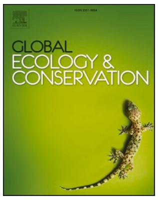
Global Ecology and Conservation 62 (2025) e03752

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco



Original research article

Best practices for mitigating seabird bycatch on Taiwanese albacore longline fishing vessels operating in the southeastern Atlantic Ocean

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ARTICLE INFO

Keywords:
Seabird bycatch
Longline fishery
Albacore
Mitigation measures
Bird-scaring line
Weighted branch line

ABSTRACT

Seabird bycatch—particularly involving albatrosses and petrels—remains a significant conservation concern in pelagic longline fisheries. This study evaluated the effectiveness of three mitigation measures—bird-scaring lines (BSLs), weighted branch lines, and night setting—in reducing seabird bycatch in the Taiwanese albacore (Thunnus alalunga) longline fishery operating in the southeastern Atlantic Ocean. Observations were conducted aboard a commercial vessel during 103 longline sets in 2013. Four BSL treatments were tested: single and double conventional BSLs and single and double experimental BSLs recommended by the International Commission for the Conservation of Atlantic Tunas (ICCAT), each combined with either weighted (60 g at 3 m from the hook) or unweighted branch lines. A total of 298 seabirds were caught during line setting, with an additional 18 birds caught and released alive during hauling and trolling. Night setting emerged as the most effective mitigation measure, with a bycatch rate of 0.046 birds per 1000 hooks—substantially lower than the 1.101 birds per 1000 hooks recorded during daytime setting. While BSLs effectively deterred seabird attacks within their aerial extent, their efficacy declined when baited hooks remained within the diving range of seabirds beyond this zone. Weighted branch lines reduced seabird bycatch by 61 %; however, they were also associated with a potential decrease in albacore catch rates. Our findings highlight that the effectiveness of best practice mitigation—namely, the combined use of BSLs and weighted branch lines—depends on ensuring that baited hooks reach depths beyond seabird diving capabilities before exiting the aerial extent of the BSLs. Further optimization is needed to balance conservation outcomes with fishery performance.

1. Introduction

Many seabirds face significant threats from human activities at sea (Melvin et al., 2023; Votier et al., 2023). Among all the threats, fisheries bycatch poses one of the most severe risks, particularly for species with large body sizes, slow reproductive rates, specialized

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https://doi.org/10.1016/j.gecco.2025.e03752
Received 1 January 2025; Received in revised form 22 June 2025; Accepted 13 July 2025

diet and distinct foraging behaviors, such as albatrosses and petrels within the Procellariiformes (Jimenez et al., 2010, 2011; Richards et al., 2024, 2020; Robertson et al., 2006; Seco Pon et al., 2007). The impact of fisheries on seabird conservation has been widely studied across various spatiotemporal dimensions and seabird species (Collins et al., 2021; Li et al., 2016; Votier et al., 2023), with bycatch rates commonly used as a key metric to evaluate these effects (Lewison et al., 2004). Currently, seabird bycatch rates are primarily determined by four factors: overlap between seabird and fishery distributions, fishing gear configuration, seabird behaviors, and seabird abundance (Anderson et al., 2011; Huang and Yeh, 2011; Jiménez et al., 2020).

Although multiple factors influence seabird bycatch, their effects can vary widely depending on how they interact in specific ecological and fishing operational context. While spatial overlap between seabirds and fisheries plays a crucial role in determining bycatch rates (Calado et al., 2021; Jiménez et al., 2020), changes in fishing gear configuration can significantly reduce seabird bycatch risks (Oliveira et al., 2015). Studies have demonstrated that modifying gear design and fishing operations to reduce seabird access to bait can markedly decrease bycatch (Melvin et al., 2013, 1999). Seabird behavior also strongly affects bycatch rates. For example, white-chinned petrels (*Procellaria aequinoctialis*) aggressively compete for bait, offal, and discards, leading to high bycatch rates in the Southern Ocean longline fisheries (Weimerskirch et al., 2000). In contrast, white-bellied storm petrels (*Fregetta grallaria*) and black-bellied storm petrels (*Fregetta tropica*) frequently attend longline vessels but rarely attack bait, leading to low bycatch rates (Bugoni et al., 2008). From the perspective of seabird abundance, fisheries with a high likelihood of bycatching endangered species require specific regulations (Geernaert, 1999).

