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An innovative fishing gear to enhance the release of non-target species in coastal shark-control programs: The SMART (shark management alert in real-time) drumline

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ABSTRACT

In response to a spate of shark attacks in Reunion Island in the southwest Indian Ocean since 2011, local authorities developed an experimental shark-control program based on those conducted for decades in Australia and South Africa. In order to greatly reduce, if not eliminate, the impact of such a shark fishing program on bycatch and undersized target shark species, the use of conventional "drumlines" was improved by the addition of an innovative "Catch-A-Live"® system, making the drumlines 'SMART' (Shark Management Alert in Real Time). This is a real-time strike alert system based on an adapted triggering mechanism, which links the fishing line to a GPS buoy connected to the Iridium satellite. This system alerts fishers on duty via a computer-based communication system within just a few minutes, enabling immediate intervention. Off Reunion Island, up to 20 SMART drumlines (SDLs) were deployed along the west and southwest coast in coastal waters to target bull (*Carcharhinus leucas*) and tiger sharks (*Galeocerdo cuvier*) in trials conducted between 2014 and 2017. During 58,770 h of fishing there were 269 catches of more than 14 species, of which 86.9% were retrieved alive. There were marked differences in survival among species. While the most fragile species were the giant trevally (*Caranx ignobilis*), scalloped hammerhead sharks (*Sphyrna lewini*) and small carcharhinid species, most of the other bycatch species (stingrays *Dasyatis* sp., giant guitarfish *Rhyncobathus djiddensis*, and tawny nurse sharks *Nebrius ferrugineus*) were generally found alive and in a condition suitable for tag and release. Of the target species, 94.8% of all individuals were found alive. These survival rates are far higher than those of other programs using conventional drumlines in KwaZulu-Natal (South Africa) and Queensland (Australia). There were strong diurnal and lunar catch patterns. This information is invaluable in planning fishing operations to maximise the catch of the target species, while reducing the chances of killing the bycatch. These results highlight the potential for use of SDLs in research programs aimed at tagging large sharks capable of tripping the trigger, especially in situations where catch rates are so low that it is impractical for the fishing vessel to remain at sea for the duration of each fishing operation.

1. Introduction

Globally, shark attacks have led to substantial angst amongst affected communities and have often resulted in various forms of shark fishing to catch potentially dangerous sharks in local waters. In some regions formal "shark-control programs" have been successfully introduced (Dudley and Cliff, 2010). The first of these was established in 1937 off Sydney, Australia, through the deployment of large-mesh nets set to catch and kill potentially dangerous sharks (Reid and Krogh, 1992) and known as the New South Wales (NSW) shark meshing program (SMP; Green et al., 2009). The success of this program led to the progressive but not continuous installation of other nets along the coast

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of NSW (51 beaches are now equipped) and, in 1962, into Queensland (30 nets currently fished, mostly at southern beaches; Dudley, 1997; Reid et al., 2011).

Similarly, the east coast of South Africa experienced a spate of shark attacks off its major tourist beaches in Durban, KwaZulu-Natal (Cliff and Dudley, 1992) and city authorities opted to copy the successful NSW program and similar large-mesh nets were installed in 1952 (Dudley and Cliff, 1993). These three bather protection programs have been in operation for over half a century and now represent the longest continuous coastal shark fisheries in the world, providing samples and data to numerous research programs (KwaZulu-Natal Sharks Board, 2018; New South Wales Department of Primary Industries, 2018; Queensland Department of Agriculture and Forestry, 2018). The Queensland shark-control program (SCP) experienced substantial bycatch in the northern region which, due to its location within the Great Barrier Reef Marine Park (Paterson, 1990; Gribble et al., 1998), led to efforts to reduce these catches through the use of more targeted fishing techniques such as baited hooks (Sumpton et al., 2010, 2011). These devices are popularly known as “drumlines”, due to the initial use of large 44-gallon drums as buoys, which provided considerable resistance to the hooked sharks, thereby evoking rapid mortality. In an effort to reduce bycatch in the South African shark-meshing program (Dudley and Simpfendorfer, 2006), the KwaZulu-Natal Sharks Board experimented with the use of drumlines to determine their efficacy (Dudley et al., 1998). The positive results led to their introduction in conjunction with shark nets beginning 2007 (Dudley, 2002; Cliff and Dudley, 2011). Despite the effectiveness of these programs in greatly reducing the incidence of shark attack at protected beaches (Dudley and Cliff, 2010), the frequency with which the gear is serviced is less than once per day, and the high mortalities of the bycatch in particular have resulted in increasing environmental opposition (Gribble et al., 1998).

A similar, targeted shark fishing program using baited hooks was introduced in 2004 in Recife, in northeastern Brazil, in response to a spate of shark incidents. Here drumlines fished in conjunction with offshore benthic longlines, with an emphasis on minimizing mortalities and releasing animals alive (Hazin and Afonso, 2013; Hazin et al., 2008). The two target species in this program were bull *Carcharhinus leucas* and tiger *Galeocerdo cuvier* sharks (Afonso et al., 2014) and there was a substantial reduction in shark attacks while this fishing program was active (Afonso et al., 2017 postulated a 97% reduction in the rate of shark-human interactions over an eight-year period).

Not all targeted shark fishing has proved successful. In Hawaii, where tiger sharks are the major problem, a targeted fishery caught this species in substantial numbers, but with no concomitant reduction in shark attacks (Wetherbee et al., 1994). A primary feature differentiating this initiative from the other four highly successful programs is that Hawaii constitutes a series of islands more than 3,500 km from any continent. With the advent of new technologies to monitor animal movements, several studies (Holland et al., 1999; Meyer et al., 2009; Papastamatiou et al., 2013) have highlighted how tiger sharks move large distances between islands, possibly explaining the ineffectiveness of localised fishing.

Another area characterised by large numbers of shark attacks and with calls for proactive mitigation measures is Reunion Island. Chapman and McPhee (2016) have designated Reunion Island, with only 885,000 inhabitants, as a global shark attack hotspot because of the high incidence of fatal shark attacks, mainly along its west coast for the last eight years. Between 1982 and 2011, 51.6% of attacks were fatal (McPhee, 2014). Subsequent data show that between February 2011 and September 2014, Reunion Island accounted for 10% of fatal attacks globally (Taglioni and Guiltat, 2015), with a total of nine fatalities until December 2017 (two in 2017; ISAF, 2018). Lagabrielle et al. (2018) quantified the shark attack rate, with a 23-fold increase on surfers in Reunion Island between 2005 and 2016.

This small oceanic island in the southwest Indian Ocean is 1600 km from the African mainland, with virtually no knowledge of local shark populations until 2012. This lack of knowledge changed following the spate of attacks that attracted the attention of the local research community, and resulted in several studies to characterise the situation (Blaison et al., 2015; Jaquemet et al., 2012; Pirog et al., 2015; Soria et al., 2015; Loiseau et al., 2016; Trystram et al., 2016; Lemahieu et al., 2017). The primary species responsible for the attacks is believed to be the bull shark, however the tiger shark has also been implicated (Fricke et al., 2009; Werbrouck et al., 2014).

