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Hooking efficiencies of SMART drumlines and their possible deployment rates vs gillnets for bather protection

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Introduction: For 87 years, gillnets have been deployed off up to 51 beaches in New South Wales, Australia, to reduce bites on humans by white (*Carcharodon carcharias*), bull (*Carcharhinus leucas*), and tiger (*Galeocerdo cuvier*) sharks. Recently, to minimise unwanted fishing mortalities, baited drumlines with electronic catch sensors, called 'shark management alert in real time' (SMART) have been trialled. The SMART drumlines are more selective than gillnets and because catches are quickly removed (with target sharks spatially displaced), nearly all survive. Nevertheless, important questions remain unanswered, including (1) the required number of SMART drumlines at a beach and (2) their risk of not being deployed due to adverse weather—which doesn't affect gillnets.

Methods: To answer the first question, we analysed 22,025 diurnal SMART drumline deployments across 1637 days for the frequency of proximal captures (i.e. ≥two target sharks caught in similar space and time) and dependence on the number of SMART drumlines. The second question was investigated by collating weather conditions during 31 years of target-shark catches (290 white sharks and 93 tiger sharks) in gillnets and correlating these to the known operational limitations of SMART drumlines.

Results: Among 494 hooked sharks, 71% were targets (298 whites, 43 tigers, and 9 bulls). No multiple daily catches were recorded for bull or tiger sharks, but there were 46 instances where up to five white sharks were caught off the same beach on the same day, with twenty occurrences within five km and 60 min of initial capture. Proximal captures remained independent of the number of deployed SMART drumlines or the region. The historical gillnet data revealed adverse weather would have restricted deploying SMART drumlines to 67–83% of the period gillnets were deployed, and up to ~75% of those occasions when white and tiger sharks were gillnetted.

Conclusion: While we acknowledge there would be fewer water users during adverse sea conditions, if SMART drumlines replace gillnets, their greater catching efficiency, selectivity, and survival of released animals need to be rationalised against fewer temporally comparable deployments. If the latter is acceptable, we recommend at least two or three SMART drumlines per beach to ensure a baited hook remains in the water while others are checked.

KEYWORDS

bather protection, bycatch, drumline, gillnet, shark attack, SMART drumline, shark-bite mitigation

1 Introduction

The occurrence of unprovoked shark bites on humans has increased globally since the 1980s and mostly involves white sharks (*Carcharodon carcharias*), bull sharks (*Carcharhinus leucas*) and tiger sharks (*Galeocerdo cuvier*) (Chapman and McPhee, 2016; Midway et al., 2019; Bradshaw et al., 2021). Although shark bites are rarer events than many other human-wildlife conflicts, they generate substantial community angst towards sharks, and with cascading social effects (McCagh et al., 2015; Pepin-Neff and Wynter, 2018a, b, c; Fraser-Baxter and Medvecky, 2018; Le Busque et al., 2019; Simmons and Mehmet, 2018). In some jurisdictions, the social consequences of shark bites on humans have justified resolution strategies (McPhee et al., 2021) which, as for all human-wildlife conflicts, can be broadly separated into four categories.

The first shark-bite mitigation category involves removing humans from problematic water bodies, via either legislated long-term bans (Hazin and Afonso, 2014; Guyomard et al., 2019), or short-term advice for vacating via real-time surveillance. The latter can occur directly using manned aircraft, land-based observers, or drones (Dudley and Cliff, 2010; Colefax et al., 2017, 2019; Engelbrecht et al., 2017; Butcher et al., 2019, 2021; Lipscombe et al., 2020), and/or indirectly from tagged sharks triggering acoustic receivers and subsequent telecommunications notification (Spaet et al., 2020a, b). Second, and most controversial, is the lethal use of fishing gear (typically gillnets or baited hooks and lines) to remove target sharks (Dudley and Cliff, 2010; Reid et al., 2011; Sumpton et al., 2011). Third, involves using hook and line to relocate sharks elsewhere, usually further offshore (Hazin and Afonso, 2014). The fourth strategy involves humans and sharks co-existing in similar space and time, but separated via either temporary or permanent swimming enclosures (McPhee et al., 2021), repellents (e.g., Huveneers et al., 2013, 2018), bite-resistant clothing (e.g., Whitmarsh et al., 2019), or combinations thereof (O'Connell et al., 2014).

Examples of all four approaches have been applied throughout Australia; a country with the second-highest number of unprovoked shark bites on humans (ISAF, 2024). The longest running shark-bite mitigation strategy is the New South Wales (NSW) 'shark meshing (bather protection) program', which was initiated in 1937 as a trial at 18 NSW beaches using gillnets measuring 150 m long by 6 m deep with 500–600 mm stretched mesh openings (SMO) and deployed parallel to beaches in ~10–12 m water depth and ~500 m offshore. Spatio-temporal fishing effort has increased, culminating in 51 beaches currently being continuously gillnetted for eight months each year (September to April) between Newcastle and Wollongong (Reid et al., 2011).

Gillnets were chosen in NSW, because they were assumed to continuously fish between checks, and during most weather conditions. Further north, in the adjacent state of Queensland, gillnets (180 m and 500 mm SMO) and/or baited hooks attached to anchored floats (termed 'drumlines') have been fished year-round off ~80 beaches for 56 years (Sumpton et al., 2011). The success of these two Australian strategies has been measured by ~90% fewer shark bites and associated fatalities at fished than pre-fished, or un-fished beaches; results like those observed off South Africa, which is the only other jurisdiction to consistently use lethal fishing gears to mitigate shark-bite risk (Dudley, 1997).

Current NSW and Queensland government policies support using fishing gear as the main option amongst a suite of measures for mitigating shark bites on humans; albeit with considerable controversy concerning public perceptions of both effectiveness and negative ecological impacts (Pepin-Neff and Wynter, 2018a, b, c; Fraser-Baxter and Medvecky, 2018; Huveneers et al., 2024). Beyond depleting target-shark populations off eastern Australia (Reid et al., 2011; Roff et al., 2018), gillnets and drumlines evoke mortalities among non-target animals (termed 'bycatch'), including those listed as endangered, threatened, or protected (ETP) (Dudley and Cliff, 1993; Sumpton et al., 2011; Broadhurst and Cullis, 2020; Dalton et al., 2023).

Other jurisdictions have recognised the environmental shortfalls associated with conventional fishing gears to lethally remove sharks, and some have sought technological solutions. To reduce collateral mortalities among non-target species on drumlines off Réunion Island, researchers developed an electronic monitoring system using a modified version of traditional drumlines with an MLI-s ™ satellite buoy from Marine Instruments© in Spain (Guyomard et al., 2019). This configuration was registered as "Catch-A-Live"® in Réunion Island and modified and renamed in NSW as 'shark management alert in real time or SMART' drumlines, whereby a hooked animal triggers a GPS signal via satellite to a receiver and initiates rapid attendance by fishers. Owing to the short time between when an animal is hooked and retrieved, most remain alive, and unwanted individuals can be quickly released prior to rebaiting the hook (Tate et al., 2021a).

Following their initial use off Réunion Island, during the past eight years, SMART drumlines have been trialled at various regions off NSW (Tate et al., 2021a; Lipscombe et al., 2023), including adjacent to beaches with gillnets (NSW DPI, 2017, 2018). Currently, there are 305 SMART drumlines deployed almost daily along ~300 km of coast. All live SMART drumline catches are released either at the site of capture (non-target animals) or 1000 m (target sharks) offshore. All target sharks are tagged with acoustic transmitters (Spaet et al., 2020a; Niella et al., 2022a, b; Smoothey et al., 2023). Most animals survive hooking (Tate et al., 2021a, b), incur minimal stress (Gallagher et al., 2019; Grainger et al., 2022; Tate et al., 2019) and vacate the area, with the target sharks temporarily moving further offshore before returning to their pre-catch migratory behaviour (Butcher et al., 2023). This temporary displacement is thought to reduce the short-term probability of interactions with humans, and if so, would be a preferred option to the permanent depletion of target sharks via conventional fishing gears.

When concurrently fished, catches of white sharks by SMART drumlines have exceeded those of adjacent gillnets by 15–32× and with less bycatch and mortality, but there are key differences in diel deployments and catching characteristics that make comparisons difficult (NSW DPI, 2017, 2018; Broadhurst and Cullis, 2020). In NSW, gillnets typically remain in the water throughout the fishing season and are checked at least every 72 h; although prior to 2009 they were deployed at each beach for a minimum of 9 week days and every weekend of each month whilst the checking rate was every 96 h (Reid et al., 2011).

