log-normal distributions, with parameters estimated from models fitted within Caneco et al. (2014). Catch rates and their uncertainty were estimated via Generalized Additive Models (GAMs) using log-link, Tweedie-errors models. Parameters and their standard errors are used directly. These are the means and SE's of the estimated coefficients of the linear predictor.

2.5.2 Fate model

Probability of lip- or gut-hooking: Only the style of hook is considered to influence hooking location. Afonso et al. (2011) offer species-specific estimates for J versus C hook types.

Probability of bite-off: Afonso et al. (2012) estimated shark bite-off rates. However they excluded hooks where $> 20\text{cm}$ of the line was removed. This suggests that they excluded all gut hooked fish. Their analysis was used to estimate bite-off rates of lip-hooked fish, estimates for gut-hooked fish were inferred from Ward et al. (2008) who calculated catch rate differences between wire trace and monofilament line under the assumption of zero bite-offs for the former.

Probability of mortality given bite-off: No information – expert opinion.

Probability of mortality at time of retrieval: Estimated from SPC data (Caneco et al., 2014).

Probability release in water (vs. brought-on, then released): No information – broad distribution assumed with mean of 0.5.

Probability of mortality upon release: Post-release mortality for blue sharks has been estimated to range from 15–19% (cited in Curran, 2014). In this analysis the low end of the range (15%) (Musyl et al., 2011) was used to estimate in-water lip-hooked fish as these are likely to have the highest survival rates. Mortality of in-water released gut hooked fish (19%)

was estimated from [Campana et al. \(2009\)](#). There is no information to inform specific mortality rates of silky or oceanic whitetip sharks landed on the vessel and released. [Clarke \(2011\)](#) estimated reductions in mortality when considering the effectiveness of management measures that require sharks to be released. Without any clear guidance on post-release survival a mid-point of the available data (34% mortality) was used for on board released lip-hooked fish and the top end of the range (44% mortality) for on-board gut hooked fish released.

2.6 Management scenarios examined

In this preliminary examination we have compared the implementation of four sets of rules regarding longline gear specifications and compared these to our best estimate of “current” longline gear specifications (“status-quo”). For our analysis, current, is prior to implementation of the shark CMM ([WCPFC, 2014](#)), which required CCMs to prohibit either the use of shark lines or wire leaders.

The five options considered are listed below. We stress that this model is being developed to consider a range of options and even combinations of options, but we have kept the scenarios simple here in the first instance:

Shark lines: Here we assume that all shark lines are removed.

Wire leaders: We assume that all wire leaders are switched to monofilament.

Shallow hooks: After [Watson and Bigelow \(2014\)](#) we reduced the fishing power of a longline set based on the catchability for the three hooks closest to the start/end of the basket. The hooks were not redistributed.

Circle hooks: We assumed that only circle hooks were used. These are reported to reduce gut hooking which may increase release survival, but decreases bite-offs.

Shark lines and wire traces: Here we assume that all shark lines are removed and all wire leaders are switched to monofilament.

We note that none of these options specifically model the choices that exist within the shark CMM. At this stage we do not know the choice the individual CCMs will take. If it is assumed that those that use shark lines, prohibit their use, while those that don’t use them, also prohibit their use, then the ‘shark line’ scenario represents the closest approximation to the likely implementation of the measure.

2.7 Monte Carlo simulations

All of the Monte Carlo simulations were implemented using R ([R Core Team, 2013](#)). The steps for undertaking the simulations are described below:

- Apply the ‘management scenario’ to the base fishing effort to create a new effort layer. In each scenario, hooks from a ‘restricted’ gear category were redistributed to permissible gear categories, e.g., if wire trace was restricted then all wire trace effort was transferred to monofilament leaders and other characters such as hook-type were not changed.
- Apply the catch and fate models 10,000 times – each simulation has different draws from each input distribution.
- Keep track of catch, mortality, and survival at every stage of the catch and fate models.

We compared absolute values of total catch and total mortality across scenarios, and also the different mortality options (i.e., where you can die in the process) and the relative change in fishing related mortality from the status-quo option.

3 Results

Silky shark

Of the four measures considered, only removal of shallow hooks and shark lines were ‘allowed’ to impact on the total catch (i.e., sharks initially hooked) of sharks and removal of shark lines had slightly larger catch reductions for silky shark than removal of shallow hooks (Figure 6). For silky shark all four measures resulted in a reduction in total fishing-related mortality (Figures 6, 7, and 8, and Table 4).

When comparing total mortality from a scenario, to catch from the status-quo we have an estimate of relative fishing mortality (Table 4 and Figure 4). Banning wire traces (17.6% reduction) had a slightly greater reduction in mortality than removal of shark lines (14.7% reduction). They achieved their reductions in different ways, removal of wire traces through increased bite-offs which suffered low assumed escapee mortality and removal of shark lines through reduced catches (Figures 6 and 7). Removing both wire and shark lines resulted in a 29.4% reduction. Removal of shallow hooks had an 11.7% reduction in mortality through the same mechanisms as removing shark lines (i.e., reduced catch), while use of circle hooks had only a very small benefit (2.9% reduction) as improvements in survival through lip-hooking were offset by increases in mortality associated with less shark being able to bite-off the line and therefore being retained by the gear (Figure 7).

Oceanic whitetip shark

The results for oceanic whitetip shark were generally similar to those of silky shark with slight differences due to catchability and other parameter values that differed between species (see Tables 2 and 3).

Removal of shallow hooks had a relatively smaller impact on overall catch for oceanic whitetip shark than for silky shark because oceanic whitetip shark are more vulnerable to shark lines than shallow hooks when compared to silky shark (Figures 5 and 4; panel a). Unlike for silky shark, not all measures reduced mortality for oceanic whitetip shark. In particular the use of circle hooks resulted in a predicted 3.3% increase in mortality which is driven by its higher lip-hooking tendency (and therefore lower bite-off rate). Banning of wire traces and banning shark lines both had 23.3% reductions in mortality, while removal of shallow hooks only had a 6.7% reduction due to the lower catchability of oceanic whitetip shark on these hooks. Removing both wire and shark lines resulted in a 40% reduction.

4 Discussion

This exercise is particularly useful for better understanding a complex problem, aside from the actual examination of potential management measures, it has the benefit of requiring one to specify the nature of the interactions between the two species and longlines through a model, and examine whether the necessary data/information exist to parameterize the model. We discuss these issues below.

4.1 Data / information issues

There were two general types of data/information problems encountered in this analysis, firstly those relating to data which should exist, but does not, and the second relating to new information that should be collected.

In terms of the first challenge, the analysis was again hampered by low levels of observer coverage and close to zero observer coverage for several key distant water fleets. Despite new rules regarding observer coverage, no recent observer data was available for distant water vessels from China, Chinese Taipei, Korea, and Japan. The reasons for these data gaps include data not being submitted to WCPFC, to data only recently submitted that is being entered / migrated into the data bases. Data that were available for China and Chinese Taipei, was primarily from off-shore vessels that were based in the EEZs of Pacific Island countries and therefore these data may not be representative of the larger distant-water vessels. Improved coverage of observer data will also allow the development of more fine-scale abundance surfaces. This will allow consideration of spatial management measures.

For the second issue, the development of the model highlighted some key areas where data collection should be initiated and/or particular experiments undertaken. Some of these are specifically required for better determining the likely fishing-related mortality of the two shark species for which retention is now prohibited. We recommend that, where practical, observers on longline

vessels collect hooking location, specifically whether the hook is visible (i.e. lip-hooked) or not-visible (i.e., gut-hooked) as this is an important factor in release mortality. We also recommend that information be collected on how these two species are released, specifically whether they were released while in the water or whether they were brought on-board the vessel first, and whether an attempt was made to remove the hook. In conjunction with this information, it is recommended that a set of experiments be undertaken to estimate release survival under the types of conditions of pre-release ‘treatment’ received (e.g., after [Campana et al., 2009](#)).

