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Quantifying post release mortality rates of sharks incidentally captured in Pacific tuna longline fisheries and identifying handling practices to improve survivorship

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Abstract
Shark bycatch rates are higher in pelagic longline fisheries than in any other fishery, and these sharks are typically discarded at sea. The post-release fate of discarded sharks is largely unobserved and could pose a significant source of unquantified mortality. This study assessed post release mortality rates of blue (*Prionace glauca*), bigeye thresher (*Alopias superciliosus*), oceanic whitetip (*Carcharhinus longimanus*), and silky (*C. falciformis*) sharks discarded in two tuna target fisheries in the western and central Pacific Ocean. The study found, that the condition at release (good versus injured) and the amount trailing gear left on the animals were the two factors that had the largest effect on post release fate. Animals released in good condition without trailing gear had the highest rates of survival.

Introduction
It is estimated that two-thirds of global elasmobranch species are threatened with extinction, with overfishing identified as a major contributor (Worm et al. 2013). Thus, identifying strategies that reduce commercial fishing impacts on shark bycatch populations is a critical fisheries science and conservation need. Shark bycatch rates are higher in pelagic longline fisheries than in any other fishery, and sharks are typically unwanted and discarded at sea (Oliver et al. 2015) The post-release fate of discarded sharks is largely unknown yet has the potential to pose a significant source of unquantified mortality. Additionally, the reduction of bycatch mortality is a major objective of the ecosystem approach to managing fisheries and has become a topic of interest to consumers and conservation groups (Poisson et al. 2014).

The Hawaii and American Samoa longline fisheries targeting tuna interact with several shark species, most of which are of low commercial value and are discarded at sea. In these fisheries, the highest shark catch rates are, in descending order; blue sharks (*Prionace glauca*), thresher (*Alopias spp*.), mako (*Isurus spp*.), oceanic whitetip (*Carcharhinus longimanus*), and silky sharks (*C. falciformis*) (Walsh, Bigelow, and Sender 2009). Blue sharks comprise the largest component (>85%) of the total shark catch, and in 2017, the Hawaii longline fleet caught 96,288 blue sharks, 100% of which were discarded at sea (PIFSC Data Report 2019). A satellite telemetry study on blue sharks in the Atlantic Ocean found post release—or delayed mortality—occurred in 19% of the animals that were released 'alive' from swordfish target longline fishing gear (Campana, Joyce, and Manning 2009). This source of fishing mortality goes largely

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undocumented and may have large implications for stock assessments and for the overall health of shark populations worldwide. Globally, oceanic whitetip shark populations are reported to be in decline, and this species is now listed in Appendix II of the Convention on International Trade in Endangered Species (CITES) and as threatened globally under the United States Endangered Species Act. A study of CPUE trends in the Hawaii based longline fishery found significant declines in the relative abundance of oceanic whitetips and silky sharks since 1995 (Walsh and Clarke 2011). Furthermore, in the western and central Pacific Ocean, a stock assessment of oceanic whitetip sharks concluded the population is overfished and currently experiencing overfishing (Rice and Harley 2012).

Due to these population declines, several regional fisheries management organizations (RFMO) have responded with a series of conservation and management measures (CMMs) for sharks. Within the Western and Central Pacific Fisheries Commission (WCPFC) convention area, measures have called for "policies that encourage the live release of incidental catches of sharks" (CMM 2010-07). Previous CMMs have created species-specific policies for both oceanic whitetip and silky sharks banning retention and mandating the release of any shark that is caught "as soon as possible after the shark is brought alongside the vessel, and to do so in a manner that results in as little harm to the shark as possible" (CMM 2011-04, CMM 2013-08). Banning measures are a step in the right direction but may not have the intended consequence of reducing mortality. At haul back and/or during the handling procedures to release the sharks, they may incur physiological and/or physical damage resulting in undocumented delayed mortalities (Tolotti et al. 2015). Effective sustainable fisheries management requires knowledge of the direct effects of fishing operations on stocks and populations subject to bycatch. There is an urgent need to estimate levels of unobservable mortality, account for these losses in stock assessment models, and adopt measures to mitigate sources of unobservable mortality, such as identifying best handling and release practices (Gilman et al. 2013).

There is a general consensus among shark and fishery scientists that three main factors affect shark bycatch mortality rates in longline fisheries: (1) physiological sensitivity to stress, where impacts are species specific, (2) the amount of time an animal spends on the line, and (3) handling methods used to release/remove sharks from fishing gear. Many studies have identified which species are most sensitive to capture stress through physiological investigations and by quantifying at-vessel mortality rates (e.g., Beerkircher, Cortes and Shivji 2002; Marshall et al. 2012). However, the effects that shark handling and at-vessel condition have on post release mortality and/or survival rates are only recently being explored (Hutchinson 2016; Musyl and Gilman 2018; Schaefer et al. 2019). In this study, we quantify post release mortality rates of blue, bigeye thresher, oceanic whitetip, and silky sharks that are incidentally captured in the Hawaii deep-set (HiDS) and American Samoa (AS) tuna target longline fisheries. We also investigate the effects that standard shark bycatch handling and discard practices utilized in these fisheries may have on the post release fate of discarded sharks that are in good condition at haul back of the longline gear.

Methods

To assess the factors that influence post release mortality rates of sharks discarded in Hawaii and AS tuna target longline fisheries and to identify the handling and release methods that enhance survivorship, we needed to augment the data collected by Pacific Islands Regional Observer Program (PIROP) observers during shark interactions. Currently, PIROP observers only record if an animal is alive or dead at the vessel and alive, dead, or kept for release condition. We know that there is a spectrum of vitality where sharks that are in excellent condition at haul back have better chances of survivorship than sharks that are exhausted or injured and barely moving. Thus, we created additional condition indices and codes for shark condition at the vessel and at release for observers participating in the study to record (Table 1). Handling and injury codes also were developed and tested to ascertain how sharks were removed from the fishing gear and to provide details on any injuries that the animal may have incurred during the process. This was an iterative process; the data codes were created with definitions, and observers were sent out to sea with video cameras to assess whether or not they interpreted the definitions accurately. This process began during the summer of 2015, and final definitions were adopted and implemented in December of 2016.

To quantify post-release mortality rates of incidental blue (BSH), bigeye thresher (BTH), oceanic whitetip (OCS), and silky (FAL) sharks captured in the HiDS and AS tuna longline fisheries, PIROP observers were trained to tag sharks captured and released during normal fishing operations. Tags were placed on sharks over the rail of the vessel while the shark was still in the water, using extendable tagging poles. Vessel crew then removed the shark from the fishing gear via whichever release methods they typically employed. Observers recorded additional metrics specific to the tagging event and gave detailed narratives of the handling methods including: type and quantity of trailing gear, damage to animal from gear removal, how it was landed, time out of water if sharks were boarded to remove gear, time for tagging and release, sea surface temperature (SST), sex, approximate length, and anything noteworthy regarding the interaction. Observers also recorded the tagging events using a GoPro camera so that scientists could validate data recorded by different observers.

This study used two different satellite linked pop-off archival tag (PAT) types. Survivorship PATs (sPAT) were programmed for 30-day deployment periods to archive and then transmit binned; light, temperature, and depth data to the tag manufacturer (Wildlife Computers, Inc., Redmond, WA). The tag manufacturer analyzed these data to interpret whether the animal died (the tag sank to a depth beyond 1400 m or it sank and sat at a constant depth for > 3 days), it survived to 30 days, and the tag came off as programmed or pre-maturely (due to attachment failure) and was floating at the surface. The fate of the tag ('Sinker', 'Completed Deployment', or 'Floater') and the daily minimum and maximum depth and temperature and the pop-off location were then communicated to the tag owner. These tags were placed on sharks that were alive and in good condition (AG) to get a high estimate of post release survival rates and to identify the best handling practice for maximizing survivorship potentials. To attain the low end of the post release survival rate for blue and oceanic whitetip sharks only, sharks that were alive but injured (AI) or did not meet the criteria for AG or AI at the vessel were also tagged when the vessel was cutting the line.

