Queensland Shark Control Program

Catch alert drumline trial 2022–2023

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Queensland Government

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Executive Summary

The *Queensland shark management plan 2021–2025* describes how the Queensland Government is continuing work to reduce the risk of shark bites through the traditional Shark Control Program, while researching and trialling new shark mitigation technologies and increasing community education on SharkSmart behaviours.

The catch alert drumline trial is a key initiative in the plan and part of the Queensland Government's commitment to trialling non-lethal shark bite mitigation technologies to determine their suitability for Queensland conditions.

Catch alert drumlines (CADs) are fishing apparatus used to catch dangerous sharks using baited hooks suspended from surface floats that are anchored to the seabed. The devices have been successfully used in New South Wales and at Reunion Island to reduce the mortality of non-target species. CADs differ from traditional drumlines as they include a satellite buoy that alerts relevant personnel when a shark or other marine animal is caught, allowing a timely response to the captured animal. CADs are deployed during daylight hours only, while traditional drumlines are set 24 hours a day and serviced daily.

Between 24 January 2022 and 23 January 2023, 11 CADs were alternated with 11 modified traditional drumlines (MTDs) using standardised hook and trace configurations across 4 beaches on the Capricorn Coast in central Queensland, enabling a comparison of catches and survival of marine fauna caught on the two drumline types. The MTDs caught more target sharks than CADs; however, a significant number of these were caught at night and dawn and dusk when CADs were not deployed. Catches of target shark species were more likely during the summer months, when sea surface temperatures were highest (>25°C), irrespective of drumline type.

The two most common species caught on both drumline types – bull whalers and pigeye whalers – were mostly small (mean = 1.24 m and 1.09 m total length, respectively) and likely use the turbid waters adjacent to the Fitzroy River to forage and avoid predators. Survival of bull and pigeye whalers was higher on CADs (93.8% when satellite buoys were activated) than MTDs (27.3%), due to the reduced time the animals spent hooked. Survival also increased with size. Tiger shark survival was high on both drumline types. Overall, CADs increased the survival of target and non-target species at the point of release.

Acknowledgements

We would like to thank the New South Wales Department of Primary Industries for supplying equipment for the duration of the trial, and for providing technical and scientific advice as a member of the project team. In particular, Dr Paul Butcher participated in numerous online meetings and responded to queries promptly and enthusiastically, and we thank him for his assistance throughout the trial.

We would also like to thank Nathan Everingham and his crew for participating in the trial and their diligence in recording the extra information required. The Shark Control Program Scientific Working Group provided advice and direction during the trial, and we are grateful for their input.

The trial was conducted under Marine Park Permit number G17/33288.1 and Queensland Department of Agriculture and Fisheries Animal Ethics approval CA 2021/03/1482.

Introduction

The Queensland Shark Control Program (the Program) commenced in 1962 following a number of fatal shark bite incidents across Queensland. The Program uses nets or traditional drumlines, or a combination of both, to reduce the risk of shark bites at 86 popular beaches. This and other bather protection programs have recently been subjected to increased scrutiny as a result of interactions with Threatened, Endangered and Protected Species (TEPS) such as sea turtles and whales. Further, research has shown that approximately one-third of Chondrichthyans (sharks, rays and chimaeras) are threatened worldwide with an elevated risk of extinction (Dulvy *et al.* 2021), driven primarily by capture in fisheries targeting other species. As such, there is a need to investigate non-lethal alternatives that effectively reduce shark bite risk for water users, while minimising the impact on marine fauna.

Seven shark species are targeted by the Program as they have been associated with unprovoked shark bites in Australia causing serious injuries or death:

- tiger shark (*Galeocerdo cuvier*)
- bull whaler (*Carcharhinus leucas*)
- white shark (*Carcharodon carcharias*)
- Australian blacktip shark (*Carcharhinus tilstoni*)
- common blacktip shark (*Carcharhinus limbatus*)
- dusky whaler shark (*Carcharhinus obscurus*)
- grey reef shark (*Carcharhinus amblyrhynchos*).

These species are euthanised if caught in the Program outside of the Great Barrier Reef Marine Park (GBRMP). Inside the GBRMP, where the Program operates under a permit issued by the Great Barrier Reef Marine Park Authority (GBRMPA), the Program is non-lethal, and all captured animals are released alive if possible. This permit requirement applies to both target and non-target species.

The Queensland Government has committed to trialling non-lethal alternatives to nets and traditional drumlines. It is important to trial alternatives to ensure they are suitable for Queensland conditions, which vary significantly between regions across the state. While drones have been used in the southern part of Queensland (read the *Queensland SharkSmart drone trial: Final report*), poor water clarity on inshore grounds in the northern part of the state make drones less effective in these areas.

Catch Alert Drumlines (CADs), also known as Shark Management Alert in Real Time or 'SMART' drumlines, are fishing apparatus used to catch dangerous sharks using baited hooks suspended from surface floats that are anchored to the seabed. They differ from traditional drumlines with the inclusion of a satellite buoy that alerts relevant personnel when a shark or other marine animal is hooked, allowing a timely response to the captured animal. The use of SMART drumlines has increased in recent years and the devices are now deployed at Reunion Island (Guyomard *et al.* 2020; Niella *et al.* 2021) and in New South Wales (e.g., Tate *et al.* 2021a) to reduce the risk of shark bites. There is a need to assess the efficacy of CADs for use in Queensland, particularly as the permit requires their trial and progressive roll out in the GBRMP.

The primary objectives of this trial were to:

- compare catches from CADs and drumlines traditionally used in the Shark Control Program
- quantify survival of target and non-target species, and determine the optimum response time to an alert to ensure the survival of captured marine fauna.

Methods

The trial was conducted between 24 January 2022 and 23 January 2023 at four beaches on the Capricorn Coast in central Queensland (see Figure 1):

- Mulambin Beach
- Tanby Point
- Fisherman's Beach
- Emu Park Beach.

The proximity of these beaches to the Rosslyn Bay Marina enabled convenient access for equipment servicing and response by the contractor responsible for delivering the field work component.

At these beaches, 22 traditional drumlines (TDs) are deployed approximately 500 metres from shore in a water depth of approximately 5 metres. The TDs are deployed 24 hours a day and baited up to 260 days per year, weather permitting. They are checked daily by contractors on servicing days. On non-servicing days, the drumlines are rendered ineffective by removing bait and hanging hooks up.

Figure 1: Location of 22 drumlines at the four beaches in the trial.

Traditional drumlines throughout the Program use a J-style hook and chain trace. For this trial, traditional drumlines used as control apparatus were modified to use a circle hook and wire trace similar to CADs to ensure differences in catch and survival could be attributed to drumline type rather than differences in hook and/or trace configuration.

At the start of the trial, the 22 TDs were replaced with 11 MTDs and 11 CADs, such that 11 CADs and 11 MTDs were deployed alternately across the four beaches simultaneously.

CADs were deployed during daylight hours only, on days when MTDs were operating. To control for the effects of location at each beach, the location of the CADs and MTDs were reversed every 21 days to coincide with the scheduled replacement of equipment.

Gear configuration

Modified traditional drumlines

Each MTD consisted of a 24/0 forged stainless steel circle hook attached to a 2 m trace constructed from 4 mm stainless steel wire rope. The trace was attached to a 50 mm ring, as was an A3 polyform buoy.

The proximal end of a 3 m bridle, constructed from 12 mm polyethylene rope, was attached to the ring, while the distal end of the bridle was attached to a second 50 mm ring and an A1 polyform buoy. Lastly, an anchor line, consisting of 12 m of 12 mm polypropylene rope, 10 m of 10 mm galvanised chain and a 7.26 kg Danforth anchor, was spliced to the second ring.

For all 11 MTDs, a HT-600 Lindgren-Pitman Hook Timer was crimped into the trace, such that when the bait was taken, the magnetic pin was removed, commencing the timer.

