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# Report of the Workshop on Joint Analysis of Shark Post-Release Mortality Tagging Results

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**WCPFC-SC15-2019/EB-WP-01**

**Common Oceans (ABNJ) Tuna Project**

Western and Central Pacific Fisheries Commission
Pacific Community
Communauté du Pacifique
European Commission

**PROJECT**
Sustainable Management of Tuna Fisheries
and Biodiversity Conservation in the ABNJ


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REDUCING ECOSYSTEM IMPACTS OF TUNA FISHING

# Joint Analysis of Shark Post-Release Mortality Tagging Results

**4 – 6 JUNE 2019**

WELLINGTON, NEW ZEALAND

**PROCEEDINGS**

COMMON OCEANS

Seeking to generate a catalytic change, the *Global sustainable fisheries management and biodiversity conservation in the Areas Beyond National Jurisdiction Program* was approved by the Global Environment Facility (GEF) under the lead of the Food and Agriculture Organization of the United Nations (FAO) in close collaboration with two other GEF agencies, the United Nations Environment Programme (UNEP) and the World Bank, as well as other partners.

Focusing on tuna and deep-sea fisheries, in parallel with the conservation of biodiversity, the ABNJ Program aims to promote efficient and sustainable management of fisheries resources and biodiversity conservation in ABNJ to achieve the global targets agreed in international fora.

The five-year ABNJ Program is an innovative, unique and comprehensive initiative working with a variety of partners. It consists of four projects that bring together governments, regional management bodies, civil society, the private sector, academia and industry to work towards ensuring the sustainable use and conservation of ABNJ biodiversity and ecosystem services.

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Food and Agriculture Organization of the United Nations

# Executive Summary

The Western and Central Pacific Fisheries Commission (WCPFC), with funding from the Common Oceans (ABNJ) Tuna Project and the European Union, commissioned a shark post-release mortality (PRM) study to assist in evaluating whether existing WCPFC conservation and management measures are effective in reducing mortality and conserving shark stocks. An expert workshop was convened in January 2017 to design the study which was then executed from May 2017-April 2019. This report describes the findings of a second expert workshop convened in June 2019 to analyze the data and provide recommendations on ways to reduce shark PRM and account for it in management.

In accordance with the study design, a total of 117 ‘survival’ popup archival tags (sPAT) were attached to shortfin mako (SMA) and silky (FAL) sharks in New Zealand (n=35), Fiji (n=58), New Caledonia (n=10) and the Republic of the Marshall Islands (n=14). PRM status was determined for 110 sharks (57 SMA and 53 FAL). Tagged sharks were classified as either “alive and uninjured” or “alive and injured”; most tagged sharks of both species were uninjured (89%) and most sharks (88%) survived until tag loss or the programmed popup date. Based on a simple tally of tags that reported data, the total number of potential mortalities, i.e. confirmed mortalities, as well as tags that were ingested by warm-blooded predators and then regurgitated (which may or may not represent mortalities of tagged sharks), were 7 SMA and 6 FAL.

An initial analysis fitted a Cox proportional hazards model to the survival data for both species combined using predictor variables species, fork length, condition (injured or not), tagging region, tag site (whether tagged in the water or on deck) and gangion ratio (the ratio of the amount of trailing gangion left on the released shark to its fork length). The best fitting model (based on the Akaike Information Criterion (AIC)) included the predictors species, fork length and gangion ratio. Mortality rates were significantly higher for small sharks and for high gangion ratios. Applying the best fitting model to SMA data from the WCPFC study, PRM at 60 days was predicted to be 20.5% when fork length was set to the median value in the SPC observer data holdings (120 cm) and the gangion ratio was set to the median value observed when sharks were tagged (1.35).

Unlike for SMA, similar PRM datasets were available for FAL from studies of three other Pacific Ocean regions: American Samoa, Ecuador/Costa Rica and Palau. When those three datasets were combined with the data from the WCPFC study, there was no significant effect of tagging study, so all four datasets were pooled for a joint analysis. The best fitting model (based on AIC) for the combined FAL dataset included the predictors condition and gangion ratio. Mortality rates were significantly higher for injured sharks and for high gangion ratios. PRM at 60 days was predicted to be 4.3% for uninjured FAL and 50.0% for injured FAL when the gangion ratio was set to the median observed value (1.35). An overall PRM estimate for FAL of 15.4% was obtained by calculating a condition-class weighted average using the proportion of sharks observed in each condition class of the SPC observer data (75.7% alive and uninjured, and 24.3% alive and injured).

To obtain overall mortality estimates due to fishing (i.e. the sum of haulback, handling and post-release mortality), the workshop combined the estimates, by species, of the percentage of sharks released alive and not dying from tuna longlines in the SPC data and the PRMs estimated from this tagging study. A reasonable estimate of the proportion of sharks that survive all three stages of a fishery interaction is 0.44 for SMA and 0.56 for FAL. However, these proportions are caveated by the potential for the shark lengths used in the analysis to be an underestimate (since large sharks are difficult to handle and thus tend not to be measured) and the pooling of data across all fleets.

The workshop recommended minimizing the length of trailing gear left on released sharks as this was found to be a significant factor in determining PRM for both SMA and FAL. This can be accomplished by bringing the shark close to the vessel while still in the water, and using a line cutter to cut the line as close to the hook as possible. The workshop also found that although the WCPFC study provided no data showing that hauling sharks on deck contributed to PRM, it did show that injured sharks are less likely to survive, and it considered that the probability of injury is higher when sharks are hauled onboard.

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# 1 Introduction

The purpose of fisheries management is to control the mortality rates of exploited populations within sustainable, or otherwise acceptable, limits. Proper fishery management thus requires that the mortality due to fishing activities be accurately estimated and taken into account in population status assessments and management measures. Mortality due to fishing activities has long been synonymous with catch but there is a growing recognition that catch statistics, particularly those representing landed catch, may greatly under-represent the actual number of fish removed from the current and future stock. This is especially true for fishes such as sharks which may be discarded or released in large numbers either because of regulations or lack of market demand. In many cases, discarded or released sharks are often not enumerated at all; if they are enumerated there is often no record of their condition; and even if there is a record of their condition that condition may not be a reliable predictor of their survival. As a result, there is considerable uncertainty about the number of sharks killed through fishing activities and this uncertainty leads to a lack of clarity in defining and refining shark conservation and management.

The Areas Beyond National Jurisdiction (ABNJ, or Common Oceans) Tuna Project is a Global Environment Facility (GEF)-funded, FAO-implemented programme of work designed to encourage and reinforce sustainable tuna fisheries. The ABNJ Tuna Project addresses a number of aspects of global tuna fisheries including supporting a systematic application of a precautionary and ecosystem-based approach to management, reducing illegal fishing and improving compliance, and mitigating adverse impacts of bycatch on biodiversity. Under the third component, the Western and Central Pacific Fisheries Commission (WCPFC) is leading work on shark data improvement, shark assessment and management, and bycatch mitigation. The need for better estimates of mortality for sharks in tuna fisheries cuts across each of these themes. Therefore, in addition to working toward improving the data collected by fishers and observers, the ABNJ Tuna Project has identified that tagging studies designed to quantify the survival of discarded/released sharks are required to provide critical new inputs for assessment and mitigation studies. In particular, such studies will assist in evaluating whether existing WCPFC conservation and management measures (CMMs) prohibiting retention of all oceanic whitetip (*Carcharhinus longimanus*, OCS), silky (*C. falciformis*, FAL) and whale (*Rhincodon typus*, RHN) sharks are effective in reducing mortality and conserving these shark stocks. In support of such work, the European Union (EU) granted WCPFC additional funding for shark post-release mortality (PRM) tagging studies.

Under WCPFC Circular 2016/51, the WCPFC, in partnership with the Pacific Community (SPC) convened an expert workshop in 2017 to design a shark PRM tagging study having optimal scientific rigor, cost-effectiveness and consistency with past and ongoing studies (Common Oceans (ABNJ) Tuna Project 2017). The goal of the exercise was to provide a set of scientifically robust and practical protocols for shark PRM studies in general, as well as a specific design for the ABNJ- and EU-funded work which addressed the technical objectives and could be achieved with the available budget and timeframe. The ABNJ- and EU-funded study was designed to assist in evaluating the effectiveness of WCPFC no-retention measures and in better estimating fishing mortality in assessments.

The National Institute of Water and Atmospheric Research (NIWA) of New Zealand offered to host the workshop at its facilities at Greta Point, Wellington. Experts from six WCPFC member countries and participating territories, as well as independent academic and technical experts, convened for the workshop from 4-6 June 2019 (**Annex A**). The workshop was chaired by Shelley Clarke of FAO and Malcolm Francis of NIWA and rapporteured by Shelley Clarke, Brit Finucci and Warrick Lyon of

NIWA. This report represents the record of the meeting and was agreed by participants on the final day of the workshop and finalized through circulation.

# 2 Background to the Data Analysis

## 2.1 WCPFC shark PRM tagging study objectives and workshop aims

S. Clarke (WCPFC) provided an opening presentation on the background and objectives to the WCPFC's shark PRM studies as follows:

> *The Common Oceans (ABNJ) Tuna Project is a GEF-funded, FAO-implemented project designed to ensure sustainability and biodiversity conservation in the world's high seas tuna fisheries. Phase 1 of the project was initiated in 2014 with a five-year programme but work has continued into a sixth year under a no-cost extension. The WCPFC in conjunction with SPC have been executing a $3.2 million USD programme of work involving shark data improvement, shark assessment and management, and bycatch mitigation including post-release mortality (PRM) tagging for sharks. The EU also provided funding for shark PRM tagging in the form of a €400,000 grant to WCPFC. One of the lessons learned through this project is that the cost of shark PRM tagging is considerably more than the cost of the tags themselves: it is estimated that more funding has been expended on coordination, equipment, survey design and analysis than on tagging hardware per se. The study was designed to construct shark PRM estimates by fleet and for the WCPFC as whole in order to inform questions about no-retention measures and assist with catch reconstructions and other stock assessment inputs. An expert workshop was held in January 2017 and produced a survey design focused on silky (FAL) and shortfin mako (SMA) sharks in longline fisheries (Common Oceans (ABNJ) Tuna Project 2017). The workshop determined that sPAT tags reporting for at least 30 days and deployed by observers on actual observer trips would be optimal. The design aimed for tagging in two fleets for FAL and three fleets for SMA using protocols developed by the United States National Oceanic and Atmospheric Administration (NOAA) and in accordance with the vessel's standard handling practice for sharks (i.e. in water or on deck). Tagging began in New Zealand in May 2017 and in Fiji in September 2017. Additional tagging programmes were initiated in New Caledonia and the Republic of the Marshall Islands (RMI) in July 2017. All tagging was halted at the end of March 2019 in order to allow for data analysis and report writing. The current workshop represents the final activity under the project and aims to a) review lessons learned from the shark tagging; b) estimate PRM rates from this study; c) integrate data from this study with data from other studies and re-estimate PRM rates; d) feed new PRM estimates into an overall mortality model to re-visit management advice; e) recommend further research and management; and f) submit a report to the WCPFC's Scientific Committee in August 2019.*

## 2.2 Pre- and Post-Deployment Coordination

W. Lyon (NIWA) and C. Sanchez (SPC) collaborated to present the pre-deployment coordination of the project, which included observer training, data requirements, survey design and logistics. This was followed by a summarization of the post-deployment coordination, including deployment results, tagging rewards, data compilation and tag demobilization. The presenters provided the following summary:

> *The WCPFC shark post release mortality PRM study ran from 2017 to 2019 in the Western Central Pacific, using fisheries observers and vessel captains to tag sharks from commercial*

> *surface longline vessels. In total, 117 tags were deployed on shortfin mako sharks (SMA, also referred to simply as "mako" in this report) and silky sharks (FAL) in New Zealand, Fiji, New Caledonia, and the Republic of the Marshall Islands. A total of 62 personnel were trained to tag sharks, and 24 observers and three captains deployed tags from 29 longline vessels. This WCPFC study was coordinated by NIWA in collaboration with the New Zealand Ministry for Primary Industries (MPI), the Fijian Ministry of Fisheries (MOF) and Fiji Fishing Industry Association (FFIA), SPC, the New Caledonian Fisheries and Marine Environment Department (DAM), and the Marshall Islands Marine Resources Authority (MIMRA). Fiji tagged both SMA (n=15) and FAL (n=43), New Caledonia tagged only SMA (n=10), New Zealand tagged only SMA (n=35) and the Marshall Islands tagged only FAL (n=14). Most FAL were tagged in the water, whereas about half the SMA tagged in New Zealand (53%) were tagged on deck. GoPro cameras were used to verify data collected on tagging logsheets. A lottery system was developed to encourage and reward shark tagging. The lottery details varied among countries, with separate lottery draws being provided for observers and/or crew, with the prize pool being based on the number of sharks tagged. At the completion of tagging, datasheets, videos and tagging kits were retrieved from taggers, and the data were error-checked and punched ready for analysis. Further details are provided in* ***Annex B****, and tagging instructions are provided by Lyon et al. (2017).*

One participant suggested that in addition to the condition codes that observers were trained to use, that a simple reflex test could be used to help assess shark condition. Aside from health and safety concerns for observers and crew, it was noted that such reflex tests may be difficult to administer when sharks are tagged in the water. A common reflex test in sharks involves touching the nictitating membrane of the eye and watching for movement, but this membrane is only present in some species of sharks (order Carcharhiniformes).

The following key points were noted for the consideration of future tagging studies:

a. GoPros (or similar video devices) are highly recommended to verify the tagging situation.
b. It is important to understand and consider observer deployment patterns, i.e. to account for when observer deployments might be halted when required coverage levels are reached or when fisheries open or close.
c. Observers suggested a dip net be made available so that the tag could be retrieved in the event that it failed to anchor when tagging.
d. Observers also suggested that an in-water rope-based measuring tape be provided to facilitate taking shark length measurements when sharks are tagged in the water.
e. The tagging pole can be used to roll the shark after tagging in order to determine the sex.

The study team noted that in order to avoid duplication of data collection effort it was intended that the operational characteristics of the sets during which sharks were tagged would be recorded by observers on their standard observer forms and not written on the shark tagging data sheets. However, as some tagging was conducted by fishing vessel crew without the presence of an observer, some of these operational characteristics were not captured.

Options for filling in these missing data were discussed including:

a. using expert judgement to make assumptions based on similar vessels;
b. using vessel logsheets (e.g. by contacting the fishing companies); or
c. using a Bayesian imputation algorithm.

Logsheet information was requested from some of the fishing companies but the workshop was unable to receive the data in time to be used in the workshop analyses.

## 2.3 Summarization of Tagging-related Observer Data

T. Peatman (SPC) provided an overview of WCPFC longline fisheries based on observer data held by SPC from May 2017 to April 2019:

> *Tag releases were matched to SPC's observer data using vessel name and tag release time to identify sets and trips with tag releases. Multiple comparisons of gear configurations and shark condition at release were presented to inform discussion of whether PRM estimates from the tagged sharks were likely to be representative of PRM for the fleets that deployed tags, and for longline fleets operating in the WCPFC Convention Area in general (Tables 1-3). Comparisons focused on variables that were identified as potentially relevant to PRM at the first workshop. Gear configurations of tagging fleets did not demonstrate substantial within or between trip variation. However there was some variation in gear configurations between the different tagging fleets, particularly for fleets with SMA tag releases. High-level comparisons of gear configurations at a flag-level demonstrated some variation in gear configuration, particularly gangion[1] lengths and hook shapes and sizes. Tagged sharks appeared to be representative of observed captures of FAL and SMA, both in terms of condition at release and proportions of individuals cut free. However, comparison of condition code information between tagging forms and corresponding observer information was complicated by the different classifications used for the respective forms.*

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[1] We use the term gangion in this report to refer to the terminal fishing gear that attaches to the mainline. The gangion includes a hook, a length of line (monofilament nylon or stainless steel) that connects the hook to the mainline, an attachment mechanism (usually a snap fastener), and sometimes a swivel. Other commonly-used synonyms for gangion include snood and branchline.

**Table 1.** **Summary of operational characteristics for longline fleets with a) SMA and b) FAL releases, during the duration of tagging effort (May 2017-April 2019) as held by SPC at the time of the workshop: mean hooks between floats (hbf); mean latitude; mean soak time (hours); proportion of observed effort with wire trace; mean gangion length (m); dominant hook shape (C=circle hook) and corresponding proportion of observed effort; dominant hook shape and size combination; dominant bait type (fsh = finfish, sqd = squid); and, % of bait that was finfish.**

a) SMA

| Flag | Sets | HBF | Lat | Soak time | Wire trace | Gangion length | Hook shape | Hook shape proportion | Hook type | Bait type | Bait % fish |
|---|---|---|---|---|---|---|---|---|---|---|---|
| FJ | 2352 | 33 | -17.9 | 12.7 | 0.14 | 12.5 | C | 0.97 | C-14/0 | fsh | 100% |
| NC | 150 | 31 | -21 | 10.6 | 0 | 10.8 | C | 1 | C-16/0 | fsh | 100% |
| NZ | 352 | 13 | -38.5 | 15.4 | 0 | 47.2 | C | NA | C-16/0 | sqd | 3% |

b) FAL

| Flag | Sets | HBF | Lat | Soak time | Wire trace | Gangion length | Hook shape | Hook shape proportion | Hook type | Bait type | Bait % fish |
|---|---|---|---|---|---|---|---|---|---|---|---|
| FJ | 3320 | 33 | -17.7 | 12.7 | 0.14 | 12.7 | C | 0.97 | C-14/0 | fsh | 100% |
| FM | 95 | 25 | 5.5 | 12.2 | 0 | 19.9 | C | 0.8 | C-12/0 | fsh | 100% |
| MH | 44 | 26 | 5.1 | 11.3 | 0.33 | 19.3 | J | 0.3 | C-14/0 | fsh | 100% |

**Table 2.** **Summary of operational characteristics for all longline fleets during the duration of tagging effort (May 2017-April 2019) as held by SPC at the time of the workshop: mean hooks between floats (hbf); mean latitude; mean soak time (hours); proportion of observed effort with wire trace; mean gangion length (m); dominant hook shape (C=circle hook, JP=Japan tuna hook) and corresponding proportion of observed effort; dominant hook shape and size combination; dominant bait type (fsh = finfish, sqd = squid); and, % of bait that was finfish. Rows above the dashed line represent those fleets from which some vessels participated in the tagging study. See text for caveats regarding the summarized nature of the data and its appropriate use.**

| Flag | Sets | HBF | Lat | Soak time | Wire trace | Gangion length | Hook shape | Hook shape proportion | Hook type | Bait type | Bait % fish |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NZ | 593 | 13 | -38.3 | 14.8 | 0 | 45.4 | C | NA | C-16/0 | sqd | 4% |
| FJ | 4150 | 33 | -17.9 | 12.8 | 0.12 | 12.7 | C | 0.97 | C-14/0 | fsh | 100% |
| NC | 426 | 31 | -20.6 | 10.6 | 0 | 10.9 | C | 1 | C-16/0 | fsh | 100% |
| MH | 451 | 24 | 5.7 | 11.8 | 0.05 | 20.8 | JP | 0.39 | C-14/0 | fsh | 97% |
| FM | 245 | 25 | 7.2 | 12.2 | 0 | 19.9 | C | 0.69 | C-12/0 | fsh | 96% |
| CK | 372 | 32 | -11.9 | 12.9 | 0 | 14.2 | C | 0.84 | C-14/0 | fsh | 100% |
| CN | 141 | 24 | 4.2 | 12.3 | 0.09 | 21.5 | JP | 0.51 | C-13/0 | fsh | 93% |
| JP | 1153 | 16 | 10.5 | 12 | 0 | 24.1 | C | 0.69 | NA | fsh | 100% |
| PF | 675 | 31 | -16.1 | 12.6 | 0.02 | 8.6 | C | 0.65 | C-14/0 | fsh | 100% |
| PG | 93 | 23 | 2.8 | 13.6 | 0 | 18.1 | C | 1 | NA | fsh | 100% |
| SB | 62 | 24 | -9.9 | 13.3 | 0 | 19.8 | C | 1 | C-14/0 | fsh | 96% |
| TO | 42 | 12 | -12.9 | 14 | 0.31 | 13.3 | C | 0.83 | C-14/0 | fsh | 77% |
| TV | 105 | 29 | -9.6 | 13.4 | 0 | 18.8 | C | 1 | C-14/0 | fsh | 100% |
| TW | 6626 | 17 | 0.6 | 13.6 | 0.28 | 23 | C | 0.45 | JP-3.2 | fsh | 100% |
| US | 6163 | 24 | 19 | 12.8 | 0.88 | 12.5 | C | 0.89 | C-15/0 | fsh | 100% |
| VU | 74 | 31 | -12.3 | 13.2 | 0 | 15.3 | C | 0.65 | C-14/0 | fsh | 100% |
| WS | 49 | 17 | -16.7 | 11.9 | 0.76 | 3.9 | C | 1 | C-12/0 | fsh | 100% |

**Table 3.** **Observed releases of a) SMA and b) FAL by flag from May 2017 to April 2019 as held by SPC at the time of the workshop, including proportions of releases cut-free and individuals by condition at-release. Flags with fewer than 20 releases were excluded.**

a) SMA

| Flag | # released | Prop cut free | Alive - unknown | Alive - healthy | Alive - injured | Alive - dying | Dead | Unknown |
|---|---|---|---|---|---|---|---|---|
| NZ | 483 | 0.46 | 15 | 288 | 27 | 10 | 123 | 20 |
| FJ | 228 | 0.95 | 6 | 125 | 29 | 2 | 49 | 17 |
| NC | 108 | 0.86 | 3 | 58 | 6 | 0 | 17 | 24 |
| US | 1586 | NA | 1273 | 0 | 0 | 0 | 313 | 0 |
| JP | 214 | NA | 0 | 123 | 0 | 13 | 73 | 5 |
| PF | 75 | 0.98 | 0 | 55 | 0 | 0 | 19 | 1 |
| TW | 62 | 0.61 | 23 | 0 | 1 | 0 | 18 | 20 |
| WS | 37 | 0.55 | 0 | 16 | 12 | 0 | 6 | 3 |

b) FAL

| Flag | # released | Prop cut free | Alive - unknown | Alive - healthy | Alive - injured | Alive - dying | Dead | Unknown |
|---|---|---|---|---|---|---|---|---|
| FJ | 525 | 0.81 | 5 | 312 | 72 | 10 | 121 | 5 |
| MH | 101 | 0.61 | 0 | 2 | 52 | 8 | 17 | 22 |
| FM | 49 | 0.73 | 4 | 11 | 15 | 6 | 3 | 10 |
| TW | 1561 | 0.84 | 427 | 5 | 23 | 0 | 333 | 773 |
| US | 745 | NA | 545 | 0 | 0 | 0 | 200 | 0 |
| JP | 303 | NA | 0 | 170 | 3 | 4 | 122 | 4 |
| PG | 247 | 1 | 0 | 0 | 0 | 0 | 0 | 247 |
| NC | 145 | 0.93 | 11 | 100 | 7 | 3 | 20 | 4 |
| PF | 132 | 0.94 | 2 | 90 | 0 | 0 | 29 | 11 |
| SB | 55 | 1 | 0 | 1 | 24 | 0 | 3 | 27 |
| VU | 44 | 0.92 | 0 | 27 | 3 | 2 | 8 | 4 |
| WS | 23 | 1 | 0 | 4 | 13 | 2 | 4 | 0 |

Note: Proportions cut free were not provided for US and JP flagged vessels, given low data coverage for this field in SPC's data holdings, potentially due to incomplete mapping of fate codes from US and Japanese observer programme data when consolidating the data with SPC's observer database. The US observer programme only records shark condition as "alive", "dead" or "kept".

Participants discussed why the operational characteristics of the New Zealand tagging vessels indicated a much longer mean gangion length, a longer mean soak time, and a lower usage of fish bait than other sets during which tagging was conducted. This was because most of the New Zealand fleet were targeting southern bluefin tuna.

Participants considered whether the within-fleet variability in operational characteristics was substantial enough that using a variable assigned based on "fishery" or "fleet" identity would not likely represent a consistent manner of fishing. T. Peatman explained that his review of the data indicated that the sets during which tagging occurred appeared to be generally representative of the sets conducted during that fishing trip, and also representative of the overall characteristics of the fishing operations conducted by each flag.

Some participants were concerned that simply summarizing operational characteristics by flag would over-simplify the characterization of some large and diverse fleets such as those of the distant water fishing nations. T. Peatman noted that the summary table (Table 2) is intended as a simple characterization by flag for the purpose of assessing the representativeness of the shark tagging; it should not be used for analytical purposes as it does not necessarily capture the diversity within some of the flag categories.

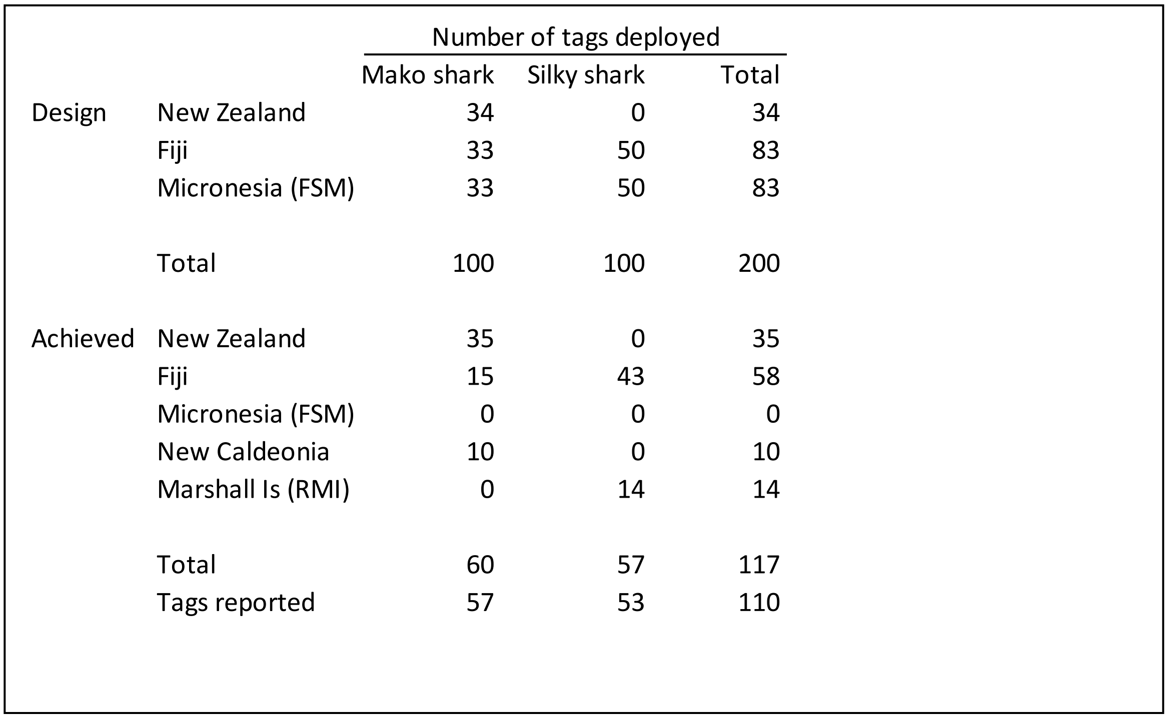
With respect to shark condition codes, T. Peatman's review of observer data revealed that most sharks are classified as "alive and healthy", followed by "dead", "alive but injured" and "alive but condition unknown". This information aligns well with the proportions recorded on the tagging sheets and suggests that the conditions of tagged sharks are representative of the conditions of sharks recorded in the fisheries by observers in general.