4.2 Model

We developed a two-step model building on previous studies of factors impacting shark catch rates and mortality ([Clarke, 2011](#); [Bromhead et al., 2013](#); [Caneco et al., 2014](#)) and other models ([Patterson et al., 2014](#)). The model made quite strong assumptions about what factors impact catch rates (e.g., location and hook depth) and what impacts on release mortality (e.g., hooking location and how released). This model can be expanded to include new processes and factors that are likely to be important. These could include shark size, bait type, location/water temperature (for release survival), but the main limitation will be the development of the effort surface that contains these characteristics.

Further development in the model and/or the results of any experiments could result in new potential data needs. One benefit of a model such as this is that it can be used to assess the sensitivity of mortality estimates to uncertainty in particular parameters and processes. Such analyses could be used to help prioritize observer data collection and research experiments.

This model was developed in the R software ([R Core Team, 2013](#)) which makes it relatively accessible to other scientists, but we are particularly interested in implementing the model using [Shiny](#)⁴ which is a set of libraries within R that allow the development of web-based applications. It is possible to develop the application so that it runs on a website accessible to all, and users have the ability to change model inputs and build new scenarios to test. We welcome the consideration of SC11 as to whether this is considered a priority at this time.

4.3 Mitigation measures

Notwithstanding the concerns raised above, we have used available data to evaluate some measures and the main goal of the exercise was to compare different mitigation measures for silky shark and oceanic whitetip shark. Both species are assessed to be below SB_{MSY} and experiencing levels of fishing mortality well in excess of F_{MSY} . It is now prohibited to retain either of these species ([WCPFC, 2011, 2013](#)). From 2015, the use of either shark lines or wire trace has been prohibited ([WCPFC, 2014](#)), so evaluation of this measure was one of the major undertakings in this analysis.

⁴<http://shiny.rstudio.com/>

Based on observer estimates of shark line use, the banning of this approach does have scope to have a significant impact on overall mortality of these two species, with estimates of reductions in fishing-related mortality of 14.7% for silky shark and 23.3% for oceanic whitetip shark. What is promising about this measure is that there should be minimal impact on the catch of other species which are likely to be of value (Bromhead et al., 2013). A similar measure is the removal of shallow hooks, i.e., the three hooks closest to the start/end of the basket. This is likely to have a greater impact on catch of other species (Watson and Bigelow, 2014), and from our analysis could result in reductions in fishing-related mortality of 11.7% for silky shark and 6.7% for oceanic whitetip shark. As noted by Watson and Bigelow (2014) the reductions in catch of desirable species could be itself mitigated by redistributing the shallow hooks in the middle of the basket (i.e., make them deep hooks), but we have not considered this here.

Both of those measures directly reduce the catch of the longline gear, i.e., by reducing hooks placed in the shallow water inhabited by these two species (Musyl et al., 2011), while other measures examined attempted to improve the ‘fate’ of a shark once it was hooked. Removal of wire traces had the greatest impact on fishing mortality for both silky shark (17.6% reduction) and oceanic whitetip shark (23.3% reduction). This was primarily driven by the increase in sharks biting-off and escaping, assuming these fish experienced low mortality relating to the bite-off process.

The requirement to use circle hooks had very little impact on overall fishing mortality and in fact predicted an increase in mortality for oceanic whitetip shark. The key driver of this result is the expectation that circle hooks lead to more lip-hooked sharks and these are less able to bite-off the gear and therefore suffer higher mortality. This result is will be sensitive to the relative release mortality experienced by lip- and gut-hooked individuals and will hopefully be addressed in any release mortality experiments.

The current CMMs have the following requirement for releasing captured silky shark and oceanic whitetip shark: *“to release any silky shark that is caught in the Convention Area as soon as possible after the shark is brought alongside the vessel, and to do so in a manner that results in as little harm to the shark as possible”*. This does not make specific requirements around removal of hooks and whether sharks can be brought on-board. Further experimental work and simulation modelling could inform further consideration of these provisions to obtain better reductions in mortality for these two shark species.

As noted above, the levels of fishing mortality experienced by these two species is well in excess of F_{MSY} and the first impression from the analysis conducted here is that giving the option of prohibiting shark lines or wire traces is unlikely to be sufficient to reduce fishing mortality to levels that will rebuild these populations – though at the time of this analysis we do not know which options CCMs have taken. Banning both would have considerable stronger benefits. SC11 should consider whether further measures are warranted at this time and/or whether the results of this analysis be incorporated into projection runs for the two shark species integrating both current levels of fishing effort and the likely impact of the ban on shark lines.

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Table 1: Proportion of longline gear use characteristics by vessels for the flags considered in this analysis.

	Wire	Mono	J	Tuna	Circle	ShkLn	NoShkLn	Shllw	NoShllw
CK	0.005	0.995	0.383	0	0.617	0	1	1	0
CN	0.140	0.860	0.369	0	0.631	0.142	0.858	1	0
FJ	0.269	0.731	0.198	0	0.802	0.264	0.736	1	0
FM	0.129	0.871	0	0	1	0.289	0.711	1	0
JP	0.834	0.166	0.503	0	0.497	0.018	0.982	1	0
KR	0.834	0.166	0.503	0	0.497	0.018	0.982	1	0
MH	0.608	0.392	1	0	0	1	0	1	0
PF	0.418	0.582	0.680	0	0.320	0.002	0.998	1	0
PG	1	0	1	0	0	0.943	0.057	1	0
TW	0.168	0.832	0.380	0	0.620	0.402	0.598	1	0
US	0.900	0.100	0	0	1	0	1	1	0
VU	0.350	0.650	0.867	0	0.133	0.868	0.132	1	0
WS	0	1	0	0	1	1	0	1	0

Table 2: Parameters and distributions underpinning the simulations for oceanic whitetip shark. Lognormal distribution parameters are expressed on the log-scale. Beta parameters are expressed as a mean (p conceptually probability of success) and n which controls variance (conceptually the number of trials). Large n implies high-precision low-variance.

Silky shark (FAL)				
Simulation component		Distribution	Params.	Notes
Effort/Number of hooks		N/A	N/A	SPC provisioned
Basket size		N/A	30	Est SPC data (Caneco et al., 2014)
Catch rate (per 100 hooks):	Shark lines	Lognormal	$\mu = -0.78330$ $\sigma = 0.05189$	Est SPC data (Caneco et al., 2014)
	Shallow hooks	Lognormal	$\mu = -4.56537$ $\sigma = 0.03520$	Est SPC data (Caneco et al., 2014)
	Deep hooks	Lognormal	$\mu = -3.98790$ $\sigma = 0.02983$	Est SPC data (Caneco et al., 2014)
Prob. lip-hook (else gut) given:	J-hook	Beta	$p = 0.2$ $n = 14$	Afonso et al. (2011) est. from plot
	T-hook	Beta	$p = 0.33$ $n = 14$	Little information SPC prelim est.
	C-hook	Beta	$p = 0.7$ $n = 14$	Afonso et al. (2011) est. from plot
Prob. bite-off given:	Mono leader and lip-hooked	Beta	$p = 0.33$ $n = 190$	Afonso et al. (2012) ⁵
	Mono leader and gut-hooked	Beta	$p = 0.40$ $n = 32$	Ward et al. (2008)
	Wire leader	N/A		Assume negligible
Prob. mort. given bite-off:	Lip-hooked	Beta	$p = 0.0323$ $n = 20$	Little information SPC prelim est.
	Gut-hooked	Beta	$p = 0.0625$ $n = 20$	Little information SPC prelim est.
Prob. mort. at landing:	Lip-hooked	Beta	$p = 0.1974$ $n = 11,470$	Est. SPC data (Caneco et al., 2014) ⁶
	Gut-hooked	Beta	$p = 0.1974$ $n = 11,470$	Est. SPC data (Caneco et al., 2014)
Prob. release in water (vs. brought-on, then released)		Beta	$p = 0.5$ $n = 10$	Little information speculative & broad
Prob. mort. given:	Water release and lip-hooked	Beta	$p = 0.15$ $n = 100$	Musyl et al. (2011)
	Water release and gut-hooked	Beta	$p = 0.19$ $n = 100$	Campana et al. (2009)
	Landed release and lip-hooked	Beta	$p = 0.34$ $n = 100$	Clarke et al. (2011)
	Landed release and gut-hooked	Beta	$p = 0.44$ $n = 100$	Clarke et al. (2011)

Table 3: Parameters and distributions underpinning the simulations for oceanic whitetip shark. Lognormal distribution parameters are expressed on the log-scale. Beta parameters are expressed as a mean (p conceptually probability of success) and n which controls variance (conceptually the number of trials). Large n implies high-precision low-variance.