Shark attack is not a recent phenomenon on the island (Van Grevelynghe, 1994). It is uncertain why the number of shark attacks has increased so suddenly along the west coast, but several hypotheses have been put forward. Historically several species of sharks, including bull and tiger sharks, were caught by commercial fisheries around the island (Le Manach et al., 2015), thereby probably inadvertently reducing the risk of attacks. This fishing/exploitation gradually ceased more than 15 years ago due to a ban on the sale of coastal shark species for human consumption due to the possible presence of carchatoxins in the tissue (Quod et al., 2000; Hossen et al., 2013). At the same time, it has been also postulated that over-fishing of local reef sharks by recreational fishers (Vergnes et al., 2014) created vacant niches that have been filled by the recovery of more productive, adaptable tiger sharks or philopatric species like bull sharks (Tillet et al., 2012; Whitney and Crow, 2007). It has also been suggested that the increased urbanisation and resultant increased rainwater run-off on the west coast of Reunion Island (Chapman and McPhee, 2016) may have benefitted bull sharks, which are known to favour more turbid and less saline waters, especially as neonates or for females to give birth (Curtis et al., 2011; Daly et al., 2013; Heupel and Simpfendorfer, 2008; Simpfendorfer et al., 2005; Tillet et al., 2012), whereas historically these conditions were only encountered along the east coast of the island. Additionally, some locals have suggested that the establishment of a west coast marine reserve in 2007 (Thomassin et al., 2010), where most of the recent attacks have taken place, may have led to increased food resources for these apex predators, accentuated by a spearfishing ban in many parts of the reserve. Overall, the rapid development of the island in recent decades may have resulted in changes in nearshore utilisation for foraging and/or reproductive activities by bull and tiger sharks (Jaquemet, 2017; Taglioni and Guiltat, 2015).

Due to the severity of shark attacks and their socio-economic consequences on local water sports and tourism activities, a temporary ban on swimming, surfing and other nautical activities was implemented in 2013 at all open water beaches. This ban has been continually renewed by the local authorities ever since. In parallel the authorities funded research activities and a fishing program with the aim to control bull and tiger shark populations to reduce the risk of attacks. The use of traditional shark fishing gear was undesirable due to the high risk of bycatch, including non-dangerous sharks, which could only be avoided if the fishers remained at sea to facilitate the rapid release of such individuals. The low catches recorded on the west coast by Blaison et al (2015) clearly indicated that it would be impractical to do so.

The main aim of this article is to describe the characteristics and use of a novel fishing gear and highlight the interest of such fishing gear to release any part of the catch, especially bycatches, after a limited fighting time. It was developed for deployment in a shark attack mitigation program but could be widely used in any study of the movement patterns and residency of marine predators through the use of telemetry. In addition, as this new fishing device provides valuable information of the exact time of capture of every individual, some results are shown to illustrate its potential benefits in terms of fisheries management and ecological studies.

2. Materials and methods

From 2014–2017, along the west coast of Reunion Island in the southwestern Indian Ocean (Lat 21° 6.356′S, Lon 55° 29.420′E), modified conventional drumlines have been deployed after the decision of

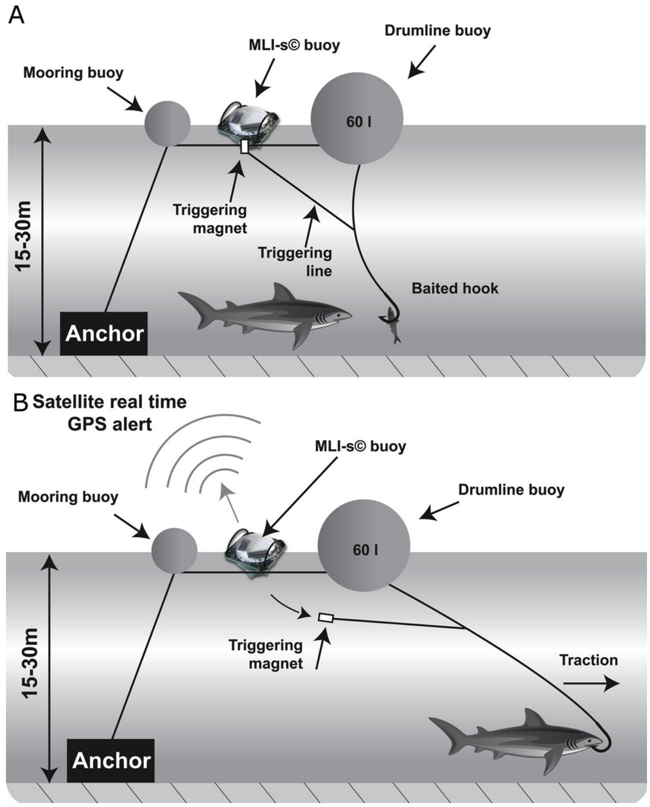

Fig. 1. A SMART drumline and its real-time strike alert system (A: before strike; B: after strike and alert).

setting up an experimental shark-control program. Collected data on fishing effort and detailed description of catches have permitted to address the specific issues associated to the setting up of such a program, such as to assess whether the new fishing gear allows to better release non-target catches.

2.1. The SMART drumline

The Shark-Management-Alert-in-Real-Time (SMART) drumline (SDL) was devised and developed in Reunion Island, for deployment in two shark research programs conducted from 2014 to 2017. A SDL is a conventional drumline to which the "Catch-A-Live"® system has been added (Fig. 1). This system utilizes a GPS satellite buoy (MLI-S©, Marine Instruments, Spain), with a triggering mechanism, which immediately transmits its position via the Iridium satellite network to the user when its magnetic contact is broken. It is also equipped with a duplicate power system (solar panels connected to a rechargeable battery plus a pack of alkaline batteries), and a flashlight to aid location and recovery at night. The Iridium satellite network system provides global coverage, with unlimited duration due to its solar power. The triggering line is secured to the hook leader at the one end and at the other it is attached to the GPS buoy by a magnetic contact. When the bait is pulled with a force greater than that exerted by wind, swell or current, typically by a hooked fish, the magnetic contact is broken and the alert signal is emitted by the MLI-S© buoy (Fig. 1).

2.2. Alert management communication system

When a MLI-S© buoy is triggered, its manufacturer, Marine Instruments, sends an email to a predefined recipient list every 5 min until the magnet is reattached. This system, despite being reliable, shows severe limitations in the context of an operational fishing program. When SDLs are deployed at night, though both the fishing and administrative teams can rarely be awakened, this can occur at any hour of the night. Also, the use of emails may not be appropriate due to poor wireless network data coverage in coastal areas and the small number of fishers who have access to email at sea via a smartphone. These issues have been overcome through the addition of a catch management system that minimizes staff involvement while ensuring that the catch is handled as quickly as possible. It does not impact the reliability and shows a marginal cost compared to the overall cost of MLI-S© buoys. The server of the catch management system receives the emails from Marine Instruments MLI-S© buoys and responds based on a database containing each buoy's information as well as the contact details of fishers and coordinators. The server then notifies the appropriate fishers by sending them an email, an SMS and a phone call every 3 min. These messages only cease when one of the recipients responds by SMS or email with a "Yes" if he can retrieve the buoy or otherwise "No". In this latter case, or if after 30 min none of the fishers accepts responsibility for action, the program coordinators receive the same notifications until it is deactivated with a response. As soon as the fisher retrieves the buoy and reattaches the triggering magnet, Marine Instruments stops reporting the activated MLI-S© buoy position to the server. After 10 min without an update from Marine Instruments, the server assumes that the buoy has been retrieved, closes the event and notifies the coordinators accordingly.

2.3. Fishing gear deployment and data collection

The SDLs were deployed during two successive experimental fishing programs, first from January to November 2014 and in April-June 2015, and then from June 2015 to February 2017), as well as during one "post-attack" operation in August 2016 on request from local authorities. During the whole period (January 2014 to February 2017), six attacks (two fatalities and four serious injuries) have occurred along the West coast of Reunion Island (Fig. 2): four of them were located on sites where SDLs were subsequently deployed (regularly at Saint-Leu and Etang Salé, and during a single three days "post-attack" operation at Boucan Canot in the marine reserve; Fig. 3) and two other were located on sites where fishing operations were limited and have not been monitored (at Les Aigrettes in the marine reserve and at Le Port; Fig. 2).