Gillnets will opportunistically catch both actively feeding (i.e., biting) and non-feeding animals during both night and day. In comparison, while SMART drumlines can be nocturnally deployed (Guyomard et al., 2019), in NSW they have been restricted to diurnal deployments (~06:30–1900 h) to coincide with peak beach usage, and as such only catch animals actively or opportunistically feeding during the day. Also, unlike gillnets, SMART drumlines are not deployed if there are doubts concerning capacity to respond to alerts (i.e., >20 kn of wind or >3.5 m swell). However, on average over the past 7 years, weather conditions have permitted 24–30 fishing days month^{-1} (Tate et al., 2021a).

Notwithstanding discourse over the utility of either permanently or temporarily displacing target sharks from beaches in terms of bather protection (Hazin and Afonso, 2014), the possibility for at least some reduction in the risk of shark bites with fewer ecological impacts supports ongoing trials of SMART drumlines and/or their permanent use as a shark-bite mitigation measure (Tate et al., 2021a, b). Considering the operational differences between gillnets and SMART drumlines, at least two questions remain, and are investigated in this paper. The first question is how many SMART drumlines would be required to replace a gillnet, while still maintaining the same probability of catching a target shark in the immediate vicinity? The second question is what would be the relative risk of not having fishing gear in the water to potentially catch a target shark, if diel-deployed gillnets were replaced with diel-deployed SMART drumlines, acknowledging that under such conditions there would be fewer water users?

2 Materials and methods

Two gear-specific data sets detailing various environmental variables and catches were used to answer the research questions. The first data set encompassed operational restrictions and catches of bull, tiger and white sharks caught during various trials of multiple SMART drumlines off NSW during 2016–2018 (Tate et al., 2019, 2021a, b). The second data set described catches of various sharks (including white and tiger sharks separated, but bull sharks combined with other carcharhinids) caught in bather-protection gillnets off central NSW during 1990–2021. Specific details are provided below.

2.1 Assessing spatio-temporal variability in target-shark catches on multiple, adjacent SMART drumlines

A total of 75 SMART drumlines were diurnally deployed during separate trials at six regions along the NSW coast (Figure 1). This work included trials at Ballina (28.81° S, 153.61° E – 20 SMART drumlines) and Evans Head (29.11° S 153.44 ° E – 15 SMART drumlines) from December 2016 to November 2018, and six-month trials at Forster (32.18 ° S 152.52 ° E – 10 SMART drumlines) and Coffs Harbour (30.31 ° S 153.16 ° E – 10 SMART drumlines), between August 2017 and February 2018, and Kiama (34.67 ° S, 150.84 ° E – 10 SMART drumlines) and Ulladulla (35.36 ° S, 150.46 ° E – 10 SMART drumlines) between November 2017 and May 2018 (Figure 1).

Each SMART drumline included an anchor (2.0-m section of 10 mm diameter (Ø) galvanised chain attached to a 4.5 kg Danforth®) and 20–30 m of rope (8 mm Ø polypropylene; PP) and an anchor buoy (300 × 400 mm) (Figure 2A). A second 2.0-m 'sacrificial elastic cord' (8-mm Ø) was attached to a 'SMART buoy' (MLI-s satellite buoy; Marine Instruments) and then a 0.5-m holding line (8 mm Ø PP rope) and a 'drumline buoy' (400 × 500 mm). Two 1.1-m elastic 'shock sleeves' (10 mm Ø) were suspended from the drumline buoy and spliced to a perpendicular 2.3-m 'trigger line' terminating at a 'trigger magnet' in the SMART buoy and to a wire-cable trace (1.6 or 3.2-m and 3.0 mm Ø) attached to a circle hook (Mustad™ © 39937NP-DT). The hooks were baited with ~0.8–1.0 kg (40–50 cm) of sea mullet (*Mugil cephalus*) or eastern Australian salmon (*Arripis trutta*). When an animal bit the hook, the trigger line separated the magnet in the SMART buoy, and a signal was transmitted via satellite, electronically alerting responders.

At ~06:00 on each fishing day at each region, the swell height, wind direction and strength and sea state were checked at the port, and if the skippers thought their vessels could safely leave and return (within the next six hours), either 10, 15 or 20 SMART drumlines were deployed ~500 m from shore and in waters ~4–19 m deep, depending on the region (Figure 1). The site-specific spatial configurations of SMART drumlines varied depending on local topography (i.e., sandy, and frequently used beaches) with minimum and maximum adjacent distances of 150 and 2000 m. Ten or 15 sampling sites were established at the start of the deployment period at each region. However, after 10 May 2017,

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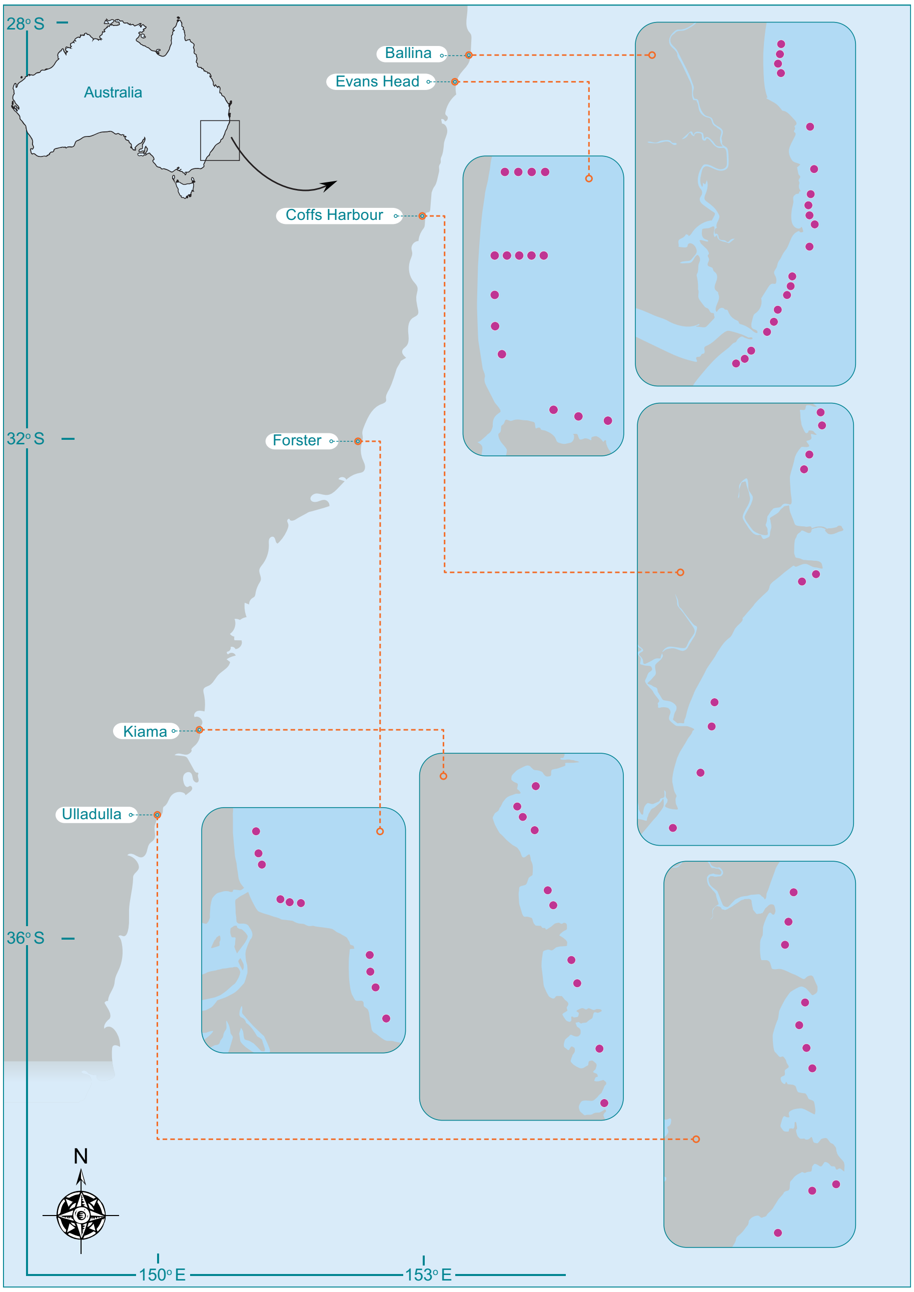

FIGURE 1
Locations of shark-management-alert-in-real-time (SMART) drumlines for each of the six trial regions off New South Wales, Australia.

the number of sites increased from 10 to 15 at Evans Head and 15 to 20 at Ballina, due to a perceived need to increase protection from shark bites. At all other regions, the same fishing effort was maintained throughout the reported period.