With one of the largest distant-water fishing fleets in the world, Taiwan has implemented various mitigation measures to reduce seabird bycatch in its high-seas longline fisheries, in line with international conservation efforts and recommendations from Regional Fisheries Management Organizations (RFMOs). In support of these efforts, Taiwan established its National Plan of Action for Reducing the Incidental Catch of Seabirds in Longline Fisheries (NPOA-Seabirds) in 2014 (Fisheries Agency, 2014). These measures aim to minimize interactions between seabirds and longline fisheries, thereby promoting seabird conservation and reducing bait loss (FAO, 1999). These measures can be categorized as those that prevent seabirds from seeing bait and those that render baited hooks inaccessible. Measures that reduce bait visibility include discarding offal on the opposite side of baited hooks to distract seabirds, and setting longlines at night (Gilman et al., 2008). Measures that render baited hooks inaccessible include installing a hook-shielding device, deploying bird-scaring lines (BSLs) and using weighted branch lines to increase the sink rate of baited hooks beyond the reach of seabirds (Melvin et al., 2014). Among those measures, the simultaneous use of BSLs, weighted branch lines, and night setting are recommended best practice by the Agreement on the Conservation of Albatrosses and Petrels (ACAP) (ACAP, 2024). All five tuna RFMOs have adopted seabird conservation measures that require vessels operating in areas overlapping with seabirds to implement a combination of mitigation measures selected from approved options.

BSLs are streamers that hang from a line attached at a high point near the stern of a fishing vessel, creating a barrier to prevent seabirds from accessing baited hooks (Løkkeborg, 2003). Evidence suggests that BSLs are particularly effective in regions with less diverse seabird assemblages that are dominated by shallow-diving albatrosses (Melvin et al., 2014; Sato et al., 2013). However, they are less effective in regions where seabirds exhibit greater diving abilities (Baker and Wise, 2005). The effectiveness of BSLs is also influenced by gear configuration and fishing operations (Melvin et al., 2014; Yokota et al., 2008). To optimize the aerial coverage of BSLs, adjustments can be made to the height of the tori pole, the length and material of the main line, the towed object (to prevent tangling), and the arrangement of streamers (Melvin et al., 2004; Proceedings of the Symposium, 2001; Yokota et al., 2008).

Weighted branch lines increase the sink rate of baited hooks, thereby reducing their accessibility to seabirds (Robertson et al., 2010, 2006). This is achieved by using branch lines with lead cores or adding lead weights near the hooks. The sink rate, which is typically measured at specific depths (e.g., 2, 5, and 10 m) and by the distance astern of the vessel to reach these depths, can help with evaluating the effectiveness of line weighting regimes (Anderson and Mcardle, 2002; Melvin et al., 2014). Appropriate benchmark depths are determined by factors such as the diving abilities of seabirds, the speed of a vessel during line setting, and the aerial coverage of BSLs.

Night setting is another highly effective mitigation measure for reducing seabird bycatch (Løkkeborg, 2008) because many seabird species are most active near dawn and dusk (BirdLife International Global Seabird Programme, 2009). Sánchez and Belda (2003) demonstrated in the area around the Columbretes Islands (northwestern Mediterranean) that Cory's shearwaters (*Calonectris diomedea*) are active at night, but despite this, bait loss from seabird attacks was approximately 80 % lower when setting lines at night than during sunrise or sunset. However, since the duration of daytime can be long in the high latitude in the summer, deploying a complete set at night can be challenging for fisheries operating at high latitude (Melvin et al., 2014). In some pelagic longline fisheries, due to the significant impact of operating times (day versus night) on the composition of catch species, there may be a reluctance to adopt seabird bycatch mitigation measures such as night setting (Orbesen et al., 2017). Thus, night setting is often rejected in favor of other mitigation measures. In addition, the effectiveness of night setting in reducing seabird bycatch, particularly albatross bycatch, decreases as moon illumination increases, necessitating the use of additional measures such as BSLs to achieve optimal outcomes (Jiménez et al., 2020).

Studies on the effects of different mitigation measures on target catch have reported diverse findings, highlighting the variations in fishing practices and target species behaviors (Avery et al., 2017; Robertson et al., 2013). Some studies have indicated that mitigation measures such as BSLs, night setting, and weighted branch lines can markedly reduce seabird bycatch without reducing target catch (Avery et al., 2017). However, other studies have suggested that although weighted hooks reduce seabird bycatch, they can alter fishing dynamics, necessitating adjustments in fishing techniques to avoid reductions in target catch (Sato et al., 2016; Yokota et al., 2008).