Oceanic whitetip shark (OCS)				
Simulation component		Distribution	Params.	Notes
Effort/Number of hooks		N/A	N/A	SPC provisioned
Basket size		N/A	30	Est SPC data (Caneco et al., 2014)
Catch rate (per 100 hooks):	Shark lines	Lognormal	$\mu = -0.47969$ $\sigma = 0.04487$	Est SPC data (Caneco et al., 2014)
	Shallow hooks	Lognormal	$\mu = -4.94498$ $\sigma = 0.03262$	Est SPC data (Caneco et al., 2014)
	Deep hooks	Lognormal	$\mu = -4.16491$ $\sigma = 0.02528$	Est SPC data (Caneco et al., 2014)
Prob. lip-hook (else gut) given:	J-hook	Beta	$p = 0.3$ $n = 12$	Afonso et al. (2011) est. from plot
	T-hook	Beta	$p = 0.33$ $n = 12$	Little information SPC prelim est.
	C-hook	Beta	$p = 0.9$ $n = 12$	Afonso et al. (2011) est. from plot
Prob. bite-off given:	Mono leader and lip-hooked	Beta	$p = 0.33$ $n = 190$	Afonso et al. (2012) ⁷
	Mono leader and gut-hooked	Beta	$p = 0.72$ $n = 14$	Ward et al. (2008)
	Wire leader	N/A		Assume negligible
Prob. mort. given bite-off:	Lip-hooked	Beta	$p = 0.0323$ $n = 20$	Little information SPC prelim est.
	Gut-hooked	Beta	$p = 0.0625$ $n = 20$	Little information SPC prelim est.
Prob. mort. at landing:	Lip-hooked	Beta	$p = 0.1867$ $n = 6,361$	Est. SPC data (Caneco et al., 2014) ⁸
	Gut-hooked	Beta	$p = 0.1867$ $n = 6,361$	Est. SPC data (Caneco et al., 2014)
Prob. release in water (vs. brought-on, then released)		Beta	$p = 0.5$ $n = 10$	Little information speculative & broad
Prob. mort. given:	Water release and lip-hooked	Beta	$p = 0.15$ $n = 100$	Musyl et al. (2011)
	Water release and gut-hooked	Beta	$p = 0.19$ $n = 100$	Campana et al. (2009)
	Landed release and lip-hooked	Beta	$p = 0.34$ $n = 100$	Clarke et al. (2011)
	Landed release and gut-hooked	Beta	$p = 0.44$ $n = 100$	Clarke et al. (2011)

Table 4: Overall mortality rate (deaths/catch) for silky shark for the status quo and each management scenario in terms of percentiles from Monte Carlo distributions.

	Percentile		
	10	50	90
Status-quo	0.31	0.34	0.38
No Shark lines	0.26	0.29	0.33
No wire	0.25	0.28	0.32
Only circle hooks	0.30	0.33	0.37
No shallow hooks	0.27	0.31	0.34
No Shark lines or wire trace	0.21	0.24	0.27

Table 5: Overall mortality rate (deaths/catch) for oceanic whitetip shark for the status quo and each management scenario in terms of percentiles from Monte Carlo distributions.

	Percentile		
	10	50	90
Status-quo	0.27	0.30	0.34
No Shark lines	0.21	0.23	0.26
No wire	0.20	0.23	0.27
Only circle hooks	0.27	0.31	0.35
No shallow hooks	0.25	0.28	0.31
No Shark lines or wire trace	0.15	0.18	0.21

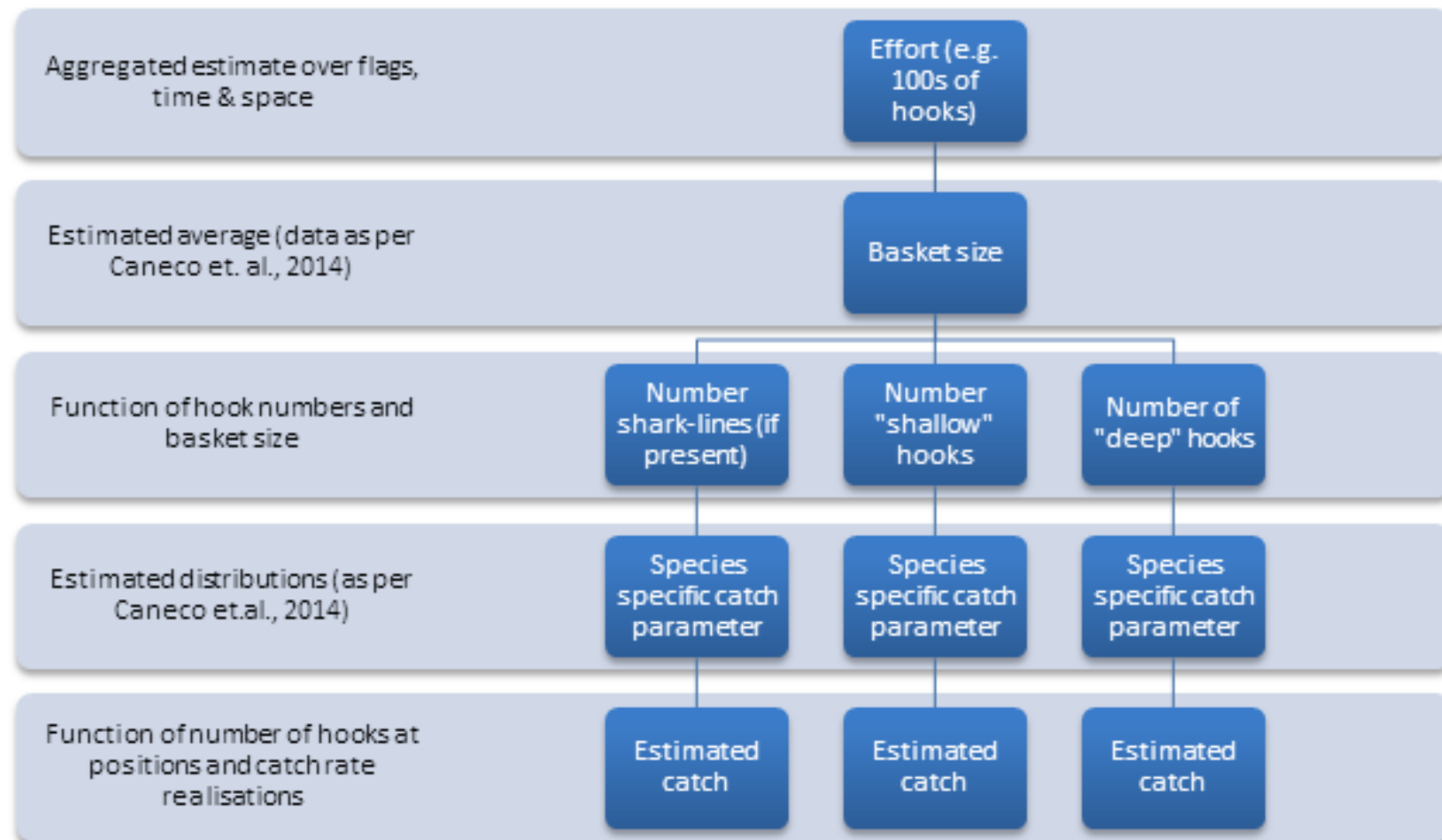


Figure 1: Part 1 of the theoretical model: the catch component.