## 2.4 Tag Deployment Summary

M. Francis (NIWA) summarised data from the shark tags deployed under this study, including horizontal and vertical movements and temperature.

The tagging design called for the deployment of 200 tags across the two species and three fisheries/regions (Table 4). For a variety of reasons, including low numbers of live sharks caught on vessels, the design was not met within the allotted timeframe, and 117 tags were ultimately deployed. Tagging locations are shown in Figure 1. Sharks were tagged in New Zealand, Fiji, New Caledonia and Marshall Islands (Table 4). Data suitable for assessing PRM were received from 110 tagged sharks (57 mako sharks and 53 silky sharks).

**Table 4. Summary of sharks tagged under the WCPFC shark post-release mortality tagging study**



| | | Number of tags deployed | | |
|---|---|---|---|---|
| | | Mako shark | Silky shark | Total |
| Design | New Zealand | 34 | 0 | 34 |
| | Fiji | 33 | 50 | 83 |
| | Micronesia (FSM) | 33 | 50 | 83 |
| | Total | 100 | 100 | 200 |
| Achieved | New Zealand | 35 | 0 | 35 |
| | Fiji | 15 | 43 | 58 |
| | Micronesia (FSM) | 0 | 0 | 0 |
| | New Caldeonia | 10 | 0 | 10 |
| | Marshall Is (RMI) | 0 | 14 | 14 |
| | Total | 60 | 57 | 117 |
| | Tags reported | 57 | 53 | 110 |

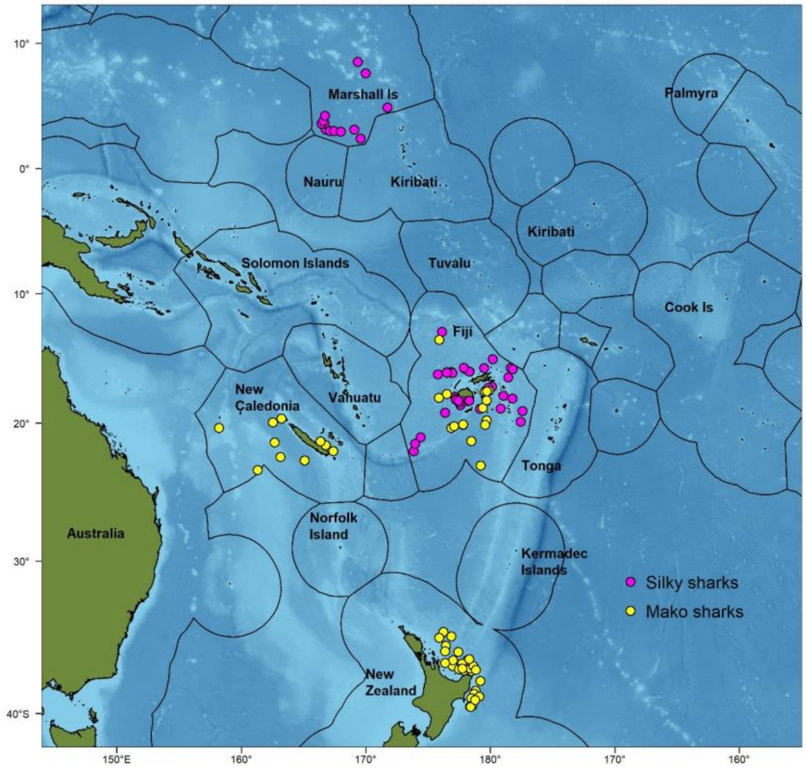


**Figure 1. Tagging location of sharks in the WCPFC shark post-release mortality study**

Tags were deployed in all months of the year for both species, but there were peaks in June-August for SMA and July-September for FAL (Figure 2). Most tagged sharks were in the range 80-160 cm, and based on reported lengths at maturity (Francis & Duffy 2005, Joung et al. 2008), most would have been immature (Figure 3). However, the lengths of many sharks were estimated while they were in the water, so these distributions are approximate.

High proportions of sharks were unsexed (35% of SMA and 23% of FAL) (Figure 3). Furthermore the ratio of males to females was low for sharks that were sexed. Since many sharks were tagged while in the water, and often at night, the presence of claspers may have been difficult to determine, especially for immature males in which the claspers do not extend beyond the ends of the pelvic fins. This could explain both the high number of unsexed sharks and the female-biased ratio.

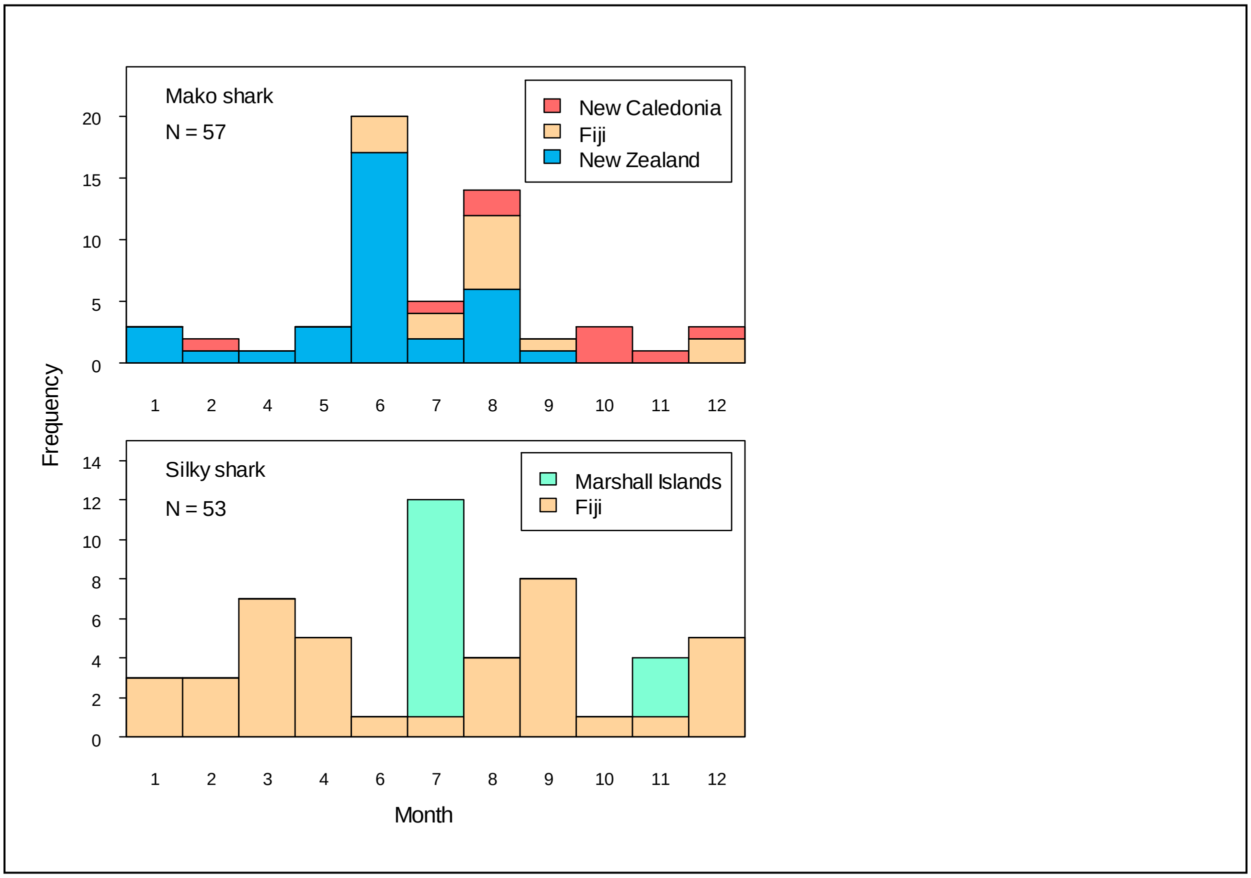


**Figure 2.** **Summary of sharks tagged by month for each species and tagging region. Only those tags that reported are shown.**

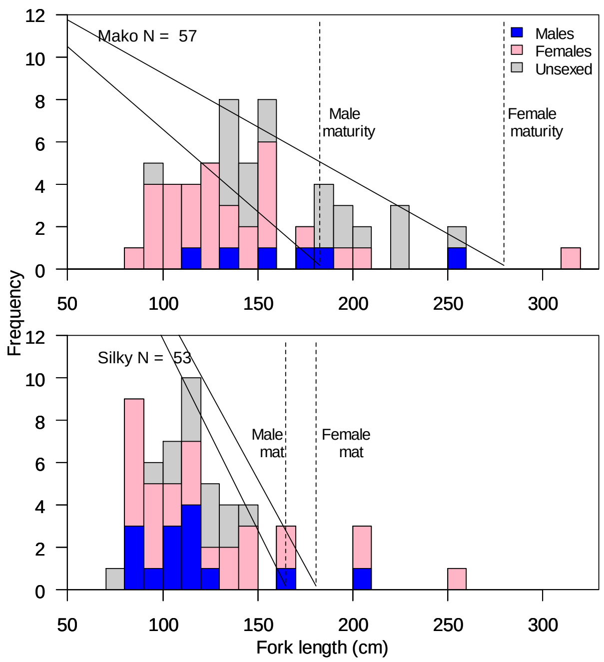


**Figure 3.** **Summary of sharks tagged by length for each species and sex. The length at maturity is shown with dashed lines in each plot. Only those tags that reported are shown.**

Nearly all FAL were tagged in the water, whereas about one-third of SMA were tagged on deck (Table 5). All of the SMA tagged on deck were tagged in New Zealand, where on-deck tagging accounted for over half of the SMAs tagged.

**Table 5.** **Summary of sharks tagged in water and on deck by species (left) and summary of SMA tagged in water and on deck by fleet (right).**

| | Mako | Silky |
|---|---|---|
| On deck | 18 | 2 |
| In water | 39 | 49 |
| Unknown | 0 | 2 |

| | NZ | Fiji | NC |
|---|---|---|---|
| On deck | 18 | 0 | 0 |
| In water | 16 | 14 | 9 |

Of the 117 tags deployed, PRM status was determined for 110 sharks (57 SMA and 53 FAL) (Table 6). The remaining seven tags either did not transmit via the satellite or did not transmit sufficient data to be useful. The tags used also collect information on depth and temperature, and such data were successfully transmitted for 108 sharks. However, the depth sensors in some tags malfunctioned (these tags were replaced under warranty by Wildlife Computers), and useful depth and/or temperature data were obtained from 104 sharks. These sensor failures did not affect the ability to determine survival.

**Table 6. Tag performance for survival, depth and temperature data.**

| | SMA | FAL | Total |
|---|---|---|---|
| **Tags deployed** | **60** | **57** | **117** |
| **Tags reported** | **57** | **53** | **110** |
| **Survival determined** | **57** | **53** | **110** |
| **Full depth/temperature received** | **56** | **52** | **108** |
| **Depth sensor functioned properly** | **55** | **49** | **104** |

Many tags detached prematurely from the sharks owing to the tag anchor working free from the muscle and skin or the pin holding the tag to the tether breaking. In those situations, the tags floated to the surface and reported via satellites. Only 47% of the SMA tags and 36% of FAL tags reached their design deployment term of 60 days (Figure 4). Premature tag detachment might be expected to be greater for sharks tagged in the water than those tagged on deck because of the difficulties involved in tagging a moving shark with a long pole. We investigated this possibility using the New Zealand tagged SMA, but found that premature detachment was greater for sharks tagged on deck (22% reached the 60-day target deployment) than for sharks tagged in the water (75% remaining until 60 days) (Figure 5). However, sample sizes were small, and other factors, such as a tagger's experience, are probably important.

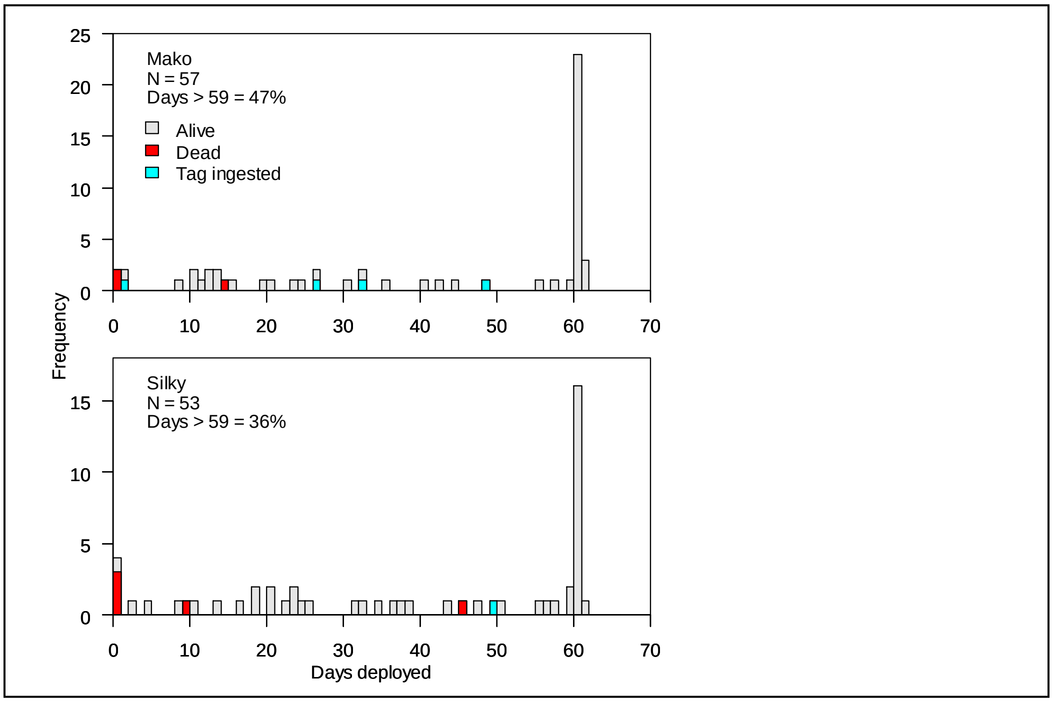


**Figure 4.** Tag performance by species. Histograms show the number of days a tag was attached to the shark. Also shown are the sharks that died and the sharks whose tags were ingested by a warm-blooded predator.

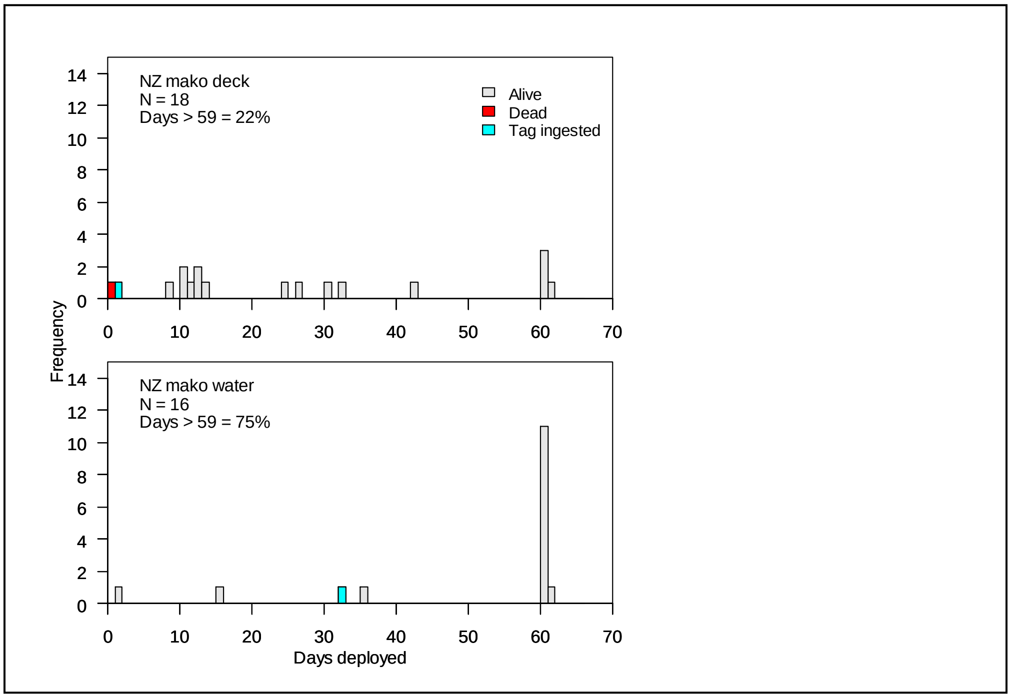


**Figure 5.** Comparison of tag performance in terms of days reporting for those tags attached to New Zealand SMA on deck (upper panel) versus tags attached in water (lower panel). Also shown are the sharks that died and the sharks whose tags were ingested by a warm-blooded predator.

Four tags attached to SMA and one tag attached to FAL were ingested by warm-blooded predators, as evidenced by an abrupt increase in the temperature, and a decrease in the daily range of light intensity, recorded by the tag (Figures 6 and 7). Marine mammals, lamnid sharks (e.g. mako, porbeagle and great white sharks) and some large tunas maintain their body temperatures above ambient levels, and could all have been responsible for the ingestions. However, the presence of lengthy dives probably rules out marine mammals, which need to come to the surface regularly to breathe. The ingested tags were eventually regurgitated, after which they floated to the surface and transmitted data via satellites.

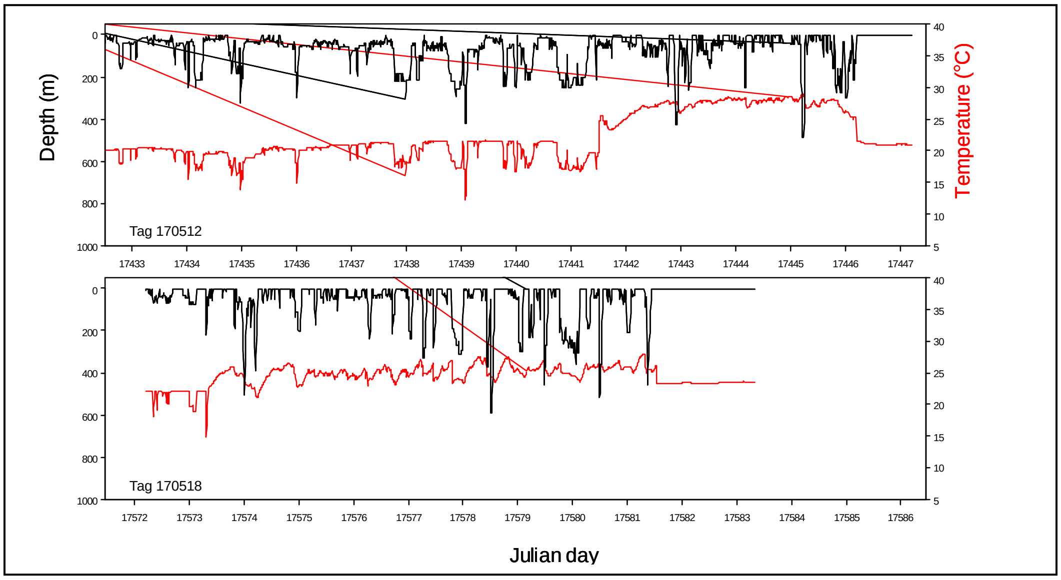


**Figure 6. Depth (black) and temperature (red) traces for two SMA whose tags were ingested by a warm-blooded predator. The times of ingestion and regurgitation of the tags are indicated by abrupt increases and decreases in temperature respectively.**

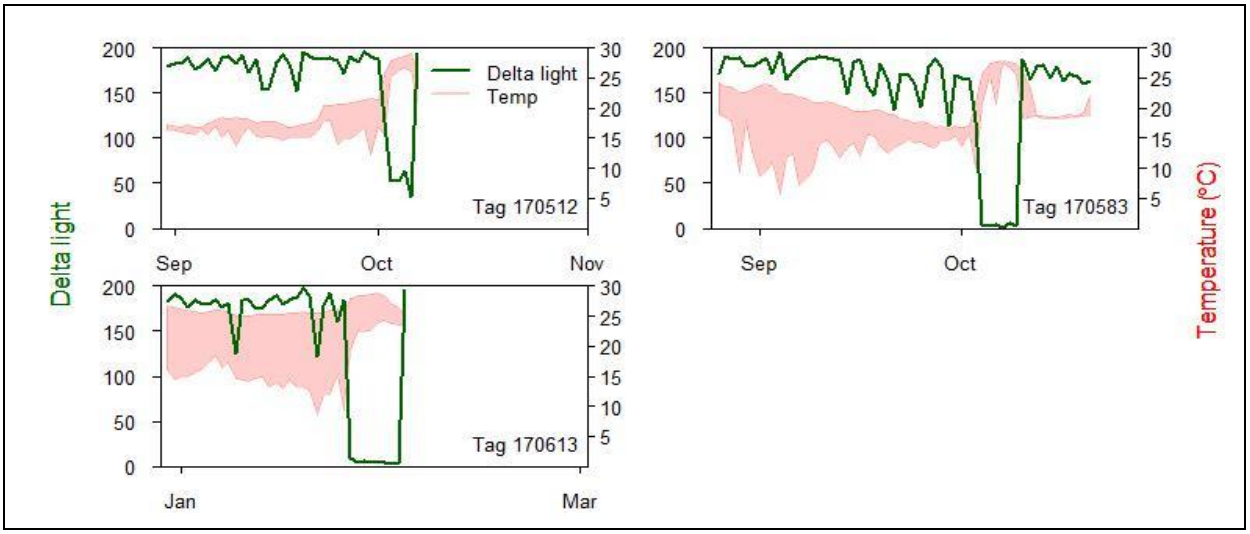


**Figure 7. Ingestion of tags by warm-blooded predators was confirmed by the drop in daily range of light levels to low or zero values (green lines) at the same time as temperatures (pink polygons) increased based on tags attached to three SMA. Light levels return to normal after regurgitation of the tag.**

In discussion, M. Francis explained that failures in the sPAT depth sensors were encountered in a few cases, but these tags were replaced by Wildlife Computers.

When discussing the number of tags which remained on the shark (half of those for SMA and one-third of those for FAL) for the full term of the programmed deployment (i.e. 60 days), one participant cited a study by Musyl et al. (2011) as suggesting that tag shedding could be caused by stress or a removal of body mucus resulting in infection. The workshop also discussed whether tagging sharks in the water provides for deeper anchoring of the tags due to the greater momentum when thrusting the tagging poles from a greater height above the shark (i.e. from the deck to the waterline).

M. Francis formulated three hypotheses in relation to tags which appeared to have been ingested by a predator:

a. The tag detached and was later consumed by a predator and the tagged shark survived;
b. The predator bit off the tag while it was still attached to the tagged shark but the shark survived;
c. The predator attacked the tagged shark and consumed the tag, and the tagged shark died

The workshop considered these possibilities and decided that each hypothesis was plausible and could apply to some of the ingested tags. However, not all hypotheses were considered equally likely. As a conservative assumption it was recommended that all observed mortality and tag ingestion events be considered as mortalities, and be included in the models noting that this may inflate the PRM estimates if hypotheses a) or b) were true. Participants noted that tagged sharks may be more likely to attract predators, and that smaller sharks may be more impaired by tagging than would larger sharks. In addition, some studies have shown that smaller sharks are more likely to suffer hooking or haulback mortality than large sharks. Some participants considered that nuptial biting might be the cause of some tag ingestion, but other participants opined that a tag ingested through nuptial biting would be promptly regurgitated.

## 2.5 Horizontal and Vertical Movements, and Water Temperatures

M. Francis provided the environmental outputs from the tags, including horizontal and vertical movements, and water temperature.

SMA showed strong latitudinal movements patterns between temperate and tropical waters, with New Zealand-tagged sharks moving northwards and Fiji-tagged sharks moving south (Figure 8). SMA tagged in New Caledonia showed a predominantly southward movement pattern. These results were consistent with SPOT-tagged SMAs tracked in a previous New Zealand based study (Francis et al. 2019). From the Marshall Islands, FAL tagged in July all headed eastward (Figure 9), whereas those tagged in November showed little movement. Fiji-tagged FAL showed little movement and their activity patterns were considered random.

High resolution depth and temperature data were recorded (every 10 seconds) for New Zealand-tagged SMA, and for the last 5 days of the deployment for all other sharks. Minimum and maximum daily depth and temperature values were available for all sharks throughout their deployments (except for tags in which the depth sensor failed). SMA experienced a broad range of temperatures in shallow waters on account of their wide latitudinal movements (Figure 10). FAL exhibited markedly different depth and temperature profiles in Fiji and the Marshall Islands. The maximum depths recorded by SMA and FAL were 1407 m and 928 m, respectively. These deep dives were believed to be live animals and were not considered mortalities. SMA tended to dive deeper than

FAL (Figure 11). The mode of the maximum depths was at 400-700 m for SMA and at 200-500 m for FAL.