Catch alert drumlines

The configuration of the CADs was similar to that used previously by Tate *et al.* (2021a). For each CAD, the hook and trace configuration was the same as that used on the MTDs. The trace was attached to the lower end of a 1.1 m shock sleeve, consisting of two 50 mm stainless steel rings separated by two lengths of elasticised “bungy” cord, encased in a polypropylene sleeve. The upper ring of the shock sleeve was attached to an A3 polyform buoy.

The proximal end of a 3 m bridle was shackled to the upper ring of the shock sleeve, before the distal end of the bridle was threaded through the lugs of a Marine Instruments MLi-S Satellite Buoy, so that the satellite buoy was 40–50 cm from the upper end of the shock sleeve. The distal end of the bridle was then attached to an anchor line and A1 polyform float identical to that used on the MTDs.

Finally, a 1.5 m length of 2 mm diameter monofilament fishing line connected the magnetic trigger pin of the satellite buoy to the trace. When a bait was taken, the magnetic trigger pin was displaced, prompting an SMS, phone message and email alert to the contractor.

Gear servicing

At the start of each fishing month, the 22 drumlines were deployed and baited with a piece of shark (*Carcharhinus* spp.) weighing 600–800 g, between 5:30am and 7:00am. Generally, the drumlines were serviced from north to south, so that the those at Mulambin Beach were serviced first and those at Emu Park were serviced last.

At the start of each service day, abiotic data were recorded including sea surface temperature (SST, °C), wind speed (knots), sea condition (smooth, slight, moderate, rough), cloud cover (%), water clarity (clear, cloudy, very cloudy, muddy), and swell height (m).

The drumlines were serviced daily at approximately the same time and each animal caught on the MTDs was identified to species, with size (pre-caudal length, PCL, fork length, FL, and total length, TL, for sharks and Rhinopristiformes) and sex recorded.

Where possible, the hook was removed carefully (either directly or by cutting the hook if required) from live individuals before they were released at the capture site: however, live bull whalers and tiger sharks were relocated approximately one km to sea before release. Bull whalers and tiger sharks were tagged with a Hallprint plastic tipped dart tag and large (>1.5 m) bull whalers and tiger sharks were also tagged externally with an Innovasea V16 coded acoustic tag. Any dead animals were transported seaward before being discarded. Once captured animals were processed, the MTDs were re-baited, as were those MTDs which caught nothing, irrespective of the amount of bait left on each hook.

After the end of each service day, the trace, shock sleeve, A3 float, satellite buoy and bridle were removed from each CAD, leaving just the anchor line and A1 float in situ. During the daily servicing, these elements were re-attached to the anchor line and baited as per the MTDs.

On receiving an alert, the contractor attended the CAD as soon as possible and preferably within one hour. On arrival at the activated CAD, the contractor recorded the same biotic and abiotic data recorded at the time of servicing, along with logistical data of interest including time-of-alert, time-at-CAD, and time-of-release. After each captured animal was processed, the CADs were re-baited. The CADs were retrieved at approximately 16:00-17:00 each day, although fishing time was affected by the prevailing seasonal (e.g., sunrise and sunset time) and weather conditions.

CADs were deployed up to 260 days per year, depending on weather, with increased focus on school holidays and public holidays, when swimmer numbers are generally higher. After 21 days, all gear was replaced. Removed equipment was inspected, cleaned, and repaired for future use or disposed of if it failed to meet quality standards.

It should be noted that, where a CAD was activated and a call-out occurred, contractors travelled directly to the relevant CAD without inspecting any other MTDs or CADs while in transit to ensure that servicing of MTDs was representative of standard practices in the GBRMP to the greatest extent possible.

Statistical analysis

Catch comparisons

Preliminary analysis revealed that a significant number of target sharks were caught on MTDs at times when the CADs were not deployed. Using hook timer information, the MTD catch data were restricted to those animals caught during the periods where all CADs were deployed to better compare the efficacy of catching target sharks as a function of drumline type.

Given the low sample size, catches were aggregated by week, beach and drumline type. Catches were modelled as a binary variable (0=no capture, 1=capture) using a generalised linear mixed model (GLMM), where beach and week were added as random terms, drumline type was added as a fixed term and lunar phase, SST (°C) and rainfall (mm) were added as continuous covariates. Lunar phase was a continuous measure of moon brightness each day (0=new moon to 1=full moon) and the variable added to the GLMM was the average moon brightness for those days of the weeks in which target sharks were caught. Further, SST for each week was calculated from the days on which the gear was deployed, and rainfall was the total weekly rainfall (in mm) recorded at Yeppoon from the Bureau of Meteorology.

The probability of capture on each drumline type was estimated using R statistical software (Version 4.2.1, R Foundation for Statistical Computing, Vienna, Austria, see R-project.org accessed 3 April 2023), via the 'glmer' function within the 'lme4' package (Bates *et al.* 2015). Any factor or covariate found to have had no effect on the probability of capture was dropped from the final model. The 'bootMER' function within the 'lme4' package was used to calculate 95% confidence intervals.

These analyses revealed the incidence of satellite buoys and hook timers failing to activate when an animal was hooked was 51.5% and 27.2%, respectively. A GLMM was used to assess the factors affecting the probability of a satellite buoy or hook timer activation by all Carcharhiniformes combined (bull whaler, common blacktip whaler, great hammerhead, pigeye whaler, sandbar whaler, sharptooth shark, silky whaler, spot-tail whaler and tiger shark) as a binary response variable (0=not activated, 1=activated). Beach was added as a random term, drumline type and month were added as fixed terms and depth (m), total length (m) and SST were added as covariates.

Survival

Where sample size permitted, the survival of animals caught was quantified following methods described by Campbell *et al.* (2018). A GLMM was used to assess the probability of survival as a binary response variable (where 0=dead and 1=alive), where beach was added as a random term, drumline type and sex were added as fixed terms and total length (m) and SST (°C) were added as continuous covariates.

It should be noted that response time, defined as the time between the activation of either the hook timer or satellite buoys and the time the contractor arrived at the respective drumlines, was excluded from these analyses due to the high incidence of failed activations described above. For example, of the 70 bull whalers caught, the hook timer or satellite buoys failed to activate for 23 individuals (see Table 2 in Appendix 1).

To determine the response time that ensures the survival of captured marine fauna, survival data were again restricted to the Carcharhiniformes which activated either the satellite buoy or hook timer on capture. A GLMM was used to assess the probability of survival as a binary response variable (0=dead and 1=alive), where beach was added as a random term, species and sex were added as fixed terms and response time (mins), total length (m), SST (°C) and lunar phase were added as continuous covariates. In this case, response time is as defined previously.

Preliminary analyses revealed that size affected survival and, as such, probability of survival was quantified at the mean total length of the sharks used in the GLMM to determine the response time corresponding to 90% survival of mean-sized sharks. Further, the probability of survival as a function of the contractor's mean response time (the time between a CAD alert and the arrival of the contractor) was also quantified.

Gear comparisons

The effect of altering the terminal gear (traces and hooks) was determined by comparing catches during the trial to those in the period 2014–2018. The period immediately prior to the trial (2019–2021) was ignored due to inconsistent deployment, gear configuration and servicing.

Five drumline categories were assessed:

- traditional drumlines (2014–2018) at trial beaches
- traditional drumlines at non-trial beaches
- traditional drumlines used outside the trial area which are now serviced daily
- modified traditional drumlines used during the trial
- catch alert drumlines used during the trial.

Three catch components were analysed:

- bull and pigeye whalers combined
- tiger sharks
- other sharks.

Too few individuals of the remaining species caught throughout the trial precluded robust analyses. Bull and pigeye whalers were combined due to identification issues prior to a workshop conducted in 2019, at which contractors were instructed on differentiating the two species.

Catches at trial beaches (Mulambin Beach, Tanby Point, Fisherman's Beach and Emu Park Beach) during 2014–2018 were compared to those during the trial. Size was also compared, using simple *t*-tests, to determine if the size distribution of sharks caught on the smaller circle hooks differed from those caught on the *J*-hooks used throughout the program.