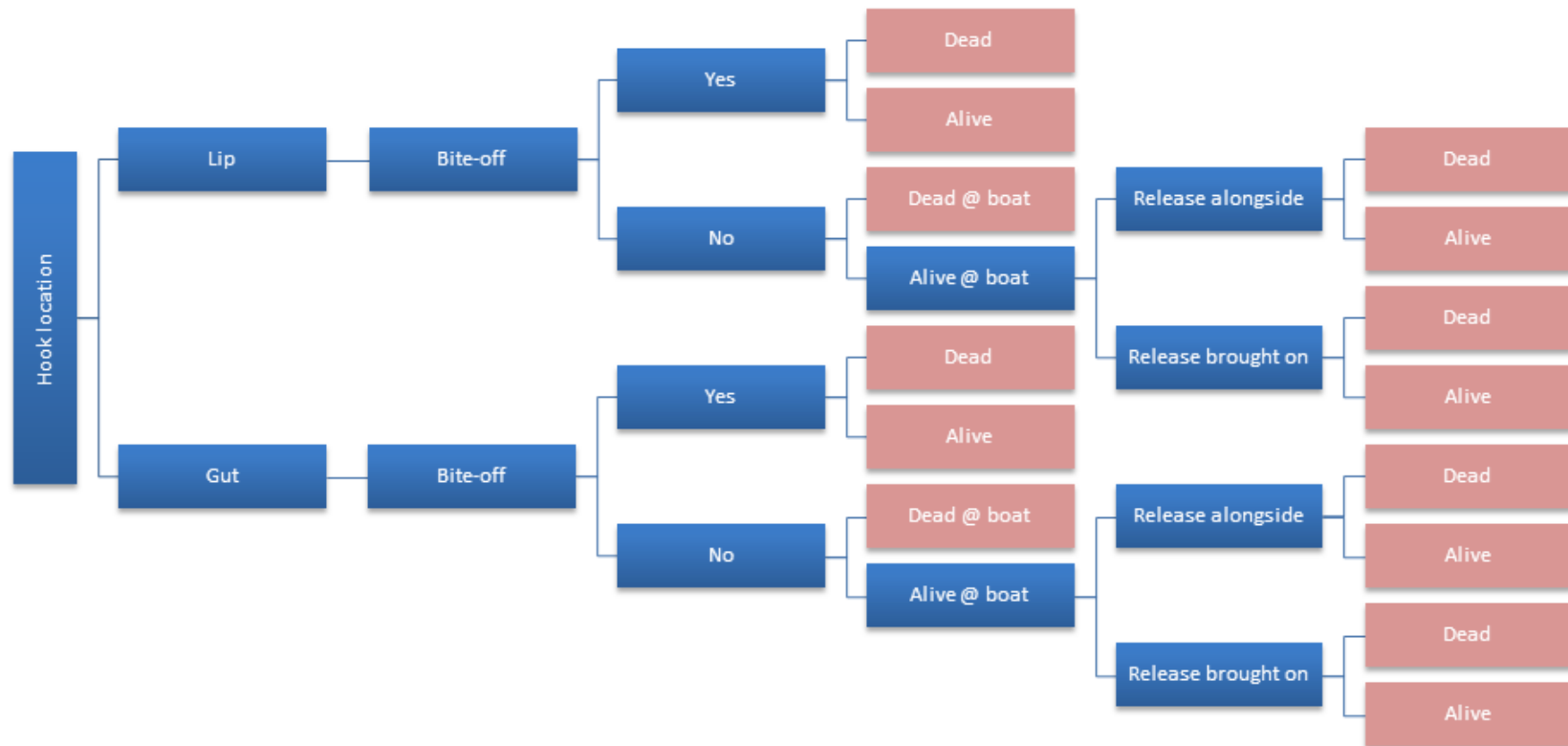


Figure 2: Part 2 of the theoretical model: the fate component.

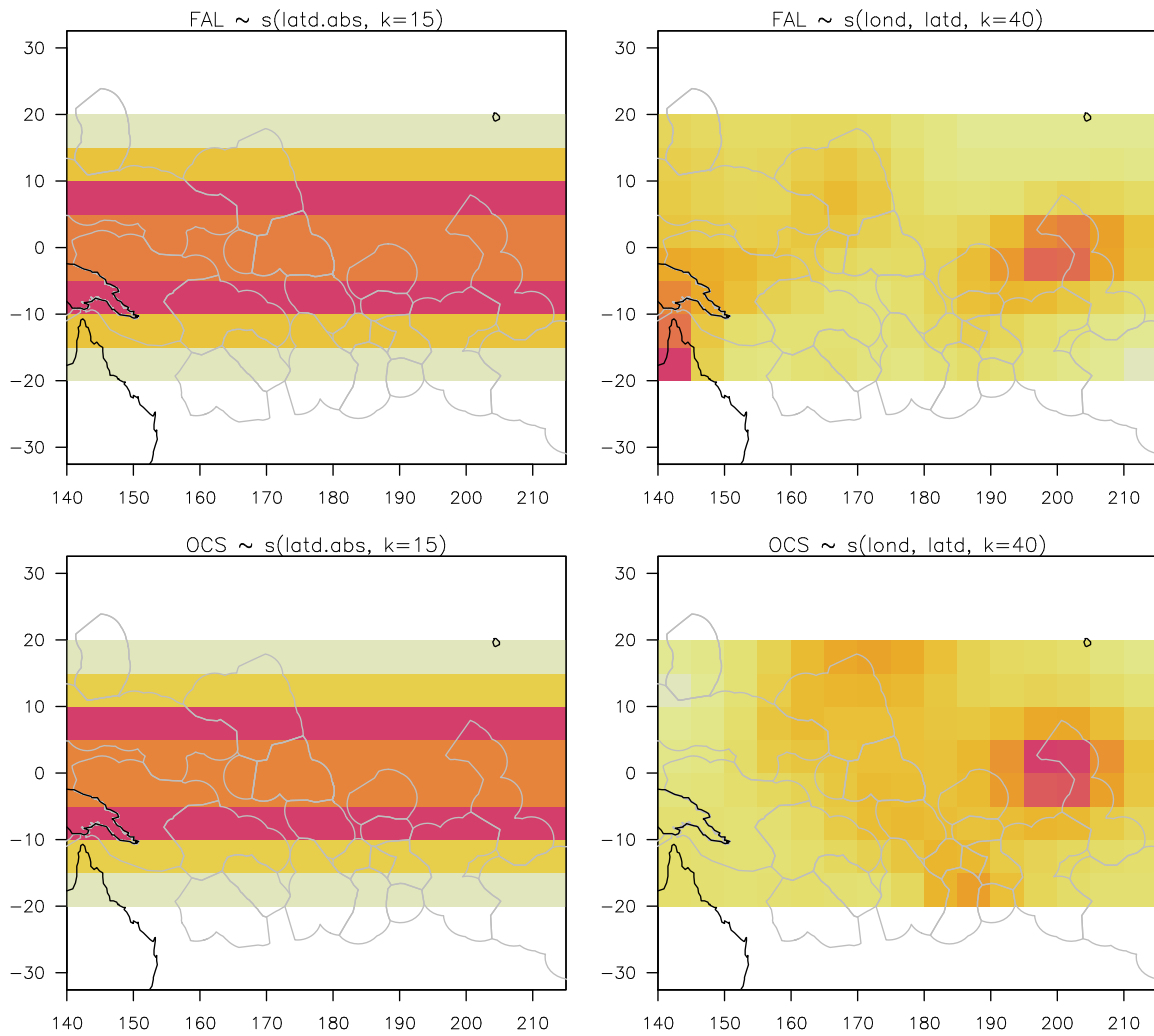


Figure 3: Predicted relative abundance surfaces for silky shark (FAL; top) and oceanic whitetip shark (OCS; bottom) for the absolute value of latitude model (c; left) and latitude/longitude model (a; right). See Section 2.4 for further details.