All SMART drumlines were deployed by 08:00 and retrieved at either 16:00 during part of the research period or 2 h before sunset for ongoing contracts. Earlier retrievals occurred if weather conditions deteriorated. Once a hooking alert was received, a vessel travelled to the SMART drumline to assess the catch. The data collected during each capture event including the sex and fork length (FL to the nearest 1 cm) of each shark, along with capture details (time, date, and latitude/longitude). The wind compass direction (degrees), moon phase (rising, falling, new, and full), sea surface temperature (SST; °C), sea state (Beaufort scale; Bf), barometer (hPa), water visibility (fifths; scale of 0 muddy to 5 clear), cloud cover (oktas) and water depth (m) were recorded using onboard equipment or visual observations, or where not available, regional government websites (i.e., https://mhl.nsw.gov.au/, http://www.bom.gov.au/).

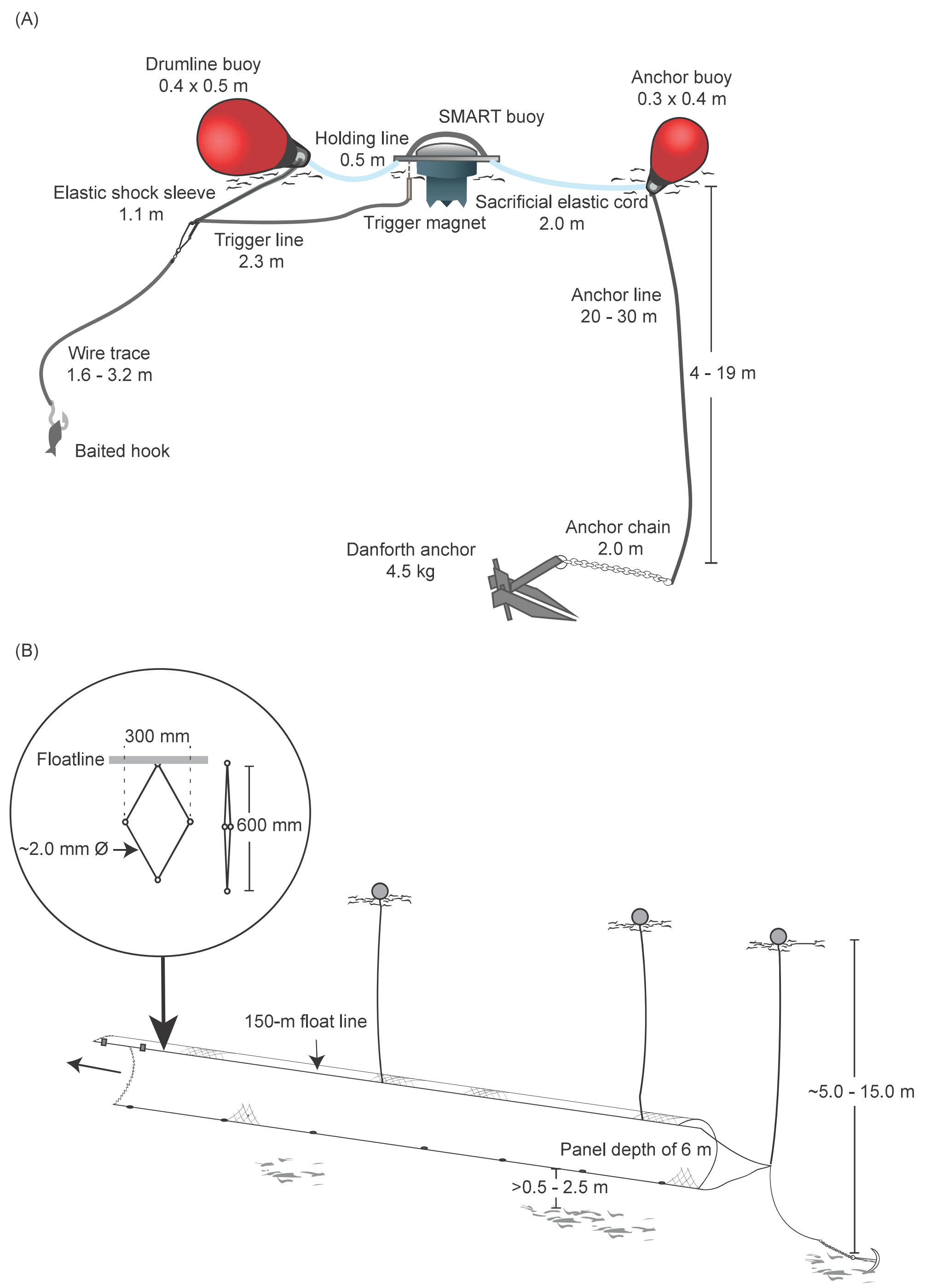

FIGURE 2
Configurations of the **(A)** shark-management-alert-in-real-time (SMART) drumlines and, **(B)** gillnets fished off New South Wales, Australia. Ø, diameter.

2.2 Relative risk of not having fishing gear in the water to catch an actively feeding target shark

Data describing the catches of 51 bather-protection gillnets fished off beaches within seven regions (Illawarra, south-, central- and north- Sydney, south- and north- Central Coast and Hunter– Figure 3) between Stockton (-32.91 ° S 151.80 ° E) and Wollongong (-34.42° S 150.92 ° E), NSW, Australia were collated between 1990 and 2021. Gillnet configurations have varied slightly over time, but typically they measured 150 m long and 6 m deep with 500–600 mm SMO made from multifilament, flat-braided polyethylene twine (minimum 160 kg breaking strength) and attached at a 0.67 hanging coefficient to a buoyed float line comprising 8–10 mm Ø PP rope and an 8-mm Ø weighted PP foot rope (Figure 2B). Gillnets were anchored (~30 kg Danforth® at each end) parallel to beaches in