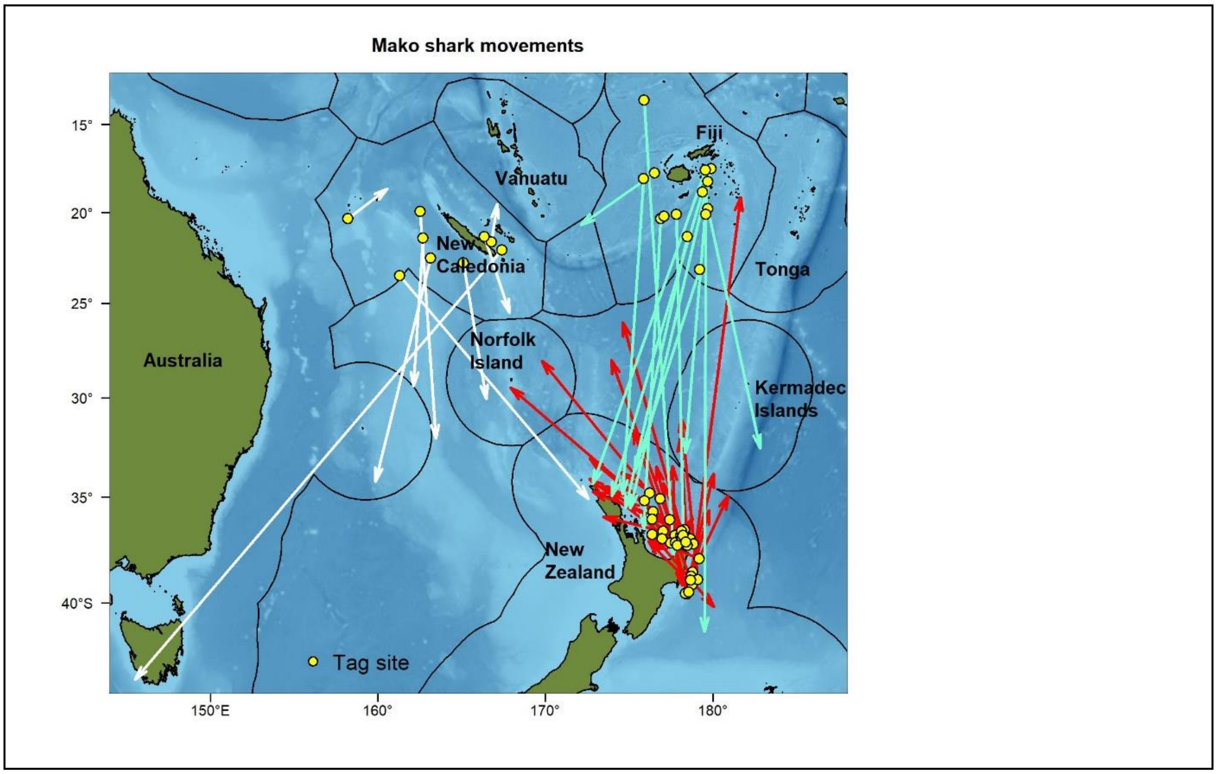


**Figure 8.** SMA movements showing tag attachment site (circles) and tag pop-up location (arrow heads). Tags attached in New Zealand (red), Fiji (blue) and New Caledonia (white) are shown.

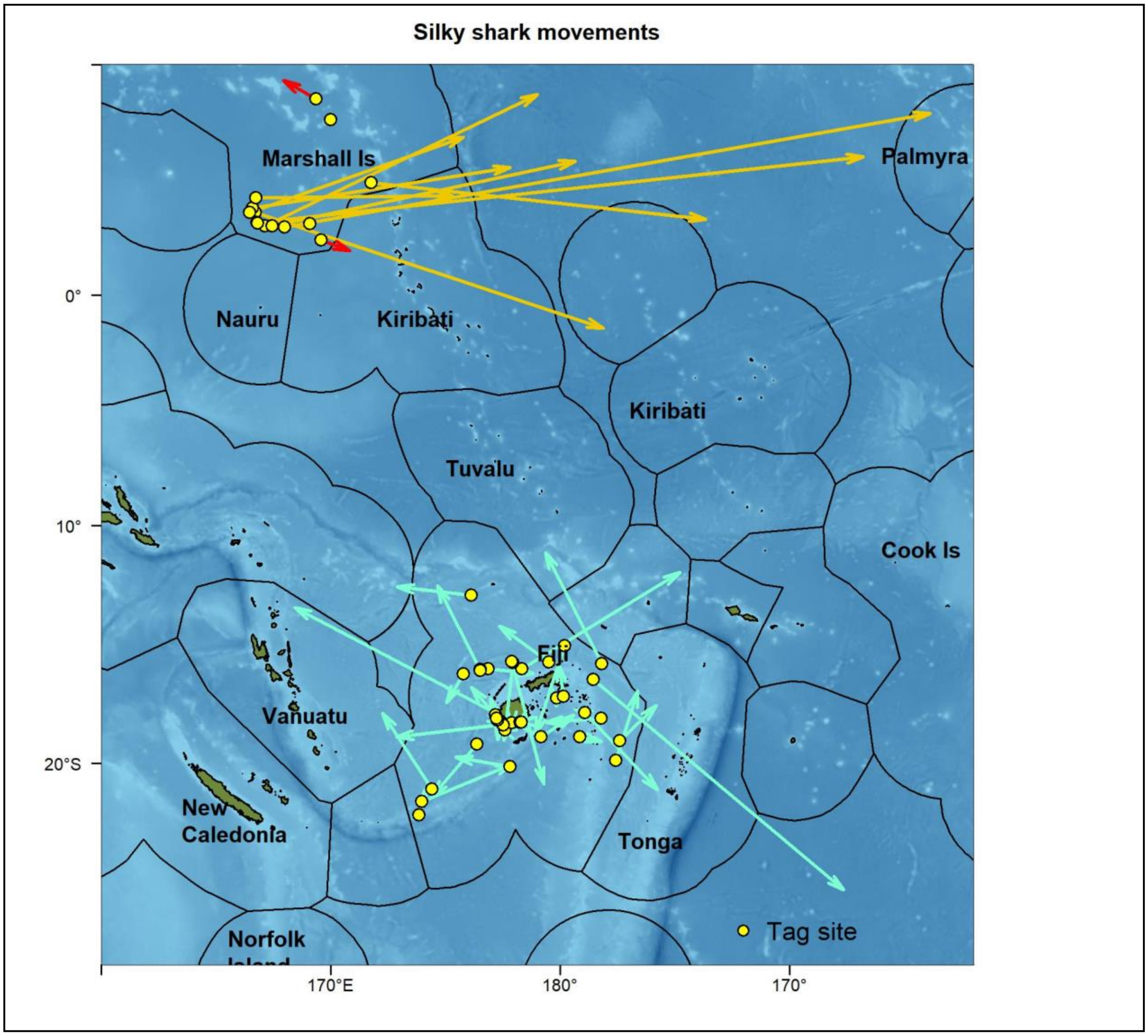


**Figure 9.** **FAL movements showing tag attachment site (circles) and tag pop-up location (arrow heads). Tags attached in Fiji (blue) and RMI (yellow and red) are shown. For RMI-tagged sharks, yellow arrows were for sharks tagged in July and red arrows for sharks tagged in November.**

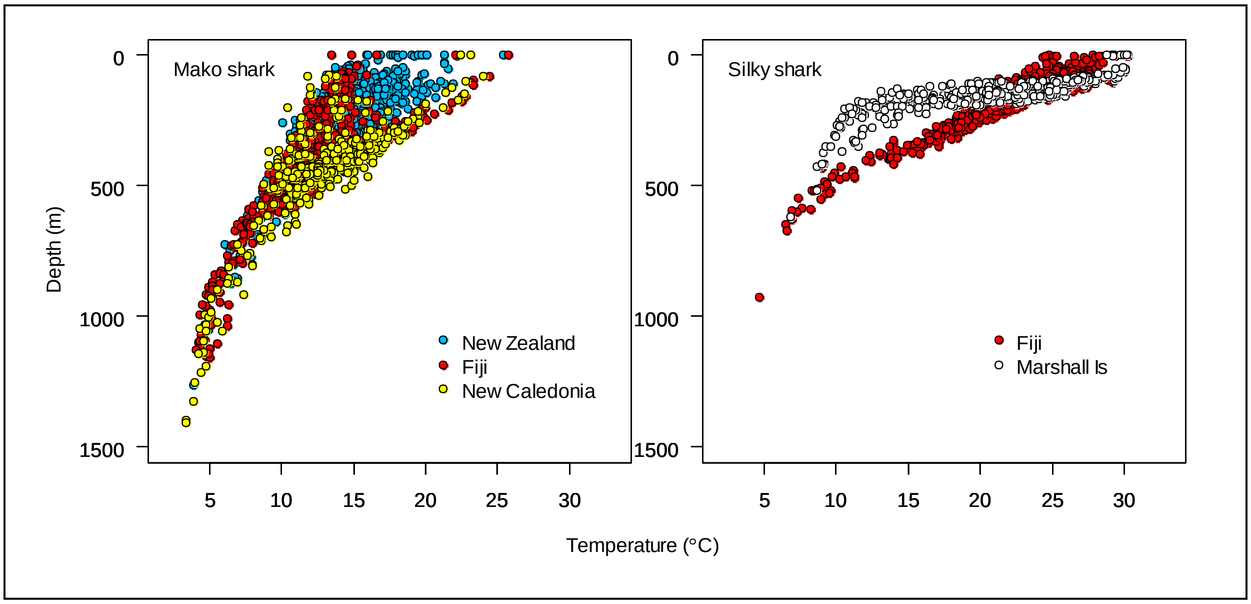


**Figure 10.** **Depth-temperature profiles for SMA (left) and FAL (right) tagged in various regions (colored circles). Data points show the paired daily values of minimum depth/maximum temperature, and maximum depth/minimum temperature.**

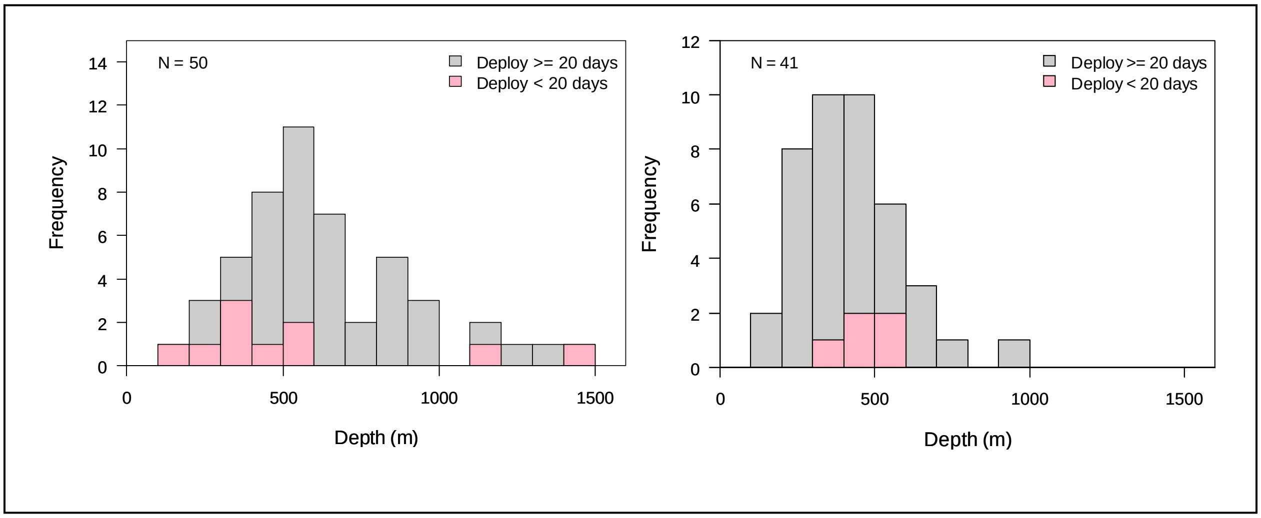


**Figure 11.** **Maximum depths observed for deployments of less than and greater than or equal to 20 days for SMA (left, maximum depth of 1407m) and FAL (right, maximum depth of 928 m). Note that plots exclude mortalities and deployments of less than 9 days.**

## 2.6 Methods and Data Issues for Estimation of PRM from WCPFC tags

M. Francis introduced the Kaplan-Meier and Cox proportional hazards models to estimate survival rates and the factors which influence it. He also provided further background on the tagging data as it relates to decisions required for constructing survival models.

Kaplan-Meier (K-M) survivorship curves were fitted to the data from tags for which PRM was determined. K-M curves track the loss of sharks from the tagged population as they die, and the fitted function can be used to predict the proportion of survivors in the population at any time. Tags that released prematurely were also lost from the population, but are not regarded as mortalities because the sharks were alive at the time of release. K-M models involve two components, a survival component (the time between tagging and the death of each shark known to have died) and a status component (whether the shark was alive at the last observation of the tag immediately before popup). The latter component is coded in a 'censor' variable for which live sharks are represented by a zero and dead sharks are represented by a one.

Estimation of the mortality rate (1 - survival rate) and the effect of potential predictor variables were done with two types of models: (a) parametric models based on the Weibull distribution (the Weibull distribution is very flexible as it can deal with hazards (i.e. risk of dying) that change with time (e.g. declining mortality rate)); and (b) semi-parametric Cox proportional hazards models.

<u>Input data and explanatory variables</u>

The condition status of sharks at tagging may influence their mortality rates. Taggers recorded condition status using multiple categories or injuries and other signs, but many were not used, and we collapsed the categories down to two: alive and uninjured (AU) and alive and injured (AI). Most tagged sharks of both species were uninjured (89%) and most sharks (88%) survived until tag loss or the programmed popup date (Table 7).

**Table 7. Condition at tagging (injured or uninjured) and life status (dead or alive) at tag popup, both species combined. Dead sharks include ingested tags.**

| | Dead | Alive | Total | Percentage Dead |
|---|---|---|---|---|
| Injured | 2 | 10 | 12 | 17 |
| Uninjured | 11 | 87 | 98 | 11 |
| **Total** | **13** | **97** | **110** | **12** |

The predictor variables considered for use in the survival modelling are shown in Table 8, along with notes on any limitations or problems with the available data. Two variables, sex and hook type, were not considered further because the recorded sex was often missing or potentially wrong, and hook type showed no contrast with most sharks being caught on circle hooks. Species, length of gangion and tagging region were available for all tagged sharks, but other variables had missing data, particularly for variables obtained from the observer database held by SPC at the time of the workshop (i.e. some observer datasets were not yet available for the most recently tagged sharks, and some sharks were tagged when observers were not present). Shark lengths were often estimated rather than measured but are probably accurate to within 20 cm. A variable was calculated from the length of gangion left attached to the shark to test the possible effect of trailing fishing gear on shark survival; the new variable was the ratio of the length of trailing gangion to the fork length of the shark (hereafter called the gangion ratio). The distributions of the continuous variables used in the modelling are shown in Figure 12.

**Table 8. Potential explanatory variables in the WCPFC shark tagging data set and their problems and limitations. Entries in red indicate variables which were excluded from the analysis (see text).**

| Variable | Problems and limitations |
|---|---|
| Species | None |
| Tag site (tagged on deck or in water) | Most FAL tagged in water, half of NZ SMA tagged on deck |
| Condition | 11% of sharks injured, rest uninjured |
| Fork Length | Most lengths estimated rather than measured |
| Sex | Many unsexed, bias towards females |
| Soak time | Available for 64% of sharks |
| Hook type | 96% circle hooks, where known (n=82) |
| Gangion length | Available for 70% of sharks |
| Hooks between floats | Available for 70% of sharks |
| Length of gangion left attached to shark | None |
| Gangion ratio | Most lengths estimated rather than measured |
| Tagging region | None |

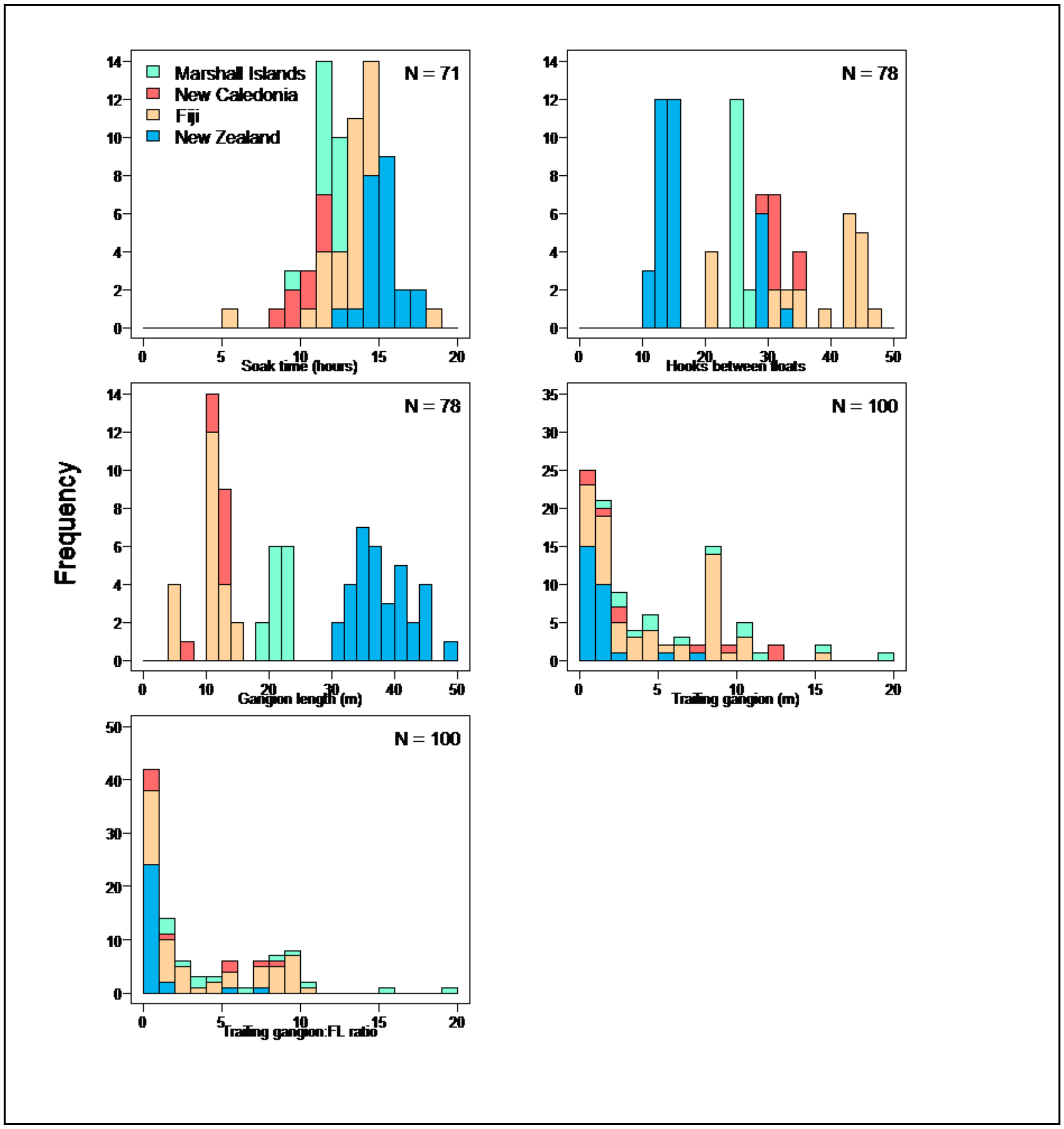


**Figure 12. Distributions of continuous predictor variables in the WCPFC shark tagging data set.**

Workshop participants discussed the importance of making data from this study available in the public domain to inform future studies. WCPFC and the Common Oceans (ABNJ) Tuna Project confirmed that raw tag data would be provided as an annex to the workshop report (**Annex C**).

Survival modelling

K-M curves by species and region are shown in Figure 13. Eight sharks died (3 SMA and 5 FAL), with most mortality occurring in the first 15 days (Figure 4). Tag ingestions occurred throughout the deployment period, with four recorded for SMA and one for FAL. Therefore, the total numbers of known mortalities and ingested tags were 7 SMA and 6 FAL (Figure 4).

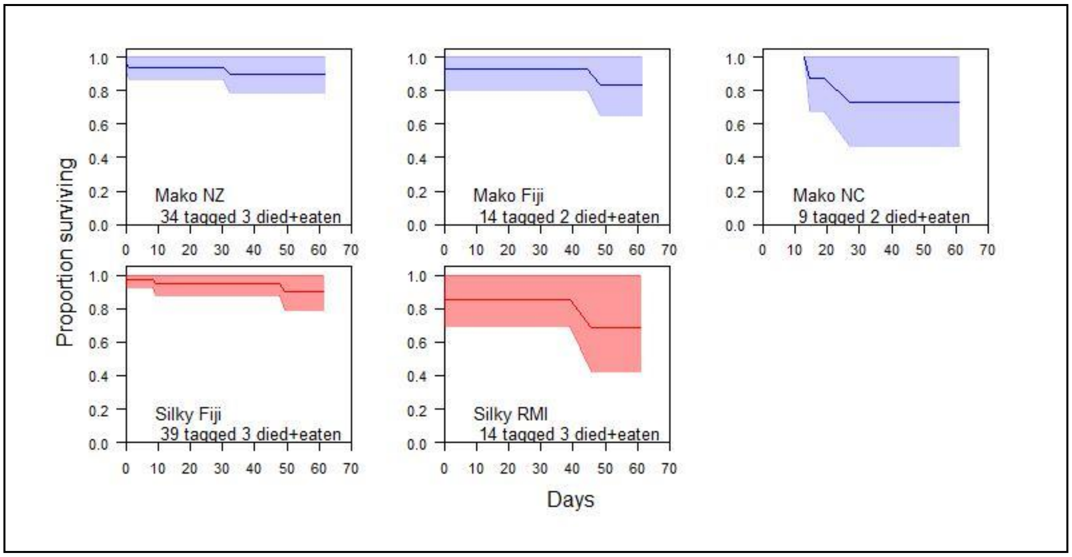


**Figure 13.** **K-M survivorship curves by species and region. Note that the K-M curves produced by R software start at the time of the first event (either a mortality or tag detachment); the first event occurred on day 13 for SMA tagged in New Caledonia (top right), so that graph begins at day 13. A downward step in the curve represents a mortality event and the 95% confidence intervals are the shaded regions.**

Workshop participants discussed whether survival rates to 60 days fully reflected acute and chronic mortality arising from the shark's encounter with the fishery, as well as a background natural and fishing mortality rates (i.e. which would apply regardless of whether the shark had interacted with the fishery). It was recommended that all observed mortality and tag ingestion events be considered as mortalities, and be included in the models, because it is important to capture all of the contributions, including predation, to mortality. Participants also discussed the timeframe over which mortality rates should be assessed. Various opinions were expressed regarding the timeframe of acute and chronic effects ranging from a few days to 14 days to 40 days or longer. Although this study's tags were programmed to report after 60 days, estimating mortality rates over a one-year period was suggested in order to best capture the cumulative impacts of all mortality sources. To support the estimation of informative mortality rates it was suggested that post-release mortality rate studies always provide both the total number of sharks surviving as well as the number of days each shark survived before dying. Tradeoffs between monitoring survival for the maximum number of days on one hand, and the probability of tag failure and the higher cost of tags with longer reporting rates on the other, were noted.

The significance of K-M survival curves crossing over time for two different factors was discussed in terms of whether it indicates that the proportional hazard assumption is not met. An alternative explanation suggesting that such curves might cross whenever they are relatively similar and uncertainty is present was also discussed.

Participants considered that there could be acute damage caused by injury and stress during the encounter with the fishery and also chronic damage caused by, for example, long lengths of trailing gear left on the shark. Both types of impacts need to be considered.

Participants cautioned against overfitting the models to the data with some guidance being provided from the epidemiological literature that there should be at least ten mortalities for each factor included in the model. Participants then discussed which factors they considered most important to try to fit and what parameterization they should take:

a. <u>Gangion Length</u>: Regarding the length of gangion left on the shark, this was recommended to be expressed as a function (i.e multiples) of shark body length, and it was agreed that the models would be re-run with this variable instead of the measured length of gangion left attached.
b. <u>Time on the Line</u>: The time the shark spends hooked (e.g. using soak time as a rough proxy) was considered very important in understanding the amount of stress the shark undergoes before being tagged. However, without hook timers or any other reliable way of understanding the true length of time the shark spends hooked, it is not likely that this factor can be appropriately assessed.
c. <u>Species</u>: Some participants recommended that the data be separated by species and separate models be run for each species. Others considered that this might reduce sample size and analytical power to insufficient levels. Instead, it was proposed to test all species' data in one model with a species interaction term against one individual factor at a time.
d. <u>Fishery/Fleet characteristics</u>: Participants revived the discussion regarding whether fishery or fleet characteristics are different in ways that would influence PRM and if so, how this could best be captured. Noting that there is always the potential for important differences to exist but not be identifiable in available data, participants considered that for the fisheries or fleets sampled (i.e. New Zealand, Fiji, New Caledonia and RMI) there was

reasonable consistency in operational characteristics within these locations and so even if factors such as gangion material were not explicitly tested, such differences would be represented by the fishery/fleet label. One participant suggested that frailty models might be the ideal way to account for such differences. Another participant suggested that environmental variables, such as temperature could be adequately represented by fishery/fleet labels for the four tagging countries in the study. There was some discussion of whether the RMI tags should be split into RMI and FSM fleets but, given the low sample size, this was considered unwise.

## 2.7 Estimation of PRM from WCPFC tagging study

M. Francis presented analytical results for the current study's tagging data incorporating suggestions from the workshop (see Section 2.6). These results included:

a. Creation of a new variable representing trailing gear called "gangion ratio" which consists of the length of gangion left on the shark at release as a ratio of the shark's fork length.
b. Creation of a "tagging region" variable to represent the four countries in which tagging occurred, i.e. New Zealand, Fiji, New Caledonia and RMI (incorporating both FSM and RMI, see discussion above).
c. Incorporation of a species interaction term for factors which are considered important in the model and possibly varying by species.

A full model was created with nine explanatory variables (Table 9) and using a backwards stepwise model selection methodology, variables were sequentially excluded, leaving fork length as the only retained variable.