Further, catches from non-trial beaches in the Capricorn Coast region (Cooee Bay, Farnborough Beach, Kemp Beach, Lammermoor Beach and Yeppoon Beach) during 2014–2018 were compared to those from the trial period to determine if abundance varied temporally at these beaches. Again, sizes were also compared using simple *t*-tests. The number of sharks in each category that died as result of capture was also assessed.

Results

The CADs and MTDs were deployed on 266 days during the trial. Generally, the CADs and MTDs were serviced by approximately 07:10 am (range=05:45–09:09 am) each day. On average, the retrieval of CADs commenced at 14:58 pm (range=10:10 am –17:00 pm) and was completed by 15:48 pm (range=10:54 am –18:00 pm).

On those days when the gear was deployed, mean SST was 22.3°C and ranged between 15.2°C and 29.3°C. The mean water depth in which the drumlines were deployed was 5.5 m (S.D.=1.06 m, range=3.8–8.1 m). Water clarity was generally poor and was categorised as 'clear' (10 days), 'cloudy' (55 days), 'very cloudy' (16 days) and 'muddy' (12 days) on days when a capture occurred.

A total of 165 individual animals, from 16 taxa, were caught on the 22 drumlines during the trial (see Figure 2 below and Table 1 overleaf). Three species comprised ~85% of the total catch:

- bull whalers (*n*=70)
- pigeye whalers (*Carcharhinus amboinensis*, *n*=51)
- tiger sharks (*n*=19).

The bull whalers and pigeye whalers were generally small with a mean size of 1.24 m (S.D.=0.49) and 1.09 m (S.D.=0.39), respectively (see Figure 6 in Appendix 1). The common blacktip whaler (*n*=3) was the other targeted species caught during the trial. Green turtles (*Chelonia mydas*, *n*=7), sharptooth sharks (*Negaprion acutidens*, *n*=3) and tawny sharks (*Nebrius ferrugineus*, *n*=3) were the only other species from which multiple individuals were captured, whereas only one of each of the remaining species was caught. Catches were highest at Emu Park and lowest at Mulambin Beach (see Table 3 in Appendix 1).

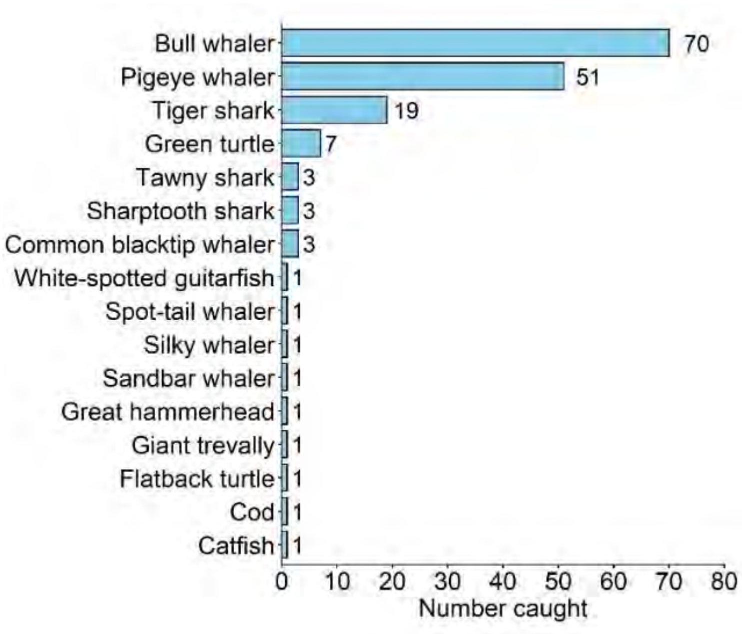
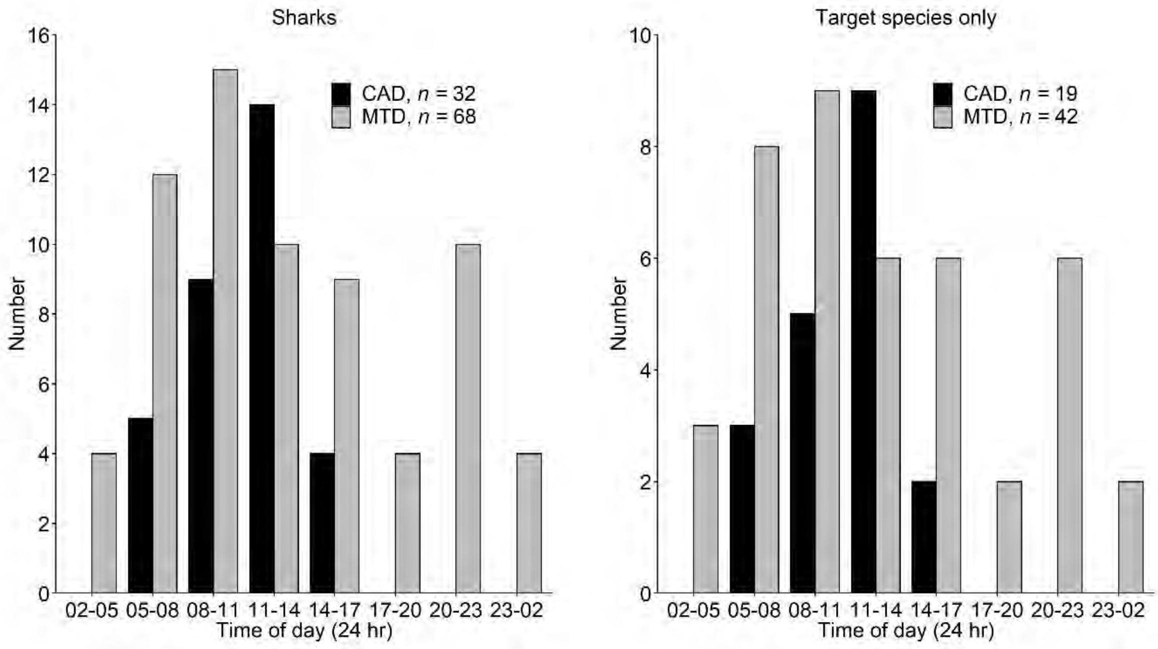


Figure 2: Catch composition during the Catch Alert Drumline trial conducted on the Capricorn Coast between 24 January 2022 and 23 January 2023.

Of the 165 animals caught during the trial, 99 (60%) were caught on MTDs and 66 were caught on CADs. Fewer bull whalers, pigeye whalers and tiger sharks were caught on CADs, compared to MTDs, throughout the trial. These differences in catch were directly related to the amount of time each drumline type was deployed, which necessitated the assessment of times when catches occurred, informed by the activation of either satellite buoys or hook timers. However, only 32 of the 66 (48.5%) animals caught by CADs activated the satellite buoy, and 72 of the 99 (72.7%) animals caught on MTDs activated the hook timers. For the Carcharhiniformes, GLMM indicated the probability of satellite buoy or hook timer activation increased (β=1.14, S.E.=0.34) significantly (χ^2=11.57, d.f.=1, P<0.001) with animal total length (see Figure 7 in Appendix 1).

Of the 68 Carcharhiniformes that activated the hook timers on the MTDs, 22 (32.4%) were caught at times when the CADs were not deployed (see Figure 3a). Similarly, catches of these sharks were higher on MTDs in the time periods when the CADs were being deployed (05:00–08:00am) and retrieved (14:00–17:00pm). A similar pattern in catch was observed when the data were restricted to target species (bull whalers, common blacktip whalers and tiger sharks) (see Figure 3b).

Of the 42 target sharks captured on MTDs, 29 activated hook timers at times when the CADs were deployed. Catch rates of target sharks were highest in the spring and summer months (see Figure 8 in Appendix 1), whereas very few target sharks were caught during winter. This result was confirmed by the GLMM which indicated that SST positively (β=0.17, S.E.=0.08) affected (χ^2=4.79, d.f.=1, P=0.029) the probability of capture of target sharks. Drumline type (χ^2=0.42, d.f.=1, P=0.515), lunar phase (χ^2=1.98, d.f.=1, P=0.160) and rainfall (χ^2=0.53, d.f.=1, P=0.467) had no effect on catch rates. Care should be used when interpreting this result given the low sample size and that 15 target sharks (11 bull whalers and four tiger sharks) caught on MTDs failed to activate the hook timer.