This study aims to identify the most effective mitigation measures for reducing seabird bycatch while minimizing impacts on target species catch in Taiwan's longline fishing fleet operating in the Atlantic Ocean. The Taiwanese longline fishery operates in the southeastern Atlantic Ocean and targets albacore (*Thunnus alalunga*). Previous observations have revealed that 28 seabird species are caught as bycatch by this fleet in the Atlantic, and the most frequently caught of these species are black-browed albatross (*Thalassarche melanophris*), yellow-nosed albatross (Atlantic) (*Thalassarche chlororhynchos*), wandering albatrosses (*Diomedea exulans*), spectacled petrel (*Procellaria conspicillata*), and southern giant petrel (*Macronectes giganteus*) (Yeh et al., 2013). Longline fishing in the study area is subject to regulations under the International Commission for the Conservation of Atlantic Tunas (ICCAT). ICCAT adopted Recommendation 11–09, which requires longline vessels located south of 25°S to implement at least two mitigation measures chosen from BSL, weighted branchline, and night setting. Although these recommendations are based on scientific evidence (Jiménez et al., 2020; Melvin et al., 2023; Rollinson et al., 2017), their effectiveness may vary across fleets and encountered species assemblage, necessitating performance evaluations for commercial longline fleets (Favero and Seco Pon, 2014; Melvin et al., 2019). Therefore, we conducted an experiment to assess the effectiveness of BSLs configured according to the conventional practices of Taiwanese skippers, comparing them to BSLs that meet ICCAT standards. Additionally, we examined whether the simultaneous use of BSLs with weighted branch lines,