**Table 9. Results of Cox models to test the effect of variables on survival for the WCPFC tagging data set with all variables in one model (no interaction terms) and ingested tags treated as mortalities. The least informative variables were removed by stepwise backward removal using the AIC. The retained variables are indicated at the top of the table, and removed variables are shown in the lower part of the table along with the improvement in the AIC that resulted from their removal.**

| Retained variables: | AIC | N |
|---|---|---|
| fork length | 72.156 | 59 |
| | | |
| Removed variables: | Delta AIC | |
| | | |
| species | 0.646 | |
| condition | 0.899 | |
| soak | 1.321 | |
| tag.site | 1.719 | |
| gangion.ratio | 1.852 | |
| hbf | 1.980 | |
| gangion.length | 1.991 | |
| region | 3.687 | |

However, because of missing values, only 59 of the tagged sharks (across both species) could be used in the model. Consequently, variables with many missing values (soak time, gangion length and hooks between floats) were dropped. In the resulting reduced model (Table 10), i.e. using fewer variables but a larger sample size, the retained variables were species, fork length and gangion ratio.

**Table 10. Reduced Cox model to test the effect of variables on survival for the WCPFC tagging data set with reduced number of variables in one model and ingested tags treated as mortalities. The least informative variables were removed by stepwise backward removal using the AIC. The retained variables are indicated at the top of the table, and removed variables are shown in the lower part of the table along with the improvement in the AIC that resulted from their removal.**

| | | |
|---|---|---|
| Retained variables: | AIC | N |
| species, gangion.ratio, fork length | 101.970 | 96 |
| Removed variables: | Delta AIC | |
| condition | 0.640 | |
| tag.site | 1.920 | |
| region | 4.880 | |

In order to test the species interactions, separate models were run with a) a species x fork length interaction (Table 11); and b) a species x gangion ratio interaction (Table 12). Neither interaction term appeared to be significant. Therefore the most appropriate base model was considered to include main effects of species, fork length and gangion ratio only (Table 10).

**Table 11. Cox models to test the effect of variables on survival with reduced number of variables in one model and interaction of species with fork length. Ingested tags are treated as mortalities. The least informative variables were removed by stepwise backward removal using the AIC. The retained variables are indicated at the top of the table, and removed variables are shown in the lower part of the table along with the improvement in the AIC that resulted from their removal.**

| | | |
|---|---|---|
| Retained variables: | AIC | N |
| species, gangion.ratio, fork length | 101.970 | 96 |
| Removed variables: | Delta AIC | |
| species * length | 0.910 | |

**Table 12. Cox models to test the effect of variables on survival with reduced number of variables in one model and interaction of species with gangion ratio. Ingested tags are treated as mortalities. The least informative variables were removed by stepwise backward removal using the AIC. The retained variables are indicated at the top of the table, and removed variables are shown in the lower part of the table along with the improvement in the AIC that resulted from their removal.**

| | | |
|---|---|---|
| Retained variables: | AIC | N |
| species, gangion.ratio, fork length | 101.970 | 96 |
| Removed variables: | Delta AIC | |
| species * gangion ratio | 1.960 | |

The effect of treating ingested tags as mortalities is shown by comparing K-M survivorship curves with and without those tags in Figures 14 and 15. The effect was greater for SMA than for FAL because of the greater number of ingested SMA tags. Patterns for both species were nearly identical when ingested tags were included (Figure 15).

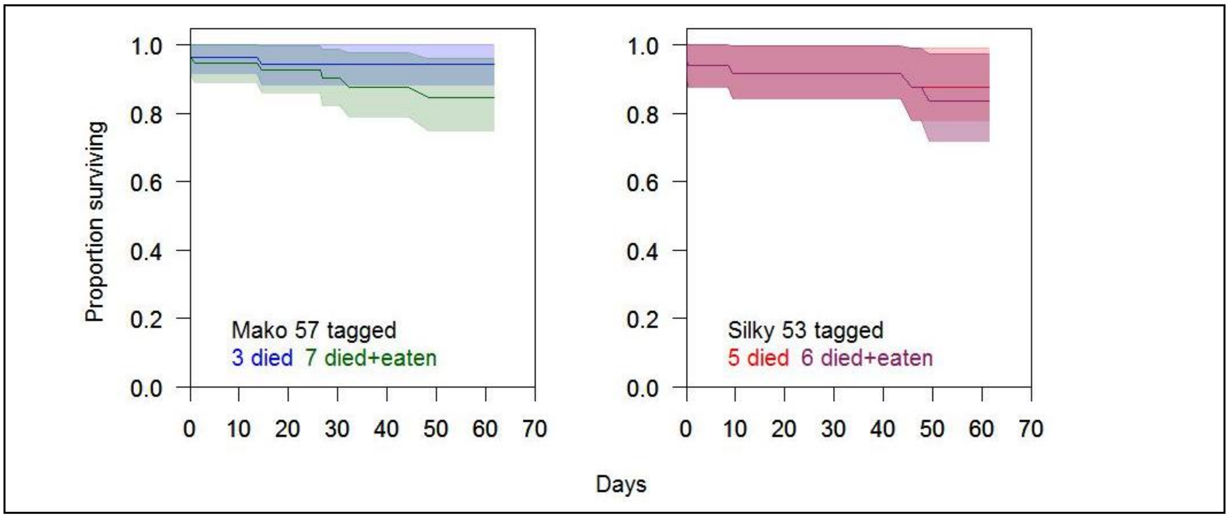


**Figure 14.** **Kaplan-Meier survivorship curves by mortality assumption (whether ingested tags were excluded (top line, either blue or red) or included (bottom line, either green or purple)) for SMA (left) and FAL (right).**

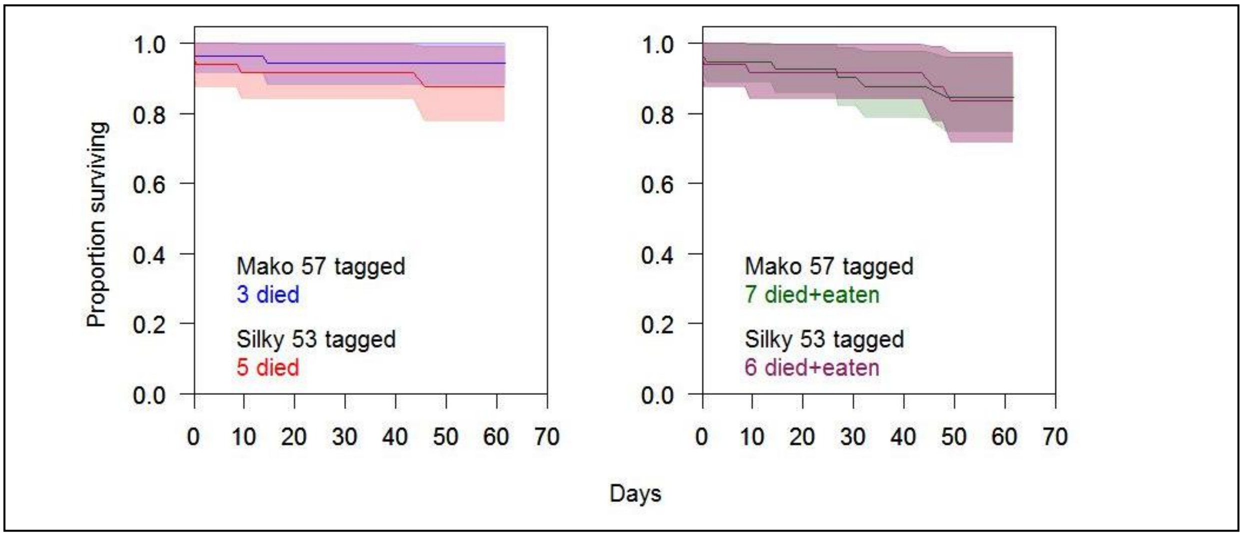


**Figure 15.** **Kaplan-Meier survivorship curves by species by mortality assumption (whether ingested tags were excluded (left) or included (right). Lines are color-coded by species.**

K-M curves indicate that the mortality rate of sharks (both species combined) was greater for small sharks (defined as those less than 160 cm fork length) than for large sharks (Figure 16).

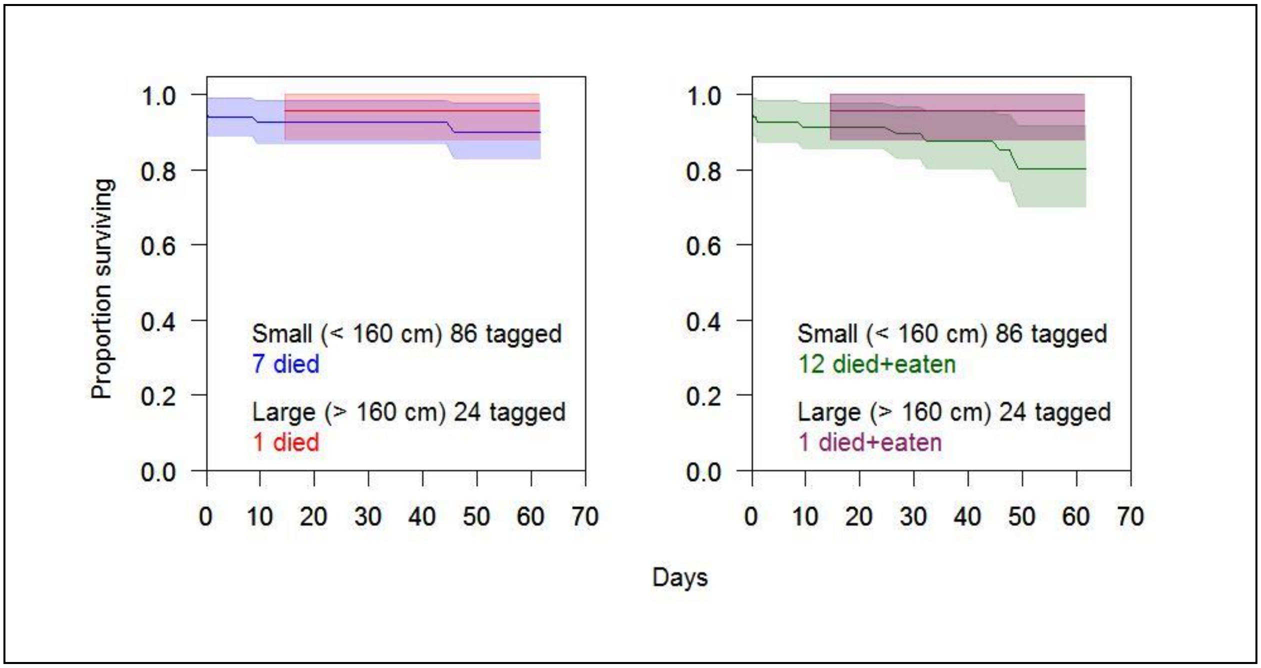


**Figure 16. Kaplan-Meier survivorship curves by mortality assumption (ingested tags excluded (left) and ingested tags included (right)) and shark length (small or large) for both species combined (SMA and FAL). Lines are color-coded by size.**

PRM was predicted for SMA[2] using the base model with variables species, fork length and gangion ratio (Table 10). For the prediction, species was set to SMA, fork length was set to the median value in the SPC observer data holdings (120 cm fork length) at the time of the workshop (see Section 5), and the gangion ratio was set to the median value calculated from the data collected by observers when sharks, regardless of species,were tagged (1.35). The predicted PRM at 60 days was 20.5%. The workshop attempted to produce confidence intervals but was not clear on how to interpret confidence intervals from the Weibull distribution. The effects of a) time since tagging, and b) fork length on SMA PRM are shown in **Annex D**.

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[2] Silky shark results, based on a larger dataset that combined the WCPFC data with data from other similar Pacific Ocean studies, are presented in Section 4.

The workshop discussed how to interpret the results for the new variable gangion ratio given that there is considerable uncertainty in the measurement of both the length of gangion left on the shark and the shark's fork length. The workshop referred to the histograms of gangion ratios and gangion lengths by tagging region (Figure 12). K-M curves are usually constructed on the basis of a categorical variable (i.e. one curve per category) but since gangion ratio is a continuous variable it is not easily presented in the same format. The workshop agreed that for the purposes of illustration separate curves could be presented for categories of gangion ratio (i.e. short versus long, or other arbitrarily defined categories containing both survival and mortality outcomes), although the model should retain the continuous form of the gangion ratio variable for statistical purposes. K-M curves for short and long gangion ratios are shown in Figure 17.

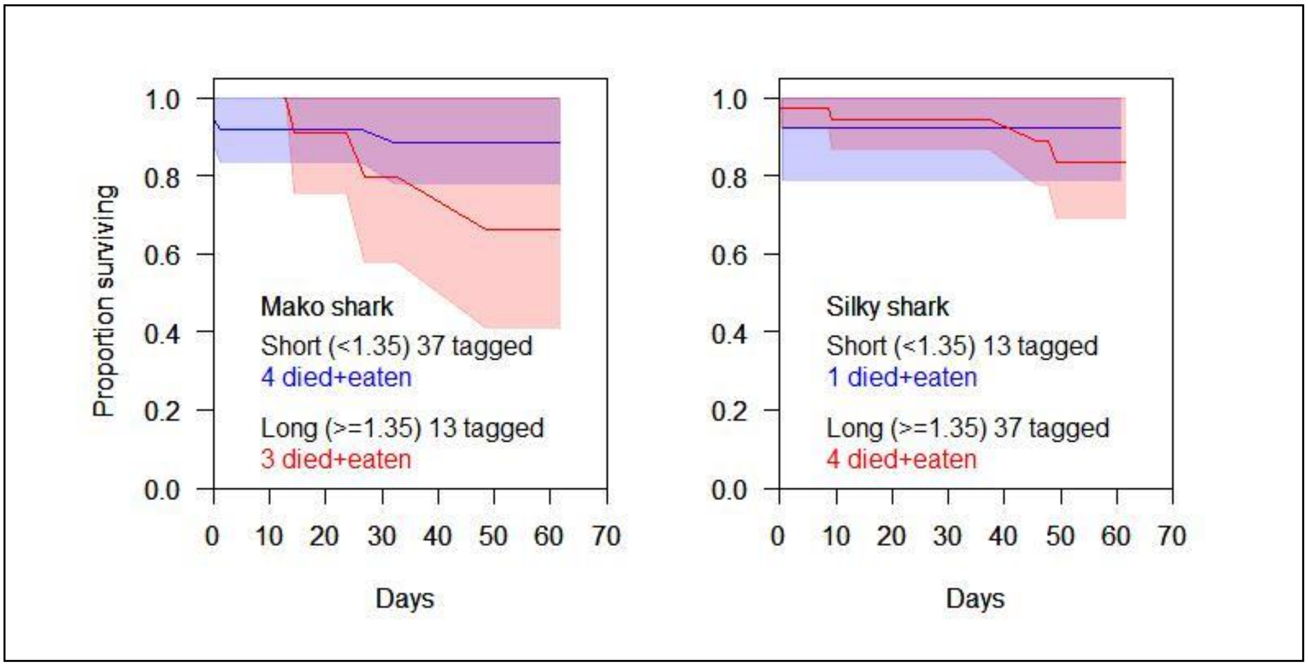

**Figure 17.** **Kaplan-Meier survivorship curves for SMA and FAL by gangion ratio (short and long, where 'short' is gangion ratio <1.35 and 'long' is gangion ratio ≥1.35. The median gangion ratio for all tagged sharks in this study regardless of species is 1.35. Ingested tags are included. Lines are color-coded by gangion ratio.**

# 3 Other Shark PRM Tagging Studies

## 3.1 Individual Studies

M. Francis commenced the session with a summarization of a recent PRM study of Northwest Atlantic shortfin mako shark by Campana et al (2016):

> *Based on more than 21 000 fisheries observer records and the results of 109 popup satellite archival tags, all sources of fishing-induced mortality (harvest, capture, and post-release) were estimated for blue sharks (*Prionace glauca*), shortfin mako (*Isurus oxyrinchus*), and porbeagle (*Lamna nasus*) in the Canadian pelagic longline fishery between 2010 and 2014. Hooking mortality ranged from 15 to 44%, with porbeagles and makos experiencing much greater mortality than blue sharks. The post-release mortality rate varied between 10 and 31%, with porbeagle and mako again having the highest mortality rate. Overall, about one-half of the hooked porbeagles and makos died during or after fishing, with most of the post-release mortality occurring within 2 d of release. Landed catch accounted for less mortality in porbeagle and blue sharks than did the combination of hooking and post-release mortality. These results indicate that the conservation benefits of mandatory release regulations for pelagic longline gear are not nearly as great as is now assumed.*

Participants discussed whether five mortalities in Campana et al. (2016) should be removed or retained given that Campana considered that there was extreme handling mortality associated with these tags. Noting that the authors had recommended removing these mortalities, as well as the fact that effects of the individual tagger or crew handling sharks for tagging can be significant, the workshop suggested that these five mortalities would best be removed.

M. Hutchinson (NOAA-Joint Institute for Marine and Atmospheric Research, University of Hawaii) presented on silky sharks captured incidentally and released at sea in the American Samoa permitted tuna longline fishery (Hutchinson et al., in prep):

> *No retention measures for silky sharks call for fishers to release sharks in a manner that will minimize harm but there are no recommendations for which handling and discard practices improve post release survival rates. In this study we worked with the Pacific Islands Regional Observer Program to place survivorship pop-off archival tags on incidental silky sharks that were in good condition at haul back to get the most optimistic and quantitative estimates of post release survival rates by discard method. Observers tagged 29 silky sharks while they were still in the water and instructed the fishers to release the animals however they normally do. We found that sharks are typically released by cutting the line that they were captured on leaving various quantities of trailing gear attached to each animal. Twenty-four of the sharks tagged in this study were released by cutting the line, two animals were boarded and had the gear removed and two sharks broke free after tagging. All of the silky sharks tagged in this study survived the interaction indicating that silky sharks that are in good condition at haulback have high post release survival probabilities.*

Some participants noted the importance of considering handling mortality, in addition to haulback mortality and post-release mortality.

M. Hutchinson made a presentation on behalf of K. Schaefer (Inter-American Tropical Tuna Commission (IATTC)), describing the domestic longline fishing fleets of Costa Rica and Ecuador that commonly target and retain sharks:

> *For this study (Schaefer et al. 2019), a handling method recommended by the fishers of those fleets to optimize post-release survival (PRS) was evaluated. The PRS rate estimated from Kaplan–Meier survival analyses was 94.3% (95% CI: 87.0%–100%) for 38 silky sharks,* Carcharhinus falciformis*, captured by longline fishing vessels of Costa Rica and Ecuador in the equatorial eastern Pacific Ocean following tagging and release with pop-up satellite archival tags (PSATs). The 36 silky sharks that survived the interaction were at liberty with PSATs attached for an average of 100.6 d (range: 5–180 d).*

The workshop discussed whether the Ecuador and Costa Rica tags should be treated as separate studies (or fleets) or whether these tags should be treated a single study. It was noted that the authors analysed the tags as two separate datasets but found no significant difference between them. For this reason, the workshop considered that the Ecuador and Costa Rica tags could be treated as a single study.

M. Musyl (Pelagic Research Group) presented a recent PRM study of silky sharks released from a commercial longline fishery in Palau (Musyl & Gilman 2018):

> *Forty-eight blue (*Prionace glauca*) and 35 silky sharks (*Carcharhinus falciformis*) were tagged with pop-up satellite archival tags to monitor post-release fishing mortality ($F_r$) rates from pelagic longline vessels in the western tropical Pacific Ocean. There is a paucity of $F_r$ studies at low latitudes and identifying factors that significantly explain $F_r$ is critical for understanding fishing mortality. Mean $F_r$ rates were 0.17 [95% CI 0.09–0.30] for blue shark and 0.20 [95% CI 0.10–0.36] for silky shark. When it occurred, $F_r$ was acute with 87% of mortalities within 2 days of release. Several prognostic operational, environmental, biological and handling variables were evaluated to assess their influence on survival outcomes. Using Kaplan–Meier survival curves, logistic regression, accelerated failure time and Cox proportional hazards models to screen variables, the only significant prognostic or risk variable was health condition at haulback. There was close correspondence (~83% accuracy) between condition at haulback and survival outcomes. Reliable methods to classify at-vessel condition represent an inexpensive and simple metric for estimating both $F_r$ and at-vessel ($F_c$) mortality rates. Examining $F_c$ rates in detail in longline fisheries using capture information on depth, temperature and dissolved oxygen that may act in synergy with condition code and hooking duration is a research priority. Results suggest that a large proportion of sharks survive following release and that $F_r$ rates can be increased by improving the haulback condition of captured sharks.*

One participant noted that if non-fouling coatings are not used bio-fouling is more likely to accumulate on a tag, overcoming its positive buoyancy and preventing the tag from transmitting.

R. Coelho (Instituto Portugês do Mar e da Atmosfera, IPMA) introduced some of the tagging components of the ongoing International Commission for the Conservation of Atlantic Tunas (ICCAT) Sharks Research and Data Collection Program (ICCAT/SRDCP):

> *Within this program several shark species have been tagged, prioritizing 1) species that are being assessed, mainly shortfin mako and porbeagle, and 2) species under no-retention regulations, mainly silky shark, oceanic whitetip, hammerheads and threshers. The presentations focused mostly on preliminary results for shortfin mako. The shark satellite tagging program in ICCAT started in 2015, and to date a total of 93 tags have been acquired. Of those, 43 tags (29 miniPATs and 14 sPATs) have been deployed on shortfin mako, by*

> *observers on vessels from Portugal, Uruguay, Brazil, Spain and the US, operating in the temperate NE and NW, Equatorial and SW Atlantic regions. Data from 41 tags/specimens are available, and a total of 1656 tracking days have been recorded. In terms of post-release mortality, data from 35 tags were used to estimate preliminary results, as those were the tags where either a mortality event or survival was recorded for ≥ 30 days. Tags that detached prematurely for unknown reasons or failed to transmit were not considered for the post-release mortality estimations. There was evidence of 8 mortality events (22.8%). Larger individuals exhibited lower post-release mortality rates than smaller ones, specifically 15.4% PRM for specimens ≥ 180 cm FL, and 23.8% for specimens < 180 cm FL. In 2019, 17 additional miniPATS have been acquired. The species that are currently being prioritized in the new phases of the project are mostly silky sharks and oceanic whitetip.*

Participants noted that the mortality rate for shortfin mako sharks in these studies was similar to that observed by Campana et al. (2016) in the Atlantic. In response to a question about which operational factors were determining mortality the author explained that analysis was still underway, and these findings are not yet available.

## 3.2 Meta-analysis

M. Musyl recently published a meta-analysis of post-release mortality in pelagic sharks. He summarized the results from his study, with the abstract of this publication (Musyl & Gilman 2019) provided here:

*Robust assessments of the effects of fishing require accounting for components of fishing mortality, including post-release fishing mortality ($F_r$). Random-effects meta-analysis synthesized $F_r$ in seven pelagic shark species captured, tagged and released with 439 pop-up satellite archival tags compiled from 34 studies and three gears (longline, purse-seine, rod & reel). The majority of $F_r$ outcomes occurred within days of release, and the summary effect size for $F_r$ was 0.27 [95% CI: 0.19–0.36], ranging from a low pooled effect size of 0.17 for blue shark (*Prionace glauca*, Carcharhinidae) to 0.38 (silky shark,* Carcharhinus falciformis, *Carcharhinidae). $F_r$ rates in blue shark were consistent over dissimilar spatial and temporal scales, and results from earlier meta-analysis were replicated, which is the most powerful way to authenticate results. Condition at tagging was a strong predictor, and dichotomized survival outcomes in silky shark and no sex-, size-, location-or gear-specific $F_r$ rates were demonstrated. Meta-analyses and sensitivity analyses indicated exposure to risk factors and conditions whilst caught on the gear probably had the largest explanatory effect on $F_r$, rather than stressors incurred during handling and release. Records from 549 tagged istiophorid billfishes (six species, three gears, 43 studies) demonstrated they are more robust to stressors sustained during capture, handling and release than pelagic sharks. Findings from previous meta-analysis on $F_r$ rates in white marlin (*Kajikia albida*, Istiophoridae) were replicated. Synthesized $F_r$ rates enable prioritizing approaches to mitigate by-catch fishing mortality, to improve the quality of stock and ecological risk assessments and to expand our knowledge of factors influencing trophic structure.*

In response to a question, the presenter clarified that some studies' tags were partitioned into different analytical groups on the basis of condition code. In other words, it is condition code and not gear type (i.e. purse seine or longline) that determines the similarity of survival rates. The presenter stressed the need for harmonized condition codes among studies, as well as improved handling practices which can enhance survival.

# 4 Integration of Datasets and Joint Analysis

## 4.1 Data compilation and selection

Workshop participants produced a table summarizing the key variables from each of the datasets presented to the workshop (see Section 3; Table13).

For SMA the only potential data for combination with the WCPFC shark tagging dataset were the data from Campana et al. (2016) in the Northwest Atlantic Ocean. The workshop discussed the potential reasons why the Atlantic tagging region might have a higher post-release mortality than the Western and Central Pacific Ocean (WCPO), noting that not only the Campana et al. (2016) study but also the recent ICCAT studies show this higher level of mortality. One hypothesis is that a greater proportion of smaller sharks were tagged in the Atlantic despite the fact that the overall range of sizes of tagged sharks was similar between Campana et al. (2016) and the current study. Differences in gangion type were also discussed. There was some doubt about the appropriateness of combining the WCPFC and Campana et al. (2016) datasets, but it was agreed to proceed with the combined analysis and to carefully consider the results to determine whether such joint analysis is appropriate (in particular the explanatory variable relating to tagging region).

For silky sharks, the potential data to be combined included the WCPFC data, the NOAA study in Hawaii and American Samoa (Hutchinson et al., in prep), the Nature Conservancy (TNC) study in Palau (Musyl & Gilman 2018), and the IATTC study in Costa Rica and Ecuador (Schaefer et al. 2019).