During this period of nearly three years, up to 20 SDLs were deployed along the west and southwest coasts of Reunion Island, in depths ranging from 12 to 35 m (Fig. 2). Fishing was conducted at different coastal sites, some for only a single or a few sessions, with one to four SDLs used at the same time at each site (Fig. 3 shows the calendar of the deployments for the seven locations fished). The SDLs were only set at night in Saint-Gilles, Trois Bassins, Saint-Leu and Etang Salé, when there were far fewer boats at sea and because some sea users, especially scuba divers, objected to shark fishing devices being deployed nearby during the day. Six teams of professional fishers were trained to use the SDLs and handle any catches to optimize their survival. This involved identifying, measuring and tagging (insertion of an external "spaghetti" tag from Hallprint, Australia, in the muscle below the first dorsal fin) the catch. Baits were mainly a pair of frozen ± 750 g milkfish *Chanos chanos* imported from Indonesia, but included various species from the local artisanal professional fishery, such as tuna (*Thunnus* sp.), skipjack (*Katsuwonus pelamis*), trevally (*Caranx* sp.), emperor (*Lethrinus* sp.), rainbow runner (*Elagatis bipinnulata*), generally less than 2 kg each. Mainly middle-sized circle hooks (Mustad 39,950 NP-BN-18/0) were used. Hooks were removed before the catch was released. In order to target bull sharks, which favour bait set close to the seabed, the length of the hook leader was adjusted according to the water depth and the prevailing current, so that the bait was ± 1 m above the bottom. The duration of each fishing session (defined as the time between consecutive baiting or between setting and removing the baited fishing gear), the position of the SDL and the nature of the bait and its condition at the end of a fishing session were also recorded.

After June 2015 data recording was facilitated by equipping the

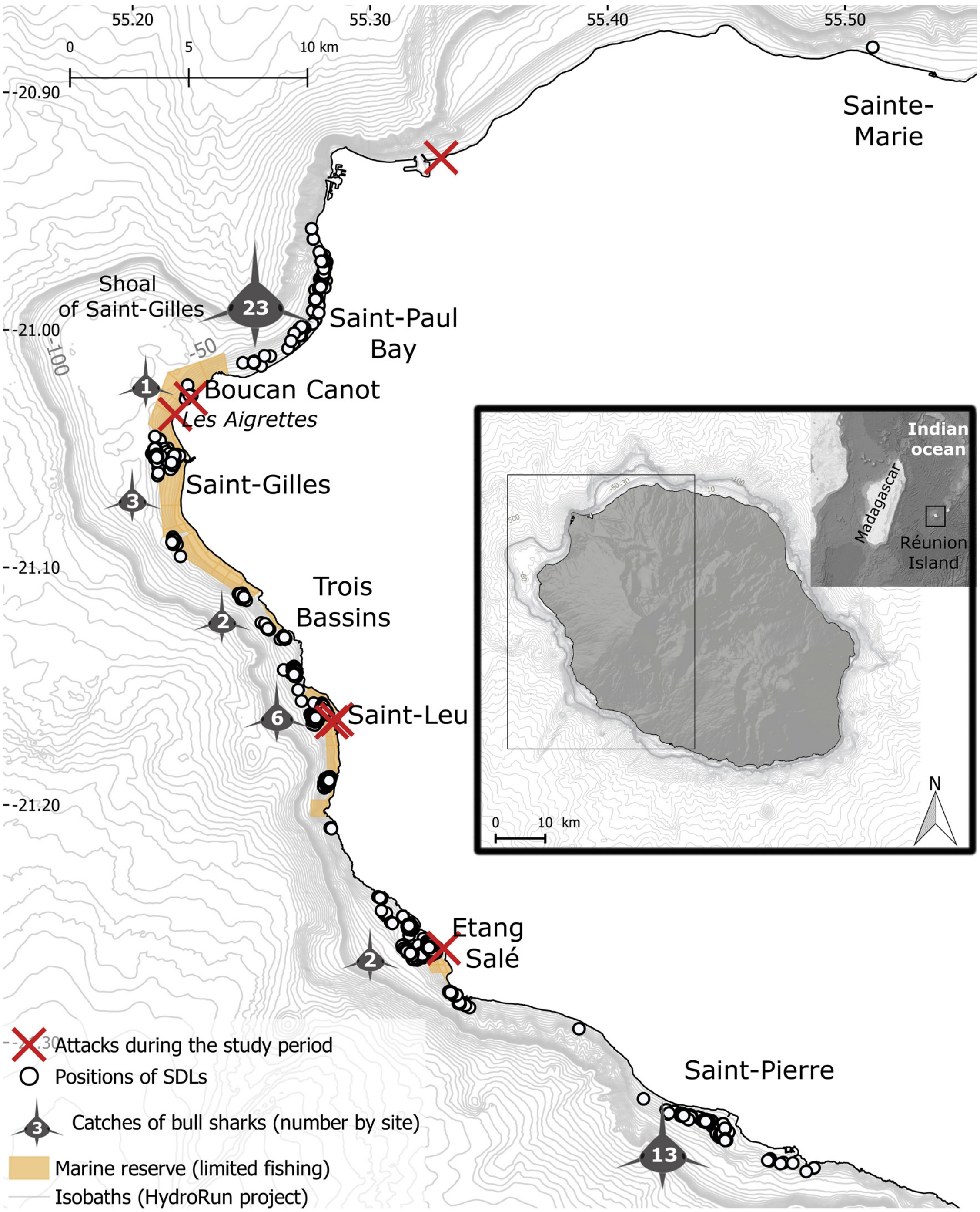

Fig. 2. Map of the west coast of Reunion Island, with the position of the marine reserve, the locations of shark attacks, the locations of the SDLs deployed and the numbers of bull sharks caught by site during the study period (Jan. 2014 – Feb. 2017).

fishers with GPS beacons, allowing them to send messages in real time via the Iridium satellite network to an online database when setting or removing the fishing gear: thus position and time were automatically recorded for each SDL fishing period. In order to document and validate their work, fishers were also asked to take photographs of their catch. Observers from local associations randomly participated on-board the fishing vessels, in addition to the scientific and operational coordinators of the two Caprequins programs.

When responding to an alert, fishers were asked to document both the time of alert and their arrival time on site. The time of the alert was also automatically recorded by the server, and time of arrival was verified as a matter of control when the alert messages stopped following reattachment of the magnet to the MLI-S© buoy. There may have been a slight delay in reattaching the magnet if the fisher had to deal with an entangled shark. A careful note was made of the condition of each catch, according to one of the following descriptors: alive and strong; alive and weak but strong enough to be released; alive but too weak to be released; dead and intact; dead and scavenged (with detailed comments and, when possible, photographs of the type of bites or marks). Bait condition was also documented: retrieved intact, scavenged by small marine organisms (generally by crabs or fish), clearly bitten by a shark (bite marks photographed when possible), or lost. Technical problems, such as line entanglement or triggering magnet broken, were also recorded. In the event of a catch, the hooking