During the initial phases of data collections, we learned that most sharks were released by cutting the line with varying amounts of trailing gear still attached to the animal (Table 2). The project was therefore expanded to assess the long-term effects of trailing gear on survivorship of incidental blue sharks using longer term PATs. The miniPAT (Wildlife Computers, Inc., Redmond, WA) archives light, temperature, and depth time series data, but the sampling intervals and deployment periods can be programmed by the tag owner. These tags were programmed for 180 (n=2) and 360 (n=10) day deployment periods with 10 minute sampling rates and placed on sharks that were AG at the vessel and released by cutting the line.

Fishery participation in the study was voluntary. Observers were only asked to tag a small number of sharks (2–3) per trip to ensure that vessels did not represent a large burden for participating in the project and to avoid observer or trip-specific biases in the data.

The covariates most likely to influence the post release survival times, in days, were investigated with the Kaplan-Meier and Cox proportional hazard models in the "survival" package (Therneau 2015) using R (R Core Team, 2019). The predictor variables considered for use in the survival modelling included; species, fishery, catch condition, release condition, handling code, trailing gear, approximate fork length, ratio of trailing gear to approximate fork length, and sex. Sex had to be removed because it was undetermined for most animals, while the effect of fishery was assessed for OCS alone since they were the only species tagged in both fisheries (Table 3).

Results

Observers collected shark condition and handling data on 19,572 incidental elasmobranchs captured during 148 fishing trips that occurred between January 2016 and June 2019 on 76 different vessels. During 111 of these trips, 148 sharks were tagged by observers and fishers. The handling and damage data recorded by trained observers indicated that most sharks (93.22%; Table 2) were released by cutting the branchline. In the Hawaii-based tuna fishery this means that most sharks were released with an average of 9.02 meters of trailing gear (Figure 1a), which typically includes a stainless-steel hook, 0.5 m of braided wire leader, a 45-gram weighted swivel, and monofilament branchline ranging in length from 1.0–25.0 m. Sharks released by cutting the line in American Samoa were released with an average of 3.038 m of trailing gear which is composed of a stainless-steel hook to an all monofilament line ranging in length from 1.0–9.0 m (Figure 1a). Some species are released with more trailing gear than others (Figure 1b). This was primarily due to how quickly the fishers were able to ascertain that the catch was a shark and not a target species. The behavior of some species often predicts where the line will be cut; for example, blue sharks surface far away from the vessel and are easy to identify so the line is often cut further away from the vessel than for some other species (Figure 1b).

Observers based in American Samoa tagged FAL (n = 31) and OCS (n= 17, Table 4). In the HiDS fishery, observers tagged BSH (n = 44), BTH (n = 28), and OCS (n = 17) with sPATs (Table 4). HiDS observers also tagged BSH (n = 12) with miniPATs programmed for 180 and 360 day deployments (Table 5). Two of the sPATs were shed immediately (one BSH and one FAL) and could not be used in analyses and are not included in Table 4. There were 10 sPATs that reported mortalities that had to be removed from analyses due to either a manufacturer malfunction (some tags were negatively buoyant with the leader and thus, if shed early, would have falsely indicated a mortality; n = 7) or the effect of the tagging event could not be ruled out after video review (n = 3). One of the miniPAT tagged BSH (16P1632) that died after 15 days was also removed from the survival analysis after video review of the interaction revealed that it was an irregular handling event and could not rule out the effect of the tagger on the mortality (Table 5). Results from the sPAT deployments showed that survivorship to 30 days is relatively high (93.1%) for sharks captured in good condition (Table 4). This may be an overestimate of survival rates because we had to discard ten of the mortalities that occurred in the study, and we tagged a disproportionate number of animals in good condition. Survival rates are also higher for all species that are released by cutting the line (96.2%) than removing the gear (83.3%). Gear removal requires additional handling, and animals are sometimes brought on deck (sometimes using a gaff) and exposed to air which may impact release condition. Some are pulled up to the fish door where hooks are cut out. Gear removal is infrequent (Table 2) and depends on the size of the animal and the vessel's operating procedures as large sharks are typically left in the water.

Initially, only sharks that were alive and in good condition (AG) were tag candidates, and later some tags were allocated for BSH and OCS that were alive but did not meet the criteria for AG. These animals would have been characterized as either Alive (A) or Alive but Injured (AI; see Table 1 for definitions). Most OCS are typically captured in AG condition (54.6%) or they are dead (33.6%; Table 6) so encounter rates with OCS in compromised conditions was too uncommon to tag the desired quantity these animals. Despite this limitation, mortality rates were found to be somewhat higher for individuals that did not meet the AG criteria.

All of the BTH mortalities (n = 3 of 28 tagged) were animals that had been tail-hooked, and although four other BTH were also tail-hooked, they survived to 30 days. All FAL tagged in AS survived the interactions. Two of the four OCS mortalities were sharks that did not meet the AG criteria and were in compromised conditions. Both were captured in AS. The two mortalities for OCS in AG condition were captured in both the HiDS and AS fisheries.

The results of the long-term tag deployments (miniPATs) on BSH showed that delayed mortality rates are quite high. Of the twelve tags that were deployed, two did not report and were not included in any subsequent analysis. Of the ten tags that reported, two survived and eight tags indicated mortalities. Three of the animals died immediately while the remaining five deaths occurred between 15–188 days post release (Table 6). One of these was a tag that was ingested by a thermo-regulating animal on day 28 of the deployment. There were also two SPATs that reported light, depth, and temperature data indicating the tags had been ingested and later regurgitated. These occurred on days 19 for a BSH that had the gear removed and day 17 for a tail-hooked BTH that was released with three meters of trailing gear (Table 4). All three of the ingested tags were considered mortalities, although it is understood that there are other scenarios where an ingested tag does not necessarily reflect a mortality.

The Kaplan-Meier (KM) survivorship function (Kaplan & Meier, 1958) was used to estimate the probability of survival over time, post release, and the Cox proportional hazards model (Cox, 1972) was used to assess the impact of different variables (Table 3) on the survivorship data. The KM survival rates were assessed for all data combined ('Combined'; Figure 2, Tables 7 & 8). Survivorship was estimated to 300 days since some BSH had tag deployments that went beyond 300 days. The Cox regression model showed that trailing gear and the condition of the animals upon release had the greatest impact on survival rates (Table 7). KM survival rates were also investigated for all four species combined when they were in good condition at capture (AG; Figure 3, Table 9) and for each individual species (BSH; Figure 5, Table 10, BTH; Figure 6, Table 11 and OCS; Figure 7, Table 12). This analysis could not be conducted on the FAL dataset alone because it requires at least one event (mortality) to run the model and all FAL survived to the point when the tags came off in this study. Cox proportional hazard models were also run for each of the above datasets (Table 7). For each dataset, variables were sequentially excluded using a backwards stepwise methodology. Table 7 shows which variables were retained and the Delta AIC values that resulted from removal of other predictors. For all species in good condition at capture, trailing gear and handling method (line cut or gear removed) had the greatest impact on post release survival times (Table 7, Figure 4). Figure 4 shows how gear removal results in higher immediate mortality while large amounts of trailing gear increases mortality rates over time. Long trailing gear was considered to be > 2.5 m and short lengths were ≤ 2.5 m. This length was arbitrarily chosen as this was the median amount of trailing gear left on all animals in the dataset. Trailing gear also had the largest effect on survival rates for BSH (Table 7, Figure 5) and for BTH (Table 7, Figure 6). The BTH data set requires further assessment as some nuances were not addressed in this analysis. Many of the BTH were hooked in the tail; these animals are often easier to bring closer to the boat to remove more fishing gear. Hooking location may be a better predictor of survivorship for this species and will be addressed in future analyses. We were able to assess the impacts that the two different fisheries may have on survival rates of OCS in addition to; catch condition, release condition, handling code, approximate length, trailing gear and ratio of trailing gear to body length, since only OCS were tagged in both fisheries. Fishery was retained in the final model along with handling code (Table 7, Figure 8). For OCS tagged in AS, mortality rates were higher than those that were tagged in the HiDS fishery. Gear removal was also shown to reduce survival probabilities over release by cutting the line (Figure 8).