**Table 13. Summary of post-release mortality studies presented to the workshop. Species codes: SMA=shortfin mako shark, FAL=silky shark. 'Mappable' indicates whether the study used comparable condition codes to the WCPFC shark tagging study, and the codes are available.**

| Study | Year | Species | Region | Sample size | Tag type | Shark length | Soak time | Hook type | Gangion material | Length of gangion left on | Tagging location | Shark condition | Reference | Combine in this study? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ABNJ | 2017-2018 | SMA | NZ, Fiji, New Caledonia | 57 | sPAT (60 d) | Yes | Yes | Circle (mainly) | Yes | Yes | Mostly in water | Mappable | This study | NA |
| ABNJ | 2018-2019 | FAL | Fiji, Marshall Is | 53 | sPAT (60 d) | Yes | Yes | Circle (mainly) | Yes | Yes | Mostly in water | Mappable | This study | NA |
| Campana | 2011-2013 | SMA | Northwest Atlantic | 27 | MK-10 PAT (up to 12 mo.) | Yes | No* | Circle (mainly) | No* | Yes | Mostly in water | Mappable | Campana et al. (2016) | Yes |
| NOAA | 2016-2018 | FAL | American Samoa | 28 | sPAT (30 d) | Yes | Yes | Circle | Yes | Yes | Mostly in water | Mappable | Hutchinson et al. (in prep.) | Yes |
| IATTC | 2016-2017 | FAL | Ecuador, Costa Rica | 38 | Mini PAT (90 & 180 d) | Yes | No | Circle (mainly) | Yes | Yes | All on deck | Mappable | Schaefer et al. (2019) | Yes |
| TNC | 2016 | FAL | Palau EEZ | 35 | sPAT (30 d) | Yes | Yes | Circle hooks (3 types) | Yes | Yes | All on deck | Mappable | Musyl & Gilman (2018) | Yes |

* Not in dataset but potentially available from author

## 4.2 Joint Analysis

M. Francis presented the results of the analysis of the combined datasets. For SMA data from the Campana et al. (2016) study, the six tags from one observer trip and the associated five mortalities were excluded from this analysis as recommended by the authors. The Kaplan-Meier survival curve from the Campana et al. (2016) study was noted to steeply decline in the initial period but in the longer term to approximate the slope of the survival curve resulting from this study (Figure 18). Using the same stepwise backwards selection process (based on AIC) as used for the analysis of the current study's data (see above) the full model contained the explanatory variables tagging region, condition, gangion ratio and fork length only (due to data limitations arising from comparability between studies), and the final model was reduced to tagging region only (Figure 18). Given this result, the workshop considered it inappropriate to combine the datasets, and the WCPFC tagging dataset was thus considered a stand alone result for SMA (see Section 2.7).

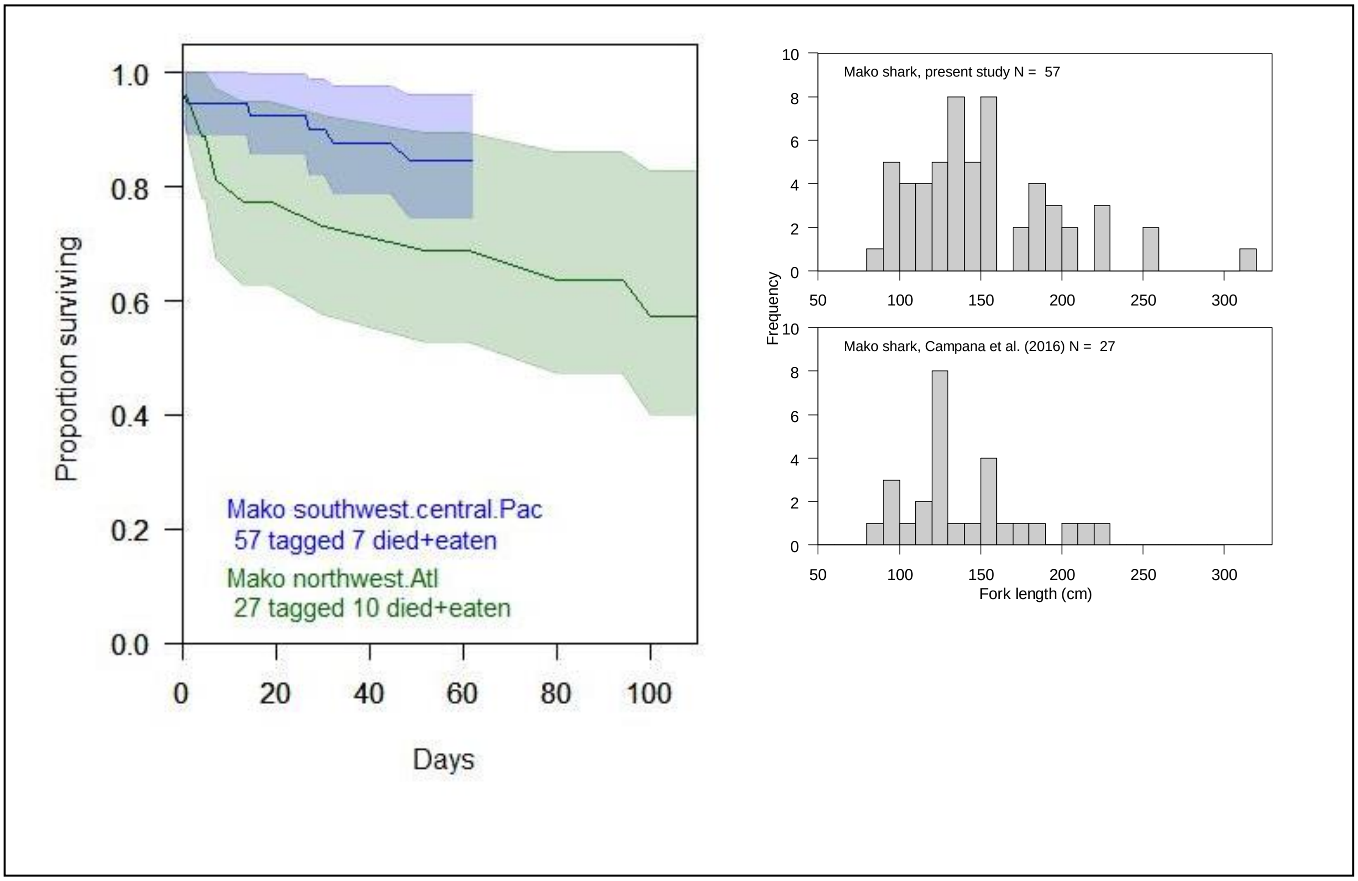

**Figure 18.** **Kaplan-Meier survivorship curves by study for shortfin mako shark. The length frequency distributions from the two regions are shown.**

For silky sharks, it was noted in the K-M survival curves that the WCPFC tags and those from the Palau-based study both show an initial, steep drop in survival with relatively stable rates thereafter (Figure 19, left panel). The 95% confidence limits of the K-M curves from the WCPFC tags overlapped those from the other studies (Figure 19, left panel). Therefore, all four FAL datasets listed in Table 13 were aggregated (Figure 19, right panel) and a joint Pacific Ocean FAL PRM analysis was conducted.

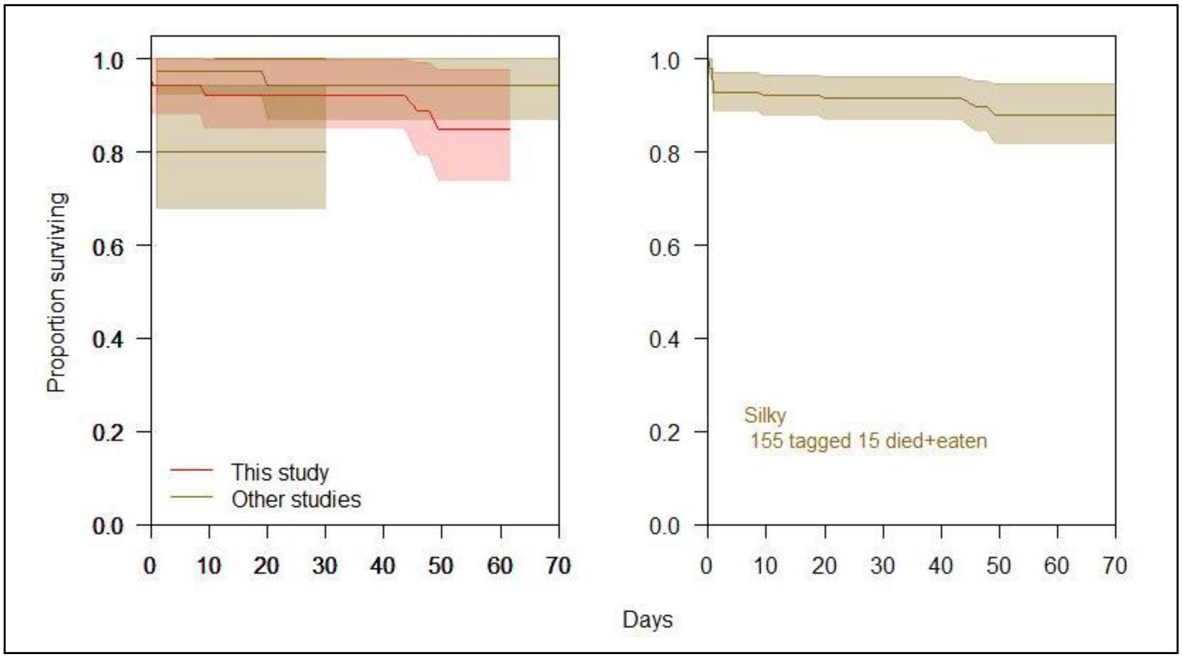

**Figure 19. Kaplan-Meier survivorship curves by study (left) and for all datasets combined (right) for silky shark.**

After a backwards stepwise regression only the variables condition and gangion ratio remained (Table 14).

**Table 14. Results of Cox models to test the effect of variables on survival for the joint analysis for silky shark.**

| Retained variables: | AIC | N |
|---|---|---|
| condition, gangion.ratio | 102.260 | 150 |
| Removed variables: | Delta AIC | |
| fork length | 0.250 | |
| region | 0.420 | |

K-M survival curves by condition indicated that if the shark is uninjured (AU) the mortality rate is low, whereas if the shark is injured (AI) there is a sharp drop in survival in the first few days with little mortality observed thereafter. It was noted that the confidence intervals for the injured shark curve are broad because the sample size is small (Figure 20).

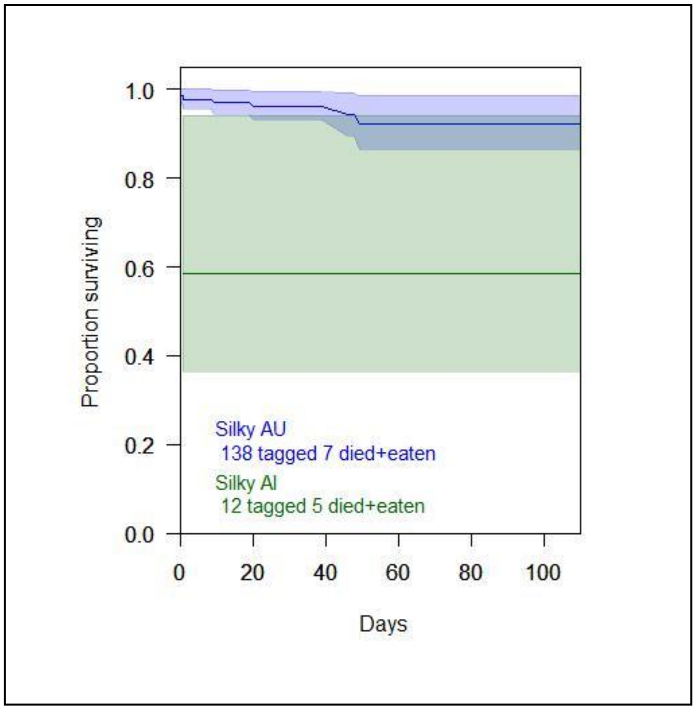

**Figure 20.** **Kaplan-Meier survivorship curves for silky shark, studies combined, by condition category (alive uninjured (AU), alive injured (AI)).**

Curves plotted by gangion ratio divided into “short” (tagged FAL with gangion ratio<1.35) and “long” (tagged FAL with gangion ratio≥1.35) showed short gangion ratios have a few mortalities initially and then no further mortalities, whereas long gangion ratios show continued mortality through the reporting period (Figure 21). The latter result was attributed to drag or wrap-around injuries arising from the longer gangion length left attached.

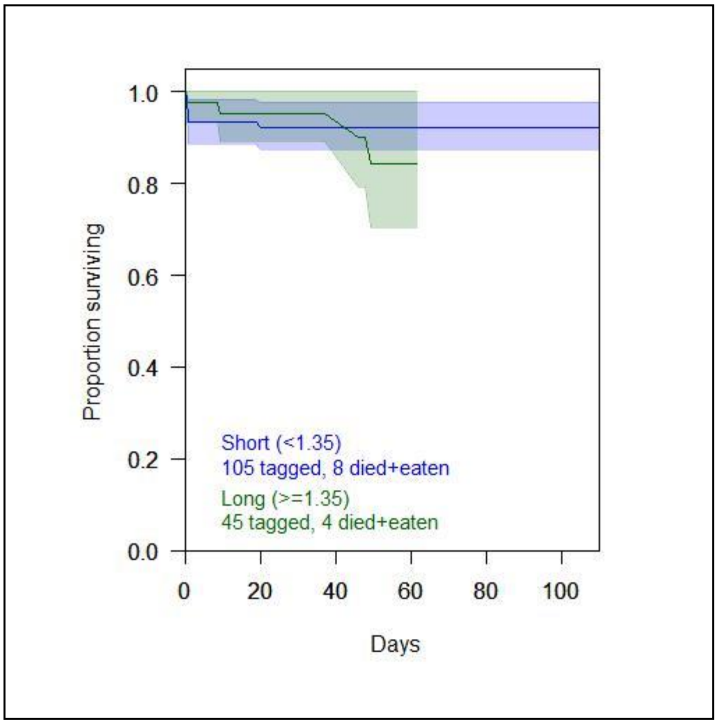

**Figure 21. Kaplan-Meier survivorship curves for silky shark, studies combined, by gangion ratio where 'short' is gangion ratio <1.35 and 'long' is gangion ratio ≥1.35.**

PRM was predicted for silky shark using the base model with variables condition and gangion ratio (Table 14). For the prediction, the gangion ratio was set to the median value calculated from the data collected by observers when sharks, regardless of species, were tagged (1.35). The predicted PRM at 60 days was 4.3% for condition AU and 50.0% for condition AI. The workshop attempted to produce confidence intervals but was not clear on how to interpret confidence intervals from the Weibull distribution. The effect of time since tagging on PRM is illustrated in **Annex E**, as is the condition-weighted average PRM. The 60-day value of the latter is 15.4%.

The workshop discussed whether the combined results of several studies for SMA and FAL indicated that there were species-specific differences in PRM such that results should not be generalized across species. It was noted that some of the differences in results between SMA and FAL models can be attributed to the differences in data availability between studies and the total sample size available for each species. It was suggested that PRM by species should be compared to haulback mortality rates for those species in order to more clearly identify where there are species-specific differences.

Participants revisited the discussion of predicting PRM rates over a longer period in order to account for background natural mortality. Participants acknowledged that PRM rates estimated from any tagging study, regardless of how many days the tags report, would represent a combination of mortality arising from the shark's interaction with the fishery (both PRM and fishing mortality) as well as mortalities that would occur naturally (i.e. predation, senescence even in the absence of fishery interactions). The workshop agreed that predicting beyond the timeframe in the available data was problematic, noting that natural mortality is an inherent component of the survival curves but cannot be well-estimated with existing data. Concerns about the validity of projections related to the fact that there are limited data available for long tag deployments, yet mortalities have been observed in long tagging periods (e.g. at 188 days) and some studies have shown "bathtub"-shaped mortality curves (i.e. mortalities rising again after appearing to stabilize at a low level). Projecting from gradually declining K-M curves (such as those produced in the workshop) would not account for these late-term mortalities.

The workshop also considered that some of the tags that are found detached from sharks and considered to have experienced attachment failure from a live shark may actual arise from a fishing operation killing a shark and throwing away the tag. In such cases, the mortality of the shark would be unreported and thus our mortality rates would be under-estimated. Participants noted that if the tagged shark is killed but the tag remains on the vessel, the fate of the shark (i.e. mortality) can be inferred from the tag track. Nevertheless, the potential to under-estimate shark mortalities in this way was noted as an important element of data interpretation.

# 5 Estimating overall shark mortality for the WCPO

S. Hoyle (NIWA) presented a summary of the paper by Harley et al. (2015), which combined a catch model and a fate model to simulate silky and oceanic white tip shark mortalities in WCPO longline fisheries:

> *Model parameters in the fate component included catch rates, release rates, hook locations, and mortalities at different stages of the catch and release process, with uncertainty included via Monte Carlo methods. Prior to the workshop the fate component of the model was replicated (**Annex F**), along with assumed catches. However, there was uncertainty about some aspects, such as how catch-per-unit-effort (CPUE)'s of shark lines and shallow sets were combined with effort to generate catches, and whether handling mortality (between haulback and release) is accounted for. These issues will need to be clarified before the model is used.*

T. Peatman presented an overview of SPC's observer data holdings that could be used to update the parameterization of the Harley et al. (2015) model relating to the proportion of individuals cut free, and the proportion of catches released alive and so subject to PRM. The majority of shortfin mako and silky sharks were cut-free, though with some variation between flags (Table 3). Estimates of proportions of sharks released alive were generated using the approach of Clarke (2011). Individuals were considered to be released alive if they had a condition at-vessel of alive –

unknown, alive – healthy or alive – injured, and did not have a condition at-release of alive – dying or dead (Table 3). Of the sharks captured with known fate and condition at-vessel66% of silky sharks were released alive (95% CI 0.58 – 0.72) and 55% of shortfin mako released alive (95% CI 0.47 – 0.63; Table 15) with the remainder discarded in dead or dying condition, or retained in the case of SMA. It was noted that the estimation approach pooled data across all flags, with no consideration of between fleet variability.

**Table 15. Observed captures of WCPFC key shark species (n) during the duration of tagging (May 2017 to April 2019) as held by SPC at the time of the workshop, the proportion of catches released alive and 95% confidence intervals obtained by bootstrapping from observations.**

| Species | n | Prop of catches released alive | CI |
|---|---|---|---|
| Silky shark | 2409 | 0.66 | 0.58 - 0.72 |
| Shortfin mako | 3581 | 0.55 | 0.47 - 0.63 |
| Bigeye thresher | 2564 | 0.71 | 0.62 - 0.78 |
| Blue shark | 94840 | 0.61 | 0.5 - 0.72 |
| Hammerhead sharks | 97 | 0.50 | 0.33 - 0.68 |
| Longfin mako | 333 | 0.61 | 0.51 - 0.7 |
| Mantas & mobulids | 103 | 0.81 | 0.59 - 0.97 |
| Oceanic whitetip shark | 1066 | 0.75 | 0.71 - 0.79 |
| Porbeagle shark | 1049 | 0.45 | 0.32 - 0.57 |
| Thresher sharks | 495 | 0.63 | 0.54 - 0.72 |

The workshop noted that many of the parameters used in the Harley et al. (2015) paper were not particularly well-informed and were either based on expert judgement or drawn from published studies in other oceans. Although the SPC dataset may not currently contain sufficient information to robustly specify these parameters' values and their distributions, nevertheless it is likely that in some cases more representative estimates could be drawn from recent observer data, even if sparse. It was noted that recently agreed Regional Observer Programme Minimum Standard Data Fields (effective in 2016) should begin to provide information on whether species of special interest (i.e. silky and oceanic whitetip sharks) are 'hooked in mouth', 'hooked deeply (throat/ stomach)', or 'hooked externally' and whether the 'hook and/or line removed' when released.

Some participants considered that the model could provide a useful framework for examining assumptions about management measures as well as new information collected from observer programmes on shark mortality. It was noted, however, that the model was specifically designed to address no-retention species and so it is more easily applied to silky shark than to shortfin mako as the latter is commercially valuable and thus often retained. Initially, the workshop considered whether it would be useful to re-run the 2015 model with updated data on haulback, handling and post-release mortality. This was not done because it is was not clear exactly how these particular factors were parameterized (i.e. mortality was specified for in-water and on-deck releases of lip- and gut-hooked sharks which seemed to blend a combination of handling and post-release mortality).

After reviewing the available data and models, an alternative was proposed involving combining the estimates, by species, of the percentage of sharks released alive and not dying from the SPC data and the post-release mortality rates estimated from the tagging study. To support this approach the SPC data were used to estimate:

- The median length of observed shortfin makos (120 cm); and

- The proportion of silky sharks in each condition class (75.7 % alive and uninjured, and 24.3 % alive and injured).

The results of model output when using the shark size, condition class and gangion ratios as input data for a PRM prediction at 60 days using the combined data models are presented above in Section 2.7 for shortfin mako and Section 4.2 for silky shark. An overall post-release mortality estimate for silky shark was obtained by calculating a condition class weighted average using the proportion of silky sharks in each condition class given in the bullet point above and the condition-specific PRMs from Section 4.2 (Table 16).

The PRM rates estimated in this workshop were applied to the estimates of the proportion of sharks released alive and not dying as represented in observer data and shown in Tables 3 and 15 to estimate the total proportion of catches that died as a result of PRM. The calculations show that considering both factors, a reasonable estimate of the proportion of sharks that survive a fishery interaction is 0.44 for SMA and 0.56 for FAL. There are several caveats associated with these calculations. First, the length of sharks in the SPC observer data holdings may be an underestimate of shark length as large sharks are difficult to handle and thus tend not to be measured. Second, these figures represent data pooled across all fleets and would more accurately represent the true situation if fleet values were weighted by their proportion of catch of the species of interest. However, this was not possible with the data available to the workshop.

**Table 16. Combination of SPC observer shark condition data and PRM estimates from this study. *=excluding bite-offs.**

| | A | B | C | D |
|---|---|---|---|---|
| Species | Proportion of Catch Released Alive (Table 15) | PRM Rate (60-day) (Sections 2.7 and 4.2) | PRM as Proportion of Catch (A x B) | Proportion surviving a fishery interaction* (A-C) |
| FAL | 0.66 | 0.154 | 0.102 | 0.56 |
| SMA | 0.55 | 0.205 | 0.113 | 0.44 |

# 6 Recommendations

## 6.1 Recommendations for Reduction of Shark PRM

1. Given the finding in this workshop and in other published studies that the length of trailing gear left on the shark, as a function of body length, is a significant factor in determining PRM for both SMA and FAL, the workshop recommended when releasing no-retention species, or other species that are voluntarily released, to minimize the length of the trailing gear left on the shark. This could be accomplished by bringing the shark close to the vessel while still in the water, and using a line cutter to cut the line as close to the hook as possible.

2. The workshop recommended that further work should be conducted to determine whether existing sea turtle line cutter mitigation devices are appropriate for removing trailing gear from sharks, or whether other more appropriate devices should be developed.

3. The workshop noted that hauling the shark close to the vessel before release would not only facilitate the removal of trailing gear from the shark but also aid species identification by either an observer or an electronic monitoring system.

4. Noting that the WCPFC no-retention measures require sharks to be released with minimal harm, the workshop examined whether sharks released in water and on deck had different probabilities of survival. In the case of silky sharks this study provided no data on this point. In the case of shortfin mako sharks some tagged individuals were hauled on deck but this was not found to be significant factor in their PRM, however, this result may be due to low statistical power for this factor. Furthermore, the workshop noted that the condition of silky sharks, i.e. injured or not, was a significant factor in determining PRM, and considered that the probability of injury is higher when sharks are hauled onboard.

5. The workshop highlighted the importance of collecting data on a) handling practices and release methods, b) condition at haulback and condition at release; c) shark length; d) length of trailing gear; e) gangion material; and f) hooking location and hook type for further evaluation of shark mitigation effectiveness.

## 6.2 Recommendations for use of the mortality estimates and for further research

6. Noting that several shark PRM studies have recently been published or are underway around the world, the workshop considered that PRM results from different studies and fisheries should be subject to further joint analyses in order to better understand PRM in various regions and work toward harmonized best practice for safe release, perhaps through the Joint t-RFMO (Kobe) Bycatch Working Group.

7. This WCPFC study used a reporting period of 60 days but the workshop considered that there might be chronic effects of fishery interaction beyond this period, and that longer tagging periods would be informative with regard to background mortality. In general, longer reporting periods would thus be preferred noting that longer deployments represent a higher cost and a higher probability of tag failure.

8. The workshop suggested that all studies report non-reporting tags and other performance and reliability data to inform future studies. In addition, all studies should report not only the number of survivors and mortalities but also the survival times.

9. The workshop noted that there are species-specific differences in PRM rates. Therefore analysts should exercise caution when applying the range of PRM estimates from studies on other species. At-vessel mortality rates may be an indicator of species-specific sensitivities to fishing related stressors and therefore PRM. In the absence of PRM estimates for a given species of interest, it may be useful to consider at-vessel condition for other pelagic sharks as an indicator of post-release fate.

10. The workshop noted that shark tagging studies can be expensive, not only due to the cost of the tags. Costs for tagger training, tagging coordination, ancillary equipment and shipping, vessel and tagger costs/rewards, and data management and analysis can be considerable and potentially more than twice the cost of the tag purchase.

11. The workshop considered that Harley et al. (2015) represents a useful framework for understanding the various components of shark mortality and recommended that the model be further developed and the parameter inputs updated to the extent possible in a follow-on study. Such a study would be useful in providing specific advice to managers considering the effectiveness of WCPFC shark mitigation measures.

12. Future stock assessments and projections should utilize the estimates from the WCPFC shark PRM study as well as any update to the Harley et al. (2015) model to consider the full range of mortality to the species of interest.

13. The workshop noted that the amount of time the shark spends hooked can be a significant factor in determining stress and hence PRM and other population level effects. Therefore in order to address this point more explicitly further studies should consider the use of hook timers or any other reliable way of understanding the true length of time the shark spends hooked.

14. The workshop recognized that it is important to understand and consider observer deployment patterns when designing a tagging study, i.e. to account for when observer deployments might be halted when required coverage levels are reached or when observers are re-deployed to other fisheries. It was noted that coordination needs daily attention and resourcing.

15. The workshop recommended that the results of the study be provided to the participating companies, vessel captains and observers, as well as the WCPFC Scientific Committee.

16. The workshop recommends that for continuity and consistency future tagging studies build upon the experience of participants in this and other similar studies in the region.