(a) (b)

Figure 3: Number of (a) bull whalers, common blacktip whalers, great hammerheads, pigeye whalers, sandbar whalers, sharptooth sharks, silky whalers, spot-tail whalers, and tiger sharks, combined, and (b) target sharks (bull whalers, common blacktip whalers and tiger sharks, combined) caught as a function of drumline type and time of day. Data were restricted to those individuals that activated either a satellite buoy or a hook timer.

Table 1: Number of each taxa caught and number released alive for each drumline type.

Species	Catch alert drumlines		Traditional drumlines	
	No. caught	No. released alive	No. caught	No. released alive
Bull whaler	32	24	38	5
Pigeye whaler	19	11	32	1
Tiger shark	2	2	17	13
Green turtle	4	4	3	3
Common blacktip whaler	1	1	2	
Sharptooth shark			3	1
Tawny shark	1	1	2	2
Catfish (*Neoarius* spp.)	1			
Cod (*Epinephelus* spp.)			1	1
Flatback turtle	1	1		
Giant trevally	1	1		
Great hammerhead	1	1		
Sandbar whaler	1	1		
Silky whaler	1	1		
Spot-tail whaler	1	1		
Bottlenose wedgefish			1	1

Where a satellite buoy or hook timer was activated the:

- **mean response time hh:mm** (time between alert activation and the arrival of the contractor at the CAD) was 00:33 (S.D. = 00:15, range = 00:04–01:00)
- **mean processing time hh:mm** (time between contractor arrival and the release of the animal) was 00:12 (S.D. = 00:07, range = 00:01–00:35): processing time was dependent on the species caught, with target species being tagged and relocated ~ 1km eastward of the capture site, and the size of individuals
- **mean release time hh:mm** (time between alert activation and release of the animal) was 00:45 (S.D. = 00:17, range = 00:13–01:22)
- **mean hooking time hh:mm** (time between hook timer activation and contractor arrival at the MTD) for those animals caught on the MTDs (n = 72) was 15:27 (S.D. = 06:29, range = 00:27–23:57). Excludes catches where the hook timer was not activated.

False activations of the satellite buoys occurred on 19 occasions, primarily in the summer months (n=11). These were attributed to small sharks and fish predating on baits without being hooked (N. Everingham, pers. comm.). There was no correlation between false activations and wind speed (R^2=0.021).

Of the 66 animals caught on CADs during the trial, 49 (74.2%) were released alive and 17 died (see Table 1 and Table 2 in Appendix 1). Of the 32 animals that activated the satellite buoy when hooked, all animals survived capture apart from two small (1.03 m and 0.87 m TL) male bull whalers. The 17 dead animals comprised eight bull whalers, eight pigeye whalers and one catfish. In contrast, 72 of the 99 animals (72.7%) caught on MTDs died, including 33 bull whalers, 31 pigeye whalers and four tiger sharks. All eight turtles (seven green turtles and one flatback turtle) survived capture, irrespective of drumline type.

Sufficient bull whalers and pigeye whalers were caught to assess factors affecting the probability of survival via GLMM. It should be noted that hooking time is likely to affect the probability of survival of both bull whalers and pigeye whalers: however, the high incidence of satellite buoys and hook timers not activating on capture precluded the testing of this variable in the respective GLMMs.

Drumline type (χ^2=18.45, d.f.=1, P<0.001) and total length (χ^2=5.67, d.f.=1, P=0.017) were found to have significantly affected the survival of bull whalers (see Figure 4a). The survival of bull whalers was highest from CADs (β=3.98, S.E.=0.93) and increased with total length (β=2.04, S.E.=0.86). At the mean total length of 1.24 m, the probability of survival of bull whalers from CADs and MTDs was 0.84 ($CI_{\alpha=0.05}$=0.71–0.94) and 0.06 ($CI_{\alpha=0.05}$=0.01–0.18), respectively.

Initially, higher SST resulted in decreased survival of bull whalers, however, SST and total length were strongly inversely correlated (-0.98), with smaller animals occurring in the warmer months. As such, SST was dropped from the model.

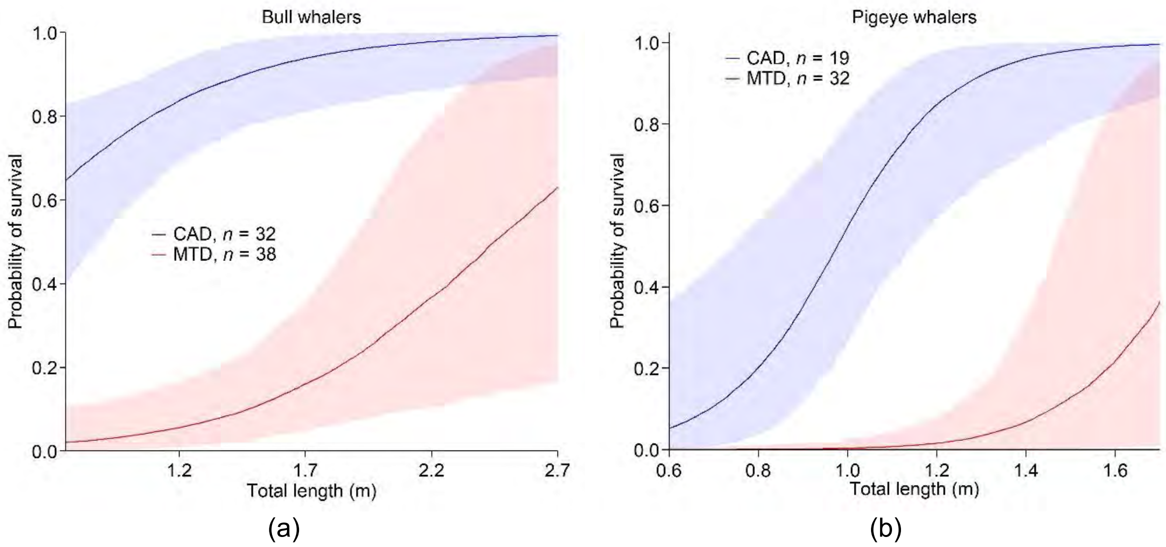
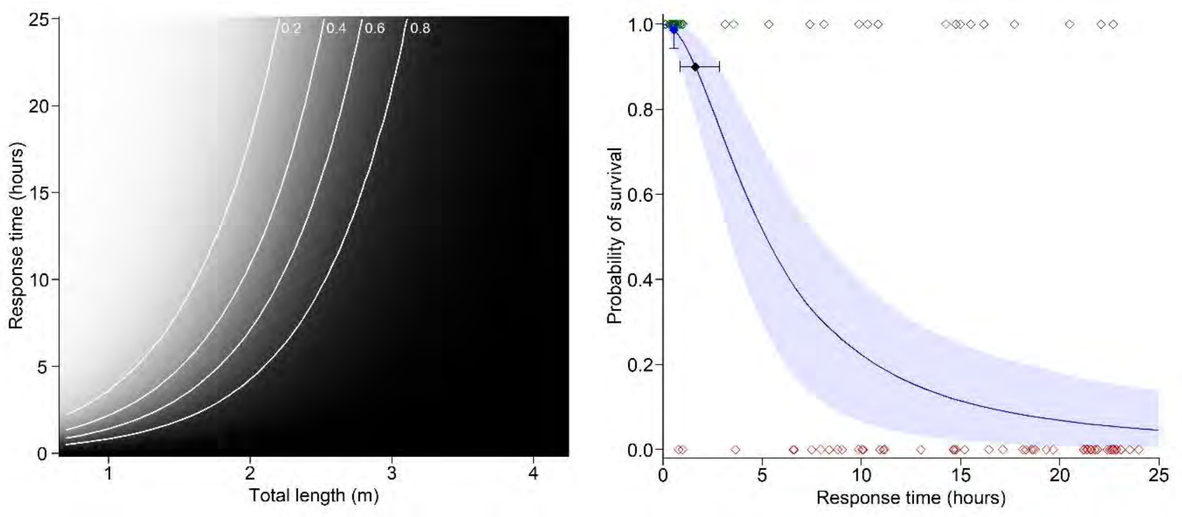


Figure 4: Probability of survival of (a) bull whalers (*n*=70) at the mean sea surface temperature of 22.3°C and (b) pigeye whalers (*n*=51) caught during the Catch Alert Drumline trial between 24 January 2022 and 23 January 2023. Ribbons are bootstrapped 95% confidence intervals.