Discussion

Longline fisheries have proven to generate the largest impact on pelagic shark populations due to the scale and magnitude of fishing effort around the globe. As some shark population assessments have shown declines due to overfishing, finding strategies that can reduce this impact are increasingly important. In regions where sharks are discarded at sea, understanding post release fate and the identification of handling practices that can improve post release survival is paramount. This study used satellite linked pop-off archival tags to elucidate post release fate for four of the most frequently captured and discarded shark species (blue, bigeye thresher, oceanic whitetip, and silky sharks in two tuna target longline fisheries in the Pacific Ocean. Our findings show that sharks released in good condition when the line is cut to remove most of the trailing gear had the highest survival rates.

It is well understood that fight time and species are correlated to at-vessel condition and post release fate. Some species are more sensitive, physiologically to capture related stress, and mortality rates often depend on the nature of the interaction and time. In longline fisheries it is often determined by how long they were on the line. While other sources of mortality may be fishery specific due to operational and gear configuration characteristics, small changes to gear or fisher behavior may improve post release survival probabilities for discarded species. For species where no-retention measures have been implemented to reduce mortality, it is important that post release fate is well understood to assess the efficacy of the measures. In the WCPFC, no-retention measures have been adopted for both OCS and FAL. The US tuna fleets are subject to these measures and mandated to release all OCS and FAL. Here we show that FAL have high post release survival rates to 30 days. While only FAL that were in good condition at the vessel were tagged, considering that this species had the highest at vessel mortality rate of all species tagged in this study, it was surprising that every FAL survived the interaction. While most FAL were released by cutting the line, there were a few that were boarded to remove the gear, and there were no mortalities. This is the only species that was tagged in just the AS fleet and was consistently released with shorter lengths of trailing gear. Good condition at the vessel and release with small amounts of trailing gear appear to assist survivorship post release for this species.

OCS are also subject to a no-retention measure and were tagged in both the HiDS and AS tuna fisheries. Our analysis showed that the fishery was an important predictor of post release fate. Immediate mortality rates were higher for OCS discarded in the AS fishery, but there were also delayed mortalities in the HiDS fishery. This may indicate the effects of trailing gear but that was not a significant factor for this species. Handling, however, did have an impact for OCS as gear removal increased mortality. This may seem intuitive, as any additional handling and potential air exposure, if the sharks are brought on deck, would have a negative impact on survival probabilities. This is powerful information to convey to fishers, particularly for a species with conservation and management measures in place calling for fishers to release sharks in a manner that reduces harm but lacks recommendations on how to accomplish this. Studies like this provide information to fisheries managers so they can implement management measures based on data and fisher participation that provide good alternatives for handling instead of telling fishers what not to do. Engagement with fisheries at the early stages of studies like this will find that implementation of regulations will be adopted by the fishery more seamlessly.

Bigeye thresher sharks were only tagged in the HiDS fishery if they were in good condition at the vessel. We found that all of the mortalities were sharks that were tail-hooked. Hooking location was not used as a predictive variable in the KM or Cox PH analyses but this work is forth coming. Tail-hooked BTH are often in poorer shape than if they are mouth-hooked. Tail-hooked animals also may have the tips of their tails cut off to retain the hook which was the case for two of the mortalities that occurred in this study. Four other tail-hooked BTH survived. The factor that did have the largest effect on survival rates was the length of trailing gear. Some sharks released with short (≤ 2.5 m) lengths of trailing gear were also tail-hooked, and initial mortalities were higher for these sharks as opposed to sharks released with longer (>2.5 m) lengths of trailing gear.

Blue sharks represent the greatest proportion of shark bycatch rates in longline fisheries across the Pacific Ocean basin, and yet the most recent stock assessment concluded that the stock was not overfished (ISC 2017). This species is characteristically robust to capture stress and, in this study, only 7.0% of blue sharks were dead at capture while 65.0% were recorded as in good condition at capture. BSH had the largest tagging effort in this study with 25 SPATs on sharks in good condition, nine on sharks that were alive but did not meet the criteria for AG or AI, six that were injured, and 12 long-term tags were placed on sharks in good condition with the line cut. Surprisingly, at vessel condition was not a factor in post release survival rates but trailing gear was, with delayed mortalities occurring 188 days post release. There was a large margin of error in the estimated post release survival rates (13.2–95.7%). To refine these estimates, patterns need to be resolved and fishery specific variables that contribute to mortality need to be identified with additional long term tagging effort.

In the combined dataset (all species in all catch conditions) and the AG dataset (species combined but catch condition is AG), trailing gear was an influential factor in post release survival rates while species was not. It is worth discussing the fact that different species are handled differently either due to behavior of the animal or the fishers. For example, in this study we found that both BSH and BTH are released with longer lengths of trailing gear than both OCS and FAL. This could be due to differences in operations between AS and HiDS fisheries, but may also be symptomatic of how the different species behave on the line. For example, BSH surface early and are seen farther away thus the vessel cuts the line as soon as they see that it is a shark. Threshers often fight very hard against the gear and either come flying out of the water or take deep dives that are characteristic of a shark; therefore, these lines are also cut when the animal is farther away from the vessel. While silky and oceanic whitetips are not seen until they are closer to the boat and are harder for some to identify to species from further away so they are brought closer to the vessel where the crew can cut more line off. Releasing sharks with large quantities of trailing gear is not only energetically costly for the animal, but may also increase susceptibility to predation and present an entanglement hazard. Mortalities that would be due to the energetic drain of trailing gear would probably occur outside the 30 day window of the deployment period of the survivorship PATs used in this study. We found that delayed mortality rates (beyond 30 days) were indeed high in the small number of blue sharks that were tagged with miniPATs programmed for 180 and 360 day deployment periods. This detail may have broad implications for the determinations of post release mortality rates derived from survivorship tags since most survival studies use tags with 30–60 day deployment periods (this study; Musyl and Gilman 2018; WCPFC 2019). It is nearly impossible to point directly to trailing gear as a cause of mortality. Yet this study and the WCPFC (2019) study both show that longer lengths of trailing gear have a negative impact on survivorship.

The results of this study should be interpreted carefully, particularly because most of the tags were placed on sharks in good condition at capture, creating an overly optimistic estimate of overall post release survival rates. This was deliberate as there were a finite number of tags and we were looking to get the high estimate of survivorship to identify the handling and discard methods that improve survival rates to make recommendations to the fleets. As the study progressed, we acquired additional resources for tags and were able to deploy some survival PATs on BSH (n = 16) and OCS (n = 7) that were in compromised condition at the vessel, but additional effort is needed to determine survival rates for animals that are injured and for those that are exhausted but do not have any signs of traumatic injury. In addition, we have shown that mortality rates beyond the 30-day window of the SPATs were high for BSH. Whether these mortalities were a direct result of the initial fishing interaction is difficult to verify. Additional work to assess delayed mortality rates due to fishing interaction and potentially the trailing gear needs to be conducted. Furthermore, the tag fate that is communicated by the tag manufacturer is a simplistic interpretation of the tag data and may not always represent the fate of the animal. For example, several of the tags deployed in this study were ingested by thermoregulating predators and subsequently regurgitated. The tag fate was determined to be a 'floater' (tag was shed due to attachment failure), but careful analysis of the tag report showed temperatures that did not change with depth and no changes in light levels. Ingested tags may be easier to detect when they are ingested by thermoregulating species, but this may not be the case when tags are ingested by poikilotherms. There is also the potential for tags to be bitten off the animal which would not always result in mortality for the tagged animal. Another scenario that may also comprise a significant portion of undetected mortality is recapture. In a separate study, a tagged OCS was recaptured by a Tongan longliner, and the tag was returned. Though the animal was dead at the vessel, the tag data showed that it was a 'floater'. Without having been contacted by the Tongan fishing company about the recapture, it is nearly impossible to distinguish a recapture that goes unreported from other 'floater' tags using the transmitted data alone.