17. The workshop noted the recommendations in the first workshop that the unused tags will be transferred to the ongoing NOAA shark PRM study. The workshop considered that the following species should be the priority for additional tagging and that a power analysis should be conducted to inform the distribution of tag numbers across these three species:

a. oceanic whitetip sharks (to increase the sample size for this species of high conservation interest);
b. shortfin mako sharks (to sample another fleet to augment the WCPFC shark tagging results for this low productivity species which is scheduled for assessment in 2021);
c. bigeye thresher sharks (to resolve mortality rates by hooking location for this very low productivity species).

# 7 Acknowledgements

On behalf of the WCPFC, the Common Oceans (ABNJ) Tuna Project, SPC and NIWA, the workshop expressed its sincere appreciation to the national fisheries scientists, observers and fishing vessel captains and crew who participated in this study, without whom the study would not have been possible:

**New Zealand**: John Annala and Daniel Kerrigan (MPI). Taggers: Matt Saunders, Ben Leslie, Rob Coy, Nigel Hollands, Shane Hart, Karl Bretherton, Steve Haddock and Karl Mattock.

**Fiji**: Jone Amoe and Apenisa Satauranga (Fiji MOF), Anare Raiwalui and Radhika Kumar (FFIA). Taggers: David Muai, Etonia Bale, George Acraman, Isikeli Tavo, Saiasi Raturina, Sevanaia VuuMawi, Timoci Vakatovolea, Ulaiasi Naqaravatu, Vaisoni Rainima and Hai To Fan.

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**Republic of the Marshall Islands**: Sam Lanwi Jr., Beau Bigler and Todd Gold (MIMRA). Taggers: Alington Abiia, Davis Tabu, Charles Facer, Sammy John Sr and Jin Liang.

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## Annex A. Workshop Participants List

| First Name | Last Name | Country/Organization | email |
|---|---|---|---|
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## Annex B. Details of pre- and post-deployment coordination

# Pre-deployment coordination

### *Observer training*

Training occurred in New Zealand, Fiji, the Marshall Islands and New Caledonia over a period of two years, with a total of 62 participants, including fisheries observers and longline vessel captains. All training included theory modules of scenario training on how to complete the shark tagging logsheet, as well as practical modules on preparing the tag pole and tags, use of the video camera, and practising tagging from a commercial longline vessel. Polo shirts were provided to each trainee.

Three training sessions were undertaken in New Zealand, resulting in five fisheries observers being trained to tag sharks. These training events took place in May and July 2017 and in March 2018 at Wellington. Fiji training took place in Suva over two days in September 2017. Twelve FFIA officers, 17 MOF observers, and six MOF staff were trained to tag sharks. Day one of the training included theory and day two had a practical session at Suva port where all participants practised tagging a frozen blue shark in the water from a surface longline vessel. Marshall Islands training took place in Majuro over two days in July 2018 with 13 MIMRA fisheries observers, and four MIMRA staff being trained to tag sharks. The first day involved theory, and on the second day all participants moved to Majuro port to practise tagging a floating watermelon from a surface longline vessel (sharks were not available for practice tagging because RMI is a shark sanctuary). Three training sessions were undertaken in New Caledonia with eight participants including two observers and two captains. These training events took place in June and August 2018 and January 2019 at Nouméa port. As New Caledonia is also a shark sanctuary, a dummy shark was created for practice tagging. The dummy shark was made of polyester, plastic, PVC tube and metal bars (sand and the metal bars were used to control the balance and reduce the buoyancy of the polyester).

### *Data collection*

Shark taggers were asked to wear a video camera on their heads during tagging to record the process, and to provide a check on data recording. If the video footage from the camera differed from the data sheet, the video footage was taken to be correct.

A copy of the shark tagging data sheet (both sides) is shown as Attachment 1 at the end of this Annex. The following data types were recorded:

- trip and set data;
- tag details;
- shark details;
- shark handling and life status;
- shark release codes;
- information on fishing gear left on the shark ('trailing gear'), and whether that represented normal practice;
- a drawing to show the tag location.

On the Marshall Islands' data sheets, set start date and time were also recorded so that maximum soak time could be calculated.

Data codes were defined on the back of the data sheet. The life-status of each shark was an important field to record, and it was used to identify what sharks should be tagged. The ‘Alive – uninjured’ life-status code was used if the shark was ’lively when observed’ and all criteria were met (see yellow box below). Taggers used the ‘Alive – injured’ life-status code (grey box below) when the ’shark appeared lively but has obvious injuries’. Taggers were instructed to record one or more of seven sub-categories. The ‘Alive – moribund’ life-status code (red box below) was used to identify if ’sharks were certain to die’ and had at least one of the injuries listed.

Additional codes on the back of the data sheet classified the hook location, how the shark swam away from the boat, and the handling codes, including whether the shark was tagged on the vessel deck or in the water (Table B1).

**Use this code if the shark is lively when observed**

**X** Alive – uninjured

Use if **ALL** of the following apply:

1. quick movements and/or response to being hauled;
2. frequent gill movement;
3. shark is not bleeding or is slowly bleeding and not from the gills (blood may be seen around mouth and/or jaw)
4. hook is visible (eg mouth hooked) and has not been swallowed or hooked in the gills;
5. jaw is intact and appears functional with injury limited to hook puncture and/or small hook extraction wound, with some bleeding possible from the wound;
6. if gear is wrapped around the shark, it is not inhibiting or it is removed with minimal damage;
7. appendages remain functional after removal of gear.

**Use this code when the shark appears lively but has obvious injuries.**

**Y** Alive – injured

Use if **at least one of** the following characteristics applies:

Y1 minimal shark movements and/or minimum reaction to being hauled;
Y2 minimal gill movement;
Y3 shark is gill hooked or hook is not visible and has obviously been swallowed;
Y4 blood is flowing freely, continuously, and shows no sign of slowing down or stopping;
Y5 jaw is damaged but still useable;
Y6 injuries (greater than hook puncture or minimal gear extraction wound) are present, but not immediately life threatening, eg fins may be frayed, damaged or torn, but are still useable;
Y7 if wounds are present on the body (muscle may be visible but not deep enough to expose internal organs).

**Use this code if the shark is expected to die (DO NOT TAG)**

**Z** Alive – moribund

Shark is alive, but *presumed* to have **at least one of** the following lethal injuries:

- Bleeding from a torn or severed gill arch (unlikely to survive if gills are bleeding)
- Multiple fins missing;
- Serious damage to eyes or head;
- Jaw broken, unusable or missing to the point where the shark will be unable to hunt or feed;
- Deep wounds with internal organs visible;
- Amount of bleeding may be used to quantify whether a shark is moribund

**Table B1: Handling codes from shark tagging data sheet**

| | |
|---|---|
| A | Hook removed by hand |
| C | Cut free |
| H | Hauled on deck |
| G | Body gaffed |
| E | Left on deck |
| Y | Hook yanked out |
| O | Hook cut off |
| D | De-hooker used |
| U | Struck with club |
| S | Trod on |
| T | Tagged and released |
| F | Cheek gaffed |
| Z | Other (specify) |

Taggers were also instructed to measure or estimate shark fork length. The minimum size for tagging was set at 90 cm fork length (FL) or 100 cm total length (TL) for both shark species. Taggers were instructed to tag all the sharks in the 'Alive – uninjured' and 'Alive – injured' life status categories. Taggers were told not to tag sharks in the 'Alive – moribund category as they were judged certain to die, and therefore their survival status was considered known. The aim was to tag a representative range of live sharks (other than those judged to be moribund) in order to encompass the full range of health conditions of sharks released by longline fishers during the normal course of their operations.

## *Study design*

The study design involved tagging 100 shortfin mako sharks and 100 silky sharks in several Pacific countries using electronic 'survivorship' tags to determine survival of sharks caught and released by surface longline vessels. Wildlife Computers' miniPAT and sPAT tags set for two-month deployments were used. The tagging programme spanned a Wildlife Computers' product upgrade of sPAT tags from one-month to two-month deployments, and the upgraded sPATs were not initially available for use. Instead, Wildlife Computers provided reprogrammed miniPAT tags designed to mimic two-month sPAT tags. These modified miniPAT tags were used for tagging sharks in New Zealand waters, while the new two-month sPATs were used in the remaining countries.

The selection of regions in which to tag sharks was based on an analysis by SPC of observer data to determine the number of sharks caught by fisheries in various countries, the seasonality of their catches, and the life status of the captured sharks. With approximately 50% of sharks being recorded as dead at the boat, and more being classified as 'expected to die', the number of sharks available for tagging was relatively low. Thus, a large pool of taggers was required to deploy the tags.

Planning a tagging study that involves observers necessitates determining the seasonal timing of observer deployments on the various fishing fleets, and the priorities of each national observer programme. These factors can strongly affect the ability of observer programmes to deploy tags.

## *Equipment and logistics*

With the support of the partner organisations, NIWA designed, sourced and built tagging equipment for each country engaged in the tagging project. Fifteen tagging kits including 30 extendable tagging poles were assembled (Figure B1). Instructions were included on how to assemble the tagging pole, tag a shark, use the video camera, and identify the shark species. Health and safety issues were identified, and data sheets were provided (Table B2). Also present in the tagging kits were country-specific information guides for taggers. These included a letter to the vessel captain explaining the project, information on the vessel assistance required by the tagger, and details of the vessel lottery (if relevant). The complete equipment and training guide can be found in Lyon et al. (2017).

Memoranda of Understanding specifying the outcomes of this study were developed with MPI and FFIA, and MoF endorsed the project by sending its staff to the local shark tagging workshop. No MOU was required with MIMRA and DAM to implement the project.

**Table B2: WCPFC/NIWA shark tagging kit contents**

- **PVC piping for pole protection**
- Long telescoping tagging poles x 2
- Short tagging pole (for on-deck tagging)
- Rubber stoppers x 3
- Bushes x 3
- Applicator needles x 3
- Spare butterfly nut & bolt for long tagging pole
- **Hard case to put all tagging equipment in**
- Short cable ties for locking hard case
- Tagging instructions folder
- GoPro camera
  - power/download cable
  - instructions
  - memory card
  - camera head harness
- Magnets x 2
- Gloves
- Electrical tape
- Self-amalgamating tape
- Rubber bands
- Allen key (imperial) for tightening bushes
- Alcohol wipes for sterilising anchor and needle
- Pencils
- Pencil sharpener
- Eraser/rubber

**Figure B1: Tag attached to the tag pole (left) and tagging kit (right). Image: Caroline Sanchez (SPC)**

## Post-deployment coordination

### *Deployment results*

Twenty-four observers and three longline captains tagged sharks for this project, with shark tagging occurring on 29 surface longline vessels across four countries. A total of 60 shortfin mako sharks and 57 silky sharks were tagged (Table B3). Fiji tagged both shortfin mako and silky sharks, New Caledonia tagged only shortfin mako sharks, New Zealand tagged only shortfin mako sharks and the Marshall Islands tagged only silky sharks.

**Table B3: Number of sharks tagged by country**

| | Number of sharks tagged | |
|---|---|---|
| | Mako | Silky |
| Fiji | 15 | 43 |
| New Caledonia | 10 | 0 |
| New Zealand | 35 | 0 |
| Marshall Islands | 0 | 14 |
| Total | 60 | 57 |

Thirty-five percent of the mako sharks and 23% of the silky sharks were unsexed (Table B4). Of the 57 mako sharks with a tag location, 32% were tagged on the vessel deck (Table B5). Nearly all of the silky sharks were tagged in the water. All of the mako sharks tagged on deck occurred in New Zealand (Table B6).

**Table B4: Sex identification by species**

| | Mako | Silky |
|---|---|---|
| Female | 32 | 30 |
| Male | 7 | 14 |
| Unsexed | 21 | 13 |
| Total | 60 | 57 |

**Table B5: Tagging location by species**

| Tag location | Mako | Silky |
|---|---|---|
| Deck | 18 | 2 |
| Water | 39 | 46 |
| Total | 57 | 48 |

**Table B6: Mako shark tag location by country**

| | Mako sharks tagged | | |
|---|---|---|---|
| | Fiji | New Caledonia | New Zealand |
| Deck | 0 | 0 | 18 |
| Water | 14 | 9 | 16 |
| Total | 14 | 9 | 34 |

### *Tagging rewards*

A lottery system was developed to encourage and reward shark tagging. The lottery details varied among countries, with separate lottery draws being provided for observers and/or crew, with the prize pool being based on the number of sharks tagged. Depending on the country, reward payments consisted of cash, shopping vouchers or handcrafts. The total amount spent on lotteries was ~US$3,500.

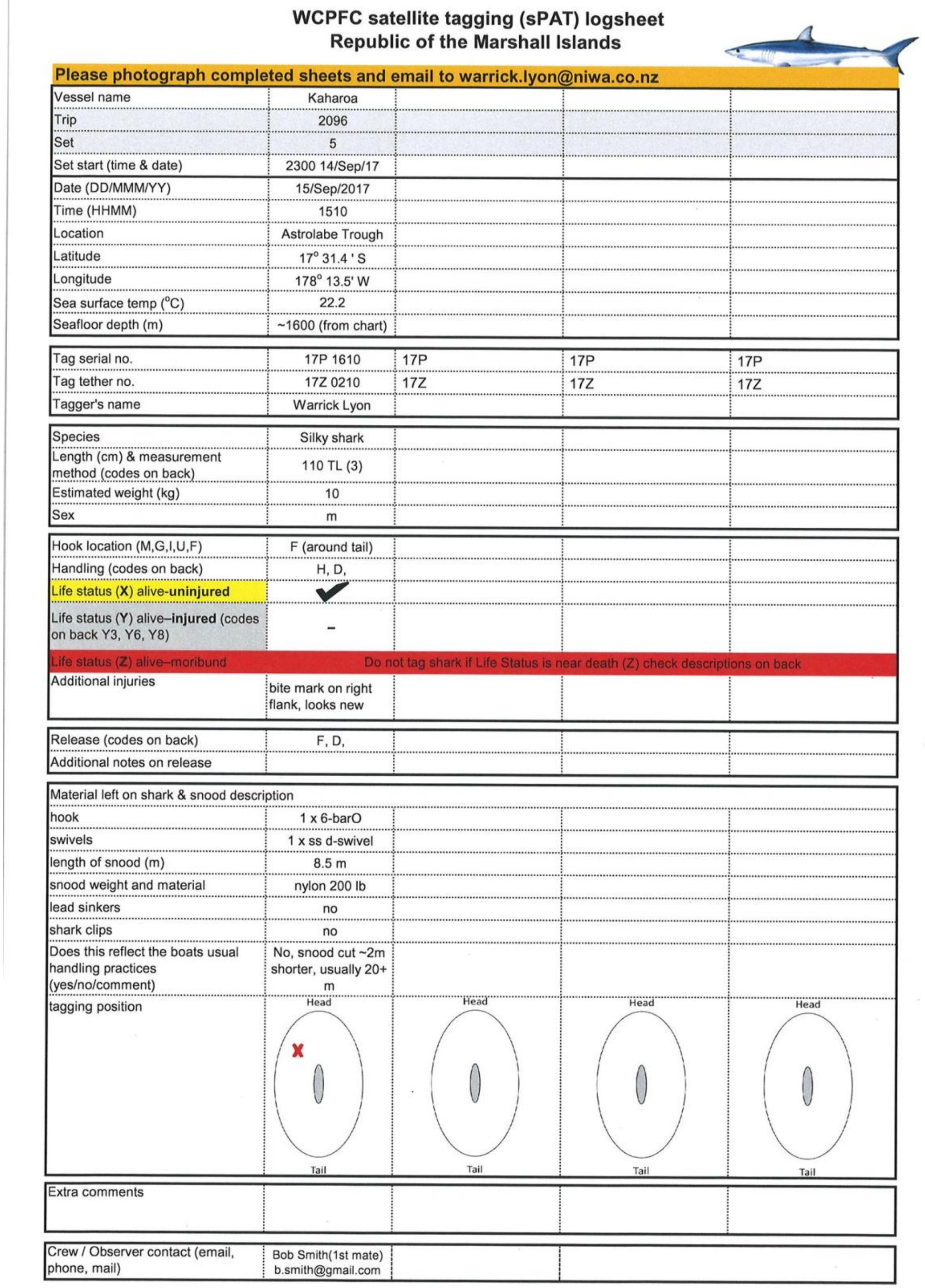
### *Data compilation*

Videos of the tagging event taken by observers or crew were examined before the tag release data were punched, to cross-check the information recorded on tagging logsheets. Data transmitted by the tags after popup were downloaded from the Wildlife Computers Portal for 110 tags. The remaining seven tags either did not report via satellite, or transmitted negligible data to be useful. Survival status of the 110 sharks was assessed from the depth profiles of each tag: dead sharks sink to the seabed and their tags auto-released at a depth of ~1400 m, or when the shark had been lying on the seabed for two days, whichever came first. Tags that detached from the shark prematurely floated to the surface and began transmitting after two days at the surface. The depth sensors of five tags leaked and failed, thus providing no information on shark depth; however, for four of the five tags, the survival status could be determined. These faulty tags were replaced by Wildlife Computers under warranty. Two Wildlife Computers' experimental tags were provided free of charge and were deployed on mako sharks in New Zealand. Only one of the two tags provided survival data, which were incorporated in the analyses below.

### *Tag and kit de-mobilisation*

Unused tags (N = 87) and the tagging kits have been cleaned and inventoried and will be used in future tagging studies. Loss of tagging equipment was minimal and consisted of one GoPro camera and five camera charging cables.

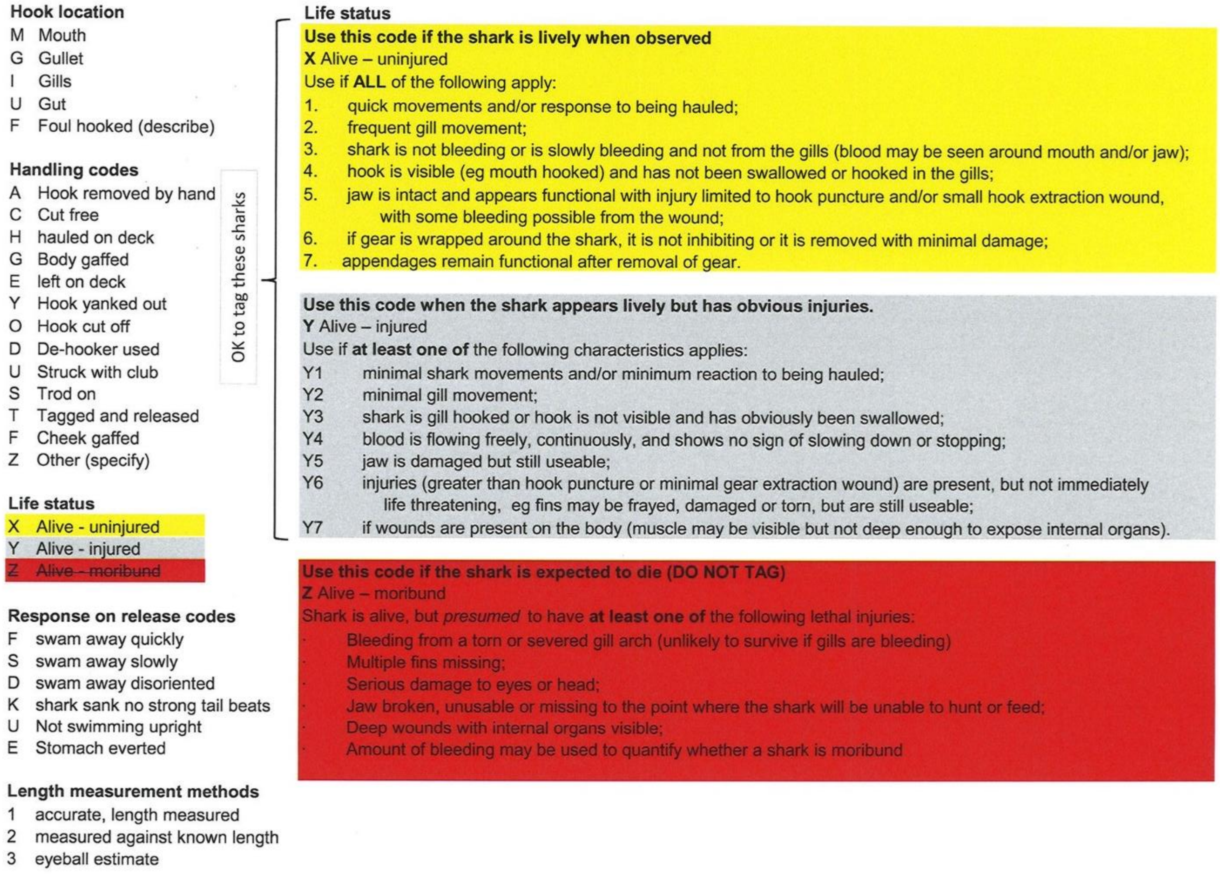
**Attachment 1:** Shark tagging logsheet (front and back) showing notional example data in the first column



## WCPFC satellite tagging (sPAT) logsheet
## Republic of the Marshall Islands

**Please photograph completed sheets and email to warrick.lyon@niwa.co.nz**

| | | | | |
|---|---|---|---|---|
| Vessel name | Kaharoa | | | |
| Trip | 2096 | | | |
| Set | 5 | | | |
| Set start (time & date) | 2300 14/Sep/17 | | | |
| Date (DD/MMM/YY) | 15/Sep/2017 | | | |
| Time (HHMM) | 1510 | | | |
| Location | Astrolabe Trough | | | |
| Latitude | 17° 31.4 ' S | | | |
| Longitude | 178° 13.5' W | | | |
| Sea surface temp (°C) | 22.2 | | | |
| Seafloor depth (m) | ~1600 (from chart) | | | |
| Tag serial no. | 17P 1610 | 17P | 17P | 17P |
| Tag tether no. | 17Z 0210 | 17Z | 17Z | 17Z |
| Tagger's name | Warrick Lyon | | | |
| Species | Silky shark | | | |
| Length (cm) & measurement method (codes on back) | 110 TL (3) | | | |
| Estimated weight (kg) | 10 | | | |
| Sex | m | | | |
| Hook location (M,G,I,U,F) | F (around tail) | | | |
| Handling (codes on back) | H, D, | | | |
| Life status (**X**) alive-**uninjured** | ✓ | | | |
| Life status (**Y**) alive–**injured** (codes on back Y3, Y6, Y8) | - | | | |
| Life status (**Z**) alive–moribund | Do not tag shark if Life Status is near death (Z) check descriptions on back | | | |
| Additional injuries | bite mark on right flank, looks new | | | |
| Release (codes on back) | F, D, | | | |
| Additional notes on release | | | | |
| Material left on shark & snood description | | | | |
| hook | 1 x 6-barO | | | |
| swivels | 1 x ss d-swivel | | | |
| length of snood (m) | 8.5 m | | | |
| snood weight and material | nylon 200 lb | | | |
| lead sinkers | no | | | |
| shark clips | no | | | |
| Does this reflect the boats usual handling practices (yes/no/comment) | No, snood cut ~2m shorter, usually 20+ m | | | |
| tagging position | Head<br>X<br>Tail | Head<br>Tail | Head<br>Tail | Head<br>Tail |
| Extra comments | | | | |
| Crew / Observer contact (email, phone, mail) | Bob Smith(1st mate)<br>b.smith@gmail.com | | | |



**Hook location**

| | |
|---|---|
| M | Mouth |
| G | Gullet |
| I | Gills |
| U | Gut |
| F | Foul hooked (describe) |

**Handling codes**

| | |
|---|---|
| A | Hook removed by hand |
| C | Cut free |
| H | hauled on deck |
| G | Body gaffed |
| E | left on deck |
| Y | Hook yanked out |
| O | Hook cut off |
| D | De-hooker used |
| U | Struck with club |
| S | Trod on |
| T | Tagged and released |
| F | Cheek gaffed |
| Z | Other (specify) |

**Life status**

| | |
|---|---|
| X | Alive - uninjured |
| Y | Alive - injured |
| ~~Z~~ | ~~Alive - moribund~~ |

**Response on release codes**

| | |
|---|---|
| F | swam away quickly |
| S | swam away slowly |
| D | swam away disoriented |
| K | shark sank no strong tail beats |
| U | Not swimming upright |
| E | Stomach everted |

**Length measurement methods**

| | |
|---|---|
| 1 | accurate, length measured |
| 2 | measured against known length |
| 3 | eyeball estimate |

OK to tag these sharks

**Life status**

**Use this code if the shark is lively when observed**

**X** Alive – uninjured

Use if **ALL** of the following apply:

1. quick movements and/or response to being hauled;
2. frequent gill movement;
3. shark is not bleeding or is slowly bleeding and not from the gills (blood may be seen around mouth and/or jaw);
4. hook is visible (eg mouth hooked) and has not been swallowed or hooked in the gills;
5. jaw is intact and appears functional with injury limited to hook puncture and/or small hook extraction wound, with some bleeding possible from the wound;
6. if gear is wrapped around the shark, it is not inhibiting or it is removed with minimal damage;
7. appendages remain functional after removal of gear.

**Use this code when the shark appears lively but has obvious injuries.**

**Y** Alive – injured

Use if **at least one of** the following characteristics applies:

Y1 minimal shark movements and/or minimum reaction to being hauled;
Y2 minimal gill movement;
Y3 shark is gill hooked or hook is not visible and has obviously been swallowed;
Y4 blood is flowing freely, continuously, and shows no sign of slowing down or stopping;
Y5 jaw is damaged but still useable;
Y6 injuries (greater than hook puncture or minimal gear extraction wound) are present, but not immediately life threatening, eg fins may be frayed, damaged or torn, but are still useable;
Y7 if wounds are present on the body (muscle may be visible but not deep enough to expose internal organs).