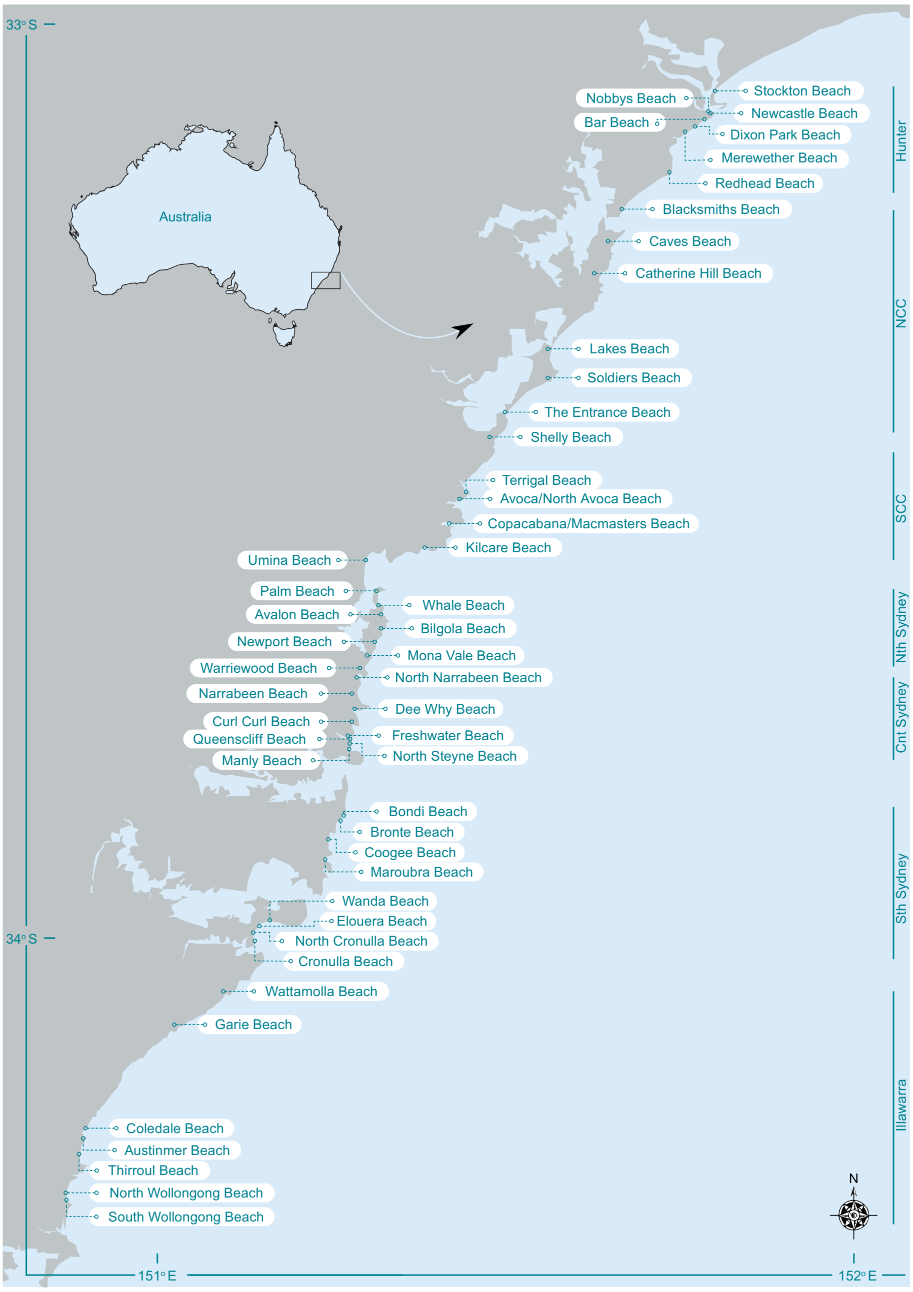

FIGURE 3
Locations of the beaches within seven regions (Illawarra, south Sydney – Sth Sydney, central Sydney – Cnt Sydney, north Sydney – Nth Syd, south Central Coast - SCC, north Central Coast - NCC and Hunter) between Newcastle and Wollongong, New South Wales, Australia where 51 bather-protection gillnets were deployed.

~10–12 m water depth across sandy substrata, and raised ~0.5 to 2.5 m off the bottom by three buoys spaced in the centre and ~15 m from each end). A single gillnet was deployed ~500 m off each beach.

For the 31-year period, gillnets were only deployed for eight of every 12 months between 1 September and 30 April and then removed to reduce whale entanglements during historically low periods of human beach use over the austral winter. Between 1990 and 2008, gillnets were deployed for a minimum of nine weekdays and every weekend per month. During this period, all gillnets were contractually required to be checked for catches within a maximum deployment time of 96 h. After January 2009, the contracts required gillnets to be continuously fished during the eight deployment months (except during gales or substantial swell events, when they were removed for the duration of the weather event only), and checked within 72 h of deployment to reduce fishing mortalities (Reid et al., 2011). Each gillnetted animal had various technical and biological information collected, including the fished beach, date of removal from the gillnet, at-vessel fate (alive or dead), sex, and size (typically FL for sharks).

Catches of white and tiger sharks were always separated from other sharks, but bull sharks and various other carcharhinids were grouped as 'whaler sharks' (Carcharhinidae) until 2010 (Reid et al., 2011). Environmental data, including the wind speed and direction, swell height and direction and SST were extracted from government websites (as per SMART drumline data sources) at 06:00 and 18:00 h for each day that target sharks were removed from the gillnets, and the preceding 96 h (until 2009) or 72 h (2009–21).

Based on the defined weather-dependent operational limits determined for SMART drumlines, we then provided a predicted binary outcome (yes or no) for their deployment on each day and night prior to and during the historical gillnet inspection days. Wind strengths to 20 (0–180°) or 30 kn (180–360°) were deemed suitable for diurnal SMART drumline deployments, but 10 (0–180 °) or 20 kn (180–360°) were the upper thresholds for nocturnal deployments. Regardless of diel period, swell heights had to be ≤3.5 m. These restrictions were based on anecdotal evidence of what was deemed safe for fishing off the gillnetted beaches. We assumed that if one or more target sharks were caught in a gillnet, then any that were actively feeding would have been vulnerable to capture on any adjacent SMART drumlines (in the absence of gillnets) and irrespective of diel phase.

2.3 Statistical analyses

2.3.1 Assessing spatio-temporal variability in target-shark catches on multiple, adjacent SMART drumlines

The data frame was set up to accommodate the proximal nature of the data. All SMART drumlines within a 5-km radius of a white, tiger and bull shark capture were included in the final data set for analyses. However, in terms of statistical analyses, sufficient catches only occurred for white sharks and are referred to directly hereafter (see Results). Within the defined radius, white sharks captured within 1 h of the first catch were then also included (collectively termed 'proximal' catches). This set of SMART drumlines/catches then formed a cluster, such that each hooked white shark had an associated cluster of SMART drumlines, some of which could have potentially caught another white shark but did not and some of which recorded a secondary proximal catch. Hence a binary response variable was formed; 0 and 1 if the SMART drumlines did or did not register a secondary proximal catch. This binary response along with recorded covariates were then analysed using a generalised linear mixed model (GLMM with a logistic-link function).

Due to the irregular spatial deployment of SMART drumlines, fishing effort was not equal among white shark captures (Figure 1). That is, the number of proximal SMART drumlines varied between white shark captures and so fishing 'effort' was included as a fixed effect, along with fishing 'region' and 'SST'. The random blocking effects initially comprised six environmental variables (moon phase, sea state, water visibility, wind direction, cloud cover and water depth), although those factors not impacting proximal catch rates were dropped from the model with their associated variance component fixed as a small positive number. Owing to the likely seasonality associated with proximal captures of white, sharks, a cubic spline term was fitted to SST.

2.3.2 Assessing the relative risk of not having fishing gear in the water to catch an actively feeding target shark

Gillnets were not checked every day, therefore all shark captures occurred at some unknown point t within a window between the discovery time (c_p) and the previous check. Here c was Julian days with day 0 being the first gillnet check and p indexing checking periods. Checking frequencies varied between 1–5 days, however, were generally 4–5 days due to the longer pre-2008 period of data used in this analysis, although there was one 6-day soak due to weather constraints. Following the discovery of a captured shark, weather conditions for subsequent days (within the 'capture window') were recorded as provided above. For these weather data, a binary variable was formed for each am and pm period, indicating whether a SMART drumline deployment would have been possible (or not) based on the weather conditions.

To model the potential deployability of SMART drumlines given the capture of a target shark (white and tigers only; see Results) in a gillnet, the data set was reduced to contain a single record for each catch and so permitted a GLMM. The response was the possible number of deployable periods (r) (weather permitting) of a SMART drumline with associated total number of deployable periods (n) for the corresponding gillnet capture window of each catch. For instance, for a shark gillnetted within a capture window of duration days, there are a total of n = 2x deployable periods, in one of which the shark was caught. Based on recorded weather data, $0 \le r \le n$ of these periods permitted SMART drumline deployments.

Fixed terms in the model included the 'species' gillnetted (i.e. white or tiger), capture 'month' (eight levels) and 'SST'. Random terms included 'beach' (51 levels), 'region' (seven levels) and 'year' (31 levels). Month and SST were partially colinear and beach was nested within region. Given the conditional nature of the data (i.e., all entries were conditional on a gillnetted target shark), it is important to note that we are not directly modelling shark captures. Rather, we modelled weather conditions in the time window between two checks given the capture of a target shark. All analyses were conducted in ASReml-R (Butler et al., 2017) using the penalised quasi likelihood (PQL) technique for estimation (Breslow and Clayton, 1993), and with Wald F-tests used to determine the significance of fixed effects.

3 Results

3.1 Spatio-temporal variability in target-shark catches on multiple, adjacent SMART drumlines

A total of 22,025 individual SMART drumline deployments during 1,637 fishing days were completed off Ballina (n = 478 days), Evans Head (547), Ulladulla (165), Forster (162), Kiama (155) and Coffs Harbour (130). Mean (± SE) environmental conditions varied across regions in terms of sea state (1.4 ± 0.7 Bf), SST (21.1 ± 2.0 °C), wind direction (231.0 ± 80.4 degrees), cloud cover (3.3 ± 2.9 oktas), barometric pressure (1016.2 ± 5.3 kPa), water depth (9.9 ± 2.7 m) and water visibility (2.6 ± 0.9 fifths).