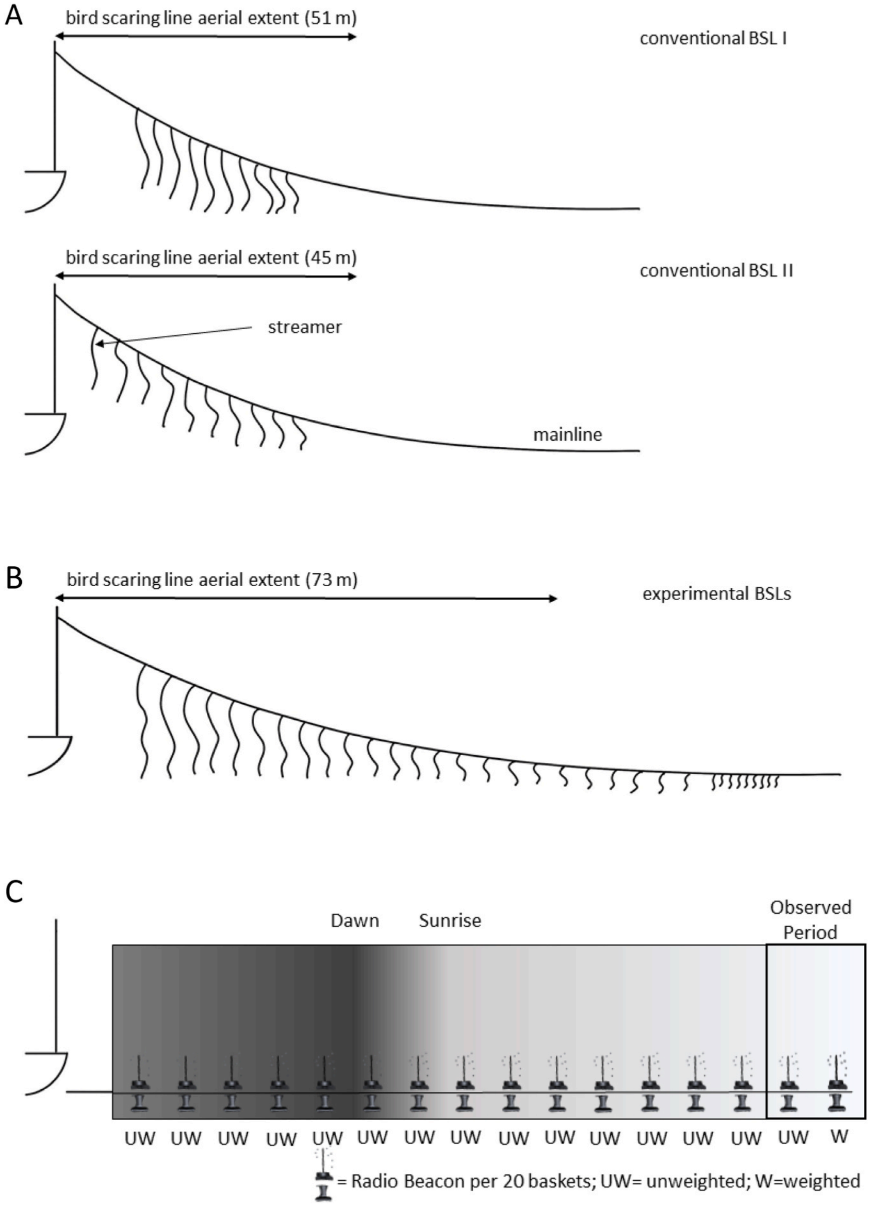

Fig. 1. A. Schematic diagrams of the conventional bird-scaring line (BSL) configuration, showing their respective aerial extents. B. Schematic diagram of the experimental BSL configuration, showing their respective aerial extent. C. Illustration of the experimental design comparing weighted and unweighted branchlines. In each set, the final segment consists exclusively of weighted branchlines, while all preceding segments use unweighted branchlines. The last two segments also correspond to the observation periods during which seabird abundance and attack behaviors were recorded. On average, approximately one-third of the sets were deployed at night.

or BSLs with night setting further improved seabird bycatch mitigation. It is important to note that the experimental BSLs used in this study did not meet ICCAT's minimum aerial extent requirement of 100 m for vessels over 35 m in length, nor did the night setting fully comply with ICCAT guidelines. This deviation reflects the operational constraints and prevailing practices of the Taiwanese longline fishery, allowing an assessment of mitigation performance under real-world conditions. In this study, we measured both seabird bycatch rates and albacore catch rates to evaluate the trade-offs between conservation and fishery efficiency. The results provide critical insights into optimizing seabird bycatch mitigation strategies for Taiwan's longline fleet while maintaining albacore catches in the Atlantic Ocean.

2. Methods

2.1. Longline vessel and gear

The experiment was conducted in 2013 aboard a commercial pelagic longline vessel targeting albacore tuna in the southeastern Atlantic Ocean. The vessel had a gross tonnage of 363 tons and a length of 42 m. Data were collected over 103 sets. Sardines (*Sardina pilchardus*) with an average weight of 86 g and an average length of 20 cm were used as bait. The conventional branch lines were 31 m long and did not have lead swivels, and each basket contained 12 conventional albacore hooks (3.2 sun). On average, 3800 hooks were used in each operation. The main line was set using a line shooter at a speed of 5.3 knots sinking to a target depth of 90–200 m. Bait was cast manually at a typical boat speed of 8.7 knots over the ground; the bait landed in a zone between the vessel and BSLs. Typically, one deployment was performed per day. Approximately 80 % of these operations began between 3 am and 6 am, with none starting later than 9 am, and around 80 % ended between 8 am and 1 pm. The average setting duration was approximately six hours, and the duration of 80 % of the operations ranged from 5.5 to 7 h.

2.2. Experimental design

2.2.1. BSLs

Four BSL-based mitigation measures (referred to as treatments) were evaluated in this study: a measure involving a single-conventional (SC) BSL, a measure involving double-conventional (DC) BSLs, a measure involving a single-experimental (SE) BSL, and a measure involving double-experimental (DE) BSLs. The conventional BSLs were designed by Taiwanese fishers, whereas the experimental BSLs were designed following the ICCAT Recommendations (ICCAT, 2011).

One conventional BSL was approximately 65 m long. It had streamers made of light blue polypropylene strips and yellow packing strap material. The streamers were 67–87 cm long and attached every 32 cm, with the exception of the first streamer that positioned closest to the stern (11 m away). The other conventional BSL was approximately 64 m long. It had streamers made of the same materials as those used in the aforementioned main line. The streamers were 72–87 cm long and attached every 73 cm, with the exception of the first streamer that positioned closest to the stern (6 m away). Both conventional BSLs were equipped with 10 streamers (Fig. 1A). The crew arbitrarily selected one of the two BSLs for SC treatment to mimic real-world conditions.

The experimental BSLs were 125 m long. These lines had streamers made of blue and red polypropylene strings and yellow packing strap material arranged arbitrarily. The first streamer was positioned closest to the stern (10 m away). The subsequent streamers were 1.5–10 m long and attached every 2.5 m for the first 100 m of the main line. Beyond this distance, the streamers were 1 m long and attached every 0.5 m (Fig. 1B). The BSLs were attached to tori poles on the upper deck, positioned to the port and starboard sides of the stern.