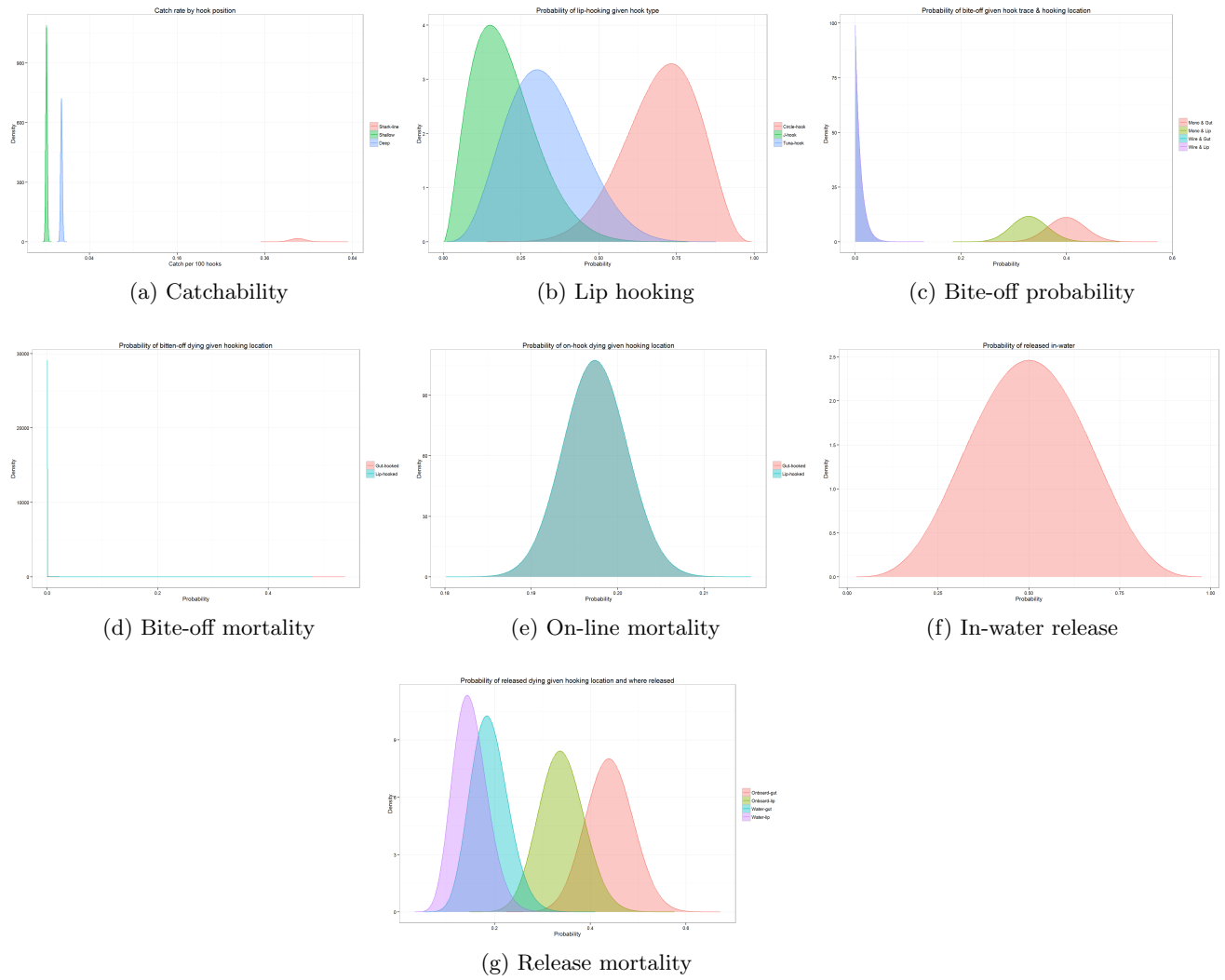


Figure 4: Sample distributions from which Monte Carlo draws were made for the silky shark analysis.

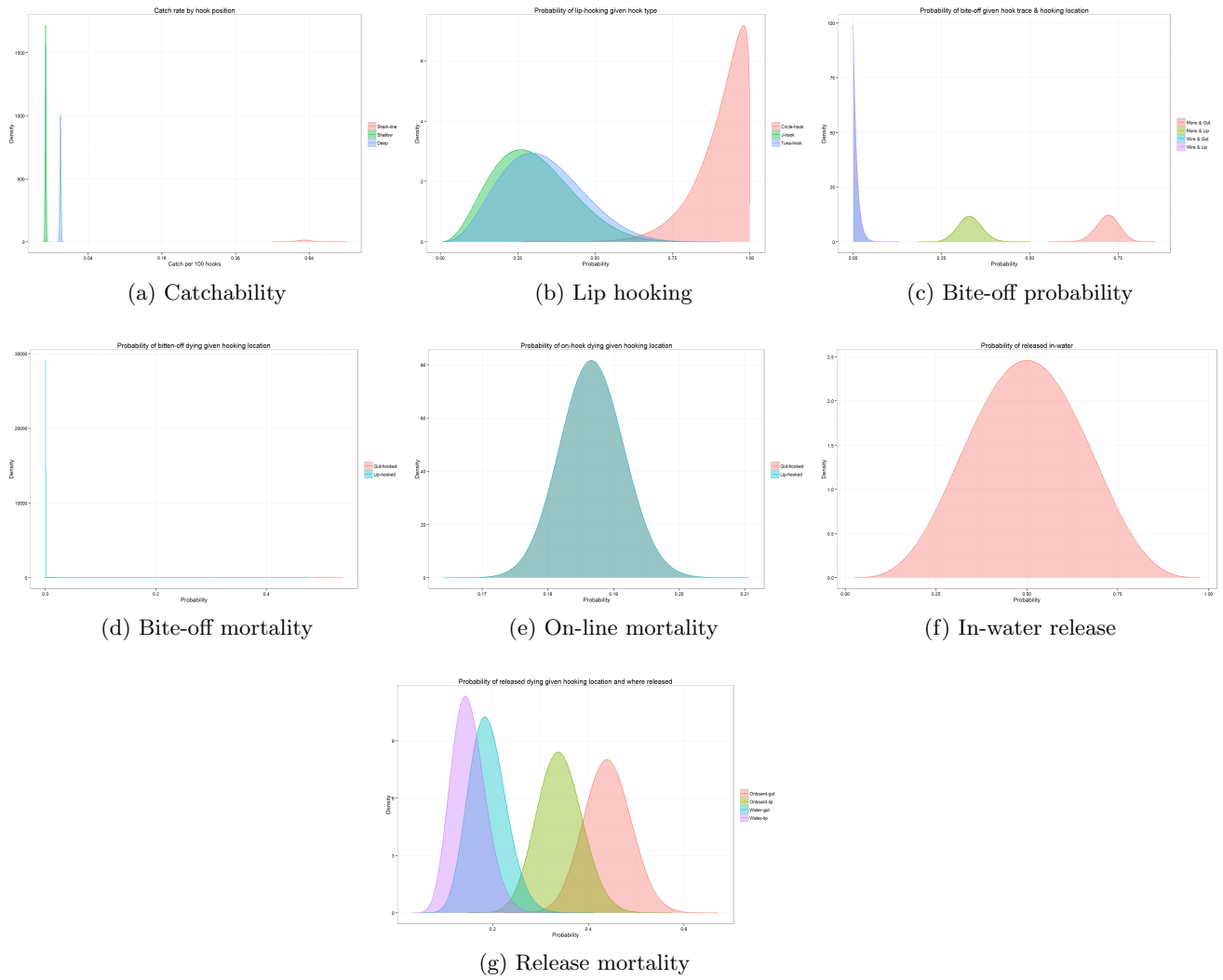


Figure 5: Sample distributions from which Monte Carlo draws were made for the oceanic whitetip shark analysis.