Drumline type (χ^2=7.17, d.f.=1, P=0.007) and animal total length (χ^2=4.31, d.f.=1, P=0.007) affected the survival of pigeye whalers. As with bull whalers, the survival of pigeye whalers was highest from CADs (β=5.02, S.E.=1.88) and increased with total length (β=6.33, S.E.=3.05) (see Figure 4b). At the mean total length of 1.09 m, the probability of survival of pigeye whalers from CADs and MTDs was 0.69 ($CI_{\alpha=0.05}$=0.00–0.90) and 0.01 ($CI_{\alpha=0.05}$=0.01–0.04), respectively.

To assess the effect of response time, the dataset was restricted to those Carcharhiniformes that activated either the satellite buoy or hook timer when hooked. This provided a measure of the length of time each animal was on the hook before the contractor arrived. Both total length (χ^2 =17.101, d.f.=1, P<0.001) and response time (χ^2 =22.85, d.f.=1, P<0.001) affected the probability of survival of Carcharhiniformes.

The probability of survival increased with total length (β=2.85, S.E.=0.69) and decreased with response time (β=-1.78, S.E.=0.37) (see Figure 5a). The GLMM indicated that a response time (hh:mm) of 1:38 (range=00:52–02:50) resulted in a probability of survival of 0.9 and the mean response time from trial of 00:33 resulted in a probability of survival of 0.98 (0.94–0.99) (see Figure 5b).



(a) (b)

Figure 5: Probability of survival of Carcharhiniformes (i.e., bull whalers, common blacktip whalers, great hammerheads, pigeye whalers, sandbar whalers, sharptooth sharks, silky whalers, spot-tail whalers, and tiger sharks), that activated either a hook timer or satellite buoy on capture (*n*=99), as a function of (a) response time and total length, and (b) response time at the mean total length of sharks (1.67 m). In (a), white shading represents zero survival and black represents 100% survival. In (b), the open diamonds represent observed survival (0=dead and 1=alive), the black point is the average response time where probability of survival is 0.9 and the blue point is the probability of survival at the average response time to an activated satellite buoy during the trial (33 minutes). Blue shading is the 95% confidence interval.

At trial beaches, 121 bull and pigeye whalers were caught during the trial, compared to a total of 105 caught over the five-year period 2014–2018 (see Figure 10 in Appendix 1). Of the 121 individuals caught during the trial, 80 died, 64 of which were caught on MTDs. The bull and pigeye whalers caught during the trial were significantly larger than those caught during 2014–2018 (t=-5.6, d.f.=69, P<0.001, (see Figure 11 in Appendix 1).

Similarly, the catch of bull and pigeye whalers from TDs was higher at non-trial beaches during the trial period, compared to 2014–2018, all but one of which was found dead on capture. Catches of tiger sharks were higher from MTDs during the trial period, compared to TDs in the period 2014–2018. In contrast, the number of other shark species caught during the trial was similar to mean annual catches observed in the period 2014–2018 and were significantly larger during the trial (*t*=-5.6, d.f.=11, *P*<0.001, (see Figure 11 in Appendix 1).

Discussion

Throughout this trial, MTDs caught more target sharks than CADs. This is a function of fishing effort (with MTDs deployed 24 hours each day and CADs deployed for approximately eight hours per day) and the diel behaviour of the species interacting with drumlines. On each day, sunrise occurred well before the last CAD was deployed and sunset occurred after the CADs were recovered. As a result, a significant number of animals were caught on MTDs at dawn, dusk and at night, when the CADs were either not deployed or being deployed. When the satellite buoys were activated, the observed survival of the hooked animals was ~93.8%, compared to 27.3% for MTDs, indicating that the use of CADs significantly improves the survival of target and non-target Carcharhiniformes.

Bull whalers were the most common species caught during the trial. In contrast to previous research (Guyomard *et al.* 2019; Niella *et al.* 2021; Tate *et al.* 2021a; Lipscombe *et al.* 2023), significant numbers of juvenile bull whalers were caught by CADs during the day. Further, 21 of the 27 (~78%) bull whalers that activated a hook timer on an MTD were caught during the day. This is likely a result of the size of the bull whalers caught during the trial and the proximity of the trial area to the Fitzroy River delta: the catch of bull whalers was highest at Emu Park, the beach closest to the Fitzroy River, and lowest at Mulambin Beach, the furthest from the Fitzroy River.

Previous research has shown that juvenile bull whalers prefer habitats with low salinity (Heupel and Simpfendorfer 2008; Froeschke *et al.* 2010; Drymon *et al.* 2014) and high turbidity (Cliff and Dudley 1991). Juvenile bull whalers use turbid waters for predator avoidance and to forage for food (Roskar *et al.* 2021) and the turbid waters adjacent to the Fitzroy River delta provide ideal habitat for juveniles. Werry *et al.* (2018) found catch rates of bull whalers increased when significant rainfall events occurred (>100 mm): however, the GLMM was unable to isolate the effects of weekly rainfall during the trial.

Like bull whalers, pigeye whalers are found inshore and in estuaries (Simpfendorfer *et al.* 2021). As with bull whalers, the turbid waters adjacent to the Fitzroy River provide habitat for pigeye whalers and catches of this species were highest at the beaches closest to the Fitzroy River. This is consistent with previous research which indicated high abundance in turbid waters (Simpfendorfer *et al.* 2014). The 19 pigeye whalers caught on CADs, and 16 of the 24 pigeye whalers that activated the hook timers on MTDs, were hooked between 06:50am–16:13pm, indicating the species forages on inshore grounds during the day.

The increased catches of bull and pigeye whalers observed during the trial (at both trial and non-trial beaches) compared to the 2014–2018 period may be a result of the La Niña weather event that developed in 2019 and continued through until 2023. Typically, La Niña is characterised by increased SST in the western Pacific Ocean, leading to increased cloud cover and higher rainfall in eastern Australia. However, the change in terminal gear (hooks and traces), combined with the increased servicing of CADs and MTDs during the trial, are likely to have contributed to the higher catches observed during the trial. The use of circle hooks has been shown to increase the catch rate of sharks, compared to J hooks (Willey *et al.* 2016) and the use of circle hooks, combined with the increased servicing during the trial, likely resulted in fewer animals escaping after hooking, compared to traditional J hooks.

The results of the trial indicate that there was no diel pattern in the catch of tiger sharks, consistent with previous research (Hammerschlag *et al.* 2017). At least eight (two on CADs and six of the 13 that activated a hook timer on MTDs) of the 17 tiger sharks caught during the trial were caught during the day. Tate *et al.* (2021a) reported that tiger sharks comprised ~10% of catches in a two-year study designed to minimise interactions and mortality of non-target species using CADs deployed during daylight hours over two years in New South Wales.

In contrast, Guyomard *et al.* (2019) found that tiger sharks were caught primarily between 20:00 pm and 05:00 am at Reunion Island and Niella *et al.* (2021) reported higher tiger shark catch rates at dusk and at night in a CAD trial conducted over a five-year period at the same location. Again, the proximity of the trial site to the Fitzroy River delta, combined with the presence of prey items such as small carcharhinids and turtles, likely contributed to the presence of tiger sharks at the trial site during the day. Too few tiger sharks were caught for scientifically robust comparisons of catch rates between drumline types and further sampling is required to identify differences.