Conclusions, Recommendations and Next Steps

In this study, we show post release survival rates are high to 30 days for BSH, BTH, FAL, and OCS **if** they are in good condition at release **and** if trailing gear is minimized. We found that the amount of trailing gear left on an animal has a negative effect on post release survival potential for multiple species and is correlated with high delayed mortality rates of BSH (beyond 30-days). Because most sharks are released by cutting the line, making recommendations to remove as much trailing gear as possible will enhance post release survival rates. In the WCPFC, no-retention measures for silky and oceanic whitetip sharks may have the intended effect of reducing mortality if the measure included recommendations to reduce the amount of trailing gear left on animals to less than 2.5 m. Improved data collections for sharks will also improve estimation of post release mortality. Here we find that species, release condition, handling and release method, trailing gear, and hooking location all influence fate and should be recorded by fishery observers.

Further investigation of post release mortality rates is required to refine the estimates garnered in this study. The survival rate confidence intervals were quite large for several of the species; therefore additional tagging is required. Because delayed mortality rates for BSH were so high, it is recommended that long term tags be used in future studies in addition to the less expensive, shorter duration SPATs.

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Table 1. Shark Condition Codes and Criteria

Condition Codes	Definition
D = Dead	Animal showed no signs of life. This code is also the **default** condition when an animal's disposition cannot be established.
AI = Alive but injured	Animal was alive but there was clear evidence of serious injury. The serious injury category is met when **ONE OR MORE** of the following injury criteria exists: **(1)** the hook has been swallowed (e.g., the bend of the hook is not in the tissue surrounding the jaw but has been ingested posterior to the esophageal sphincter or deeper), **(2)** bleeding is seen from the vent and/or gills, **(3)** stomach is everted (please specify in comments), or **(4)** other damage (e.g., depredation, entangled in gear) occurred prior to hook/gear removal.
AG = Alive in good condition	Animal appears lively and healthy with no obvious signs of injury or lethargy (animal should appear active). This condition code is used when **ALL** of the following criteria are observed and met: **(1)** no bleeding, **(2)** shark is lively and actively swimming, **(3)** not upside down and/or sinking, **(4)** no external injury, and **(5)** not hooked in the esophagus, stomach, or the gills.
A = Alive	Animal was observed to exhibit signs of life, but its level of activity or injury could not be established or the criteria for the AG or AI codes are not met. This code is the **default** for any **live** animals that could not be further categorized for any reason including the animal was too far away to discern whether or not the AG or AI criteria were met.

Table 2. Relative frequency of handling methods used to release sharks in both HiDS and AS tuna longline fisheries during the shark research trips 2015–2019.

Handling & Damage Codes Used	Proportion
Line Cut	93.22%
Escaped	3.01%
Jaw Damage	1.78%
Gear Removed	1.36%
Other	0.463%
Part Removal†	0.172%

†Part removal indicates a tail-hooked thresher that had a portion of the tail removed to recover the embedded hook.

Table 3. Potential explanatory variables for the Cox models to test effect on survival. For species the codes are; BSH = blue shark, BTH = bigeye thresher shark, FAL = silky shark, OCS = oceanic whitetip. Fishery codes; HiDS = Hawaii Deep-set tuna longline fishery, AS = American Samoa tuna longline fishery. Condition codes for both catch and release; AG = Alive, in good condition, A = Alive, AI = Alive but injured, D = Dead. Handling Codes; LC = Line Cut, GR = Gear Removed.

Variable	Levels, definitions & issues
Species	BSH, BTH, FAL OCS (FAL not assessed by species)
Fishery	HiDS, AS (Only OCS were tagged in both fisheries)
Catch Condition	AG, A, AI, D
Release Condition	AG, A, AI, D
Handling Code	LC, GR
Approximate Length	Estimated (animals tagged in water)
Trailing Gear (TG)	Length of gear left on the animal
Ratio of trailing gear to body length	TG / Approximate length
Sex	M, F, U (Most were unsexed)

Table 4. Survivorship PAT (30 day deployment period) results.

Shark Species	Condition	Line Cut		Gear Removed		Usable Tags	Survival rate (LC + GR)
		Survivor (n, %)	Mortality	Survivor	Mortality		
Blue	AG	13 (92.9%)	3^{2}	10 (90.9%)	1ﬁ	25	**92%**
	A	7 (77.8%)	3^{1}	-	-	9	
	AI	4 (66.7%)	2	-	-	6	
Bigeye Thresher	AG	$18_{[1]}$ (94.7 %)	$5^{4}_{[1]}$ ﬁ	$3_{[3]}$ (60%)	$2_{[2]}$	24	**87.5%**
Oceanic Whitetip	AG	19 (95%)	2^{1}	3 (75%)	2^{1}	24	**91.7%**
	A	3 (75%)	1	1 (50%)	1	6	**66.7%**
	AI	1	-	-	-	1	
Silky	AG	25 (100%)	1^{1}	4 (100%)	0	29	**100%**
Total Tagged		90	17	21	6		
Tags Removed		0	9	0	1		
Totals		90	8	21	5	124	**89.5%**
Survival rate (AG)		**96.2%**		**83.3%**			**93.1%**

In parentheses are the proportion of tagged animals that survived to 30 days or when the tag came off. Numbers in superscripts indicate the number of tags that were removed from survivorship analysis due to either tag manufacturer malfunction or due to tagger influence. An additional two tags are also not included here due to attachment failures on day 1 on a BSH and a FAL. BTH that were tail-hooked are shown as subscripts in brackets. ﬁ Symbol indicates a tag that was ingested.

Table 5. Results of long-term survival assessments of blue sharks released by cutting the line from vessel in the Hawaii Deep-set longline sector. Trailing gear from the hook includes; 0.5 m stainless steel braided wire leaders to a 45-gram weighted swivel to the monofilament branchline of varying lengths as recorded in the trailing gear column below.

BSH ID	Tag Fate	Days	Trailing gear (m)	Approx fork length (ft.)
16P1632*	Mortality	15	14	6
16P1603	Survivor	180	10	5
16P1604	Mortality	87	6	5
16P1633	Survivor	312	4	7
16P1607	Mortality	1	11	7
16P1606 ﬁ	Mortality	28	11	8
16P1630	Non-reporter	NA	1	7
16P1602	Mortality	114	17	8
16P1639	Mortality	1	4	4
16P1635	Mortality	1	12	5
16P1378	Non-reporter	NA	13	7
16P1379	Mortality	188	13	7

An * indicates a tag where the effects from the tagging event could not be ruled out and was removed from the survival analysis. This animal was handled in an irregular manner: it was brought on board the vessel for tagging, hooks were removed from previous interactions, and it was released with 14 m of trailing gear. The animal was also on deck for four minutes. While that may occur at sea under normal conditions, the crew typically only boards animals to remove trailing gear yet this animal was released with 14 meters of trailing gear. ﬁ Symbol indicates a tag that was ingested.