In total, 494 sharks from 13 species and one unidentified group (whaler sharks) were caught, and all with either 0.0% (most species), 0.7% (white shark) or 5.0% (common blacktip) at-vessel mortalities (Table 1). Of these sharks, 70.8% were the target species, comprising 298 white sharks (mean ± SD of 2.3 ± 0.4 m FL), 43 tiger sharks (1.8 ± 0.6 m FL) and nine bull sharks (1.7 ± 0.4 m FL) (Table 1).

Within all regions, there were no incidences of multiple daily catches for bull or tiger sharks (as defined). There was one incidence of two tiger sharks caught on the same day and five other incidences where white and tiger sharks (four incidences) or white and bull sharks (one incidence) capture events occurred within the same region, but all were excluded by the 5-km radius proximity criterion. One tiger and white shark capture event satisfied the proximity criterion at Coffs Harbour, but this was removed from further analyses given the remaining events involved only multiple white shark captures.

For white sharks, there were 46 occasions during which up to five individuals per day and region were hooked (Table 2). Of these multiple capture events, 20 (43.5%) involved more than one white shark being caught within 5 km of the first capture (Table 3). The twenty proximal captures were within, on average (± SE) 0.4 ± 0.1 h (range of 0.1 to 1.0 h) and 1.6 ± 1.4 km (0.1 to 4.9 km) (Table 3). No instances of more than two white shark proximal captures were observed, and none occurred at Kiama, Ulladulla, or Coffs Harbour (Table 3). These regions were subsequently omitted, leaving 278 independent white shark captures from Ballina, Evans Head and Forster for further analysis (Table 2).

The PQL estimates of the variance components for random terms included in the model revealed the fitted environmental terms accounted for minimal variation (15.4% accumulated) compared to the residual (84.6%) (Table 4). Neither the fished region nor effort were significant in explaining variability among proximal catches (GLMM, $p > 0.05$), but SST was ($p < 0.05$), manifesting as an increasing probability of proximal catches in cooler water (to 17°C), coinciding with the late austral winter and early spring (Table 4, Figure 4). This period was also characterised by the greatest frequency of absolute captures (and therefore shark abundances) (Figure 5A). There were no white sharks caught during the late austral summer/early autumn (Figure 5B).

TABLE 1 The species (alphabetical order) and their total numbers, at-vessel mortalities and mean (± SD) fork lengths (FL; m) caught on SMART drumlines during 22,025 individual deployments over 1637 days at seven regions off New South Wales, Australia between December 2016 and May 2018.

Species	Number	Mortality (%)	FL (m ± SD)
Bronze whaler (*Carcharhinus brachyurus*)	5	0.0	2.1 ± 0.3
Bull shark (*Carcharhinus leucas*)	9	0.0	1.7 ± 0.4
Common blacktip (*Carcharhinus limbatus*)	20	5.0	1.9 ± 0.4
Dusky whaler (*Carcharhinus obscurus*)	48	0.0	1.6 ± 0.5
Greynurse shark (*Carcharias taurus*)	26	0.0	2.2 ± 0.2
Sandbar shark (*Carcharhinus plumbeus*)	1	0.0	1.5
Shortfin mako (*Isurus oxyrinchus*)	10	0.0	1.7 ± 0.5
Silky shark (*Carcharhinus falciformis*)	1	0.0	2.3
Smooth Hammerhead (*Sphyrna zygaena*)	26	0.0	1.4 ± 0.2
Spinner shark (*Carcharhinus brevipinna*)	1	0.0	1.2
Thresher shark (*Alopias* spp.)	5	0.0	2.0 ± 0.1
Tiger shark (*Galeocerdo cuvier*)	43	0.0	1.8 ± 0.6
Whaler shark (*Carcharhinus* spp.)	1	0.0	1.0
White shark (*Carcharodon carcharias*)	298	0.7	2.3 ± 0.4

3.2 Relative risk of having fishing gear in the water to catch an actively feeding target shark

During the 31 assessed years 1,507 sharks from 10 species and two unidentified groups ('sharks' and 'whaler sharks') were gillnetted across the seven regions (Table 5). Unidentified whaler sharks accounted for most captures (556 individuals; mean ± SD of 1.9 ± 0.6 m FL) followed by white sharks (290 individuals; 2.0 ± 0.5 m FL), bronze whaler sharks (*Carcharhinus brachyurus* – 150 individuals; 2.3 ± 0.6 m FL), tiger sharks (83 individuals; 3.2 ± 0.7 m FL) and bull sharks (25 individuals; 2.4 ± 0.4 m FL) (Table 5). At-vessel mortalities were high for all species and ranged from 68% for bull sharks to 100% for silky sharks (*Carcharhinus falciformis*), although it should be noted these primarily comprised pre-2008 data, after which at-vessel mortalities of captured animals reduced to 58% (Table 5).

The mean percentage of periods during which SMART drumlines could have been deployed in the diel capture windows of all gillnetted species varied from 66.5 to 82.5% (Table 5). For gillnetted white, tiger and bull sharks (which all encompassed similar hooked sizes during SMART drumline trials), SMART drumlines could have been deployed during 72.6, 76.6 and 78.7% of their respective capture windows (Table 5).

Of the target species, bull sharks were omitted from analysis due to their low capture frequencies and lack of delineation from other carcharhinids for more than half of the time that capture data were collected from the gillnets. The final model of factors affecting the potential deployment of SMART drumlines during diel periods

TABLE 2 Summary of the fished region, frequency of white (*Carcharodon carcharias*), bull (*Carcharhinus leucas*) and tiger (*Galeocerdo cuvier*) shark catches (1–5) during a single day and the total number of days with at least one target shark capture off New South Wales, Australia between December 2016 and May 2018.

Frequency of catches	Number of days at:						Total number of days
	Ballina	Evans Head	Coffs Harbour	Forster	Kiama	Ulladulla	
One ×							
White	68	73	12	31	1	3	188
Tiger	10	2	16	2	9	2	41
Bull	7	2	0	0	0	0	9
Two ×							
White	9	14	2	8	0	0	33
Tiger	0	0	1	0	0	0	1
Bull	0	0	0	0	0	0	0
Three ×							
White	3	3	0	3	0	0	9
Tiger	0	0	0	0	0	0	0
Bull	0	0	0	0	0	0	0
Four ×							
White	0	2	0	1	0	0	3
Tiger	0	0	0	0	0	0	0
Bull	0	0	0	0	0	0	0
Five ×							
White	0	0	0	1	0	0	1
Tiger	0	0	0	0	0	0	0
Bull	0	0	0	0	0	0	0

when white and tiger sharks had been gillnetted showed much of the variance was explained by the residual (95.5%), with year and region the most influential random factors (Table 6). Among the fixed factors, only month significantly affected the probability of deploying SMART drumlines when both white and tiger sharks were gillnetted (GLMM, $p < 0.001$, Tables 6 and 7). Specifically, the greatest predicted deployment of SMART drumlines was during autumn and early spring (April and September) (Table 7, Figure 6). Late spring and summer (October to January) were associated with lower possible SMART drumline deployments (Table 7).

Both tiger and white sharks were caught during all months when gillnets were deployed, with tiger sharks primarily caught during the austral summer and autumn between December and April, and white sharks during spring and mid-summer between September and January (Table 7). These peak capture windows coincided with mean postulated SMART drumline deployments of 68.9 ± 0.9 to 82.0 ± 0.7% for tiger sharks and 69.8 ± 0.2 to 76.6 ± 0.2% for white sharks (Table 7). Across all months, the mean possible SMART drumline diel deployment percentage among regions ranged between 62.5 ± 1.3 and 87.8 ± 1.2% for the capture windows of a tiger or white shark (Table 6).

4 Discussion

Choosing an effective shark-bite mitigation strategy requires satisfying not only the implicit response variable, but also public perceptions and expectations of safety, while simultaneously minimising negative impacts to individual species or ecological communities (Pepin-Neff and Wynter, 2018c). For the few global jurisdictions (i.e., South Africa, Réunion Island, New Caledonia, and Australia) with lethal bather-protection strategies, managers are under constant pressure to implement new tools to balance financial, environmental and social criteria. This impetus triggered the current study, and while the data do not answer any questions concerning the costs or bather-protection utility of fishing gears, they contribute toward the few studies seeking to understand key factors affecting the catching efficiencies of drumlines and identify their operational limitations in terms of potentially replacing gillnets in a bather-protection program (Dudley et al., 1998; Sumpton et al., 2011).