For the remainder of the taxa caught during the trial, too few individuals were caught to enable robust comparison between drumline types. Of the 16 taxa caught during the trial, nine were represented by a single individual and each of these were non-target species. The low sample sizes observed also precluded robust survival analyses for all but two species – bull whalers and pigeye whalers.

Drumline type was the most important factor affecting the survival of both bull and pigeye whalers. In the trial, drumline type was a proxy for hooking time, a factor commonly found to affect survival in line fisheries (e.g. Morgan and Carlson 2010; Dapp *et al.* 2016a; Sulikowski *et al.* 2020). For example, Butcher *et al.* (2015) examined the effects of hooking time on a range of elasmobranchs, including sandbar whalers, tiger sharks and bull whalers caught in northern New South Wales and found that increasing hooking time resulted in reduced survival. This factor was not tested when analysing the survival of bull and pigeye whalers in this trial due to the large number of individuals that failed to activate either a hook timer or satellite buoy when hooked.

The survival of bull and pigeye whalers increased with increasing total length, consistent with previous research (Diaz and Serafy 2005; Coelho *et al.* 2012). Larger animals are more resilient to catch-and-release due to the higher volumes of glycogen produced during physical exertion compared to smaller conspecifics (Braccini and Waltrick 2019). Generally, post-release survival is species-specific and is related to a species' ability to respire during capture (Dapp *et al.* 2016b). Those animals that are required to move forward to respire (obligate ram ventilators) tend to have poor post-release survival, irrespective of the gear used (Dapp *et al.* 2016b), compared to those species that have spiracles (e.g., bottlenose wedgefish) or those that can buccal pump (e.g., tawny shark). Too few individuals from the latter two categories were caught during the trial to undertake survival analyses. Given their high survival, and the associated biases, these species were excluded from the survival analyses that informed optimum response time.

When the dataset was restricted to the 99 Carcharhiniformes that activated either a hook timer or satellite buoy, survival was affected by response time and total length. As expected, survival increased with total length and decreased with response time. The contractor was able to respond to activated satellite buoys within an hour on each occasion as specified at the start of the trial, with a mean response time to activated satellite buoys of 33 minutes. Minimising response time not only increases the likelihood of survival of hooked sharks, it may also reduce the risk of depredation, defined as the partial or complete consumption of a hooked fish by a predator before that fish can be retrieved by the fisher (Mitchell *et al.* 2018). For example, the head of a small bull whaler was found on a TD with a live 2 m bull whaler that had presumably eaten the smaller shark before being hooked.

The high incidence (51.5%) of individuals failing to activate the satellite buoy when hooked conflicts with Guyomard *et al.* (2019), who reported a failure rate of 6.7%. These authors cited entanglement as the main reason for satellite buoys failing to activate when an animal was hooked. This was not the case during this trial and, for the most part, smaller animals were less likely to activate a satellite buoy when hooked. Despite this result, larger animals also failed to activate a satellite buoy at times, and this may have been a result of the shallow water depths in which the CADs were deployed, which are characteristic of the region.

Previous studies have been conducted in deeper waters such as 4-19 m (Tate *et al.* 2021a), 5–30 m (Niella *et al.* 2021), 6–15 m (Lipscombe *et al.* 2023) and 18–23 m (Guyomard *et al.* 2020). However, the shallower water (3–8 m) during this trial may have forced a hooked animal to swim laterally, rather than downward, preventing the dislocation of the magnetic trigger from its housing located on the underside of the satellite buoy. Further research is required to develop a configuration that increases the activation of CADs in shallow water.

The distance between the hook and the A3 polyform buoy was longer on the CADs (~3 m) than the MTDs (2 m). This was due to the need for the addition of the shock sleeve on the CADs. The contractor indicated that the shock sleeve was buoyant and, as such, the bait was located at similar depths to those on the MTDs. Lipscombe *et al.* (2023) reported a higher incidence of false activations when baits were set closer to the seabed and attributed this to interactions with benthic batoids with mouthparts that are too small to ingest the hooks. Although a benthic batoid (bottlenose wedgefish, TL=1.14 m) was caught during the trial, false activations could also be attributed to small sharks and unknown teleosts given their presence at the study site. To determine the taxa responsible for false activations, cameras could be used in future trials, such as those used by Tate *et al.* (2021b): however, visibility at the trial sites is mostly poor.

Conclusion

Results from this trial indicate that MTDs caught more target sharks (bull whalers, tiger sharks and common blacktip whalers) than CADs, however a significant number of these were caught at night, and at dawn and dusk, when CADs were not deployed.

Catches of target shark species were more likely during the summer months, when SSTs were highest (>25°C), irrespective of drumline type. The two most common species caught, bull whalers and pigeye whalers, were mostly small and likely use the turbid waters adjacent to the Fitzroy River to forage and avoid predators.

Survival was highest from CADs due to rapid response times and reduced hooking times. For bull and pigeye whalers, survival increased with total length. The results suggest that CADs maintain the catch of target sharks and increase the survival of released animals.

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Appendix 1: Supplementary information

Table 2: Summary catch statistics for CADs and MTDs deployed at Mulambin Beach, Tanby Point, Fisherman Beach and Emu Park Beach on the Capricorn Coast area in central Queensland, Australia between 24 January 2022 and 23 January 2023. *n* is the number of animals caught; F,M,U are the number of females, males, and unknown sex, respectively; Length is the mean length (in m) where *n*>1 and the length of the individual where *n*=1; and Number activated is the number of individuals that activated either a satellite buoy or the hook timer when hooked.

Species	Catch alert drumlines							Traditional drumlines							
	n	F,M,U (no.)	Dead (no.)	Alive (no.)	Alive (%)	Length (m)	No. activated	*n*	F,M,U (no.)	Dead (no.)	Alive (no.)	Alive (%)	Length (m)	No. activated	TOTAL *n*
Bull whaler	**32**	16,15,1	8	24	75.0	1.12	19	**38**	19,12,7	33	5	13.2	1.34	28	**70**
Pigeye whaler	**19**	9,10,0	8	11	57.9	1.19	8	**32**	17,12,3	31	1	3.1	1.02	24	**51**
Tiger shark	**2**	1,1,0	–	2	100	2.54	2	**17**	11,6,0	4	13	76.5	2.91	13	**19**
Green turtle	**4**	0,0,1	–	4	100	1.00	–	**3**	2,0,1		3	100	0.91	1	**7**
Common blacktip whaler	**1**	1,0,0	–	1	100	1.73	1	**2**	2,0,0	2	–	–	1.51	2	**3**
Sharptooth shark	–	–	–	–	–	–	–	**3**	3,0,0	2	1	33.3	2.59	2	**3**
Tawny shark	**1**	1,0,0	–	1	100	2.80	1	**2**	1,0,1		2	100	2.70	1	**3**
Catfish	**1**	0,0,1	1	–	–	0.99	–	–	–	–	–	–	–	–	**1**
Cod	–	–	–	–	–	–	–	**1**	0,0,1		1	100	2.20	1	**1**
Flatback turtle	**1**	0,1,0	–	1	100	1.15	–	–	–	–	–	–	–	–	**1**
Giant trevally	**1**	0,0,1	–	1	100	1.01	–	–	–	–	–	–	–	–	**1**
Great hammerhead	**1**	0,1,0	–	1	100	3.64	1	–	–	–	–	–	–	–	**1**
Sandbar whaler	**1**	0,1,0	–	1	100	1.90	1	–	–	–	–	–	–	–	**1**
Silky whaler	**1**	1,0,0	–	1	100	3.20	1	–	–	–	–	–	–	–	**1**
Spot-tail whaler	**1**	1,0,0	–	1	100	3.70	1	–	–	–	–	–	–	–	**1**
Bottlenose wedgefish	–	–	–	–	–	–	–	**1**	0,1,0	–	1	100	1.14	1	**1**

***n*:** Number of animals caught
F,M,U: Number of females, males and unknown sex, respectively
Length: Mean length (m) where *n* = >1 and the length of the individual where *n* = 1
Number activated: Number of individuals that activated either a satellite buoy or hook timer