**Use this code if the shark is expected to die (DO NOT TAG)**

**Z** Alive – moribund

Shark is alive, but *presumed* to have **at least one of** the following lethal injuries:

- Bleeding from a torn or severed gill arch (unlikely to survive if gills are bleeding)
- Multiple fins missing;
- Serious damage to eyes or head;
- Jaw broken, unusable or missing to the point where the shark will be unable to hunt or feed;
- Deep wounds with internal organs visible;
- Amount of bleeding may be used to quantify whether a shark is moribund

## Annex C. Data for shark PRM tags (all programmed for 60-day deployments) in the WCPFC study (May 2017-April 2019)

| | Species | Region | Tag Argos | Tag serial | Date | Time at Tagging Location | Latitude | Longitude | Fork length | Sex | Tag site | Alive | Track days |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | FAL | Fiji | 170537 | 17P0183 | 21-Oct-17 | 18:37 | -16.287 | 175.780 | 160 | F | water | Y | 60.7 |
| 2 | FAL | Fiji | 170538 | 17P0185 | 4-Dec-17 | 19:15 | -21.057 | 174.408 | 105 | F | water | Y | 60.7 |
| 3 | FAL | Fiji | 170539 | 17P0188 | 15-Aug-18 | 21:10 | -18.910 | 179.169 | 130 | F | | Y | 59.6 |
| 4 | FAL | Fiji | 170540 | 17P0222 | 22-Nov-17 | 16:48 | -16.087 | 176.865 | 110 | F | water | Y | 60.8 |
| 5 | FAL | Fiji | 170541 | 17P0223 | 22-Nov-17 | 19:00 | -16.157 | 176.963 | 120 | F | water | No report | |
| 6 | FAL | Fiji | 170542 | 17P0224 | 2-Jun-18 | 20:10 | -15.767 | -178.358 | 149 | F | deck | No report | |
| 7 | FAL | Fiji | 170547 | 17P0233 | 2-Mar-18 | 19:54 | -22.093 | 173.851 | 115 | F | water | Y | 35.0 |
| 8 | FAL | Fiji | 170550 | 17P0238 | 22-Jun-18 | 19:32 | -20.130 | 177.812 | 110 | F | water | Y | 10.7 |
| 9 | FAL | Fiji | 170552 | 17P0332 | 24-Dec-17 | 20:16 | -16.070 | 178.332 | 140 | F | water | Y | 60.6 |
| 10 | FAL | Fiji | 170553 | 17P0339 | 11-Dec-17 | 1:53 | -16.109 | 176.502 | 140 | F | water | N | 0.4 |
| 11 | FAL | Fiji | 170554 | 17P0355 | 11-Dec-17 | 4:13 | -16.151 | 176.501 | 100 | F | water | Y | 60.3 |
| 12 | FAL | Fiji | 170555 | 17P0357 | 16-Dec-17 | 21:26 | -15.819 | 177.937 | 120 | F | water | Y | 60.6 |
| 13 | FAL | Fiji | 170556 | 17P0359 | 24-Dec-17 | 21:30 | -16.076 | 178.308 | 90 | F | water | No report | |
| 14 | FAL | Fiji | 170558 | 17P0208 | 26-Mar-19 | 5:06 | -19.070 | -177.417 | 88 | M | water | Y | 56.2 |
| 15 | FAL | Fiji | 170559 | 17P0225 | 8-Sep-18 | 20:40 | -17.912 | -178.932 | 200 | M | deck | Y | 24.6 |
| 16 | FAL | Fiji | 170560 | 17P0247 | 21-Mar-19 | 3:55 | -19.890 | -177.568 | 105 | M | water | Y | 43.5 |
| 17 | FAL | Fiji | 170561 | 17P0250 | 8-Sep-18 | 20:23 | -17.912 | -178.932 | 200 | F | deck | Y | 37.2 |
| 18 | FAL | Fiji | 170562 | 17P0251 | 9-Sep-18 | 20:38 | -18.140 | -178.218 | 250 | F | water | Y | 60.7 |
| 19 | FAL | Fiji | 170565 | 17P0255 | 6-Feb-19 | 19:46 | -18.003 | 177.165 | 84 | F | water | Y | 13.4 |
| 20 | FAL | Fiji | 170566 | 17P0257 | 10-Sep-18 | 0:02 | -15.877 | -178.187 | 110 | M | water | Y | 23.6 |
| 21 | FAL | Fiji | 170567 | 17P0258 | 2-Feb-19 | 19:23 | -18.630 | 177.578 | 97 | F | water | Y | 18.8 |
| 22 | FAL | Fiji | 170568 | 17P0259 | 2-Sep-18 | 22:59 | -15.112 | -179.803 | 87 | M | water | Y | 57.7 |
| 23 | FAL | Fiji | 170570 | 17P0261 | 7-Feb-19 | 19:57 | -18.335 | 177.893 | 84 | F | water | Y | 4.9 |
| 24 | FAL | Fiji | 170571 | 17P0262 | 15-Sep-18 | 3:45 | -16.520 | -178.564 | 105 | M | water | N | 49.3 |
| 25 | FAL | Fiji | 170572 | 17P0263 | 24-Jan-19 | 2:06 | -17.301 | 179.844 | 84 | F | water | N | 9.3 |
| 26 | FAL | Fiji | 170574 | 17P0266 | 29-Aug-18 | 16:39 | -19.203 | 176.377 | 117 | M | water | Y | 55.1 |
| 27 | FAL | Fiji | 170575 | 17P0268 | 23-Jan-19 | 21:33 | -17.238 | -179.870 | 88 | F | water | Y | 60.6 |
| 28 | FAL | Fiji | 170576 | 17P0269 | 23-Aug-18 | 0:05 | -15.782 | 177.877 | 84 | M | water | Y | 61.5 |
| 29 | FAL | Fiji | 170577 | 17P0271 | 25-Jan-19 | 23:43 | -15.807 | 179.505 | 84 | F | water | Y | 47.7 |
| 30 | FAL | Fiji | 170578 | 17P0272 | 26-Sep-18 | 16:56 | -12.984 | 176.113 | 122 | | water | Y | 18.0 |

## Annex C. (continued)

| | Species | Region | Tag Argos | Tag serial | Date | Time at Tagging Location | Latitude | Longitude | Fork length | Sex | Tag site | Alive | Track days |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | FAL | Fiji | 170580 | 17P0317 | 15-Aug-18 | 21:05 | -18.908 | 179.169 | 113 | M | | Y | 32.5 |
| 32 | FAL | Fiji | 170581 | 17P0318 | 5-Sep-18 | 15:09 | -18.900 | -179.154 | 200 | F | water | Y | 25.7 |
| 33 | FAL | Fiji | 170584 | 17P0401 | 26-Jul-18 | 2:44 | -21.556 | 173.959 | 160 | M | water | Y | 60.5 |
| 34 | FAL | Fiji | 170651 | 17P1431 | 1-Apr-19 | 19:21 | -18.212 | 177.240 | 97 | F | water | Y | 8.6 |
| 35 | FAL | Fiji | 170653 | 17P1434 | 2-Apr-19 | 20:23 | -18.282 | 177.418 | 84 | F | water | Y | 22.8 |
| 36 | FAL | Fiji | 170655 | 17P1436 | 15-Mar-19 | 21:42 | -18.248 | 177.358 | 146 | F | water | Y | 20.2 |
| 37 | FAL | Fiji | 170656 | 17P1437 | 16-Mar-19 | 2:24 | -18.412 | 177.507 | 163 | F | water | Y | 60.4 |
| 38 | FAL | Fiji | 170660 | 17P1442 | 5-Apr-19 | 17:00 | -18.303 | 178.270 | 101 | M | water | Y | 60.8 |
| 39 | FAL | Fiji | 170662 | 17P1446 | 5-Apr-19 | 16:45 | -18.305 | 178.257 | 93 | M | water | Y | 59.8 |
| 40 | FAL | Fiji | 170666 | 17P1478 | 5-Apr-19 | 17:45 | -18.298 | 178.307 | 97 | F | water | Y | 60.6 |
| 41 | FAL | Fiji | 170668 | 17P1487 | 16-Mar-19 | 23:59 | -18.208 | 177.265 | 130 | F | water | Y | 60.5 |
| 42 | FAL | Fiji | 170669 | 17P1488 | 18-Mar-19 | 21:43 | -18.145 | 177.225 | 130 | F | water | No report | |
| 43 | FAL | Fiji | 170679 | 18P0006 | 18-Mar-19 | 21:55 | -18.150 | 177.232 | 97 | F | water | Y | 0.7 |
| 44 | FAL | RMI | 170622 | 17P1166 | 28-Jul-18 | 22:23 | 4.909 | 171.751 | 140 | | water | Y | 50.7 |
| 45 | FAL | RMI | 170623 | 17P1170 | 19-Jul-18 | 16:25 | 3.021 | 167.113 | 101 | | water | Y | 36.1 |
| 46 | FAL | RMI | 170624 | 17P1189 | 22-Jul-18 | 22:55 | 3.129 | 169.082 | 125 | M | water | N | 0.1 |
| 47 | FAL | RMI | 170625 | 17P1195 | 21-Jul-18 | 22:07 | 2.960 | 167.988 | 115 | | water | Y | 60.6 |
| 48 | FAL | RMI | 170626 | 17P1197 | 19-Jul-18 | 19:44 | 3.027 | 167.446 | 130 | | water | Y | 31.2 |
| 49 | FAL | RMI | 170632 | 17P1352 | 13-Nov-18 | 21:55 | 8.532 | 169.353 | 130 | | | Y | 20.4 |
| 50 | FAL | RMI | 170633 | 17P1354 | 20-Jul-18 | 19:10 | 3.612 | 166.698 | 100 | | water | N | 45.8 |
| 51 | FAL | RMI | 170634 | 17P1356 | 17-Jul-18 | 17:00 | 3.162 | 166.785 | 110 | | water | Y | 60.8 |
| 52 | FAL | RMI | 170635 | 17P1357 | 21-Jul-18 | 20:45 | 3.812 | 166.578 | 110 | | water | Y | 23.2 |
| 53 | FAL | RMI | 170636 | 17P1386 | 18-Jul-18 | 18:40 | 3.135 | 166.813 | 110 | M | water | Y | 2.4 |
| 54 | FAL | RMI | 170637 | 17P1390 | 24-Jul-18 | 16:50 | 4.247 | 166.735 | 98 | | water | Y | 16.0 |
| 55 | FAL | RMI | 170638 | 17P1402 | 20-Jul-18 | 16:35 | 3.610 | 166.448 | 120 | | water | Y | 60.8 |
| 56 | FAL | RMI | 170675 | 17P1504 | 24-Nov-18 | 18:40 | 7.638 | 169.994 | 125 | | | N | 0.1 |
| 57 | FAL | RMI | 170690 | 18P0024 | 15-Nov-18 | 17:00 | 2.420 | 169.573 | 75 | | | Y | 38.9 |
| 58 | SMA | Fiji | 170543 | 17P0227 | 14-Aug-18 | 18:10 | -18.838 | 179.393 | 135 | F | water | Y | 60.6 |
| 59 | SMA | Fiji | 170544 | 17P0230 | 29-Jul-18 | 23:21 | -21.345 | 178.467 | 120 | F | water | Y | 60.5 |
| 60 | SMA | Fiji | 170545 | 17P0231 | 5-Dec-17 | 20:54 | -17.780 | 176.507 | 108 | F | water | Y | 20.2 |

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## Annex C. (continued)

| | Species | Region | Tag Argos | Tag serial | Date | Time at Tagging Location | Latitude | Longitude | Fork length | Sex | Tag site | Alive | Track days |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 61 | SMA | Fiji | 170546 | 17P0232 | 26-Dec-17 | 19:26 | -19.771 | 179.686 | 110 | F | water | Y | 23.8 |
| 62 | SMA | Fiji | 170548 | 17P0234 | 16-Jun-18 | 19:41 | -20.349 | 176.880 | 110 | F | water | Y | 60.7 |
| 63 | SMA | Fiji | 170549 | 17P0236 | 21-Jun-18 | 18:39 | -20.096 | 177.813 | 105 | F | water | Y | 44.5 |
| 64 | SMA | Fiji | 170551 | 17P0241 | 22-Jun-18 | 22:23 | -20.221 | 177.081 | 150 | F | water | N | 0.2 |
| 65 | SMA | Fiji | 170563 | 17P0253 | 4-Aug-18 | 0:00 | -23.163 | 179.219 | 126 | F | water | Y | 60.5 |
| 66 | SMA | Fiji | 170564 | 17P0254 | 10-Jul-18 | 22:16 | -18.079 | 175.872 | 135 | F | water | Y | 55.3 |
| 67 | SMA | Fiji | 170573 | 17P0265 | 22-Sep-18 | 5:44 | -13.585 | 175.888 | 200 | | water | Y | 60.3 |
| 68 | SMA | Fiji | 170579 | 17P0315 | 21-Aug-18 | 1:30 | -17.527 | 179.893 | 220 | | water | Y | 61.5 |
| 69 | SMA | Fiji | 170582 | 17P0322 | 18-Aug-18 | 18:47 | -17.611 | 179.566 | 170 | F | water | Y | 59.8 |
| 70 | SMA | Fiji | 170583 | 17P0364 | 17-Aug-18 | 1:40 | -18.261 | 179.685 | 108 | F | water | N | 48.4 |
| 71 | SMA | Fiji | 170585 | 17P0403 | 11-Aug-18 | 3:02 | -20.115 | 179.581 | 250 | M | water | Y | 57.2 |
| 72 | SMA | Fiji | 170586 | 17P0405 | 24-Aug-18 | 22:10 | -17.566 | 179.720 | 103 | F | deck | No report | |
| 73 | SMA | NC | 170587 | 16P2212 | 11-Oct-18 | 19:01 | -22.091 | 167.396 | 135 | | water | Y | 60.7 |
| 74 | SMA | NC | 170589 | 16P2438 | 10-Oct-18 | 15:25 | -21.638 | 166.780 | 181 | M | water | Y | 19.1 |
| 75 | SMA | NC | 170599 | 17P0407 | 3-Jul-18 | 15:58 | -23.495 | 161.304 | 227 | | water | Y | 60.9 |
| 76 | SMA | NC | 170600 | 17P0409 | 12-Aug-18 | 19:24 | -22.786 | 165.097 | 319 | F | water | Y | 60.6 |
| 77 | SMA | NC | 170611 | 17P0477 | 22-Feb-19 | 4:00 | -22.533 | 163.133 | 154 | F | water | Y | 40.9 |
| 78 | SMA | NC | 170613 | 17P0481 | 30-Dec-18 | 14:05 | -21.435 | 162.687 | 99 | | water | N | 26.9 |
| 79 | SMA | NC | 170615 | 17P0485 | 22-Oct-18 | 16:46 | -21.364 | 166.364 | 135 | | water | Y | 13.1 |
| 80 | SMA | NC | 170617 | 17P0487 | 18-Aug-18 | 16:53 | -19.648 | 163.237 | 144 | F | deck | No report | |
| 81 | SMA | NC | 170618 | 17P0516 | 20-Aug-18 | 14:08 | -19.941 | 162.534 | 209 | F | water | Y | 61.0 |
| 82 | SMA | NC | 170619 | 17P0637 | 11-Nov-18 | 22:00 | -20.354 | 158.205 | 190 | | water | N | 14.5 |
| 83 | SMA | NZ | 100001 | 16P1800 | 4-Jun-17 | 22:16 | -39.053 | 178.483 | 175 | M | water | No report | |
| 84 | SMA | NZ | 170504 | 16P1917 | 4-Jun-17 | 1:15 | -39.583 | 178.437 | 150 | | water | Y | 60.5 |
| 85 | SMA | NZ | 170505 | 16P1990 | 4-Jul-17 | 12:55 | -37.015 | 178.648 | 125 | F | deck | Y | 61.8 |
| 86 | SMA | NZ | 170506 | 16P1991 | 3-Sep-17 | 19:38 | -36.861 | 177.735 | 140 | | water | Y | 60.5 |
| 87 | SMA | NZ | 170507 | 16P1993 | 21-Aug-17 | 16:20 | -37.215 | 177.484 | 180 | | water | Y | 60.9 |
| 88 | SMA | NZ | 170508 | 16P1995 | 7-Aug-17 | 19:06 | -37.183 | 177.767 | 185 | | water | Y | 60.5 |
| 89 | SMA | NZ | 170509 | 16P1998 | 15-Aug-17 | 19:00 | -35.092 | 176.857 | 190 | | water | Y | 60.4 |
| 90 | SMA | NZ | 170510 | 16P2008 | 31-Jul-17 | 20:05 | -36.585 | 178.307 | 130 | | deck | Y | 60.7 |

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## Annex C. (continued)

| | Species | Region | Tag Argos | Tag serial | Date | Time at Tagging Location | Latitude | Longitude | Fork length | Sex | Tag site | Alive | Track days |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 91 | SMA | NZ | 170511 | 16P2033 | 28-Jun-17 | 23:49 | -36.648 | 177.017 | 145 | | deck | Y | 60.5 |
| 92 | SMA | NZ | 170512 | 16P2034 | 31-Aug-17 | 16:37 | -34.803 | 176.228 | 140 | | water | N | 32.3 |
| 93 | SMA | NZ | 170513 | 16P2035 | 25-Jan-18 | 14:50 | -36.817 | 176.367 | 150 | F | water | Y | 60.9 |
| 94 | SMA | NZ | 170514 | 16P2036 | 31-Jan-18 | 14:20 | -35.708 | 176.435 | 86 | F | deck | Y | 12.6 |
| 95 | SMA | NZ | 170515 | 16P2037 | 28-Jan-18 | 12:30 | -36.070 | 176.377 | 150 | F | water | Y | 61.0 |
| 96 | SMA | NZ | 170516 | 16P2038 | 10-Apr-18 | 16:20 | -39.168 | 178.772 | 140 | F | deck | Y | 10.1 |
| 97 | SMA | NZ | 170517 | 16P2048 | 23-Aug-17 | 21:50 | -35.172 | 175.910 | 179 | M | deck | Y | 26.5 |
| 98 | SMA | NZ | 170518 | 16P2052 | 10-Feb-18 | 16:50 | -37.258 | 178.833 | 107 | F | deck | N | 1.1 |
| 99 | SMA | NZ | 170519 | 16P1620 | 25-May-17 | 20:54 | -38.582 | 178.800 | 128 | F | deck | Y | 8.4 |
| 100 | SMA | NZ | 170520 | 16P1636 | 23-May-17 | 13:43 | -38.934 | 178.708 | 145 | F | water | Y | 35.6 |
| 101 | SMA | NZ | 170521 | 16P1768 | 28-May-17 | 18:40 | -38.769 | 178.702 | 135 | M | deck | Y | 30.5 |
| 102 | SMA | NZ | 170522 | 16P1774 | 6-Jun-17 | 20:14 | -39.565 | 178.377 | 128 | F | deck | Y | 10.4 |
| 103 | SMA | NZ | 170523 | 16P1777 | 16-Jun-17 | 14:51 | -36.880 | 178.073 | 130 | | water | Y | 60.7 |
| 104 | SMA | NZ | 170524 | 16P1780 | 18-Jun-17 | 17:01 | -36.960 | 178.156 | 150 | F | water | Y | 1.6 |
| 105 | SMA | NZ | 170525 | 16P1781 | 5-Aug-17 | 16:44 | -37.019 | 176.985 | 94 | F | deck | N | 0.0 |
| 106 | SMA | NZ | 170526 | 16P1782 | 12-Jun-17 | 15:05 | -36.650 | 178.135 | 119 | F | deck | Y | 42.9 |
| 107 | SMA | NZ | 170527 | 16P1783 | 20-Jun-17 | 13:57 | -37.345 | 178.385 | 96 | F | deck | Y | 11.7 |
| 108 | SMA | NZ | 170528 | 16P1786 | 26-Jun-17 | 17:15 | -37.248 | 178.293 | 156 | M | deck | Y | 24.3 |
| 109 | SMA | NZ | 170529 | 16P1787 | 21-Jun-17 | 13:13 | -37.320 | 178.465 | 97 | F | deck | Y | 12.6 |
| 110 | SMA | NZ | 170530 | 16P1790 | 19-Jun-17 | 20:30 | -37.317 | 177.878 | 195 | F | deck | Y | 60.5 |
| 111 | SMA | NZ | 170531 | 16P1791 | 12-Jun-17 | 19:25 | -36.850 | 178.217 | 94 | F | deck | Y | 32.7 |
| 112 | SMA | NZ | 170532 | 16P1792 | 11-Jun-17 | 19:10 | -38.933 | 179.113 | 117 | M | deck | Y | 13.7 |
| 113 | SMA | NZ | 170533 | 16P1851 | 2-Jun-17 | 23:15 | -39.508 | 178.548 | 130 | | water | Y | 60.7 |
| 114 | SMA | NZ | 170534 | 16P1976 | 11-Jun-17 | 22:10 | -37.962 | 179.200 | 220 | | water | Y | 60.6 |
| 115 | SMA | NZ | 170535 | 16P1977 | 20-Jun-17 | 15:25 | -36.100 | 177.423 | 250 | | water | Y | 60.8 |
| 116 | SMA | NZ | 170536 | 16P1980 | 23-Jun-17 | 17:35 | -37.172 | 178.405 | 150 | | water | Y | 60.8 |
| 117 | SMA | NZ | 171016 | 16P1736 | 3-Jun-17 | 14:19 | -38.967 | 178.685 | 180 | | water | Y | 15.9 |

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## Annex D. Effects of predictor variables on PRM for SMA (shortfin mako shark)

**Table D1. The predicted effect of time since tagging on PRM for shortfin mako sharks. The number of days was varied within the model while holding fork length constant at 120 cm and gangion ratio constant at 1.35 (the median value from the SPC observer data).**

| Number of Days | PRM Estimate |
|---|---|
| **5** | **0.075** |
| **10** | **0.100** |
| **15** | **0.118** |
| **20** | **0.133** |
| **25** | **0.145** |
| **30** | **0.156** |
| **35** | **0.166** |
| **40** | **0.175** |
| **45** | **0.183** |
| **50** | **0.191** |
| **55** | **0.198** |
| **60** | **0.205** |

**Table D2. The predicted effect of fork length on PRM for shortfin mako sharks. The fork length (in cm) was varied within the model while holding time since tagging constant at 60 days and gangion ratio constant at 1.35 (the median value from the SPC observer data).**

| Fork Length (cm) | PRM Estimate |
|---|---|
| **80** | **0.331** |
| **100** | **0.262** |
| **120** | **0.205** |
| **140** | **0.159** |
| **160** | **0.123** |
| **180** | **0.094** |
| **200** | **0.072** |
| **220** | **0.055** |
| **240** | **0.042** |
| **260** | **0.032** |
| **280** | **0.024** |
| **300** | **0.018** |

## Annex E. Effects of predictor variables on PRM for silky sharks.

**Table E1.** **The predicted effect of time since tagging and condition at release on PRM for silky sharks. The number of days was varied within the model while holding gangion ratio constant at 1.35 [the median value from the tagging data]). AU = alive uninjured; AI = alive injured**

| Number of Days | FAL AU | FAL AI | PRM Estimate for FAL AU and FAL AI categories combined (condition-weighted average) |
|---|---|---|---|
| 5 | 0.018 | 0.248 | 0.074 |
| 10 | 0.023 | 0.306 | 0.092 |
| 15 | 0.026 | 0.345 | 0.104 |
| 20 | 0.029 | 0.374 | 0.113 |
| 25 | 0.031 | 0.398 | 0.120 |
| 30 | 0.033 | 0.418 | 0.127 |
| 35 | 0.035 | 0.435 | 0.133 |
| 40 | 0.037 | 0.451 | 0.138 |
| 45 | 0.039 | 0.465 | 0.142 |
| 50 | 0.040 | 0.478 | 0.146 |
| 55 | 0.041 | 0.489 | 0.150 |
| 60 | 0.043 | 0.500 | 0.154 |