Previous studies simultaneously evaluating gillnets and drumlines used in bather-protection programs in Queensland and South Africa have shown that conventionally fished drumlines (~48

TABLE 3 Summary of the fished region, date and intervening distance (m), and time (hours) for the 20 white sharks (*Carcharodon carcharias*) proximally hooked at three regions (Ballina, Evans Head and Forster) off New South Wales, Australia during 2016–18.

Region	Shark no.	Date	Distance (m)	Time (h)
Ballina	1	03/05/2017	1580.8	0.1
	2	03/07/2017	3341.0	0.6
	3	26/07/2018	268.7	0.4
	4	04/08/2018	4915.2	1.0
Evans Head	5	10/12/2016	519.2	0.1
	6	04/06/2017	221.2	0.2
	7	21/07/2017	941.2	0.7
	8	21/07/2017	325.0	0.8
	9	26/08/2017	1498.7	0.3
	10	23/10/2017	2414.4	0.1
	11	24/07/2018	2512.5	0.2
	12	30/07/2018	1464.4	0.3
	13	03/08/2018	903.8	0.9
	14	07/08/2018	103.4	0.5
Forster	15	14/08/2017	302.7	0.2
	16	14/08/2017	4166.0	0.7
	17	17/08/2017	1526.0	0.3
	18	17/08/2017	2420.5	0.8
	19	19/08/2017	291.0	0.4
	20	21/11/2017	2420.5	0.1

h soaks) catch substantially fewer sharks (most species) than gillnets (Cliff and Dudley, 2011; Sumpton et al., 2011; Cardno, 2019). However, for tiger and white sharks, drumlines can offer a viable alternative to gillnets because they usually catch adequate numbers with relatively less non-target bycatch (Cliff and Dudley, 2011; Sumpton et al., 2011). Clearly, introducing the MLI-s satellite buoy as an alert system to drumlines appears to optimise species selectivity with 71% of the total catch here comprising the three target species; albeit with a strong bias to white sharks (60% of the catch).

The observation of few bull sharks hooked on SMART drumlines (restricted to Ballina and Evans Head only) despite their known distribution along the NSW coast is consistent with data from conventional drumlines fished ~90 km north (off southern Queensland), where gillnet catches of this species are 10× times greater (Lopes et al., 2024), although both Queensland gears are deployed 24 h each day. Such gear-specific differences may simply reflect a behavioural resistance among bull sharks to being hooked; reiterated in a study by Lipscombe et al. (2023), who showed variable snood lengths and other configurations failed to improve diurnal catches on SMART drumline in NSW. Certainly, two different baits were fished in the present study, with no apparent effect (given the low overall catches).

Compared to bull sharks, considerably more tiger sharks were diurnally hooked, and across all locations. Similarly, their average annual catch across all monitored gillnets was greater at ~2.7 (vs ~1.5 for bull sharks), although regardless of diel patterns, previous analyses of these data imply a bias towards capture in those gillnets closer to deep water, which probably reflects habitat preferences (Lee et al., 2018). More specifically, recent telemetry tracking and dietary analyses indicate a primarily pelagic distribution for tiger sharks off NSW (Holmes et al., 2014; Ferreira et al., 2017; Niella et al., 2022a) which is also supported by the few tagged tiger sharks being detected on up to 37 tagged shark listening stations deployed 500 m offshore along the NSW coast (NSW DPI, *unpublished data*). Such spatial separation, rather than any behavioural hesitation to hooking, might explain their sporadic capture along the NSW coast.

Unlike bull and tiger sharks, the strong bias towards catches of white sharks clearly indicates not only their spatial diurnal availability, but also their willingness to take baits, and across various configurations (Lipscombe et al., 2023). Although not quantified via comparative trials with conventional drumlines, the data here imply a considerable vulnerability of white sharks to actively fished drumlines, supporting the few data where these configurations have been concurrently fished with gillnets (NSW DPI, 2017, 2018). White sharks are most frequently implicated in shark-human interactions in Australian waters (Ryan et al., 2019), and subsequently represent the primary target species for shark-bite mitigation; however, as a protected species, ongoing mortalities in shark-control programs should be minimised whilst still enabling bather protection. Using SMART drumlines demonstrates displacement can be achieved over the short term and with nearly zero mortality or sublethal impacts (Tate et al., 2019, 2021a, b).

The low at-vessel mortality after capture on SMART drumlines in NSW reflects the protocol of attending to captures within 30 min and contrasts with the high levels of mortality reported for both traditional drumline captures (Dudley et al., 1998; Sumpton et al., 2011; Cardno, 2019) and gillnets (Broadhurst and Cullis, 2020; Dalton et al., 2023). Analyses of the physiology of white sharks caught on SMART drumlines have indicated the capture process is relatively benign (Tate et al., 2019; Gallagher et al., 2019) and that recovery of released individuals occurs within 10 h (Grainger et al., 2022). Similarly, low medium-term (>4 years) post-release mortalities have also been recorded for bull and tiger sharks fitted with telemetry tags following their capture on SMART drumlines (Lipscombe et al., 2020; Smoothey et al., 2023). These results might imply that the mortality or sub-lethal effects to sharks hooked on traditional drumlines used in other jurisdictions could be reduced via more regular checks, which would also increase catch per unit of effort (CPUE). Certainly, soak duration is positively correlated with sublethal and lethal effects among most hooked species, and especially obligate ram ventilating elasmobranchs, marine reptiles, and mammals (Butcher et al., 2015; Broadhurst and Cullis, 2020).

Notwithstanding the potentially fewer sublethal/lethal impacts, superior CPUE, and species-selectivity of SMART drumlines over gillnets, there are finer-scale considerations in terms of gear-specific

TABLE 4 (A) Penalised quasi likelihood estimates of the variance components of each random model term and, (B) summaries of fixed effects, degrees of freedom (Df) and *p*-values from Wald *F*-tests included in the generalised linear mixed model describing proximal catches of white sharks (*Carcharodon carcharias*) on SMART drumlines at three regions (Ballina, Evans Head and Forster) off New South Wales, Australia during 2016–18.

(A)		
Random factor	Component	% variance
Moon phase	0.0	–
Sea state	0.2	1.7
Water visibility	0.1	3.3
Wind direction	0.3	6.9
Cloud cover	0.1	3.5
Water depth	0.0	–
Barometer	0.0	–
spl(sea surface temperature)	0.0	–
Residual	3.3	84.6
(B)		
Fixed factor	Df	*p*-value
Sea surface temperature	1	0.00
Region	2	0.70
Effort	1	0.50

Random terms are expressed as a percentage of the total variance on the underlying (logistic) scale.

diel performances. Many studies have identified relatively greater catches among nocturnally than diurnally deployed gillnets in various commercial fisheries (e.g. Gray et al., 2005), which can be explained by some bias towards greater nocturnal activity among target species (Niella et al., 2021a, b) including diel patterns in swimming depth potentially affecting gillnet interactions (Wallace, 1972), but perhaps, most importantly, reduced visibility of the meshes (Hamley, 1975; Broadhurst and Cullis, 2020). Similarly, owing to species-specific feeding and movements, many baited-hook configurations also catch more sharks (and different species) at night (Broadhurst et al., 2014; Butcher et al., 2015). More specifically for SMART drumlines, Guyomard et al. (2019) reported that bull and tiger sharks were primarily caught on SMART drumlines set off Réunion Island at night.

In the present study, the SMART drumlines were restricted to diurnal deployments only, aligning with the dual objectives of the NSW government to minimise the risk of shark interactions when people are in the water, and to minimise impacts to sharks and other marine life. Consequently, any interpretations of relative catching performances, including the proximal catches of white sharks, along with bycatch are limited to daylight hours. Catches would probably differ during nocturnal deployments, which warrants consideration if gillnets are replaced with diel-deployed SMART drumlines to maintain a current strategy (in all jurisdictions) of continuous deployment of bather-protection fishing gear.

Regardless of confounded temporal deployments between gears here, if the number of diurnally foraging and/or transiting white sharks equates to potential risk to humans (Hazin and Afonso, 2014), SMART drumlines may provide a viable alternative to gillnets. In terms of the number required (first research question), because proximal captures were rare and the fishing effort (number of drumlines) was not a significant predictor of their occurrence, a minimum of two or possibly three diurnally deployed SMART drumlines per beach would suffice. This would mean that at least one SMART drumline was actively fishing while the other was cleared. Such a deployment strategy is supported by historical fishing effort (and the implied bather protection) for conventional (and likely much less effective) drumlines in South Africa (Dudley, 1997), but less than those in Queensland (Gribble et al., 1998a), although the latter are probably affected by de-baiting by dolphins.