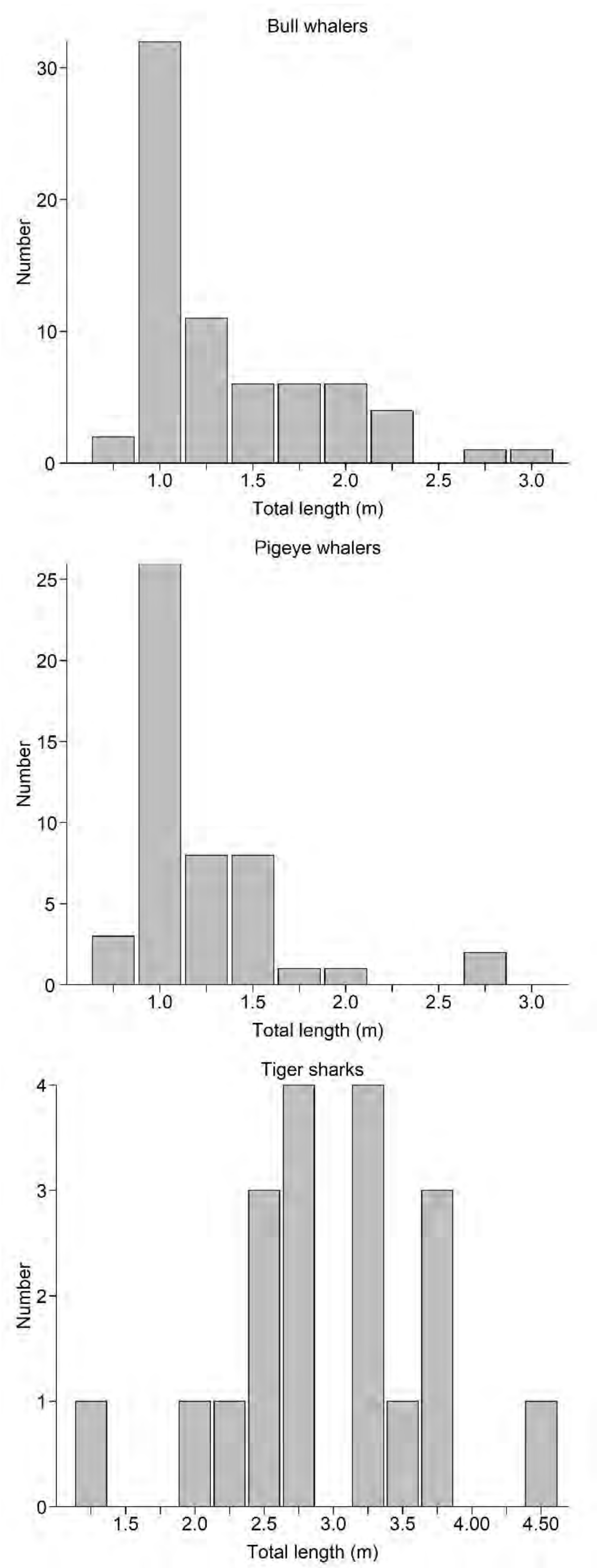

Figure 6: Length frequency histograms for bull whalers (*n*=69), pigeye whalers (*n*=49) and tiger sharks (*n*=19) caught during the trial conducted on the Capricorn Coast between 24 January 2022 and 23 January 2023.

Table 3: Catch of each species at each beach during the trial between 24 January 2022 and 23 January 2023.

Species	Emu Park	Fisherman's Beach	Mulambin Beach	Tanby Point
Bull whaler	30	16	9	15
Catfish	1			
Cod			1	
Common blacktip whaler	3			
Flatback turtle			1	
Giant trevally	1			
Great hammerhead	1			
Green turtle	2	2		3
Pigeye whaler	18	15	5	13
Sandbar whaler	1			
Sharptooth shark	1			2
Silky whaler			1	
Spot-tail whaler		1		
Tawny shark		1	1	1
Tiger shark	9	4	2	4
Bottlenose wedgefish				1
TOTAL	**67**	**39**	**20**	**39**

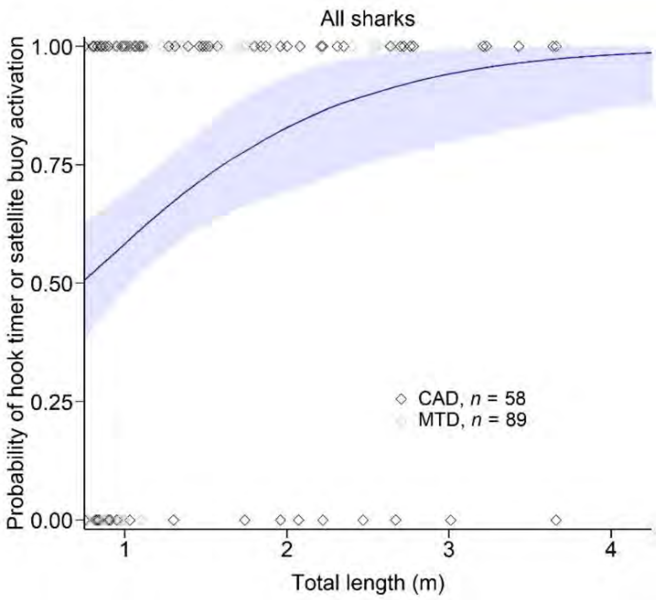

Figure 7: Probability of hook timer or satellite buoy activation as a function of total length of Carcharhiniformes (bull whalers, tiger sharks, common blacktip whalers, pigeye whalers, sharptooth sharks, great hammerheads, sandbar whalers, silky whalers and spot-tail whalers). The open diamonds represent the observed activations (0=not activated, 1=activated). Note that one bull whaler and two pigeye whalers were excluded from this analysis as depredation

precluded a measurement of length. The blue ribbon represents 95% confidence intervals around the median probability.

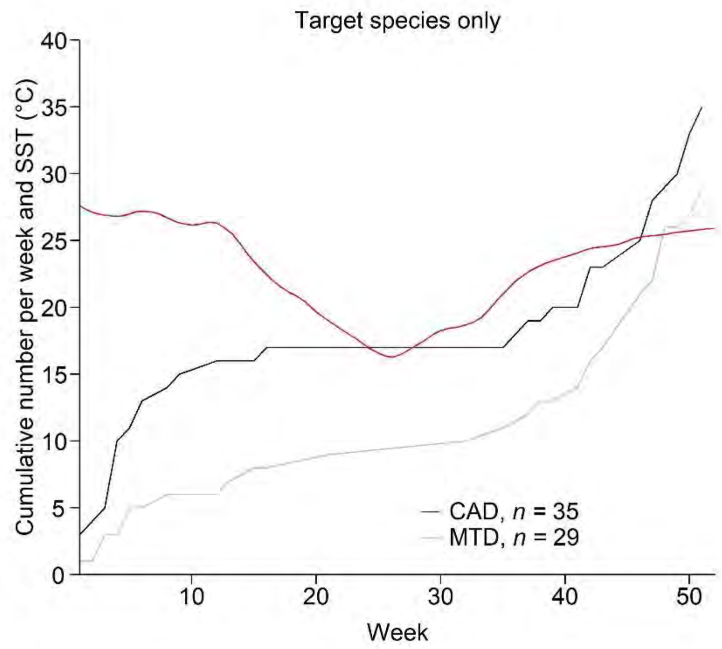

Figure 8: Cumulative number of target sharks (bull whalers, tiger sharks, and common blacktip whalers) caught during the trial conducted on the Capricorn Coast between 24 January 2022 and 23 January 2023. The catches from the MTDs are those where the hook timer was activated only. The red line is a loess smoothing curve fitted through the mean SST, as recorded by the contractor on days gear was deployed during the trial.