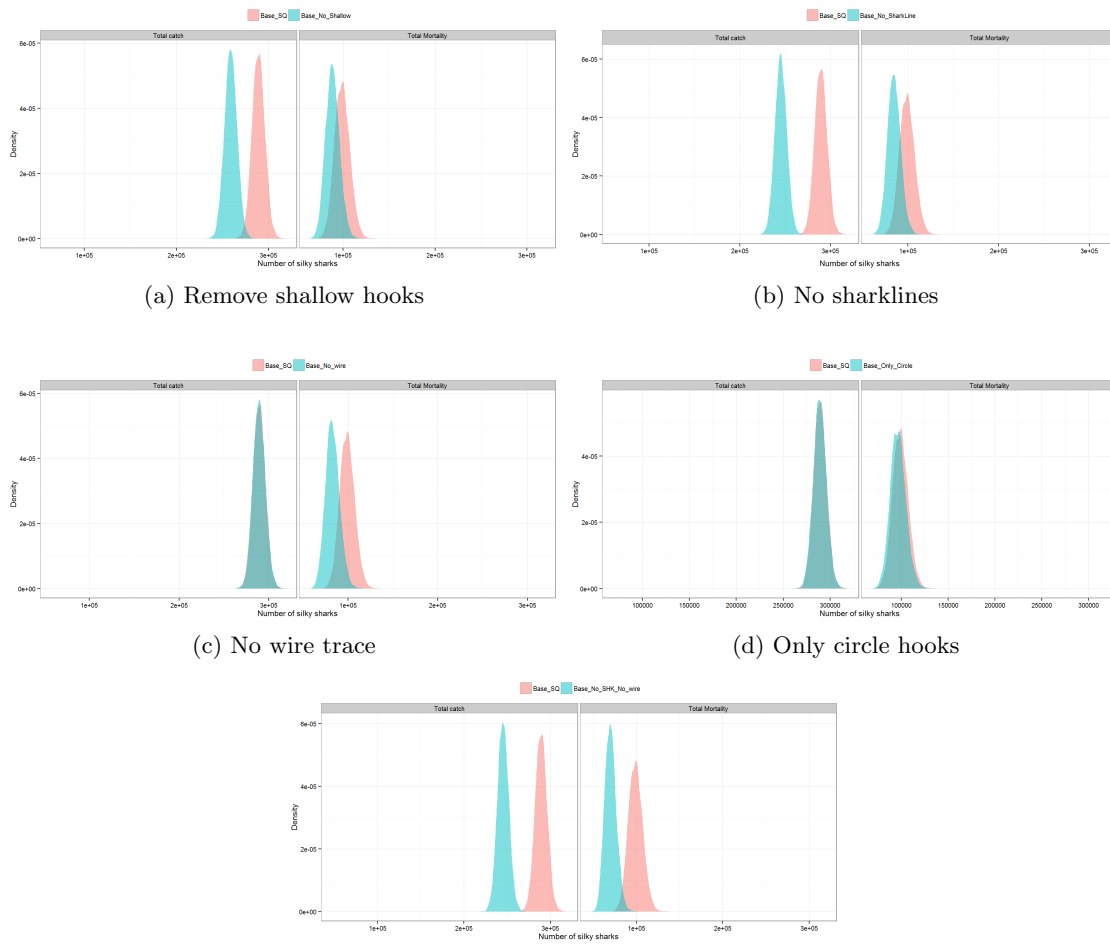


Figure 6: One-off comparisons for silky shark between the status quo (Base.SQ) and each management scenario in terms of the Monte Carlo distributions of catch (left side of the panel) and mortality (right side of the panel).

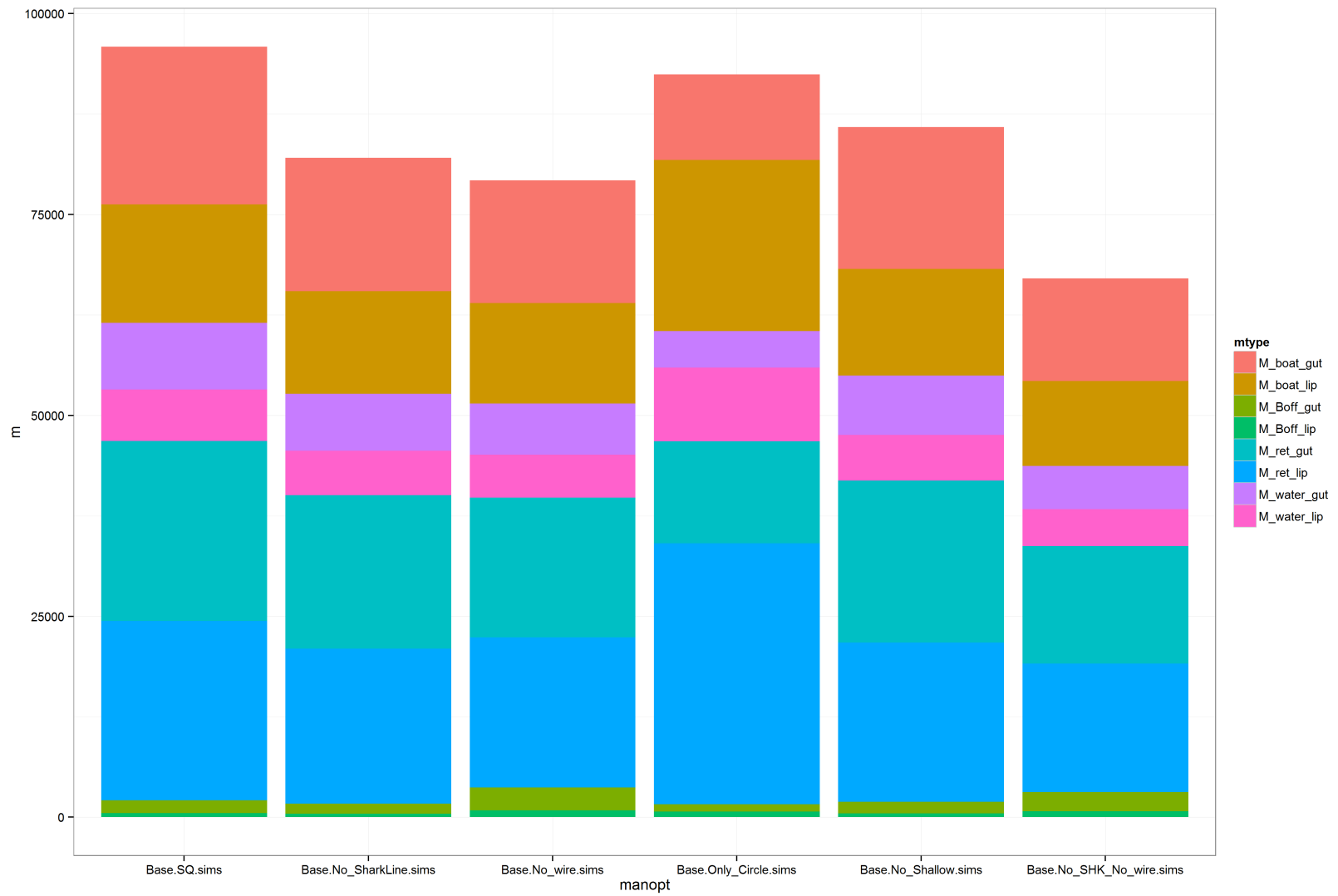


Figure 7: Median (across 10,000 simulations) mortality components for the status quo and each management scenario for silky shark.