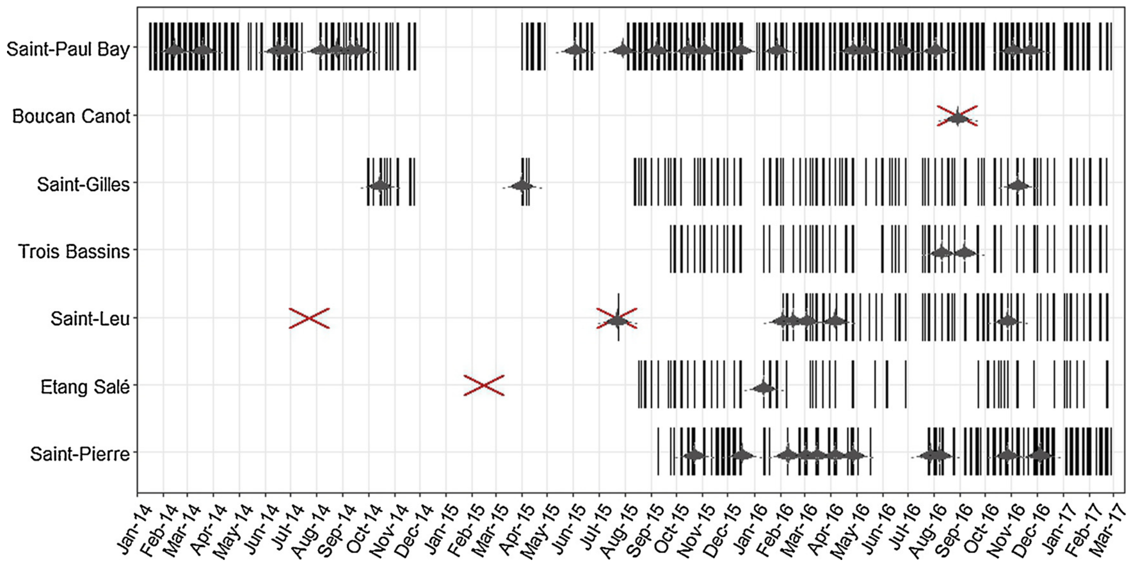

Fig. 3. The SDL deployment locations off Reunion Island between January 2014 and February 2017, with the thickness of each vertical bar indicative of the effort and duration of each deployment. The crosses represent shark attacks and the shark icons represent catches of bull sharks. The one-time drumline deployment at Boucan Canot was in response to a fatal shark attack ("post-attack" operation) and resulted in a bull shark catch. The same occurred at Saint-Leu in August 2015.

position was not recorded. In accordance with the operational rules of the political funders of the program, bull sharks < 1.5 m total length (TL) or tiger sharks < 2.5 m were released, while larger individuals were brought back to shore for necropsy and further studies (trophic ecology, reproduction, population genetics). All bycatch species and other species of sharks were released, unless too weak to survive, and tagged with an external Hallprint tag whenever possible. When the operations or scientific coordinator was on-board the fishing vessel, all sharks released were also tagged with a surgically-implanted acoustic tag. Fishers were allowed to retain dead sharks and bycatch but only for their own personal consumption. As they were remunerated for their fishing effort, with no reward for their catch, they were committed to the responsible handling and release of any bycatch and undersized or non-target sharks.

2.4. Data analysis

Basic descriptive statistics were used to characterize the results of the fishing operations (number caught per species, size, sex, condition when found and fate of each catch). Differences in frequencies of different parameters (most caught species, sex ratios; only for most numerous catches) were assessed using Chi-square test. The objective of the SDL program was to minimize the response time following a catch, thereby maximizing the animal's survival. This response time is defined as the "fight time" (Aalbers et al., 2004), and we hypothesised that the shorter the fight time, the better the retrieved condition of each catch. In order to test the effect of fight time and other factors, namely the species, the total length of caught individuals, the month and the fishing sites on hooked fish condition, we developed a general linear mixed-effects model (GLMM; Bates et al., 2015). As our response variable, the fish condition (alive or dead), provides binary outcome, we used a logistic link function. We tested various models and the selection of the optimal model (most parsimonious and explaining the most variance possible) was based on the Akaike Information Criterion (AIC; Venables and Ripley, 2002). Only species with number of individuals higher than ten and less than 100% of survival in a good state were used in the model. As the fishing effort was not evenly distributed during the day, an index was developed to account for differences in the distribution of hooks deployed during each hour. The total number of fish caught at each hour-of-the-day (multiplied by 1000) was subsequently divided by the total number of hooks multiplied by number of hours deployed for each hour-of-the-day (hourly effort), thus giving an adjusted index of the time distribution of the alerts during the day (Campbell and Young, 2012). This index was called APUE (number of Alerts Per Unit of Effort). In order to also take the elapsed time after bait setting into account, which could be important as the freshness of the bait could play a role in the catchability of the different species, the total number of SDL settings (i.e. with a new bait) by hour-of-the-day was also computed and represented for each hour of the day.

Moonlight is often considered as a factor likely to affect catch indices of large marine predators (Poisson et al., 2010), especially sharks (Wintner and Kerwath, 2017). Therefore, two lunar indexes were computed (Austin et al., 1976), in order to assess whether the number and exact time of catch differ according to the available light at night. The first index is the daily lunar phase (i.e. surface of the moon illuminated, from 'complete' at full moon to 'nil' at new moon), retrieved from the R "lunar" package and expressed in radians (0 refers to the new moon, $\pi/2$ to the first quarter, π to the full moon and $3\pi/2$ to the last quarter). The other index refers to the moon height in the sky (the higher the moon, the brighter the light), obtained by assessing the sine of the angle between the moon and the horizon at the time of the catch. As no simple algorithm exists for moon height, moonrise and moonset hours were collected from a specialized website at the most central location of our study area, i.e. Saint-Leu (Moonrise data, 2017), and the sine of the angle of the moon over the horizon was derived from the time interval in hours between moonrise and moonset. As the SDLs were deployed regularly throughout the study period (Fig. 3), the fishing effort was regarded as being fairly evenly distributed through all the various lunar phases and changes in the moon's altitude.

3. Results

Fig. 3 shows the deployment of SDLs along the west coast of Reunion Island. The project first started at Saint-Paul Bay in 2014, away from the popular swimming beaches, and then progressed southward to other locations, notably those where shark attacks had occurred in the past. Even though there were two attacks at Boucan Canot and Les Aigrettes (Fig. 2), there were only very limited fishing operations there as it is situated in an enhanced protection area of the Marine Reserve. SMART drumlines were able to regularly target and remove bull sharks, to be considered as the most dangerous species, from these sites. No shark attacks were recorded at any of the deployment sites when SDLs

Table 1
Catches on SDLs during the Caprequins programs.

Species	Number of catch	Mean TL (range)	Sex ratio (M/F)	Dead	Catch retained
Galeocerdo cuvier	86	295 (80-429, n = 86)	0.86 (n = 82)	0.06 (n = 5)	0.64 (n = 55)
Carcharhinus leucas	49	260 (180-322, n = 49)	0.75 (n = 49)	0.04 (n = 2)	0.98 (n = 48)
Dasyatis spp	36	133 (70-250, n = 15)	0.5 (n = 12)	0 (n = 0)	0 (n = 0)
Caranx ignobilis	29	122 (100-138, n = 17)	–	0.31 (n = 9)	0.34 (n = 10)
Sphyrna lewini	24	232 (120-315, n = 22)	4 (n = 20)	0.54 (n = 13)	0.5 (n = 12)
Rhynchobatus djiddensis	12	224 (150-347, n = 11)	0.5 (n = 9)	0 (n = 0)	0 (n = 0)
Nebrius ferrugineus	11	296 (280-310, n = 9)	10 (n = 11)	0 (n = 0)	0 (n = 0)
Sphyraena barracuda	8	132 (120-150, n = 6)	–	0 (n = 0)	0 (n = 0)
Carcharhinus spp	6	164 (100-300, n = 5)	0.5 (n = 3)	0.67 (n = 4)	0.67 (n = 4)
Aetobatus narinari	3	190 (n = 1)	1 F	0 (n = 0)	0 (n = 0)
Epinephelus multinotatus	2	54 (n = 1)	–	0 (n = 0)	0 (n = 0)
Carcharhinus albimarginatus	1	100 (n = 1)	1 F	1 (n = 1)	1 (n = 1)
Carcharhinus plumbeus	1	189 (n = 1)	1 M	1 (n = 1)	1 (n = 1)
Carcharodon carcharias	1	390 (n = 1)	1 M	0 (n = 0)	1 (n = 1)
TOTAL	269	245 (54-429. n = 225)	–	0.13 (n = 35)	0.49 (n = 132)

were fishing there (Fig. 3).