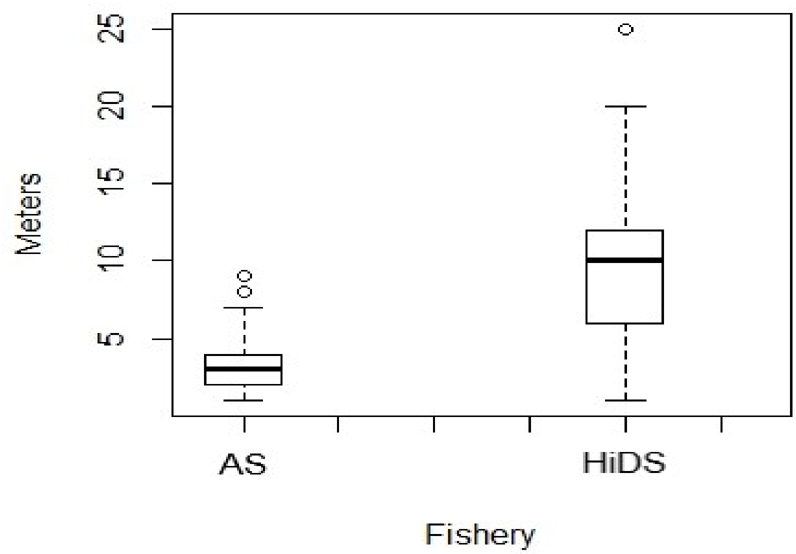
Table 6. Shark condition proportions at haul back ('Caught Condition') for blue (BSH), bigeye thresher (BTH), silky (FAL), and oceanic whitetip (OCS) sharks for all research trips in both tuna longline fisheries.

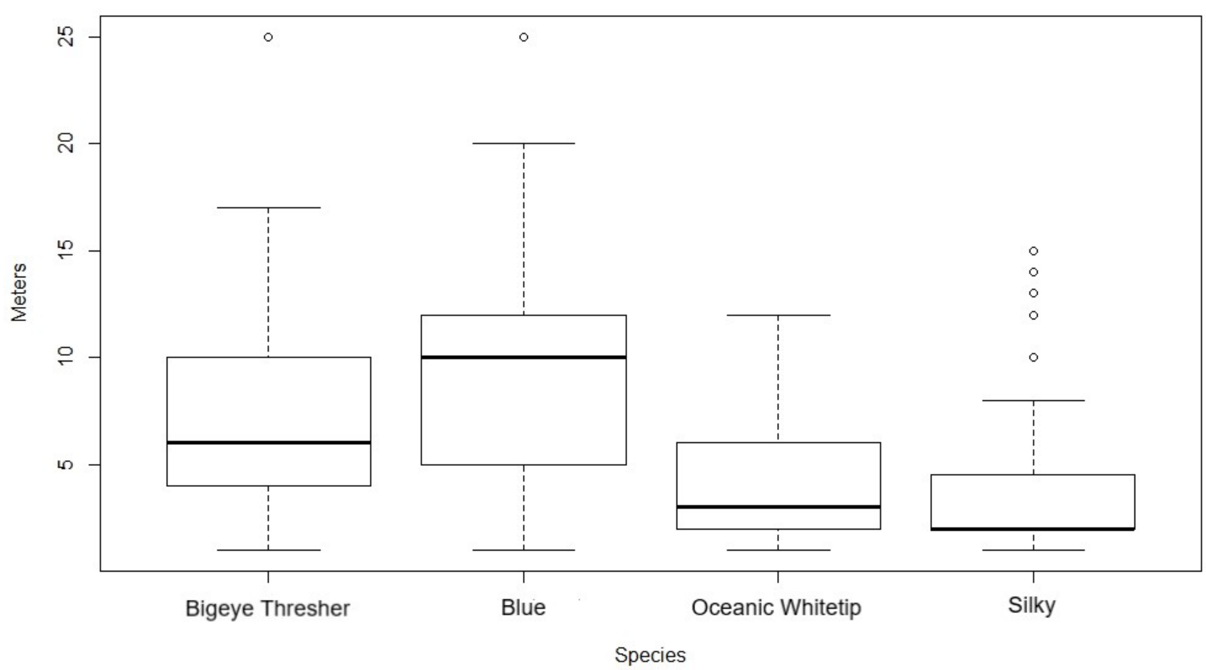
Species	Alive in Good Condition	Alive	Alive but Injured	Dead
BSH	65.0%	23.1%	5.1%	7.0%
BTH	50.7%	14.6%	5.7%	28.9%
FAL	58.4%	3.8%	2.0%	35.8%
OCS	54.6%	6.6%	5.2%	33.6%

Table 7. Results of Cox Proportional Hazard models to test the effect of variables on survival for the tagging data sets. The least informative variables were removed by stepwise backward removal using an Akaike Information Criterion (AIC). The retained variables are indicated along with the associated AIC value for each dataset, and removed variables are listed along with the improvement in the AIC that resulted from their removal. All FAL survived and thus the Kaplan Meier survival analysis for this species alone was not conducted. They were, however, retained in the 'Combined' and 'AG' datasets.

Dataset	Retained Variables	AIC	N	Removed Variables	Delta AIC
Combined – All Species & Caught Conditions	Trailing Gear, Release Condition	167.1	125		
				HC	0.04
	Log lik	*-100.2*		Species	1.27
	Chi Square	*7.51*		Gangion Ratio	1.89
	df	*2*		Approx FL	1.9
	p-Value	*0.023*	*131*	Caught Cond	3.51
AG – All species combined, Caught Cond = AG	Trailing Gear, Handling Code	116.05	105		
				Release Cond	1.33
	Log lik	*-82*		Species	1.62
	Chi Square	*8.5*		Gangion Ratio	1.74
	df	*2*		Approx FL	1.98
	p-Value	*0.014*	*109*		
Species **BSH**, all conditions	Trailing Gear	82.65	46	Approx FL	1.527
	Log lik	*-64*		HC	1.754
	Chi Square	*3.76*		Gangion Ratio	1.795
	df	*1*		Release Cond	2.151
	p-Value	*0.053*	*50*	Caught Cond	3.35
Species **BTH**, AG	Trailing Gear	16.79	23	Approx FL	0.424
	Log lik	*-12.2*		Caught Cond	0.942
	Chi Square	*4.36*		HC	1.849
	df	*1*		Gangion Ratio	2.002
	p-Value	*0.037*	*24*	Release Cond	2.357
Species **OCS**, all conditions	Handling Code, Fishery	23.98	28		
				Release Cond	1.676
	Log lik	*-13.6*		Caught Cond	1.676
	Chi Square	*8.5*		Approx FL	1.993
	df	*2*		Trailing Gear	1.997
	p-Value	*0.014*	*31*	Gangion Ratio	1.999

Figure 1a. Range in length of trailing gear estimated to remain on sharks discarded in the American Samoa (AS) and Hawaii Deep-set (HiDS) tuna longline fisheries.





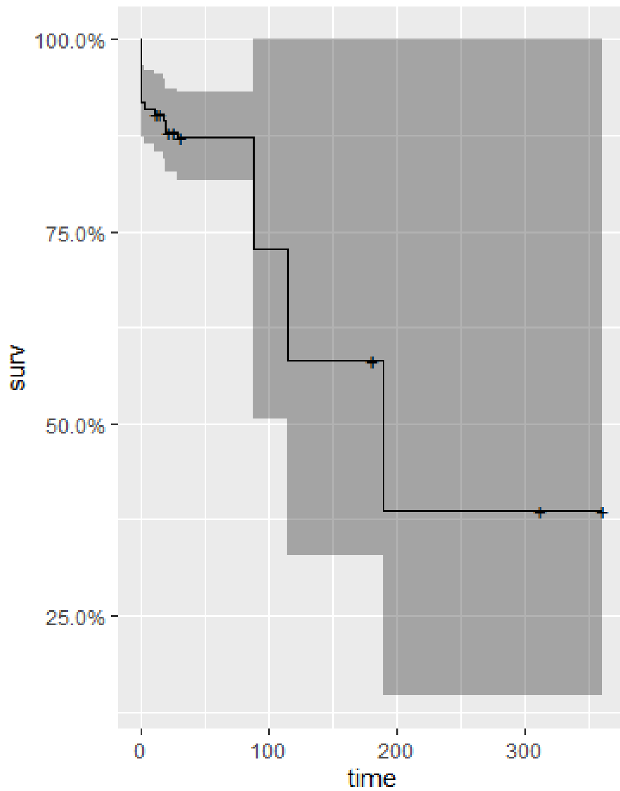


Figure 2. Kaplan Meier survivorship probabilities to 360 days for the 'Combined' dataset (all species and all conditions included). Proportion surviving on the y-axis and time in days is shown on the x-axis. The + marks indicate tags that are censored at that time. A censoring event shows when a tag left the study (floater or completed deployment) not due to mortality.