There are other considerations beyond any difference in relative catching efficiencies of SMART drumlines and gillnets. For example, there have been some community concerns over the potential of drumline baits (all types) to attract sharks into nearshore waters, thereby increasing the potential for bites (Simmons and Mehmet, 2018; Martin et al., 2022). Our results indicate the low volumes represented by SMART drumline baits (~1 kg each or ~15 kg over 5–15 km) did not elicit aggregating responses among the three target sharks during daylight. Similarly, Guyomard et al. (2020) showed that SMART drumline baits did not attract bull sharks into nearshore waters, while during a 27-month trial targeting white sharks off Gracetown, Western Australia, only two individuals were caught, despite telemetry data indicating the population of available conspecifics were within the range of sizes successfully hooked off NSW (Taylor et al., 2022). Although it remains unclear how much food and the period required to aggregate any of the target sharks, the data here indicate that deploying up to 20 hooks over a small area does not increase proximal captures, even with some lines positioned only 100–150 m apart (i.e. SMART drumlines trials at Evans Head).

Another consideration for deploying SMART drumlines instead of gillnets is a need to maintain relative size selectivity, and especially for larger sharks that may inflict more serious injuries. While the data are few and mostly spatio-temporally confounded, SMART drumlines and gillnets fished in NSW have caught similar sizes of all three species, including white sharks over 3.6 m FL. Of the 577 white, tiger and bull sharks caught in the NSW gillnets since 1990, only 17 have been over 3.6 FL. Similarly, drumlines and gillnets in Queensland have caught white sharks over 3.6 m FL but not larger than 4.4 m FL (Cardno, 2019). While low numbers of these larger white sharks were caught in either gear, which may simply reflect selectivity and/or size-specific segregation, it is also known from telemetry tracking of sub-adult and adult white sharks off eastern Australia, that large white

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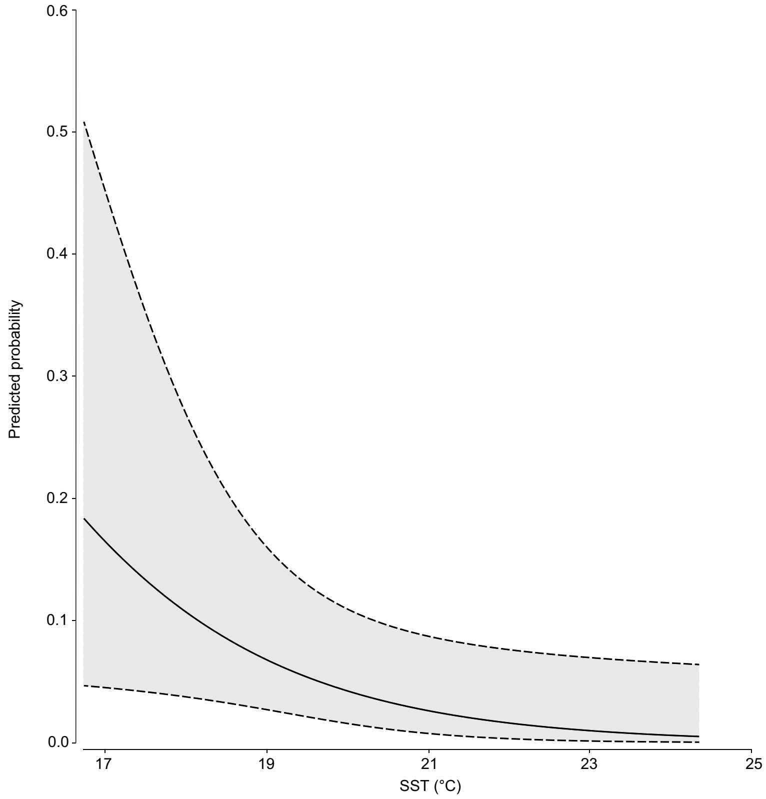

FIGURE 4
Predicted probabilities of proximal white shark (*Carcharodon carcharias*) captures on SMART drumlines at three regions (Ballina, Evans Head and Forster) off New South Wales, Australia during 2016–18 and associated 95% confidence intervals (grey bands) for the recorded sea surface temperatures (SST; °C).

sharks infrequently venture into shallow nearshore waters off eastern Australia (Coxon et al., 2022). Furthermore, although adult bull shark distributions in NSW are positively correlated to water temperatures >20°C (Smoothey et al., 2023), catches of this species in both gears were low throughout the latitudes fished, despite being frequently detected on tagged shark listening stations along the coast. Similarly, low bull shark catches have been recorded between 2001 and 2019 from gillnets (n=35) and

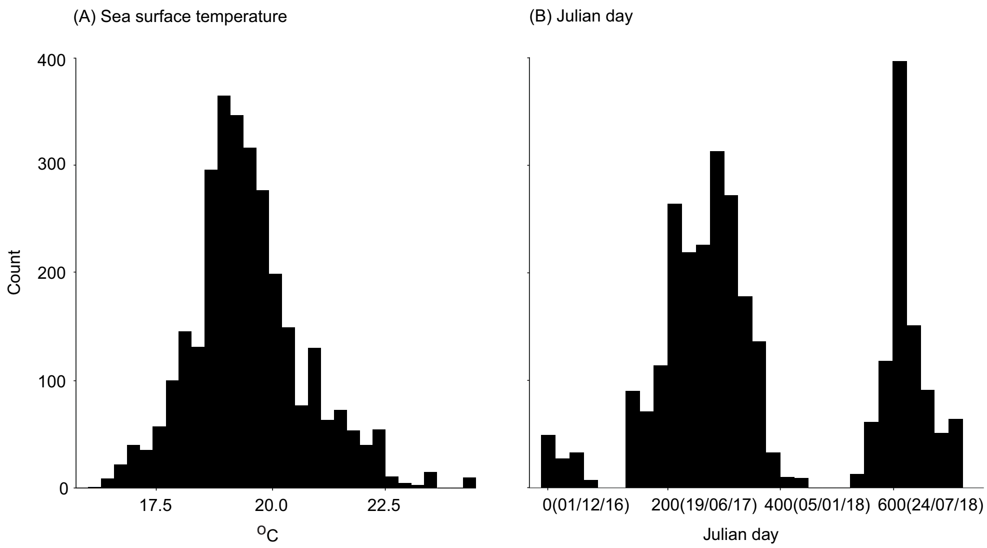

FIGURE 5
Counts of observations by **(A)** sea surface temperature (°C), and **(B)** Julian day for each proximal white shark (*Carcharodon carcharias*) capture on SMART drumlines at three regions (Ballina, Evans Head and Forster) off New South Wales, Australia during 2016–18.

TABLE 5 The species (alphabetical order), and their total numbers, at-vessel mortalities and mean (± SD) fork lengths (FL; m) caught in gillnets during 1990–2021 off New South Wales, Australia, and the mean (± SE) postulated percentage of diel SMART drumline deployments achievable within the capture windows (i.e., 72 to 96 h periods between gillnet checks that sharks were caught).

Species	Total caught	Mortality (%)	FL (m ± SD)	SD deployment (% ± SE)
Bronze whaler (*Carcharhinus brachyurus*) [1]	154	84.4	2.3 ± 0.4	79.1 ± 0.1
Bull shark (*Carcharhinus leucas*)[1]	25	68.0	2.3 ± 0.4	78.7 ± 0.7
Common blacktip (*Carcharhinus limbatus*) [1]	112	94.6	1.9 ± 0.3	74.1 ± 0.2
Dusky whaler (*Carcharhinus obscurus*) [1]	113	87.6	2.4 ± 0.9	78.5 ± 0.1
Mako (*Isurus* spp.)	10	90.0	1.6 ± 0.6	82.5 ± 1.6
Shortfin mako (*Isurus oxyrinchus*)	105	92.4	1.6 ± 0.4	74.3 ± 0.2
Silky shark (*Carcharhinus falciformis*) [1]	17	100.0	1.3 ± 0.6	80.9 ± 0.9
Spinner shark (*Carcharhinus brevipinna*) [1]	35	94.3	1.8 ± 0.5	66.6 ± 0.4
Tiger shark (*Galeocerdo cuvier*)	83	84.3	2.9 ± 0.5	76.6 ± 0.2
Unidentified sharks	7	100.0	1.9 ± 0.6	75.0 ± 0.2
Whaler sharks (*Carcharhinus* spp.)	556	93.2	2.5 ± 0.6	74.2 ± 0.0
White shark (*Carcharodon carcharias*)	290	71.7	2.0 ± 0.5	72.6 ± 0.1

[1]Species were only separated from 'whaler sharks' post 2010.

drumlines (n=10) fished off the Gold Coast in southern Queensland (Cardno, 2019). Low catches from Queensland and South Africa have led to the recommendation that a mixed-gear strategy combining gillnets and baited hooks should be used to minimise bycatch whilst maximising the capture of target sharks (Dudley, 1997; Gribble et al., 1998b).