3.1. Catches and survival rates

During the two Caprequins programs a total of 58,770 h of SDL fishing took place. In total 390 alerts were received. Eighteen catches were discovered without triggering an alert. The composition of the catches and their condition are presented in Table 1.

Animals found alive (n = 234) represented 86.9% of total catches (n = 269), with marked species-related differences in condition. The targeted species (bull and tiger sharks) represented 50.1% of the catch (n = 135), with the tiger shark catch significantly higher than that of the bull sharks ($p < 0.01$). There was no significant difference in the sex ratios of the catches for both species ($p > > 0.01$; Table 1). Both had a very high survival rate (94–96%), with only seven individuals found dead or in poor condition not suitable for release. Of the 86 tiger sharks caught, 31 were released as they were smaller than 2.5 m TL (36.0%), while only 2% of bull sharks were smaller than 1.5 m and released. The bycatch notably consisted of 36 stingrays (*Dasyatis* spp., not identified to species), 12 giant guitarfish (*Rhynchobatus djiddensis*), 11 tawny nurse sharks (*Nebrius ferrugineus*; 10 males and 1 female), 8 great barracuda (*Sphyraena barracuda*), 3 eagle rays (*Aetobatus narinari*) and 2 white-blotched grouper (*Epinephelus multinotatus*). These species all had a survival rate of 100% when retrieved.

Two other bycatch species, the giant trevally (*Caranx ignobilis*, n = 29) and scalloped hammerhead sharks (*Sphyrna lewini*, n = 24), were far more fragile, with only 20 and 11 individuals found alive and strong enough to be released, respectively. As the hooks were set quite close to the seafloor, the majority of the giant trevally (68.9%) had suffered barotrauma and nine of them were found dead. Many of the scalloped hammerheads (54.2%) were dead or in a weak condition, and although there were significantly more males than females caught ($p < < 0.01$) there was no difference in fatality between the sexes with both sometimes moribund within only a few minutes of being hooked.

The remainder of the catch comprised nine sharks (3.3% of the total catch), most of which were small individuals (x = 168 cm TL, sd 71; n = 6), including a sandbar shark (*Carcharhinus plumbeus*), a silvertip shark (*C. albimarginatus*) and five other carcharhinid sharks, which could not be identified to species (but could be differentiated from bull sharks). In addition, a 390 cm juvenile white shark (*Carcharodon carcharias*) and an unidentified large shark lost from the hook on retrieval (> 300 cm, likely to be a bull or a tiger shark) were caught. For most of them, genetic samples were collected to facilitate identification. Of the nine, only two were released alive. Two unidentified carcharhinid sharks and the silvertip shark were found scavenged; the latter had been attacked by a bull shark, which was caught on the same line. Two other unidentified carcharhinid sharks were found dead but intact.

The alert system failed in only 18 cases (6.7% of the total catch). Individuals caught during these failed alerts comprised ten different species and ranged in size from a 54 cm grouper to a > 400 cm tiger shark. The reasons for these failures were not always clear, but were mainly the result of entanglement of the fishing and mooring lines leading to the magnet not being pulled from the MLI-S© buoy, so the alert was not triggered. The other problem was a faulty triggering magnet, due to internal but invisible corrosion through emersion in seawater; this was overcome during the program by regular maintenance. In contrast to these technical problems with the fishing gear, the computer-based communication system worked flawlessly during the two Caprequins programs.

In the 251 cases when the alert signal was transmitted and received, the response time ranged from only five minutes (fisher already at sea) to up to 12 h (due to bad weather conditions which prevented the fisher from going at sea). The average response time was 73 min (sd 78), but the median was 56 min, with only 15 cases longer than 120 min. The best model to explain the condition of caught fish selected the interaction between the species and fight time as fixed factors and the site as random factor, though the site had no significant effect. The giant trevally and the scalloped hammerhead shark exhibited significant differences in their survival rate in relation with the fight time (Table 2). For these two species, the longer the response time the higher the number of dead individuals or too weak to be released. For the giant trevally, the mean response time for animals found alive and suitable for release was 63 min compared to 126 min for individuals dead or alive but to weak to be release. For the scalloped hammerhead shark, these two durations were 40 min and 61 min respectively.

3.2. Types of alerts and time of the day

Of the 390 alerts received, 64.3% were in response to a catch (n = 251), whereas 15.4% of the alerts were classified as “strike alerts” when the bait was either absent and assumed to have been taken or

Table 2
Results for generalized linear mixed models (GLMM) with species (SP), Fight duration (FT), month and site as factors affecting on fish condition (alive or dead). The best fit was determined according to the lowest Akaike’s Information Criterion (AIC).

Fixed effects	Random effects	Log-likelihood	AIC	Δ AIC
FT*SP	Site	−51.0	118.0	0
FT + SP	Site	−51.2	118.1	0.01
FT	Month	−72.6	151.2	33.2
FT	Site	−72.8	151.6	33.6
SP	Site	−86.5	168.2	50.2
TL	Site	−111.3	256.3	138.3