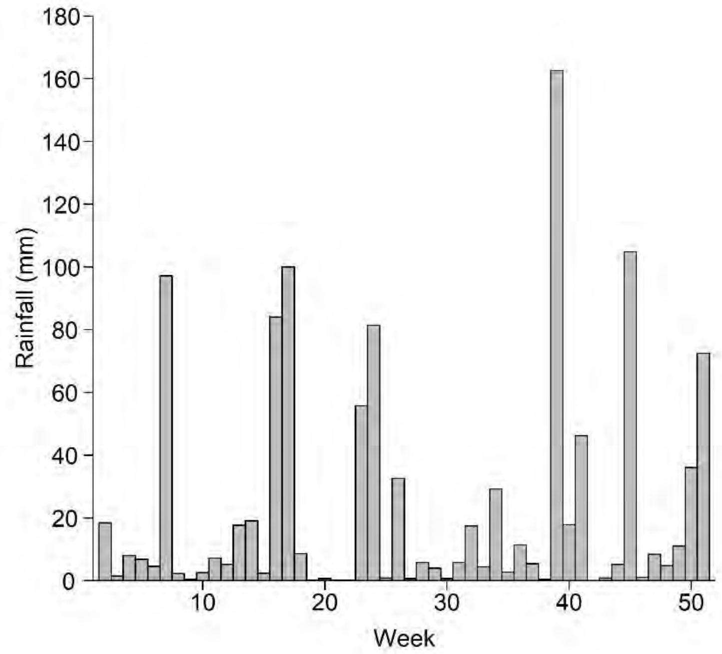

Figure 9: Total weekly rainfall (mm) for Yeppoon during the trial period between 24 January 2022 and 23 January 2023, aggregated by week.

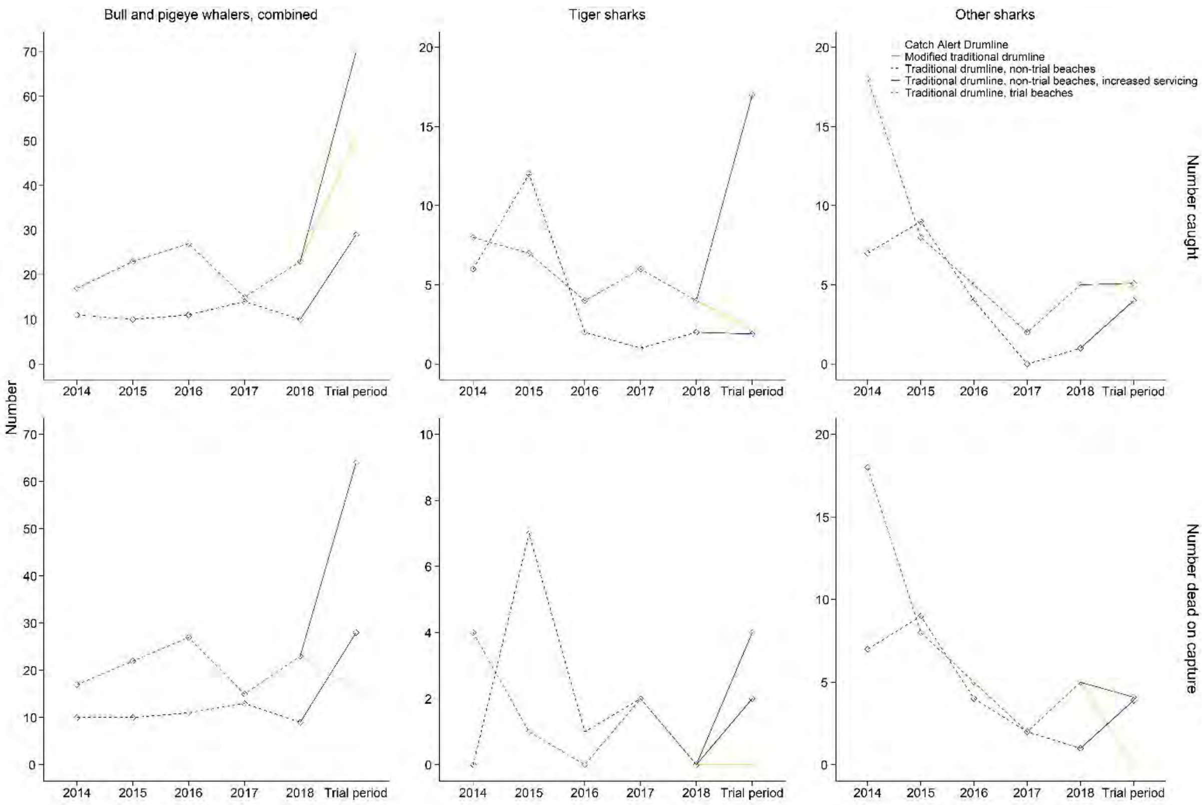

Figure 10: Observed number of bull and pigeye whalers combined, tiger sharks, and other sharks caught (top row), and found dead on capture (bottom row), for each drumline type.

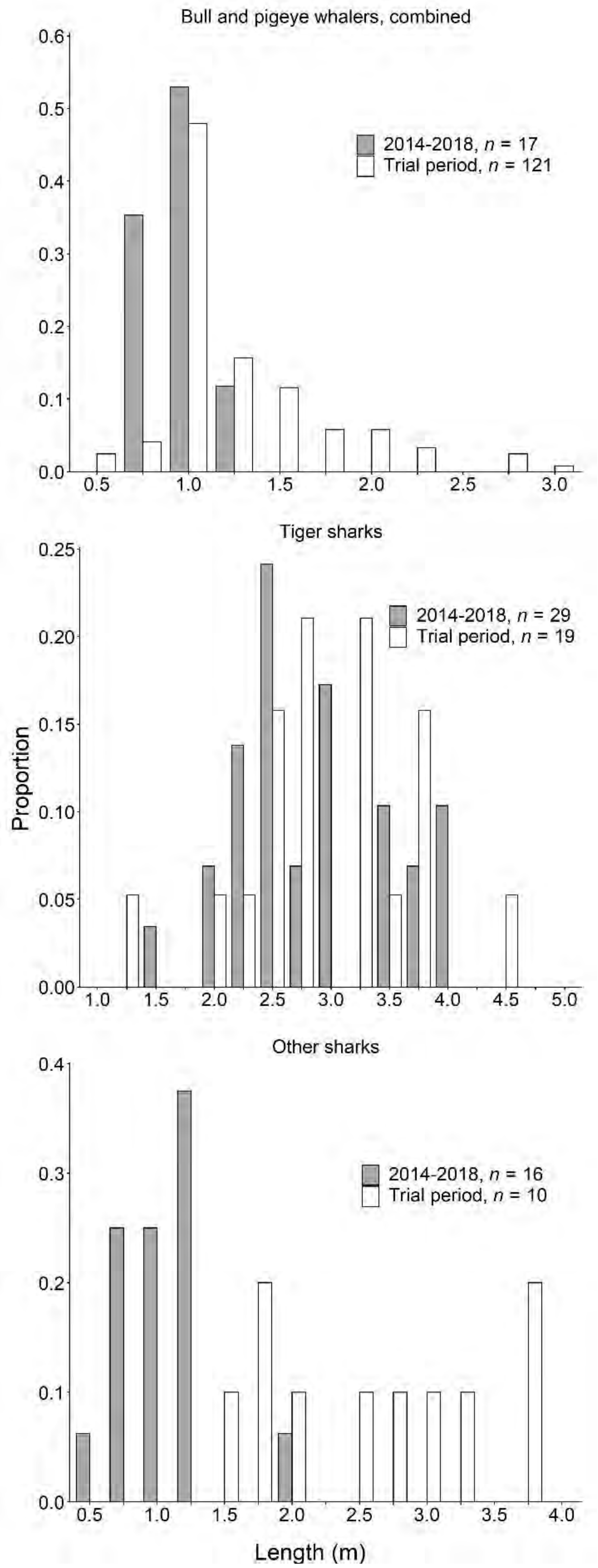

Figure 11: Size frequency distributions of bull and pigeye whalers combined, tiger sharks, and other sharks for the period 24 January 2014 to 23 January 2018, compared to the trial period (24 January 2022 – 23 January 2023).