## Annex F. R code developed for applying the ‘fate’ model of Harley et al. (2015).

```
# Code to generate shark mortality estimates
# S. Hoyle, NIWA

library(tidyverse)
library(readxl)

# load parameters from the spreadsheet
make_pars <- function(params, sp, nrnd=0) {
  par_sp <- filter(params, Species == sp)
  cpue_shkline <- filter(par_sp, param == "cpue" & qual1 == "sharkline")[c("dbn", "p1","p2")]
  cpue_shallow <- filter(par_sp, param == "cpue" & qual1 == "shallow_hook")[c("dbn", "p1","p2")]
  cpue_deephook <- filter(par_sp, param == "cpue" & qual1 == "deep_hook")[c("dbn", "p1","p2")]
  p_bto_wire_lip <- filter(par_sp, param == "p_biteoff" & qual1 == "wire" & qual2 ==
      "lip")[c("dbn", "p1")]
  p_bto_wire_gut <- filter(par_sp, param == "p_biteoff" & qual1 == "wire" & qual2 ==
      "gut")[c("dbn", "p1")]

  p_lip_J <- filter(par_sp, param == "p_lip" & qual1 == "J_hook")[,c("dbn", "p1", "p2")]
  p_lip_T <- filter(par_sp, param == "p_lip" & qual1 == "T_hook")[,c("dbn", "p1", "p2")]
  p_lip_C <- filter(par_sp, param == "p_lip" & qual1 == "C_hook")[,c("dbn", "p1", "p2")]
  p_bto_mono_lip <- filter(par_sp, param == "p_biteoff" & qual1 == "mono" & qual2 ==
      "lip")[,c("dbn", "p1", "p2")]
  p_bto_mono_gut <- filter(par_sp, param == "p_biteoff" & qual1 == "mono" & qual2 ==
      "gut")[,c("dbn", "p1", "p2")]
  p_mort_bto_lip <- filter(par_sp, param == "p_mort" & qual1 == "biteoff" & qual2 ==
      "lip")[,c("dbn", "p1", "p2")]
  p_mort_bto_gut <- filter(par_sp, param == "p_mort" & qual1 == "biteoff" & qual2 ==
      "gut")[,c("dbn", "p1", "p2")]
  p_mort_nbto_lip <- filter(par_sp, param == "p_mort" & qual1 == "no biteoff" & qual2 ==
      "lip")[,c("dbn", "p1", "p2")]
  p_mort_nbto_gut <- filter(par_sp, param == "p_mort" & qual1 == "no biteoff" & qual2 ==
      "gut")[,c("dbn", "p1", "p2")]
  p_wtr_rls_nbto <- filter(par_sp, param == "p_water_release" & qual1 == "no biteoff")[,c("dbn",
      "p1", "p2")]
  p_mort_wtr_lip <- filter(par_sp, param == "p_mort" & qual1 == "water release" & qual2 ==
      "lip")[,c("dbn", "p1", "p2")]
  p_mort_wtr_gut <- filter(par_sp, param == "p_mort" & qual1 == "water release" & qual2 ==
      "gut")[,c("dbn", "p1", "p2")]
  p_mort_lnd_lip <- filter(par_sp, param == "p_mort" & qual1 == "landed" & qual2 ==
      "lip")[,c("dbn", "p1", "p2")]
  p_mort_lnd_gut <- filter(par_sp, param == "p_mort" & qual1 == "landed" & qual2 ==
      "gut")[,c("dbn", "p1", "p2")]

  parnames <- c("cpue_shkline", "cpue_shallow", "cpue_deephook", "p_lip_J", "p_lip_T", "p_lip_C",
              "p_bto_mono_lip", "p_bto_mono_gut", "p_bto_wire_lip", "p_bto_wire_gut",
              "p_mort_bto_lip", "p_mort_bto_gut", "p_mort_nbto_lip", "p_mort_nbto_gut",
              "p_wtr_rls_nbto",
              "p_mort_wtr_lip", "p_mort_wtr_gut", "p_mort_lnd_lip", "p_mort_lnd_gut")
  pars <- do.call("list", mget((parnames)))

  for (nm in parnames) {
    a <- pars[[nm]]
    if (a$dbn == "Beta") pars[[nm]][["rnd"]] <- list(rbeta(nrnd, a$p1 * a$p2, (1 - a$p1) * a$p2))
    if (a$dbn == "logn") pars[[nm]][["rnd"]] <- list(exp(rnorm(nrnd, a$p1, a$p2)))
    if (a$dbn == "fixed") pars[[nm]][["rnd"]] <- list(rep(a$p1, nrnd))
  }
#  names(pars) <- parnames
  return(pars)
}

# Set fleet variables according to trial management regime
```

```
makefleetmg <- function(flx, mg) {
  flx <- fleet
  if(mg$shkln) { flx$ShkLn <- 0; flx$NoShkLn <- 1 }
  if(mg$wire) { flx$Wire <- 0; flx$Mono <- 1 }
  if(mg$circle) { flx$J <- 0; flx$Circle <- 1; flx$Tuna <- 0 }
  if(mg$shallow) { flx$Shllw <- 0; flx$NoShllw <- 1 }
  if(mg$shkwire) { flx$ShkLn <- 0; flx$NoShkLn <- 1; flx$Wire <- 0; flx$Mono <- 1 }
  return(flx)
}

# Estimate survival and mortality rates for each shark caught
survest <- function(flx, pars) {
  a <- list()
  # Expected catch location
  P_lip <- pars$p_lip_J * flx$J + pars$p_lip_T * flx$Tuna + pars$p_lip_C * flx$Circle
  P_gut <- 1 - P_lip

  # Biteoff mortality
  P_lip_bto <- P_lip *  (flx$Mono * pars$p_bto_mono_lip + flx$Wire * pars$p_bto_wire_lip)
  a$mort_lip_bo <-  P_lip_bto * pars$p_mort_bto_lip
  a$surv_lip_bo <-  P_lip_bto * (1 - pars$p_mort_bto_lip)

  P_gut_bto <- P_gut *  (flx$Mono * pars$p_bto_mono_gut + flx$Wire * pars$p_bto_wire_gut)
  a$mort_gut_bo <- P_gut_bto * pars$p_mort_bto_gut
  a$surv_gut_bo <- P_gut_bto * (1 - pars$p_mort_bto_gut)

  # No biteoff mortality
  P_lip_nbto <- P_lip - P_lip_bto
  P_gut_nbto <- P_gut - P_gut_bto

  a$mort_lip_nbto <- P_lip_nbto * pars$p_mort_nbto_lip
  a$mort_gut_nbto <- P_gut_nbto * pars$p_mort_nbto_gut

  # No biteoff survivors
  P_lip_nbto_srv <- P_lip_nbto - a$mort_lip_nbto
  P_gut_nbto_srv <- P_gut_nbto - a$mort_gut_nbto

  P_lip_nbto_wtr <- P_lip_nbto_srv * pars$p_wtr_rls_nbto
  P_lip_nbto_lnd <- P_lip_nbto_srv * (1 - pars$p_wtr_rls_nbto)
  P_gut_nbto_wtr <- P_gut_nbto_srv * pars$p_wtr_rls_nbto
  P_gut_nbto_lnd <- P_gut_nbto_srv * (1 - pars$p_wtr_rls_nbto)

  a$surv_lip_nbo_wtr <- P_lip_nbto_wtr * (1 - pars$p_mort_wtr_lip)
  a$mort_lip_nbo_wtr <- P_lip_nbto_wtr * pars$p_mort_wtr_lip
  a$surv_lip_nbo_lnd <- P_lip_nbto_lnd * (1 - pars$p_mort_lnd_lip)
  a$mort_lip_nbo_lnd <- P_lip_nbto_lnd * pars$p_mort_lnd_lip
  a$surv_gut_nbo_wtr <- P_gut_nbto_wtr * (1 - pars$p_mort_wtr_gut)
  a$mort_gut_nbo_wtr <- P_gut_nbto_wtr * pars$p_mort_wtr_gut
  a$surv_gut_nbo_lnd <- P_gut_nbto_lnd * (1 - pars$p_mort_lnd_gut)
  a$mort_gut_nbo_lnd <- P_gut_nbto_lnd * pars$p_mort_lnd_gut

  # Total survival
  a$tot_surv <- a$surv_lip_bo + a$surv_gut_bo + a$surv_lip_nbo_wtr + a$surv_gut_nbo_wtr +
     a$surv_lip_nbo_lnd + a$surv_gut_nbo_lnd
  a$tot_mort <- a$mort_lip_bo + a$mort_gut_bo + a$mort_lip_nbto + a$mort_gut_nbto +
     a$mort_lip_nbo_wtr + a$mort_gut_nbo_wtr + a$mort_lip_nbo_lnd + a$mort_gut_nbo_lnd
  a$tot <- a$tot_surv + a$tot_mort
  return(a)
}

# Estimate the numbers of sharks caught, given effort across the fleet
catchest <- function(flx, parx) {
  # Expected catch location
```

```
  catch_shkline  <- parx$cpue_shkline  * flx$ShkLn   * flx$effort / (100 * 30) # Assume 1 shkline per 30 hks
  catch_shallow  <- parx$cpue_shallow  * flx$Shllw       * (0.2 * flx$effort / 100) # Assume 20% shallow
  catch_deephook <- parx$cpue_deephook * (1 - flx$Shllw) * (0.2 * flx$effort/ 100) +
    parx$cpue_deephook * (0.8 * flx$effort/ 100) # Assume 80% not shallow

  # Total catch
  tot_catch <- catch_shkline + catch_shallow + catch_deephook
  return(tot_catch)
}

# Generate sets of randomized parameter values
rnd_or_mean <- function(pars, i) {  # Set i to 0 to generate the expected value, otherwise a random sample
  pm <- names(pars)
  parx <- list()
  if (i==0) {
    for (nm in pm) {
      if(parx[[nm]][["dbn"]] == "logn")
        parx[[nm]][["x"]] <- exp(pars[[nm]]$p1) else parx[[nm]][["x"]] <- pars[[nm]]$p1
          }
  } else {
    for (nm in pm) {
      parx[[nm]][["x"]] <- pars[[nm]][["rnd"]][[1]][i]
    }
  }
  return(parx)
}

# Calulate numbers of mortalities, and load results into a list
make_result_list <- function(a, survs, ctch, i){
  a$tot_surv[i,] <- survs$tot_surv  # estimate survival
  a$tot_mort[i,] <- survs$tot_mort  # estimate survival
  a$surv_lip_bo[i,] <- survs$surv_lip_bo  # estimate survival
  a$surv_gut_bo[i,] <- survs$surv_gut_bo  # estimate survival
  a$surv_lip_nbo_wtr[i,] <- survs$surv_lip_nbo_wtr  # estimate survival
  a$surv_gut_nbo_wtr[i,] <- survs$surv_gut_nbo_wtr  # estimate survival
  a$surv_lip_nbo_lnd[i,] <- survs$surv_lip_nbo_lnd  # estimate survival
  a$surv_gut_nbo_lnd[i,] <- survs$surv_gut_nbo_lnd  # estimate survival

  a$mort_lip_bo[i,] <- survs$mort_lip_bo  # estimate survival
  a$mort_gut_bo[i,] <- survs$mort_gut_bo  # estimate survival
  a$mort_lip_nbto[i,] <- survs$mort_lip_nbto  # estimate survival
  a$mort_gut_nbto[i,] <- survs$mort_gut_nbto  # estimate survival
  a$mort_lip_nbo_wtr[i,] <- survs$mort_lip_nbo_wtr  # estimate survival
  a$mort_gut_nbo_wtr[i,] <- survs$mort_gut_nbo_wtr  # estimate survival
  a$mort_lip_nbo_lnd[i,] <- survs$mort_lip_nbo_lnd  # estimate survival
  a$mort_gut_nbo_lnd[i,] <- survs$mort_gut_nbo_lnd  # estimate survival

  a$nsurv_lip_bo[i,] <- ctch * survs$surv_lip_bo  # estimate survival
  a$nsurv_gut_bo[i,] <- ctch * survs$surv_gut_bo  # estimate survival
  a$nsurv_lip_nbo_wtr[i,] <- ctch * survs$surv_lip_nbo_wtr  # estimate survival
  a$nsurv_gut_nbo_wtr[i,] <- ctch * survs$surv_gut_nbo_wtr  # estimate survival
  a$nsurv_lip_nbo_lnd[i,] <- ctch * survs$surv_lip_nbo_lnd  # estimate survival
  a$nsurv_gut_nbo_lnd[i,] <- ctch * survs$surv_gut_nbo_lnd  # estimate survival

  a$nmort_lip_bo[i,] <- ctch * survs$mort_lip_bo  # estimate survival
  a$nmort_gut_bo[i,] <- ctch * survs$mort_gut_bo  # estimate survival
  a$nmort_lip_nbto[i,] <- ctch * survs$mort_lip_nbto  # estimate survival
  a$nmort_gut_nbto[i,] <- ctch * survs$mort_gut_nbto  # estimate survival
  a$nmort_lip_nbo_wtr[i,] <- ctch * survs$mort_lip_nbo_wtr  # estimate survival
  a$nmort_gut_nbo_wtr[i,] <- ctch * survs$mort_gut_nbo_wtr  # estimate survival
```

```
  a$nmort_lip_nbo_lnd[i,] <- ctch * survs$mort_lip_nbo_lnd  # estimate survival
  a$nmort_gut_nbo_lnd[i,] <- ctch * survs$mort_gut_nbo_lnd  # estimate survival

  return(a)
}

# Histograms of mortalities
dohist <- function(dat, labs = FALSE, ti="", type = "surv", rng = NA) {
  xl <- switch(type, mort = c(.1, .5), surv = c(.5, .9), mort2 = rng, surv2 = rng)
  hist(dat, breaks = seq(0,max(xl)+1,length.out = 50), main = ti, xlim = xl, axes=F, col = "light
     blue")
  axis(1, labels = labs)
}

# Calulate total mortalities across all fleets
make_tots <- function(a) {
  nsurv_lip_bo_x <- apply(a$nsurv_lip_bo,1,sum)
  nsurv_gut_bo_x <- apply(a$nsurv_gut_bo,1,sum)
  nsurv_lip_nbo_wtr_x <- apply(a$nsurv_lip_nbo_wtr,1,sum)
  nsurv_gut_nbo_wtr_x <- apply(a$nsurv_gut_nbo_wtr,1,sum)
  nsurv_lip_nbo_lnd_x <- apply(a$nsurv_lip_nbo_lnd,1,sum)
  nsurv_gut_nbo_lnd_x <- apply(a$nsurv_gut_nbo_lnd,1,sum)
  nmort_lip_bo_x <- apply(a$nmort_lip_bo,1,sum)
  nmort_gut_bo_x <- apply(a$nmort_gut_bo,1,sum)
  nmort_lip_nbto_x <- apply(a$nmort_lip_nbto,1,sum)
  nmort_gut_nbto_x <- apply(a$nmort_gut_nbto,1,sum)
  nmort_lip_nbo_wtr_x <- apply(a$nmort_lip_nbo_wtr,1,sum)
  nmort_gut_nbo_wtr_x <- apply(a$nmort_gut_nbo_wtr,1,sum)
  nmort_lip_nbo_lnd_x <- apply(a$nmort_lip_nbo_lnd,1,sum)
  nmort_gut_nbo_lnd_x <- apply(a$nmort_gut_nbo_lnd,1,sum)
  a$nsurv_all <-
      rbind(nsurv_lip_bo_x,nsurv_gut_bo_x,nsurv_lip_nbo_wtr_x,nsurv_gut_nbo_wtr_x,nsurv_lip_nbo_l
      nd_x,nsurv_gut_nbo_lnd_x)
  a$nmort_all <-
     rbind(nmort_lip_bo_x,nmort_gut_bo_x,nmort_lip_nbto_x,nmort_gut_nbto_x,nmort_lip_nbo_wtr_x,n
     mort_gut_nbo_wtr_x,nmort_lip_nbo_lnd_x,nmort_gut_nbo_lnd_x)
  return(a)
}

# Calulate median estimates of total mortalities across all fleets
make_meds <- function(a) {
  nsurv_lip_bo_x <- median(apply(a$nsurv_lip_bo,1,sum))
  nsurv_gut_bo_x <- median(apply(a$nsurv_gut_bo,1,sum))
  nsurv_lip_nbo_wtr_x <- median(apply(a$nsurv_lip_nbo_wtr,1,sum))
  nsurv_gut_nbo_wtr_x <- median(apply(a$nsurv_gut_nbo_wtr,1,sum))
  nsurv_lip_nbo_lnd_x <- median(apply(a$nsurv_lip_nbo_lnd,1,sum))
  nsurv_gut_nbo_lnd_x <- median(apply(a$nsurv_gut_nbo_lnd,1,sum))
  nmort_lip_bo_x <- median(apply(a$nmort_lip_bo,1,sum))
  nmort_gut_bo_x <- median(apply(a$nmort_gut_bo,1,sum))
  nmort_lip_nbto_x <- median(apply(a$nmort_lip_nbto,1,sum))
  nmort_gut_nbto_x <- median(apply(a$nmort_gut_nbto,1,sum))
  nmort_lip_nbo_wtr_x <- median(apply(a$nmort_lip_nbo_wtr,1,sum))
  nmort_gut_nbo_wtr_x <- median(apply(a$nmort_gut_nbo_wtr,1,sum))
  nmort_lip_nbo_lnd_x <- median(apply(a$nmort_lip_nbo_lnd,1,sum))
  nmort_gut_nbo_lnd_x <- median(apply(a$nmort_gut_nbo_lnd,1,sum))
  a$nsurvs <-
     c(nsurv_lip_bo_x,nsurv_gut_bo_x,nsurv_lip_nbo_wtr_x,nsurv_gut_nbo_wtr_x,nsurv_lip_nbo_lnd_x
     ,nsurv_gut_nbo_lnd_x)
  a$nmorts <-
     c(nmort_lip_bo_x,nmort_gut_bo_x,nmort_lip_nbto_x,nmort_gut_nbto_x,nmort_lip_nbo_wtr_x,nmort
     _gut_nbo_wtr_x,nmort_lip_nbo_lnd_x,nmort_gut_nbo_lnd_x)
  return(a)
}
```

```
#### ---------------------------------------------

# Main body of code

nsamp = 1000  # Number of random samples to take
arx <- array(dim = c(nsamp, dim(fleet)[1]))

# Load the input parameters from excel or .csv file
# fn <- "Working mort analysis.xlsx"
# fleet <- as.data.frame(read_excel(fn, sheet = "fleets"))
# params <- as.data.frame(read_excel(fn, sheet = "params"))
fleet <- as.data.frame(read_csv("fleets.csv"))
params <- as.data.frame(read_csv("params.csv"))

for(sps in c("FAL","OCS")) {
  pars <- make_pars(params, sp=sps, nrnd = nsamp)

  for(mgm in c("alls", "shkl", "wire", "circ", "shll", "skwr")) {
    # set up the data structure
    a <- list()
    a$tot_surv <- a$tot_mort <- a$tot <- arx
    a$surv_gut_nbo_lnd <- a$surv_lip_nbo_lnd <- a$surv_gut_nbo_wtr <- a$surv_lip_nbo_wtr <-
     a$surv_gut_bo <- a$surv_lip_bo <- arx
    a$mort_gut_nbo_lnd <- a$mort_lip_nbo_lnd <- a$mort_gut_nbo_wtr <- a$mort_lip_nbo_wtr <-
     a$mort_gut_bo <- a$mort_lip_bo <- a$mort_gut_nbto <- a$mort_lip_nbto <- arx

    a$nsurv_gut_bo <- a$nsurv_lip_bo <- a$nsurv_gut_nbo_lnd <- a$nsurv_lip_nbo_lnd <-
     a$nsurv_gut_nbo_wtr <- a$nsurv_lip_nbo_wtr <- arx
    a$nmort_gut_bo <- a$nmort_lip_bo <- a$nmort_gut_nbto <- a$nmort_lip_nbto <-
     a$nmort_gut_nbo_lnd <- a$nmort_lip_nbo_lnd <- a$nmort_gut_nbo_wtr <- a$nmort_lip_nbo_wtr <-
     arx
    a$catches <- arx

    # Define management regimes to trial
    if (mgm == "alls") mg <- list(shkln=FALSE, wire=FALSE, circle=FALSE, shallow=FALSE,
     shkwire=FALSE)
    if (mgm == "shkl") mg <- list(shkln=TRUE, wire=FALSE, circle=FALSE, shallow=FALSE,
     shkwire=FALSE)
    if (mgm == "wire") mg <- list(shkln=FALSE, wire=TRUE, circle=FALSE, shallow=FALSE,
     shkwire=FALSE)
    if (mgm == "circ") mg <- list(shkln=FALSE, wire=FALSE, circle=TRUE, shallow=FALSE,
     shkwire=FALSE)
    if (mgm == "shll") mg <- list(shkln=FALSE, wire=FALSE, circle=FALSE, shallow=TRUE,
     shkwire=FALSE)
    if (mgm == "skwr") mg <- list(shkln=FALSE, wire=FALSE, circle=FALSE, shallow=FALSE,
     shkwire=TRUE)
    flx <- makefleetmg(fleet, mg)

    # Calculate everything
    for(i in 1:nsamp) {
      parx <- rnd_or_mean(pars, i)     # generate the randomised parameter estimates
      a$catches[i,] <- catchest(flx, parx) # Estimate catches
      survs <- survest(flx, parx)  # Estimate survivals and mortalities
      a <- make_result_list(a, survs, a$catches[i,], i) # Calulate total morts, and store
    }

    # Everything into data frames
    a$tot_surv <- data.frame(a$tot_surv)
    a$tot_mort <- data.frame(a$tot_mort)
    a$tot <- data.frame(a$tot)
```

```
  a$surv_lip_bo <- data.frame(a$surv_lip_bo)
  a$surv_gut_bo <- data.frame(a$surv_gut_bo)
  a$surv_lip_nbo_lnd <- data.frame(a$surv_lip_nbo_lnd)
  a$surv_gut_nbo_lnd <- data.frame(a$surv_gut_nbo_lnd)
  a$surv_lip_nbo_wtr <- data.frame(a$surv_lip_nbo_wtr)
  a$surv_gut_nbo_wtr <- data.frame(a$surv_gut_nbo_wtr)

  a$mort_lip_bo <- data.frame(a$mort_lip_bo)
  a$mort_gut_bo <- data.frame(a$mort_gut_bo)
  a$mort_lip_nbto <- data.frame(a$mort_lip_nbto)
  a$mort_gut_nbto <- data.frame(a$mort_gut_nbto)
  a$mort_lip_nbo_wtr <- data.frame(a$mort_lip_nbo_wtr)
  a$mort_gut_nbo_wtr <- data.frame(a$mort_gut_nbo_wtr)
  a$mort_lip_nbo_lnd <- data.frame(a$mort_lip_nbo_lnd)
  a$mort_gut_nbo_lnd <- data.frame(a$mort_gut_nbo_lnd)

  a$nsurv_lip_bo <- data.frame(a$nsurv_lip_bo)
  a$nsurv_gut_bo <- data.frame(a$nsurv_gut_bo)
  a$nsurv_lip_nbo_wtr <- data.frame(a$nsurv_lip_nbo_wtr)
  a$nsurv_gut_nbo_wtr <- data.frame(a$nsurv_gut_nbo_wtr)
  a$nsurv_lip_nbo_lnd <- data.frame(a$nsurv_lip_nbo_lnd)
  a$nsurv_gut_nbo_lnd <- data.frame(a$nsurv_gut_nbo_lnd)

  a$nmort_lip_bo <- data.frame(a$nmort_lip_bo)
  a$nmort_gut_bo <- data.frame(a$nmort_gut_bo)
  a$nmort_lip_nbto <- data.frame(a$nmort_lip_nbto)
  a$nmort_gut_nbto <- data.frame(a$nmort_gut_nbto)
  a$nmort_lip_nbo_wtr <- data.frame(a$nmort_lip_nbo_wtr)
  a$nmort_gut_nbo_wtr <- data.frame(a$nmort_gut_nbo_wtr)
  a$nmort_lip_nbo_lnd <- data.frame(a$nmort_lip_nbo_lnd)
  a$nmort_gut_nbo_lnd <- data.frame(a$nmort_gut_nbo_lnd)

  a$catches <- data.frame(a$catches)

  names(a$tot_surv) <- names(a$tot_mort) <- names(a$catches) <- fleet$Flag

  a <- make_meds(a)
  a <- make_tots(a)
  assign(mgm, a)
}

###########----------------------------------------------------
# Plot results
windows(10, 10); par(mfrow = c(4,4), mar = c(2,4,4,0)+.1, oma = c(0,0,1,0))
for (fl in colnames(alls$tot_surv)) {
  hist(alls$tot_surv[,fl], nclass = 100, main = fl, xlim = c(0, 1), xlab = "")
}
alls$tot_surv$total <- apply(alls$tot_surv,1,sum)
hist(alls$tot_surv$total, nclass = 100, main = "Total", xlim = c(0, max(alls$tot_surv)), xlab =
    "")
title(paste(sps, "survival"), outer = TRUE)
savePlot(paste0(sps, " survival by flag.png"), type = "png")

windows(10, 10); par(mfrow = c(4,4), mar = c(2,4,4,0)+.1, oma = c(0,0,1,0))
for (fl in colnames(alls$catches)) {
  hist(alls$catches[,fl], nclass = 100, main = fl, xlim = c(0, max(alls$catches)), xlab = "")
}
alls$catches$total <- apply(alls$catches,1,sum)
hist(alls$catches$total, nclass = 100, main = "Total", xlim = c(0, max(alls$catches)), xlab =
    "")
title(paste(sps, "catches"), outer = TRUE)
savePlot(paste0(sps, " catches by flag.png"), type = "png")
```

```
  windows(10, 10); par(mfrow = c(4,4), mar = c(2,4,4,0)+.1, oma = c(0,0,1,0))
  for (fl in colnames(alls$tot_mort)) {
    hist(alls$tot_mort[,fl], nclass = 100, main = fl, xlim = c(0, max(alls$tot_mort)), xlab = "")
  }
  alls$tot_mort$total <- apply(alls$tot_mort,1,sum)
  hist(alls$tot_mort$total, nclass = 100, main = "Total", xlim = c(0, max(alls$tot_mort)), xlab = "")
  title(paste(sps, "mortality"), outer = TRUE)
  savePlot(paste0(sps, " mortality by flag.png"), type = "png")

  dummy_nsurv <- cbind(alls$nsurvs, shkl$nsurvs, wire$nsurvs, circ$nsurvs, shll$nsurvs, skwr$nsurvs)
  dummy_nmort <- cbind(alls$nmorts, shkl$nmorts, wire$nmorts, circ$nmorts, shll$nmorts, skwr$nmorts)

  windows(width = 12, height = 10); par(mar = c(5,4,4,7)+.1)
  legtxt <- c("biteoff lip","biteoff gut","nobiteoff wtr lip","nobiteoff wtr gut","nobiteoff boat lip","nobiteoff boat gut")
  par(xpd = TRUE)
  barplot(dummy_nsurv, bty = 'L', col = terrain.colors(6), names.arg = c("Current", "No sharkline", "No wire", "Circle hooks", "No shallow", "No shkl+wire"))
  legend("topright", legend = legtxt, fill = terrain.colors(6), inset = c(-0.21,0))
  title(paste(sps, "survival components by mgmt type"), outer = TRUE, line = -1)
  savePlot(paste0(sps, " survival_barplot.png"), type = "png")

  windows(width = 13, height = 10); par(mar = c(5,4,4,7.5)+.1)
  legtxt <- c("M biteoff lip","M biteoff gut","M retained lip","M retained gut","M water lip","M water gut","M boat lip","M boat gut")
  par(xpd = TRUE)
  barplot(dummy_nmort, bty = 'L', col = terrain.colors(6), names.arg = c("Current", "No sharkline", "No wire", "Circle hooks", "No shallow", "No shkl+wire"))
  legend("topright", legend = legtxt, fill = terrain.colors(6), inset = c(-0.19,0))
  title(paste(sps, "mortality components by mgmt type"), outer = TRUE, line = -1)
  savePlot(paste0(sps, " mortality_barplot.png"), type = "png")

  windows(10, 10); par(mfrow = c(6,1), mar = c(1,4,1,0)+.1, oma = c(3,0,3,0))
  a$alls <- apply(alls$nmort_all, 2, sum)
  a$shkl <- apply(shkl$nmort_all, 2, sum)
  a$wire <- apply(wire$nmort_all, 2, sum)
  a$circ <- apply(circ$nmort_all, 2, sum)
  a$shll <- apply(shll$nmort_all, 2, sum)
  a$skwr <- apply(skwr$nmort_all, 2, sum)
  rng <- c(0, max(rbind(a$alls, a$shkl, a$wire, a$circ, a$shll, a$skwr)))
  dohist(a$alls, ti = "Current", type = "mort2", rng = rng)
  dohist(a$shkl, ti = "No sharkline", type = "mort2", rng = rng)
  dohist(a$wire, ti = "No wire", type = "mort2", rng = rng)
  dohist(a$circ, ti = "Circle hooks", type = "mort2", rng = rng)
  dohist(a$shll, ti = "No shallow", type = "mort2", rng = rng)
  dohist(a$skwr, ti = "No sharkline or wire", type = "mort2", rng = rng, labs = TRUE)
  title(paste(sps, "Mortality by mgmt type"), outer = TRUE, line = 1)
  savePlot(paste0(sps, " mortality_histograms.png"), type = "png")
}
```