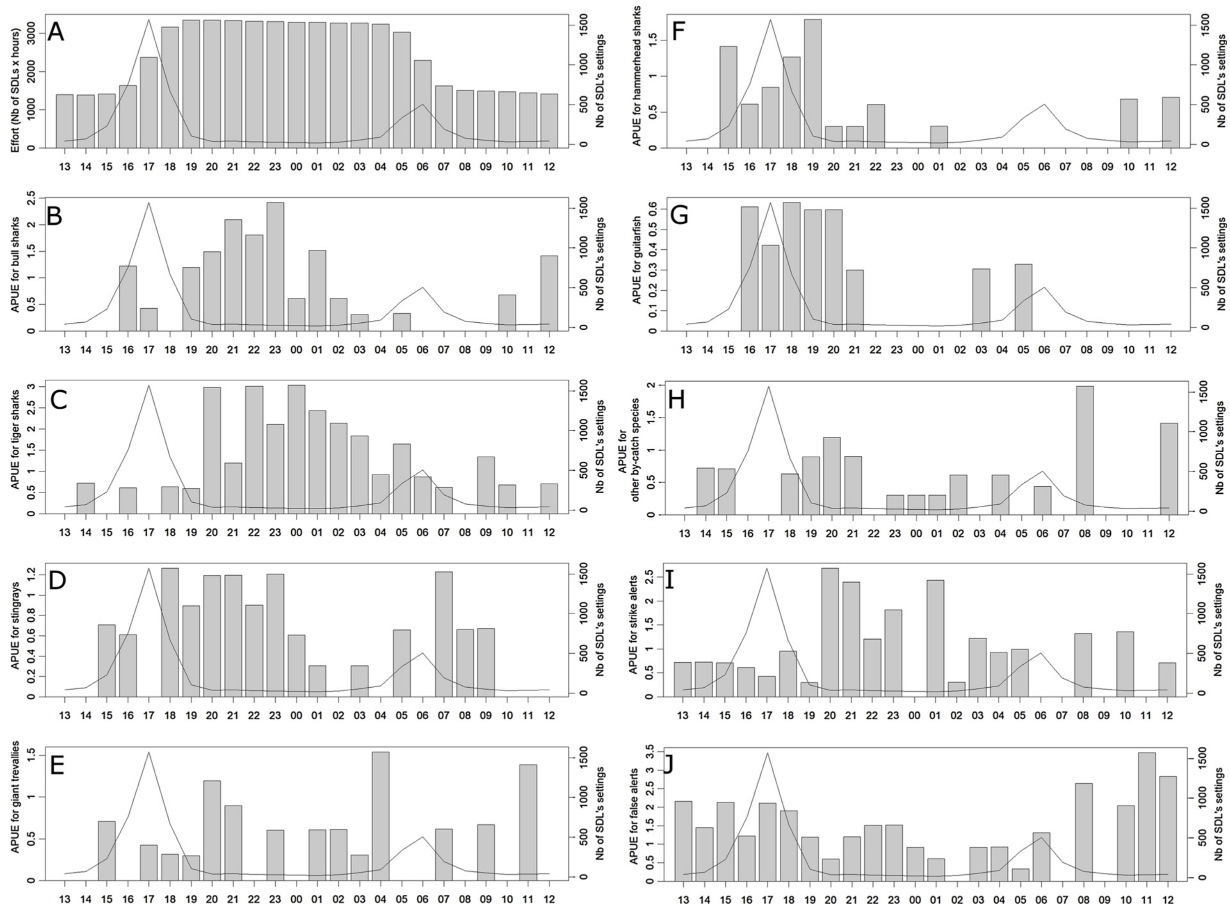

Fig. 4. Overall fishing effort and hourly catch trends on SMART Drumlines off Reunion Island. (A) Overall distribution of fishing effort over a 24-hour day; and hourly indices of Alerts Per Unit of Effort (APUE) for the most common species/groups: (B) bull sharks; (C) tiger sharks; (D) stingrays; (E) giant trevally; (F) scalloped hammerhead sharks; (G) giant guitarfish; (H) other bycatch species; (I) alerts with no associated catch (strikes); (*J*) false alerts. The line represents the number of SDL sets per hour over the course of a 24-hour cycle averaged throughout the study.

found bitten by a big fish, generally a shark (n = 60). There were 72 cases of "false alerts" (18.4%), as the bait was retrieved intact or scavenged by small animals or when a technical problem occurred. There were a further seven "unknown alerts", when the fisher failed to report on the state of the bait (1.8%). Of all the fishing sets with no alert and when the state of the bait was recorded (n = 4646), approximately one third of the baits were retrieved intact (34.3%), and another third scavenged by small animals (33.3%). 22.6% of baits were lost and a few (1.2%) were found bitten by large fish other than sharks, likely barracuda or trevally, as evident from the marks observed on the retrieved bait. Only two baits were found bitten by a shark with clear marks on it, and four other not retrieved due to entanglement and broken fishing lines.

Fishing with SDLs took place throughout the 24-hour day, with most of the effort concentrated between 17:00 and 05:00 (Fig. 4.A). Some SDL sessions were very short (a few minutes), due to almost immediate alerts and rapid intervention as the fishers were already at sea, whereas others were much longer (up to 25.75 h), sometimes due to delays encountered by the fishers in retrieving the SDLs. Despite this considerable variation, the SDLs were generally fishing for similar durations, lasting on average 11.65 h (sd 3.46). This is because the effort can be broadly separated into "day sets", usually from 06.00–17.00, and "night sets" from 17.00 to 06.00, with the night effort approximately twice the day effort, due to non-deployment near popular beaches during the day to allay concerns about the baits attracting sharks into the area.

The catch patterns of the most common species, in terms of alerts per unit of hourly effort (APUE), showed very different patterns. Bull sharks were mainly caught at night, with most catches between 19.00 and 01.00, and very few diurnal catches with the exception of a short spike in catches around midday (Fig. 4.B). Tiger sharks were caught throughout the 24-hour period, but most of the catches were also at night between 20.00 and 05.00 (Fig. 4.C). Catch rates for these two target species peaked around 23.00, 6–7 h after the commencement of the night sets at around 17.00. Stingrays were also primarily caught at night (Fig. 4.D), primarily before midnight. Giant trevally (Fig. 4.E) were caught throughout the 24-hour period, but with some evidence for a tri-modal catch rate. Most hammerhead sharks (Fig. 4.F) were caught between 15.00 and 22.00 and most guitarfish (Fig. 4.G) between 16.00 and 21.00, with both species caught mainly around sunset. For the other bycatch species (Fig. 4.H), APUE were scattered throughout the day and night, with a single peak at 08.00 just two hours after most of the day sets were initiated. Alerts with no catch occurred throughout the 24-hour period (Fig. 4.I), as did so-called 'False Alerts' (Fig. 4.*J*).

3.3. Alerts and the moon

The total catch (Fig. 5.A), as well as that of the five most common species (Fig. 5.B to F), did not seem to strongly relate to lunar phase, although it seems that more giant trevally were caught around full moon (index ˜ π; Fig. 5.E, left), and more scalloped hammerhead sharks around the last quarter (index ˜ 2π; Fig. 5.F, left). Of the target species, bull shark catches peaked around both the waxing and the waning crescent moon (index ˜ $\pi/2$ and $3\pi/2$; Fig. 5.B, left) but still with very little differences between lunar phases. There was no clear pattern for tiger sharks (Fig. 5. C).

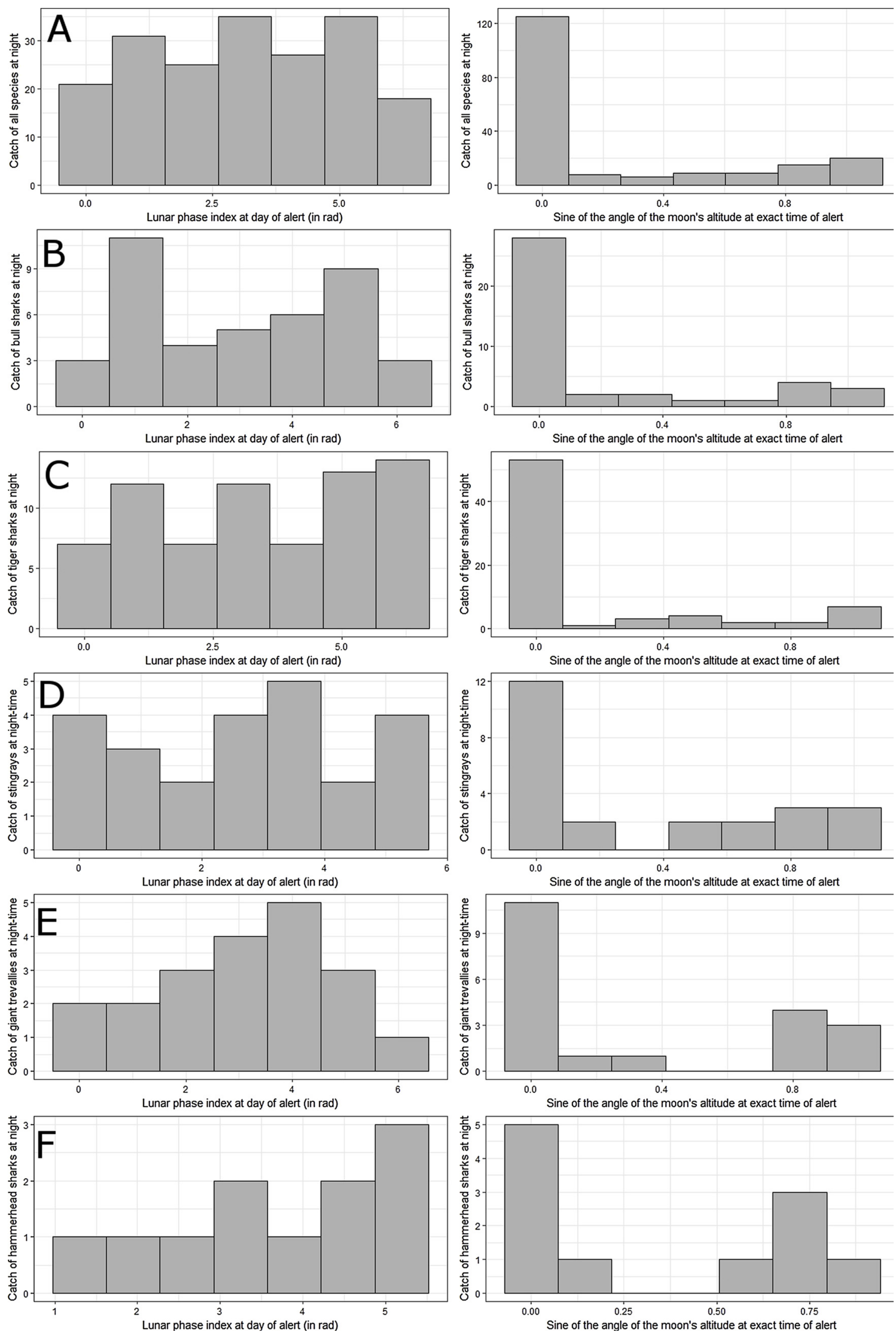

Fig. 5. Distribution of the catches in relation to the lunar phase on the day of catch (left) and the height of the moon at the hour of catch (right) for (A): bull sharks; (B): tiger sharks; (C): stingrays; (D): giant trevally; (E): scalloped hammerhead sharks and (F): giant guitarfish.