Maintaining bather-protection programs involving fishing gears that maximise catches of target sharks will depend on the priority target species and their diel nearshore presence and behaviour. To reduce bycatches and fishing mortality in NSW, SMART drumlines are only fished diurnally at present with contractors determining safety to launch in response to capture alerts. Approximately half of the ports in NSW involve passing through a river mouth and crossing a sand bar enroute to sea. This leads to daily changes in environmental conditions substantially impacting the ability to deploy and retrieve SMART drumlines and/or deal with captures, and some regions cannot currently be fished with SMART drumlines due to the lack of safe passage and/or substantially increased travel time from the nearest safe access. Such limitations do not extend to gillnets for various reasons, including that they are continuously deployed and the contractors only check within 72 h. This enables flexibility around prevailing weather conditions. If gillnets are replaced by SMART drumlines between Newcastle and Wollongong, determining the effects of reduced fishing effort (identified here as 76% of the period target sharks were caught) due to inclement environmental conditions will have to be weighed against the likelihood that any such reduction is potentially offset by fewer water users due to those inclement and/or nocturnal conditions.

Any such calculations are confounded by few empirical data to support using fishing gear to minimise shark-human interactions. Recently, Huveneers et al. (2024) compared trends in shark bites within NSW waters in relation to whether there were any mitigation measures deployed and, if so, the type, and concluded that the low incidence and variable geographical distributions precluded calculating the utility of any category of measures for reducing interactions (except intact enclosures). These results highlight the difficulty in determining the effectiveness of preventative measures for very rare events. A cluster of shark bites led to gillnetting starting off Sydney beaches in 1937 (Reid and Krogh, 1992), whilst a series of bites off northern NSW during 2014/15 precipitated a broader

TABLE 6 Summaries of (A) variance components, and percentage of total variance accounted for by each random term and (B) fixed effects, degrees of freedom (Df) and *p*-values (from Wald *F*-tests) included in the generalised linear mixed model describing catches of white (*Carcharodon carcharias*) and tiger sharks (*Galeocerdo cuvier*) in bather-protection gillnets deployed off New South Wales, Australia between 1 September and 30 April each year from 1990 to 2020.

(A)		
Random factor	Component	% variance
Region	0.1	1.8
Year	0.1	1.8
Beach	0.0	1.0
Residual	3.3	95.5
(B)		
Fixed factor	Df	*p*-value
Species	1	0.4
Sea surface temperature	1	0.9
Month	8	0.0

TABLE 7 Numbers of gillnetted tiger (*Galeocerdo cuvier*) and white sharks (*Carcharodon carcharias*) separated by each month and gillnetting region during 1990–2021 off New South Wales, Australia, and the associated mean (± SE) postulated percentage of diel SMART drumline deployments achievable within the capture windows (i.e., 72 to 96 h periods between gillnet checks that sharks were caught).

	Species		SMART drumline deployment (% ± SE)	
	Tiger shark	White shark	Tiger shark	White shark
Month				
January	15	28	74.3 ± 1.1	69.8 ± 0.6
February	10	9	82.0 ± 0.7	76.4 ± 1.4
March	10	10	71.8 ± 1.8	71.3 ± 1.9
April	19	13	80.8 ± 1.0	79.4 ± 1.7
↓ May –August (no gillnets deployed)				
September	6	73	94.6 ± 1.0	76.6 ± 0.2
October	2	65	73.8 ± 9.7	68.9 ± 0.2
November	7	52	69.3 ± 2.6	70.5 ± 0.3
December	14	37	68.9 ± 0.9	71.3 ± 0.4
Gillnetting region				
Illawarra	33	55	77.4 ± 0.6	79.1 ± 0.3
South Sydney	21	26	73.1 ± 0.7	76.4 ± 0.6
Central Sydney	6	10	75.4 ± 2.0	77.8 ± 1.3
North Sydney	8	17	87.8 ± 1.2	77.4 ± 0.8
South Central Coast	4	37	81.3 ± 2.1	67.8 ± 0.3
North Central Coast	7	67	76.4 ± 3.0	73.5 ± 0.2
Hunter	4	78	62.5 ± 1.3	66.5 ± 0.2

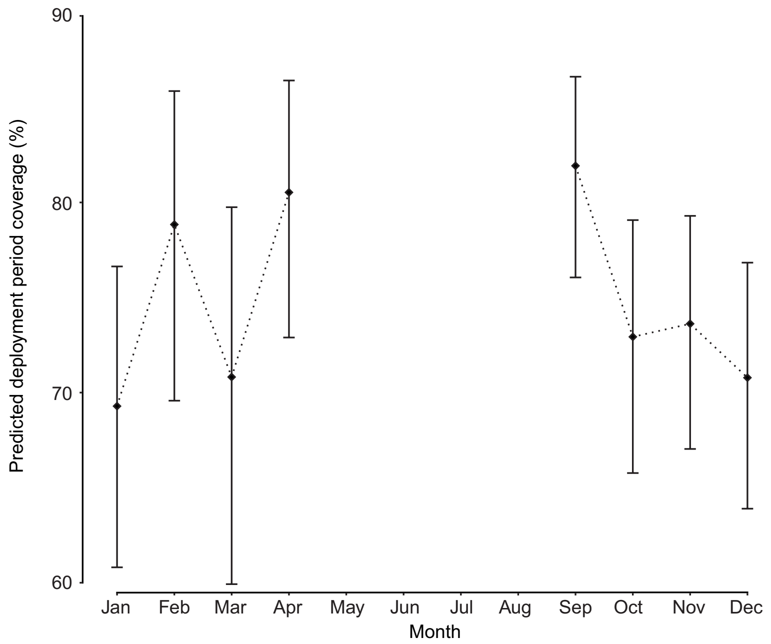

FIGURE 6
Predicted probability of SMART drumline coverage for capture period (solid line) with associated lower and upper bounds for proximate 95% confidence intervals (dashed line) for each month Note[1] no gillnets were deployed between 1 May and 31 August each year.

shark-bite mitigation trial (https://www.sharksmart.nsw.gov.au/). These reactions to shark bites highlight decadal priorities by the NSW government to improve safe bathing at popular ocean beaches. Nevertheless, often conservation concerns evoke controversy (Simmons et al., 2021), precipitating what is known as a "wicked problem" (Churchman, 1967; Niella et al., 2021a). Ultimately, resolution of this wicked problem requires greater clarity on the benefits of using fishing gear (lethal or otherwise) to displace target sharks (and presumably mitigate bites on humans), and then the acceptable ecological costs in doing so.

5 Conclusions and future work

Despite the demonstrated effectiveness of SMART drumlines for catching white sharks and minimising bycatch with low at-vessel mortality rates, this research shows gillnets can catch all three target sharks at times when SMART drumlines cannot be deployed due to inclement weather. Recognising that, except for robust swimming enclosures, none of the options within the four mitigation categories (i.e. (1) removing humans from problematic water bodies, (2) lethal fishing gear to remove target sharks, (3) relocating live sharks elsewhere, or, (4) human and sharks co-existing) are a panacea for shark-bite mitigation, policymakers should consider the relative jurisdictional costs, and respective strengths and weaknesses (McPhee et al., 2021; Huveneers et al., 2024), plus levels of societal acceptance, when developing shark-bite mitigation strategies. Other than completely separating sharks from humans, it is extremely unlikely that any single or multiple strategy can be 100% effective at negating interactions between sharks and humans at ocean beaches. This limitation highlights the importance of education among both governments and beachgoers for collective responsibility.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal study was approved by NSW DPI provided scientific (Ref. P01/0059(A)), Marine Parks (Ref. P16/0145-1.1) and animal care and ethics (ACEC Ref. 07/08, 08/06) permits. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

PB: Writing – original draft, Writing – review & editing. MB: Writing – original draft, Writing – review & editing. VP: Writing – original draft, Writing – review & editing. AM: Writing – original draft, Writing – review & editing. BC: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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