Table 8. Kaplan Meier survivorship probabilities and confidence intervals for the 'Combined' dataset (all species and all conditions included). Time = days, Risk = number of animals in the study at Time, Mortalities = number of mortalities at Time, survival = survival rate at Time. The associated standard error and the 95% upper and lower confidence intervals are also provided.

	Risk (n)	Mortalities (n)	Survival rate	Standard error	95 % Confidence Interval
1	123	11	0.918	0.0237	0.873 -0.966
10	122	1	0.910	0.0247	0.863 -0.960
20	115	4	0.880	0.0281	0.827 – 0.937
30	112	1	0.872	0.0290	0.817 – 0.931
60	6	0	0.872	0.0290	0.817 – 0.931
90	5	1	0.727	0.1349	0.505 – 1.00
120	4	1	0.581	0.1690	0.329 – 1.00
150	4	0	0.581	0.1690	0.329 – 1.00
180	4	0	0.581	0.1690	0.329 – 1.00
210	2	1	0.388	0.1943	0.145 – 1.00
240	2	0	0.388	0.1943	0.145 – 1.00
270	2	0	0.388	0.1943	0.145 – 1.00
300	2	0	0.388	0.1943	0.145 – 1.00

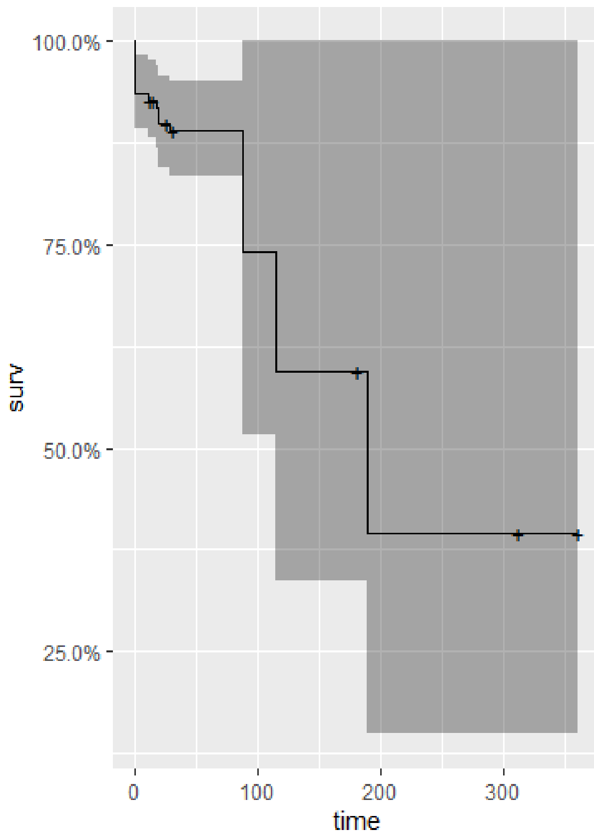


Figure 3. Kaplan Meier survivorship curve to 360 days for the 'AG' dataset (all species but capture condition is 'Alive in Good condition') only. The + marks indicate tags that are censored at that time. A censoring event shows when a tag left the study (floater or completed deployment) not due to mortality.

Table 9. Kaplan Meier survivorship probabilities and confidence intervals for the 'AG' dataset. Time = days, Risk = number of animals in the study at Time, Mortalities = number of mortalities at Time, Survival = survival rate at Time. The associated standard error and the 95% upper and lower confidence intervals are also provided.

Time (days)	Risk (n)	Mortalities (n)	Survival rate	Standard error	95 % Confidence Interval
1	104	7	0.937	0.0231	0.893 - 0.983
10	104	0	0.937	0.0231	0.893 - 0.983
20	97	4	0.990	0.0286	0.846 – 0.958
30	95	1	0.891	0.0298	0.834 – 0.951
60	6	0	0.891	0.0298	0.834 – 0.951
90	5	1	0.742	0.1378	0.516 – 1.00
120	4	1	0.594	0.1726	0.336 – 1.00
150	4	0	0.594	0.1726	0.336 – 1.00
180	4	0	0.594	0.1726	0.336 – 1.00
210	2	1	0.396	0.1984	0.148 – 1.00
240	2	0	0.396	0.1984	0.148 – 1.00
270	2	0	0.396	0.1984	0.148 – 1.00
300	2	0	0.396	0.1984	0.148 – 1.00

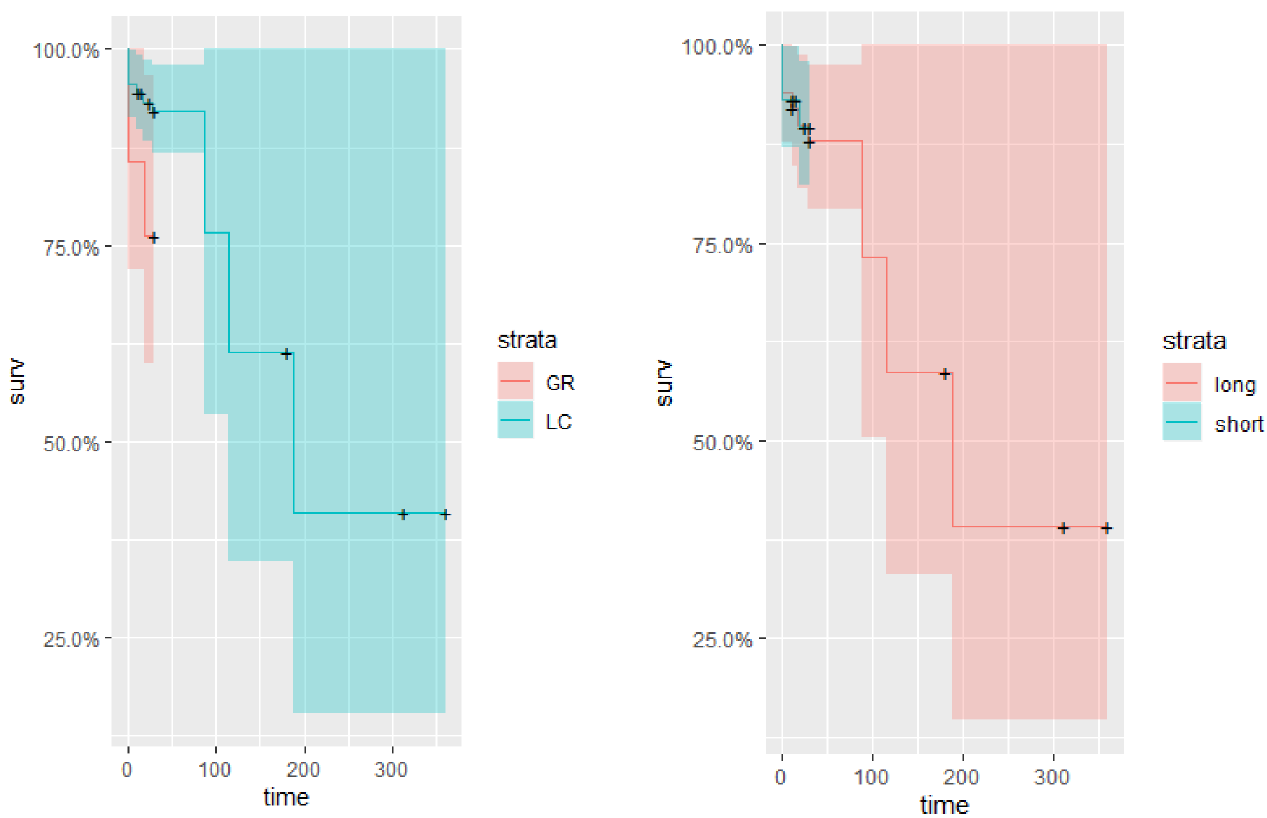


Figure 4. Kaplan Meier survivorship probabilities to 360 days for the 'AG' dataset (all species but capture condition is 'Alive in Good condition'), by the factors identified in the Cox proportional hazard analysis that were influential on post release survival times. At left is the survival curve by handling code, GR = Gear Removed, LC = Line Cut. At right is the effect of trailing gear on survival, long corresponds to gear lengths > 2.5 meters and short are gear lengths ≤ 2.5 m. The + marks indicate tags that are censored at that time. A censoring event shows when a tag left the study (floater or completed deployment) not due to mortality.