4. Discussion

Most of the catches were made at the extremities of the operation, at Saint-Paul in the north (this pattern continued even after fishing started to the south at Saint-Gilles, although the two are fairly far apart) and in the south at Saint-Pierre (Figs. 2 and 3): if the sharks are moving along the shoreline, it would make sense that the first drumlines they would encounter when swimming from the east coast to the west coast would be Saint-Paul in the north and Saint-Pierre in the south.

4.1. Shorter fight time for better survival rates

Even though conventional drumlines are recognized as more selective and generally exhibiting a higher survival rate than gill nets for animals caught in shark-control programs (Cliff and Dudley, 2011), mortality rates of non-target species, including non-dangerous sharks, are still unacceptably high. Despite having adopted a variety of mitigation measures to reduce catch (Dudley and Cliff, 2010; Sumpton et al., 2010), opposition to the bather protection programs using traditional shark capture methods continues to grow (Gibbs and Warren, 2015). In response to the new 'era' of public understanding of the importance of sharks in marine ecosystems, a more conservation-sensitive approach to bather protection was first implemented in Brazil (Hazin and Afonso, 2013). A similar approach to minimizing impact on non-target species was the driver to the development and deployment of SDLs off Reunion Island.

When hooked on a fishing line, the trauma endured by large fish, including sharks, which eventually leads to their mortality, has been summarized by Skomal (2007). There is the direct physical trauma caused by the hook, which may cause injuries in the mouth or the stomach, if swallowed. The exhaustive anaerobic muscular activity associated with the fish's violent movements to escape results in a build-up of lactate in swimming muscles. For many carcharhinid and sphyrnid shark species, which are obligate ram ventilators and therefore need to swim to expose the gills to oxygenated water (Carlson et al., 2004), entanglement on the fishing line severely impedes mobility and the ability for the blood to take up oxygen, thereby exacerbating the accumulation of lactate. Both the duration and intensity of this "fight time" can be critical for the survival of the animal.

Circle hooks are widely used in pelagic fisheries, especially where shark bycatch is a problem, as sharks are more likely to be hooked in the mouth than gut-hooked when using circle hooks, making it easier for fishers to remove the hook with minimal damage to both the gear and shark (Brooks et al., 2011; Coelho et al., 2012; Godin et al., 2012). For this reason, only circle hooks were used during the Caprequins programs, and most of the hooks were easily removed. But the primary advantage of an SDL with its real time alert system is that it enables the operator to respond to a catch within a few minutes, thus reducing the "fight time" and improving the survival rate of the catch.

As traditionally drumlines are used near popular beaches in order to "intercept" potentially dangerous sharks, they are unlikely to show the same catch rates as commercial fishing gear deliberately deployed in areas where target species aggregate, thereby resulting in higher catch returns. This is borne out by the fact that there were only 269 SDL catches in over 58,770 h of fishing, which equates to a catch every 218 h. For this reason, it was not practical for the fishers to remain at sea awaiting a catch. The SDL was developed to allow the operator to respond when a catch was detected. This rapid response to catch alerts has led to vastly improved rates of animals retrieved alive from the SDLs when compared to other traditional drumline fishing operations (Table 3).

Although the species assemblages and densities are likely to be very different in the three regions that have used drumlines in bather protection programs, the differences in the fishing gear and hook leaders (short chains with big *J*-shaped hooks in Queensland and KwaZulu-Natal vs. longer wire traces with middle size circle hooks in Reunion

Table 3
Comparisons of catches and survival rates of various species caught on drumlines in Queensland, KwaZulu Natal and Reunion Island.

	Number of catches in datasets				Survival rate			
	Queensland (Sumpton et al., 2011) – 'conventional' drumlines 1992-2008 -	Queensland (unpublished data) – 'conventional' drumlines 2015 – 2016 -	KwaZulu Natal (Cliff and Dudley, 2011) – 'conventional' drumlines Feb 2007- Feb 2010* -	Reunion Island – SMART drumlines Jan 2014 – Feb 2017 -	Queensland (Sumpton et al., 2011) – 'conventional' drumlines 1992-2008 -	Queensland (unpublished data) – 'conventional' drumlines 2015 – 2016 -	KwaZulu Natal (Cliff and Dudley, 2011) – 'conventional' drumlines Feb 2007- Feb 2010* -	Reunion Island – SMART drumlines Jan 2014 – Feb 2017 -
Carcharhinus leucas	79	163	< 3	49	25.9 %	5.5 %	100 %	95.9 %
Galeocerdo cuvier	485	467	42	86	31.0 %	41.3 %	37 %	94.2 %
Carcharodon carcharias	32	11	24	1	47.4 %	27.3 %	21 %	100.0 %
Carcharhinus plumbeus	28	6	6	1	10.7 %	0.0 %	0.0 %	0.0 %
Other species of Carcharhinus	81	276	240	7	11.7 %	4.0 %	22 %	20.0 %
Sphyrna lewini	11	7	51	24	0.0 %	0.0 %	0.0 %	45.8 %
Batoids including giant guitarfish *Rhynchobatus djiddensis*	8	9	0	51	50.0 %	77.8 %	–	100.0 %
Teleosts	2	23	9	39	0.0 %	26.1 %	11 %	76.9 %
All species	1041	1077	492	269	40.7 %	29.1 %	22 %	86.9 %

* annual catch have been multiplied by 3 to consider the full study period.

Island) may also explain the differences in catch composition. The Queensland and KwaZulu-Natal conventional drumlines catch few rays, possibly due to the fact that the bait is generally not set as close to the seabed as in Reunion Island.

Results of the GLMM suggest that the condition of hooked fish is mostly explained by the duration of fight time and the species, with two species being sensible to long fighting time. Interestingly, the fish length did not appeared as an important factor explaining the fish survivorship, though this could be the consequence of the length distribution of caught fish. There are species-related differences in survival rates on fishing gear (Morgan and Burgess, 2007; Gallagher et al., 2014; Butcher et al., 2015), and they were evident for SDL catches (Table 3). Bull and tiger sharks, the target and the most common catch in Reunion Island, showed high survival rates on SDLs and the response time did not appear to greatly affect their condition (Table 2). The high survival rate of all batoides caught with SDLs may be attributed to their ability to actively pump water over their gills while restrained by the gear.