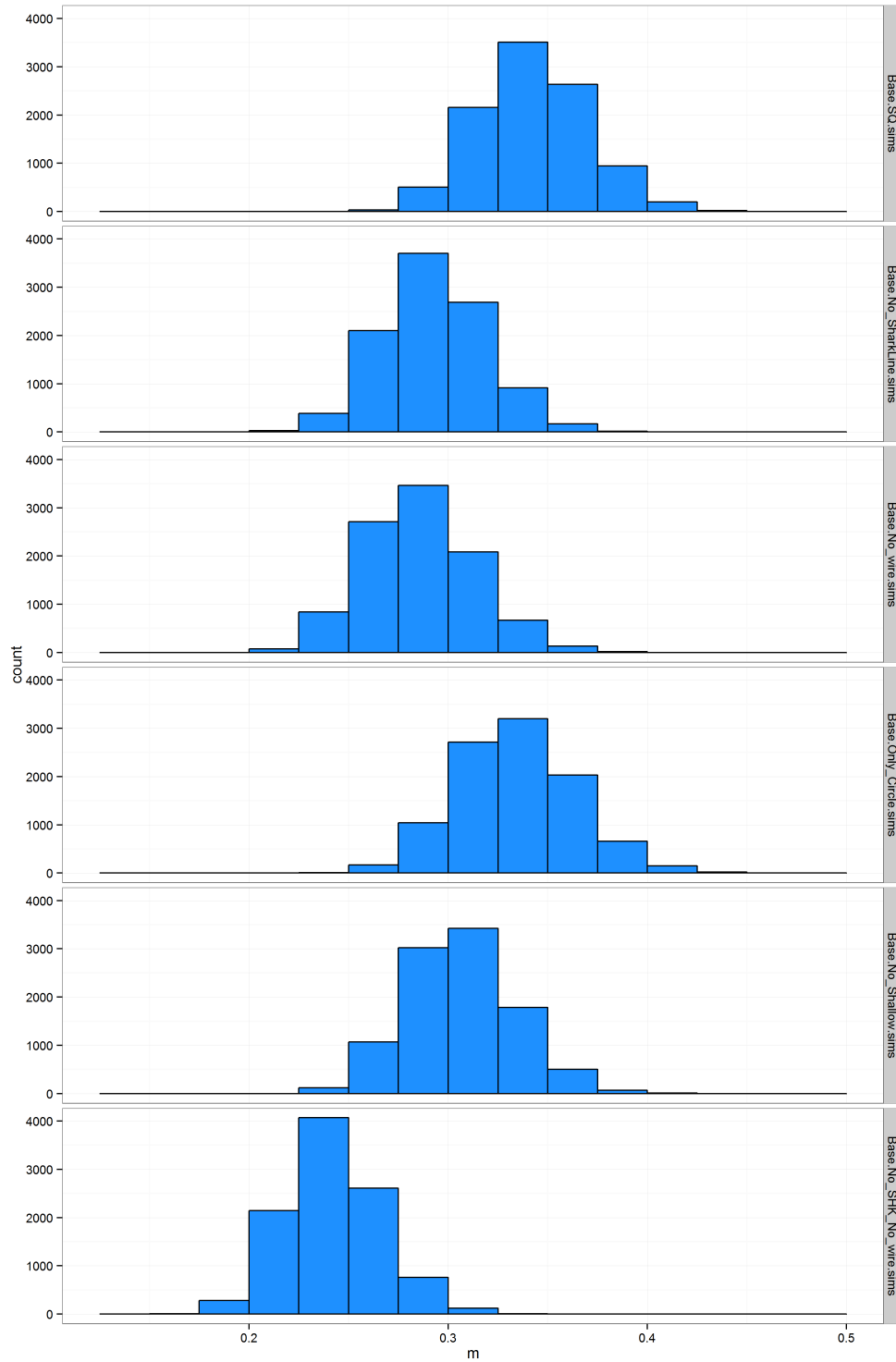


Figure 8: Monte Carlo distribution of mortality rates for the status quo and each management scenario for silky shark.

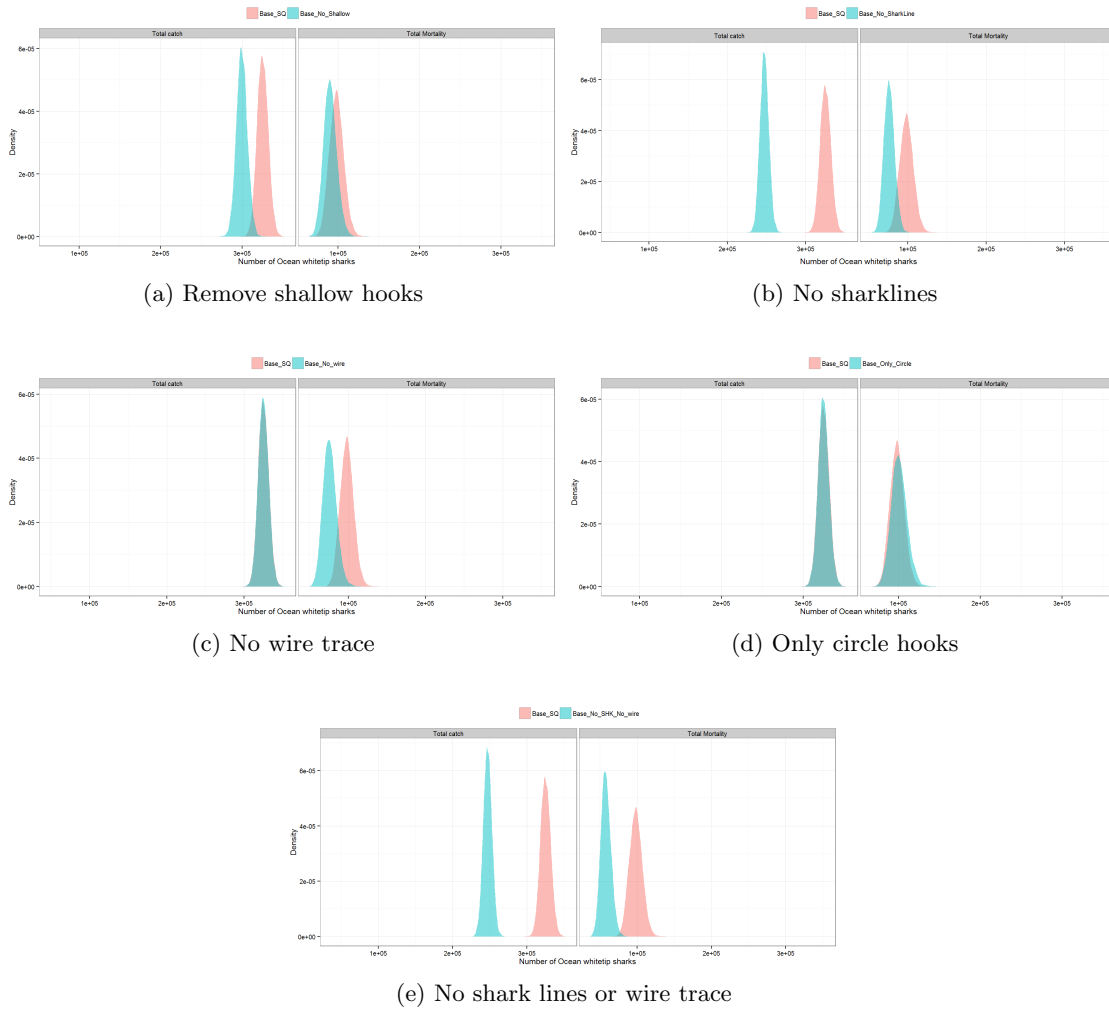


Figure 9: One-off comparisons for oceanic whitetip shark between the status quo (Base.SQ) and each management scenario in terms of the Monte Carlo distributions of catch (left side of the panel) and mortality (right side of the panel).