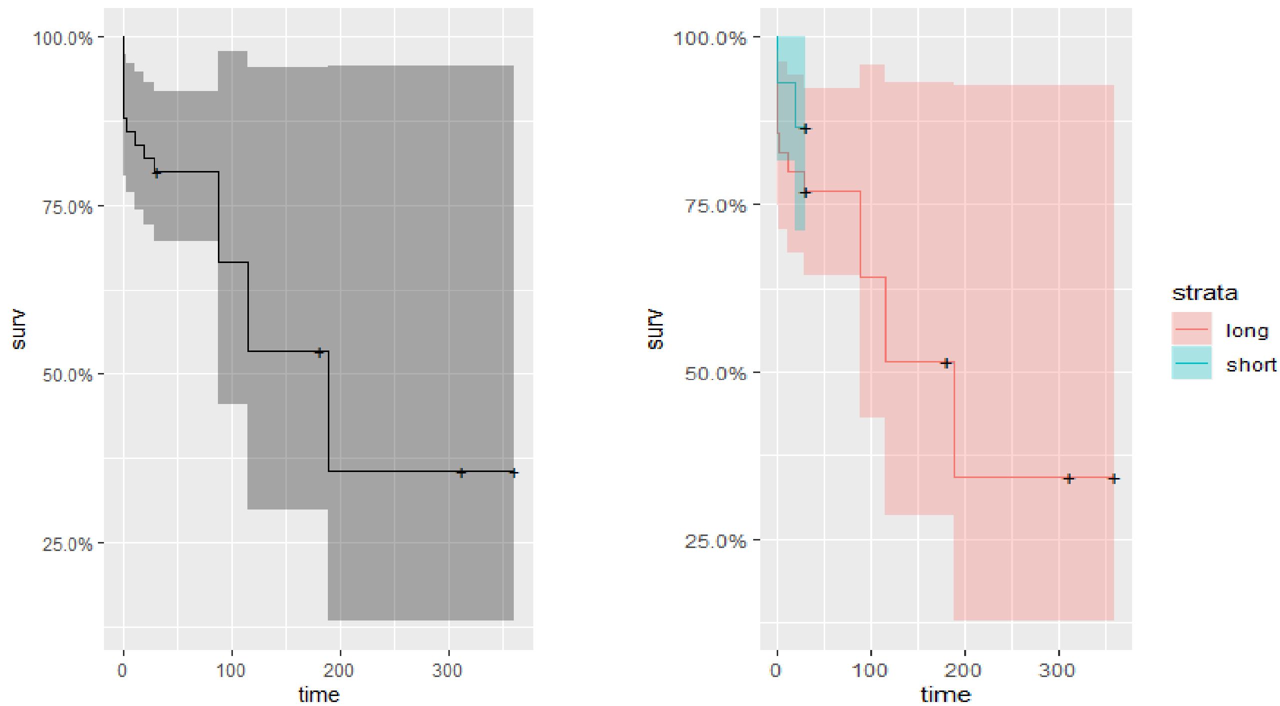


Figure 5. At left Kaplan Meier survivorship probabilities to 360 days for the 'BSH' dataset (BSH in all conditions) is shown. At right KM survival probabilities are illustrated by trailing gear (TG) length. TG was the factor identified in the Cox proportional hazard analysis that was the most influential on post release survival times for all BSH. Long corresponds to gear lengths > 2.5 meters and short are gear lengths ≤ 2.5 m. The + marks indicate tags that are censored at that time. A censoring event shows when a tag left the study (floater or completed deployment) not due to mortality.

Table 10. Kaplan Meier survivorship probabilities and confidence intervals for the 'BSH' dataset. Time = days, Risk = number of animals in the study at Time, Mortalities = number of mortalities at Time, Survival = survival rate at Time. The associated standard error and the 95% upper and lower confidence intervals are also provided.

Time (days)	Risk (n)	Mortalities (n)	Survival rate	Standard error	95 % Confidence Interval
1	44	6	0.880	0.0460	0.794 – 0.975
10	43	1	0.860	0.0491	0.769-0.962
20	41	2	0.820	0.0543	0.720 – 0.934
30	40	1	0.800	0.0566	0.696 – 0.919
60	6	0	0.800	0.0566	0.696 – 0.919
90	5	1	0.677	0.1305	0.454 – 0.979
120	4	1	0.533	0.1585	0.298 – 0.955
150	4	0	0.533	0.1585	0.298 – 0.955
180	4	0	0.533	0.1585	0.298 – 0.955
210	2	1	0.356	0.1795	0.132 – 0.957
240	2	0	0.356	0.1795	0.132 – 0.957
270	2	0	0.356	0.1795	0.132 – 0.957
300	2	0	0.356	0.1795	0.132 – 0.957

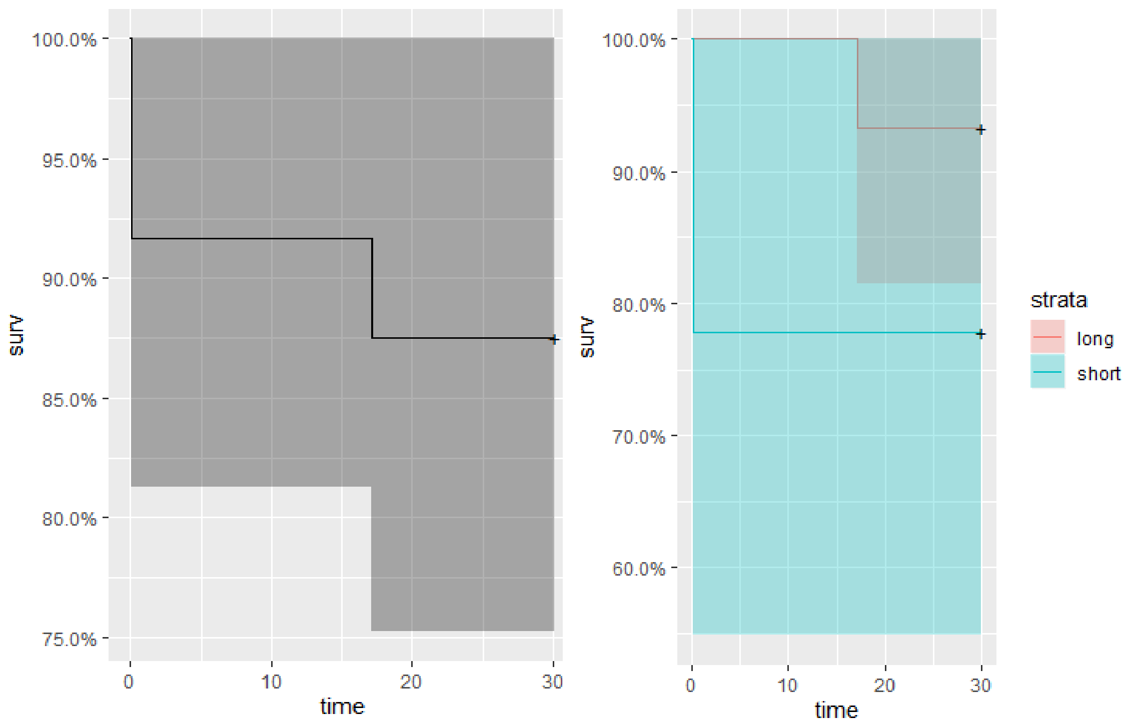


Figure 6. At left Kaplan Meier survivorship probabilities to 30 days for the 'BTH' dataset (BTH captured in good condition) is shown. At right KM survival probabilities are illustrated by trailing gear (TG) length. TG was the factor identified in the Cox proportional hazard analysis that was the most influential on post release survival times for all BTH. Long corresponds to gear lengths > 2.5 meters and short are gear lengths ≤ 2.5 m. The + marks indicate tags that are censored at that time. A censoring event shows when a tag left the study.