At the other extreme, hammerhead sharks caught on SDLs had the lowest survival rates of less than 50%, despite the rapid response times. Hammerhead species are recognized as being amongst the most vulnerable to capture stress, attributed to their smaller mouths limiting the quantity of water oxygenating their gills through their narrow mouths (Gulak et al., 2015) and their faster and greater lactate build-up (Butcher et al., 2015; Ellis et al., 2017; Gallagher et al., 2014; Hyatt et al., 2012; Morgan and Burgess, 2007). The result of the study suggests a narrow time period of high vulnerability for scalloped hammerhead sharks around 50 min, as all individuals remaining ≥61 min were all dead and those release before 40 min were all alive. As the average response times after hooking on SDLs was 52 min, it suggests that the scalloped hammerhead shark might be the only sensitive species to the SDL. This is not surprising given that Butcher et al. (2015) found that all sharks caught in experimental longlines survived at least 78 min after initial hooking. However, given the susceptibility of hammerhead sharks to fight-induced mortality, all fishers in the Caprequins programs were requested to release these sharks as rapidly as possible, even if it entailed cutting the line at the hook shank and leaving the hook in place. Although several teleost species were caught on the SDLs, the giant trevally was the most numerous teleost fish caught (Fig. 2). Teleosts caught on SDLs exhibited far higher survival rates than the other fish caught on conventional drumlines in Queensland or KwaZulu-Natal (Table 3). Giant trevally were the only species that demonstrated a significant difference in response times of "alive" and "dead" animals, with a significant difference in survivorship exhibited between 1 h and 2 h retrieval times (Table 2). Even if still alive, most individuals were found with their swim bladder inflated and had to be "vented" (the over-expanded swim bladder is deflated by puncturing it through the body wall with a hollow needle) prior to release. This method, initially tested on deep bottom species (Collins et al., 1999), is still recommended for fish found with inflated swim bladders (Brown et al., 2008), even though it has not been confirmed as being 100% effective in ensuring the long-term survival of the released fish (Wilde, 2009).

Only eight small carcharhinid sharks were caught on SDLs in Reunion Island. Only two of these small sharks could be released after being found alive, representing the lowest survival rate of all groups of species caught during the Caprequins programs and comparable in terms of survival rates of this group on conventional drumlines (Table 3). Such a negative correlation between mortality and size has previously been shown (Broadhurst et al., 2014; Morgan and Carlson, 2010).

Based on the SDL catches, a ranking of the main species in terms of survival rate is: bull shark > tiger shark > giant trevally > scalloped hammerhead sharks > small carcharhinid sharks. The greater tolerance of the bull shark in bottom longline commercial fisheries has been identified (Morgan and Carlson, 2010; Hyatt et al., 2012), but Gallagher et al. (2014) and Butcher et al. (2015) proposed a slightly different ranking with tiger sharks being the stronger species. All these studies indicate that scalloped hammerhead sharks are among the weakest species to survive capture.

Even if found alive, animals could still be at risk immediately after release as well as in ensuing days (Raby et al., 2014). Long term monitoring studies, preferably utilizing telemetry techniques, can assist in determining long-term survival following release from fishing gear. Due to the difficulties in handling large and potentially dangerous animals, especially stingrays (some > 100 kg) with their highly mobile sting, and sometimes in rough seas, not all animals released from SDLs could be tagged during the Caprequins programs. Of the 137 animals released, 53 were externally tagged with Hallmark dart tags and 16 were acoustically tagged to monitor their movements in a coastal VR2W receiver's network (Guyomard, 2016 and unpublished data). Based solely on the presence of an external tag, only four animals (1 tiger shark, 1 giant trevally, 1 eagle ray and 1 grouper) were recaptured, several days (min 34 days) to several weeks (max 1.25 years) after release. Of the animals tagged with internal acoustic tags, six of the eight tiger sharks, three of the four giant trevally, both tawny nurse sharks, as well as one juvenile bull shark, were detected up to several months after release, indicating that they had survived. The single barracuda with an acoustic tag was not detected. Although these visual and acoustic detections are few, they do attest to high post-release survival from the SDLs. This is in line with observations for sharks caught in commercial fisheries (Gurshin and Szedlmayer, 2004; Hyatt et al., 2012), despite high inter-species variability (Manire et al., 2001). These studies confirmed that the shorter the fight, the higher the survival rate.

Due to their ability to minimize the "fight time", SDLs have thus shown to significantly reduce the mortality of the catch compared to conventional drumlines, which is paramount when the fishing occurs in high biodiversity areas. The sensitivity of the alert system has enabled the release of animals as small as a 3 kg grouper.

4.2. Use of time of the catch in catchability studies

The peak in APUE for "strike alerts" (35 "strikes" from 20.00 to 01.00 h) corresponds very closely to the night peaks observed for the two most common species, bull and tiger sharks, with a combined catch of 82 during these five hours. This suggests that some of these baits may have been taken by either bull or tiger sharks, without being hooked.

It is noticeable that the peak in catches for both bull and tiger sharks is not immediately after the night set peak around 18.00, but 6–7 h later. This suggests that the relatively small baits, all < 2 kg, do not attract sharks from a great distance, as their odor plume rapidly vanishes with soak time, with an 80% loss within 2 h (Westerberg and Westerberg, 2011), and that sharks take time to find the bait during their movements in the coastal waters where the SDLs are set. Similarly, catch analysis against soak time in longline gear indicated it took time for sharks to take the bait after gear had been set, with Carcharinids and tiger shark catches increasing a few hours after sunset (Broadhurst et al., 2014). Temporal variation in shark species' abundance and distribution in coastal waters may contribute to variation in SDL catch rates, as evidenced by tiger sharks showing a strong diurnal pattern, generally frequenting coastal waters at night and presumably moving offshore during the day (Blaison et al., 2015).

Analysis of the hourly distribution of alerts is of particular importance in order to improve the targeting process. It is noteworthy that scalloped hammerhead sharks are mainly caught at dusk, and in order to prevent catches of this sensitive, protected species (Ellis et al., 2017), it would be advisable to avoid setting SDLs before 20.00. Broadhurst et al. (2014) also suggested that bycatch of hammerhead sharks could be reduced through restricting the deployment and retrieval of longline gear to the night. Our data suggest this would also limit the catches of giant guitarfish, while capitalizing on the peak bull and tiger sharks capture period. The catch of giant trevally, stingrays, other bycatch species and "false alerts" would also be greatly reduced by not setting SDLs in the morning or before 13.00. However, considering the temporal characteristics of bull shark catches between 10.00 and 16.00 during this study, deployment of SDLs during this timeframe would potentially benefit bather safety against shark attacks as these increased catches coincide with peak bather activity.

Catch data from the SDLs in Reunion Island suggest a limited influence of moon phase on catches, although more catches seem to occur before under low light (i.e. before the moon rose or while it was very low in the sky). Lunar phase has not previously been shown to impact tiger shark catches in game fishing tournaments (Lowry et al., 2007), but bull shark catches decreased in shark nets off NSW during full moon (Lee et al., 2018), suggesting increased lighting enhanced net-avoidance behaviour. Substantial research into white shark movements and predation activity in relation to lunar phase have suggested greater predation success and nearshore habitat use during lower light conditions (new moon; Lee et al., 2018); however, currently little such data exist for tiger and bull sharks. On-going use of SDLs in coastal regions will hopefully allow such analyses to enable enhanced efficiency of this new shark attack mitigation technology.

5. Conclusion

SDLs are based on a simple alert principle for when baits are taken. This technology has proven highly effective in catching sharks and other big fish and retrieving them alive in coastal areas, where a rapid response by the fisher is possible. Their deployment has greatly enhanced the survival rate of the catches, which is of particular importance for non-target or bycatch species, especially those that are either considered endangered or protected under various regional or international conventions. In the context of highly controversial "shark-control programs", the use of such SDLs may constitute a meaningful compromise between the need to target potentially dangerous species, such as bull, tiger and white sharks, and the requirement to release, and possibly tag, the bycatch species. Alternatively, in the new conservation-conscious era for bather protection strategies, SDLs may also provide an opportunity to translocate and release further offshore any shark species caught, as per the successful strategy initiated in Brazil (Hazin and Afonso, 2013), or be used as a research tool for tag and release programs particularly in coastal areas where low shark densities may not warrant vessels being on standby waiting for suitable catches.

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