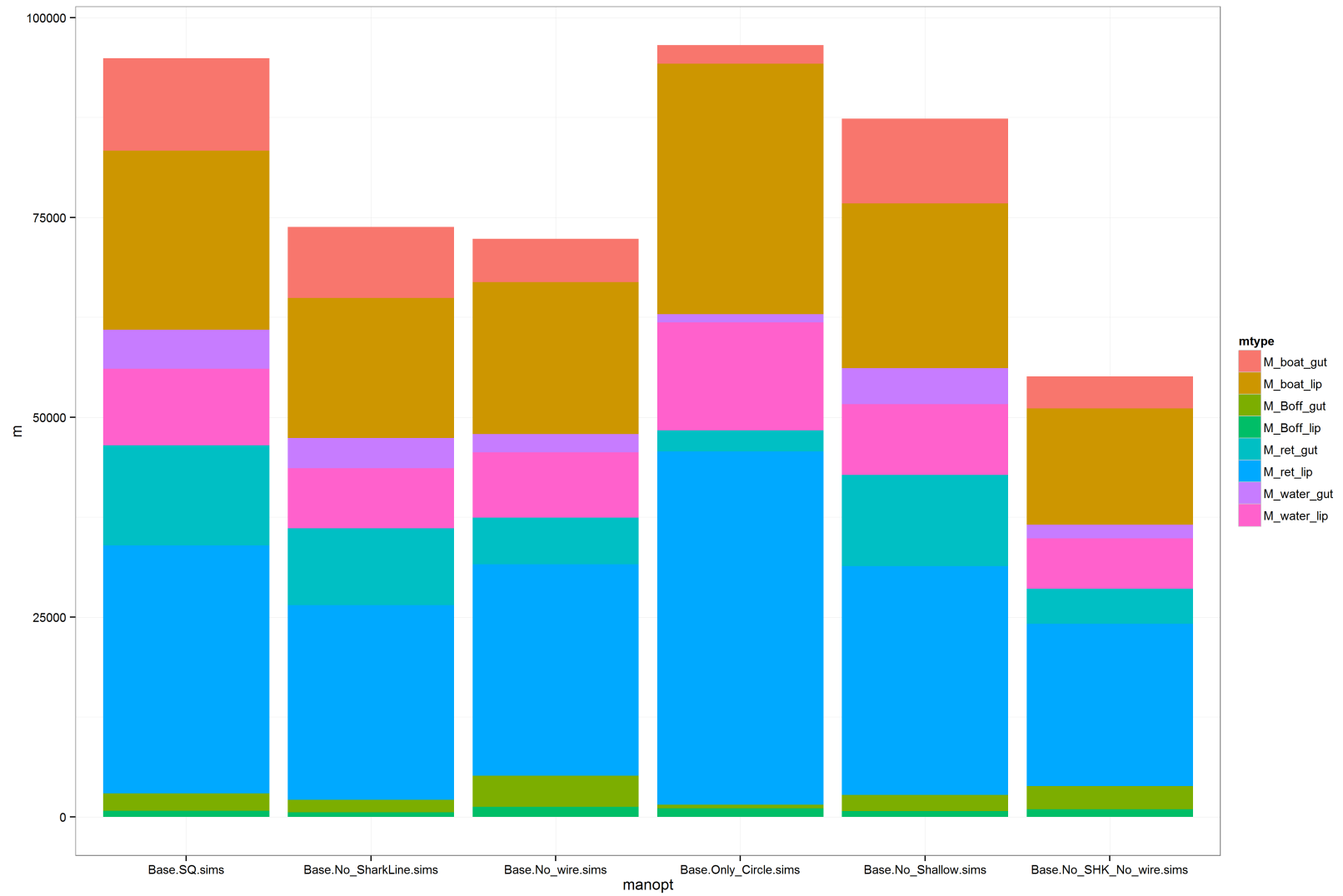


Figure 10: Median (across 10,000 simulations) mortality components for the status quo and each management scenario for oceanic whitetip shark.

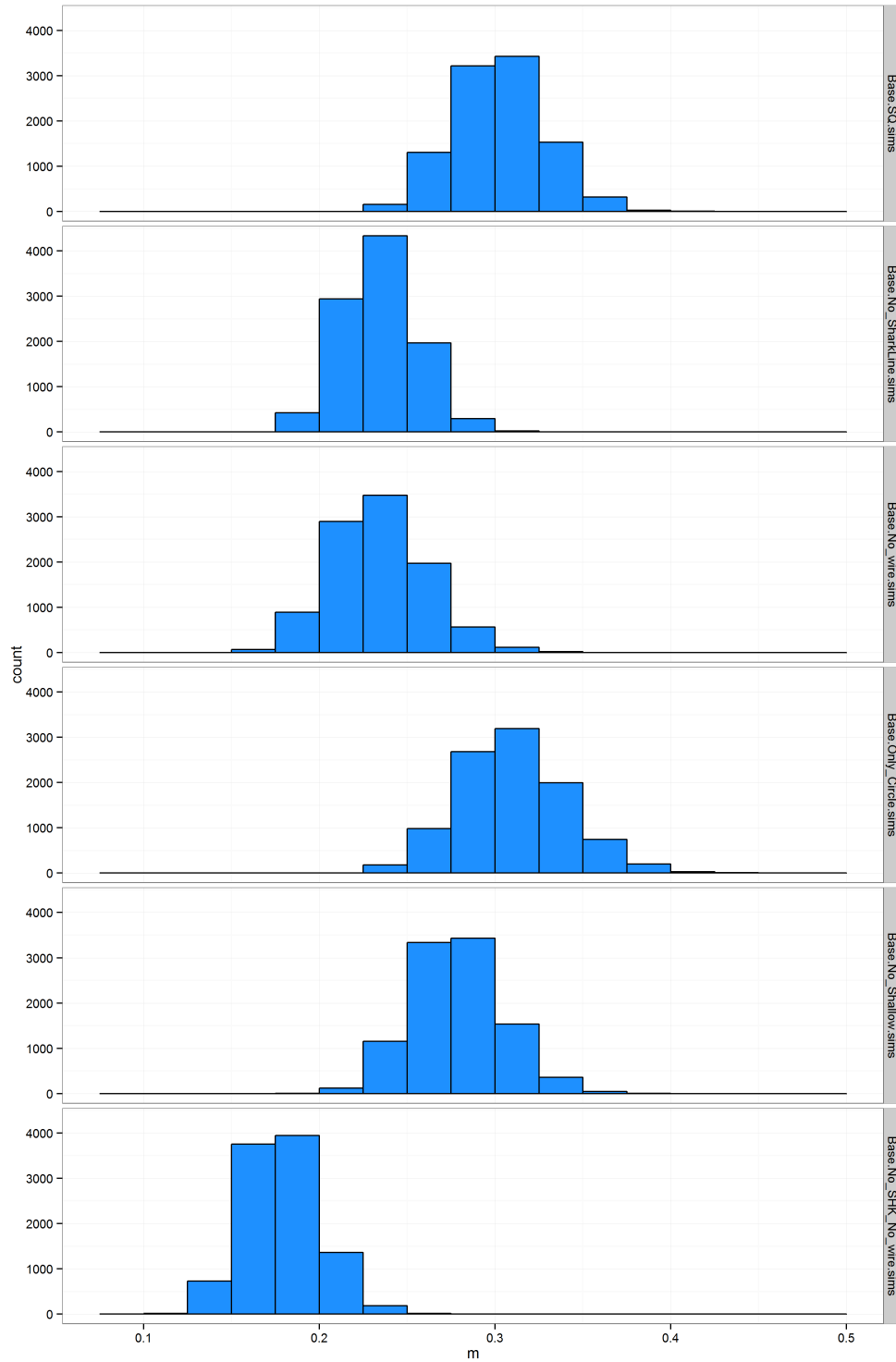


Figure 11: Monte Carlo distribution of mortality rates for the status quo and each management scenario for oceanic whitetip shark.