Table 11. Kaplan Meier survivorship probabilities and confidence intervals for the 'BTH' dataset. Time = days, Risk = number of animals in the study at Time, Mortalities = number of mortalities at Time, Survival = survival rate at Time. The associated standard error and the 95% upper and lower confidence intervals are also provided.

Time (days)	Risk (n)	Mortalities (n)	Survival rate	Standard error	95 % Confidence Interval
1	22	2	0.917	0.0564	0.813 – 1.00
10	22	0	0.917	0.0564	0.813 – 1.00
20	21	1	0.875	0.0675	0.752 – 1.00
30	21	0	0.875	0.0675	0.752 – 1.00

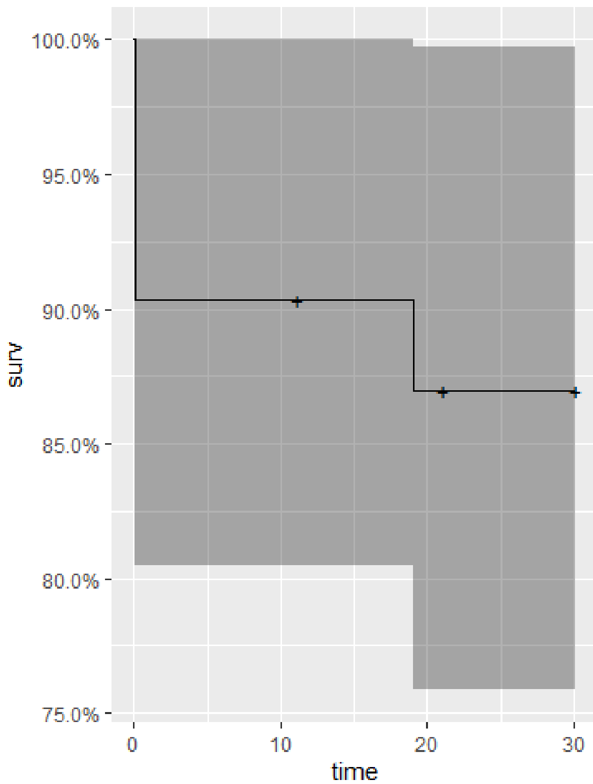


Figure 7. Kaplan Meier survivorship curve to 30 days for the 'OCS' dataset (all OCS in all capture conditions). The + marks indicate tags that are censored at that time. A censoring event shows when a tag left the study (floater or completed deployment) not due to mortality.

Table 12. Kaplan Meier survivorship probabilities and confidence intervals for the 'OCS' dataset. Time = days, Risk = number of animals in the study at Time, Mortalities = number of mortalities at Time, Survival = survival rate at Time. The associated standard error and the 95% upper and lower confidence intervals are also provided.

Time (days)	Risk (n)	Mortalities (n)	Survival rate	Standard error	95 % Confidence Interval
1	28	3	0.903	0.0531	0.805 – 1.00
10	28	0	0.903	0.0531	0.805 – 1.00
20	26	1	0.870	0.0608	0.758 – 0.997
30	25	0	0.870	0.0608	0.758 – 0.997

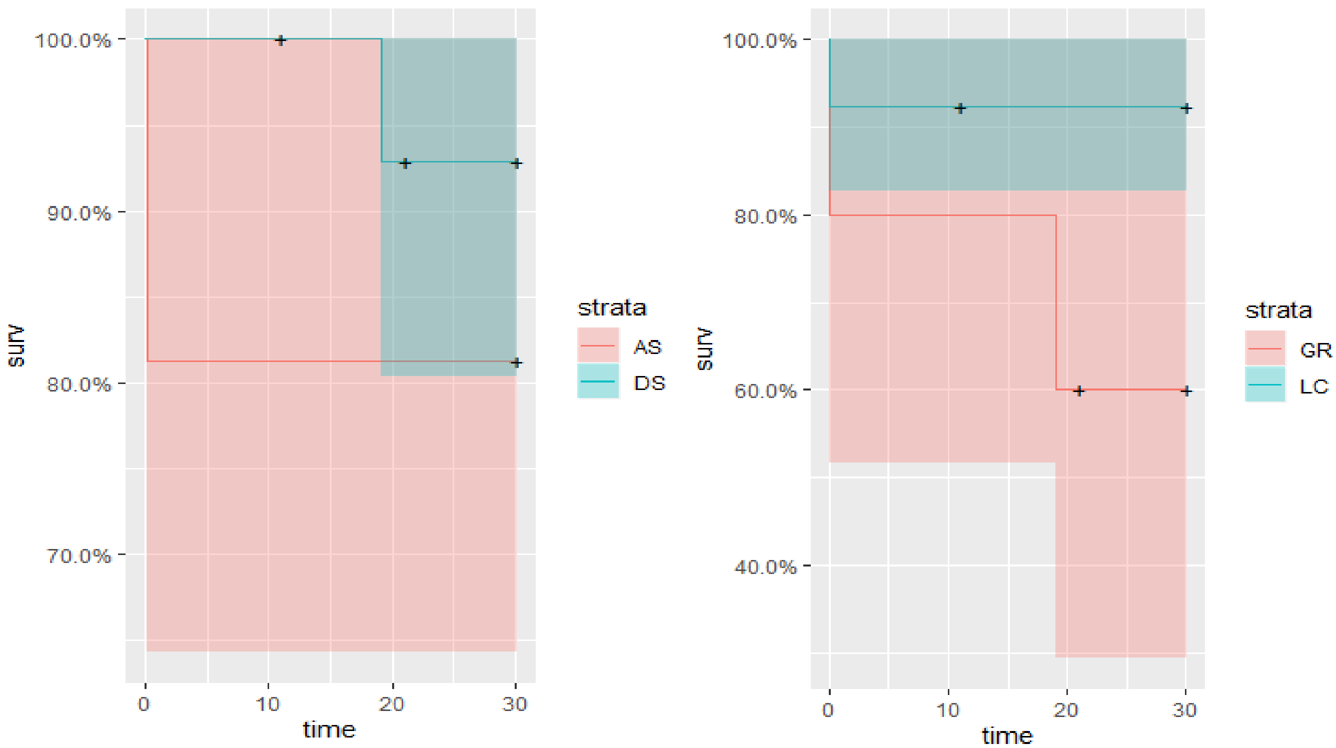


Figure 8. Kaplan Meier survivorship probabilities to 30 days for the 'OCS' dataset by the factors identified in the Cox proportional hazard analysis as influential on post release survival times. At left is the survival curve by Fishery, AS = American Samoa, DS = Hawaii Deep-set. OCS were the only species tagged in both fisheries so this was the only dataset where the effects of the fishery could be assessed. At right is the survival curve by handling code, GR = Gear Removed, LC = Line Cut. The + marks indicate tags that are censored at that time. A censoring event shows when a tag left the study (floater or completed deployment) not due to mortality.