A set was treated as an experimental unit. Considering feasibility constraints on a commercial vessel, we adopted a systematic design instead of randomization. To ensure a balanced distribution of data across treatments, the trip duration (days) was divided into specific sequences. For the first 20 days, the treatments were assigned in the following order: SC, DC, SE, and DE. In the subsequent days, the treatments were applied in a reverse order: DE, SE, DC, and SC. In total, 103 sets were conducted.

2.2.2. Weighted branch lines

Each set was stratified into several segments by radar beacons; each segment comprised 20 baskets, with a total of 240 hooks. To avoid interference in commercial fishing operations, a 60-g lead swivel was attached 3 m above the hook on branchlines in the last (20th) basket of each set. A total of 240 lines per set were deployed with line weights (6.25 % of all hooks set). Our focus was on the sink rate of baited hooks (Fig. 1C).

To estimate the sink rate of baited hooks for each set, four time–depth recorders (TDRs) were attached to the shallowest (closest to the floats) and deepest (furthest from the floats) hooks of two adjacent baskets in both unweighted and weighted branch lines. The TDRs were positioned 0.3 m above the hooks. The sink rate of baited hooks was assumed to be independent of other hooks (Anderson and Mcardle, 2002). On the basis of the depth of the baited hooks and the presence of a 60-g swivel weight, we formed four experimental configurations: shallow without weight, shallow with weight, deep without weight, and deep with weight.

2.3. Data collection

Data pertaining to the physical environment and vessel operations were collected during line setting. The collected data included the latitude and longitude at the setting location, maximum visibility, moon phase, sea surface temperature, set duration, BSL's aerial coverage, swell height, total hook count, vessel speed, and wind speed (Beaufort Sea state) and direction.

Trained observers recorded the numbers of seabird attacks on baited hooks and seabird sightings during the daylight hours of each set during both the setting and hauling processes. The observers recorded primary and secondary attacks during the setting and hauling of the last gear segment of unweighted branch lines and the gear segment of weighted branch lines; each observation lasted approximately 15–20 min per segment. Therefore, a total of 49,440 hooks were observed during line setting operations, based on 40 baskets sampled per set across 103 sets.

A primary attack was considered to be an individual bird attempting to take bait from a hook, typically by making a dive, lunge, or plunge directly over a sinking hook. A secondary attack was considered to be a case in which another bird or a group of birds attempted to steal bait from a bird that had successfully taken it to the surface after a primary attack. A foraging guild was defined as the primary foraging strategy used by a species. Wilman et al. (2014) quantified the foraging strategies of various species by assigning scores ranging from 0 % to 100 % for each guild, with these scores reflecting the relative usage of specific strategies. On the basis of these scores, this study categorized the seabirds into divers and surface feeders. Each seabird species was classified into either guild in accordance with its predominant foraging strategy, determined by a score of $\geq$ 50 %.

During line setting, both diving and surface foraging attacks were recorded in 1 of 21 locations delineated by 7 longitudinal areas (0–25, 26–50, 51–75, 76–100, 101–125, 126–150, and 151–200 m astern) and 3 lateral areas (within the 2 BSLs, port side of the port line, or starboard side of the BSL). Markers were inserted into the BSLs to establish reference points for estimating distance astern. In addition, gear floats were used as reference points; floats were positioned between the baskets, and the distance between two consecutive floats was approximately 330 m. This distance was estimated by calculating the total distance between the coordinates at the start of the first hook and the end of the last hook, divided by the total number of baskets. Observers visually recorded the longitudinal areas using these two reference points. Seabirds sighted (in the air and on water) within a 250-m hemisphere centered at the stern midpoint were counted and stratified by species before the estimation of attack rates.

During hauling, one observer recorded fish catches by species over two 4-hours observation periods as well as the order and specifications of the hooks that caught the fish. Another observer recorded seabird bycatch by species during the retrieval of all hooks as well as the order and specifications of the hooks that caught the seabirds.

Based on these records and the assumption that the setting operation was conducted at a constant speed, this allowed us to distinguish whether specific baskets were deployed during daylight or nighttime operations. During hauling operations, observers recorded the basket number where fish and seabird bycatch events occurred. By integrating these records, we retrospectively determined whether caught fish and bycaught seabirds were captured by the night or daylight setting operations.

The Star-Oddi DST Centi–TD loggers were used as TDRs, measuring depth with ±0.4 % accuracy. Data were recorded at 1-s intervals while hooks were in the water. Depth and time were sampled at 0.5-m and 1-s intervals, respectively.

2.4. Statistical analysis

Given the availability of species-specific data and the assumption that adjacent segments within each set were subject to similar environmental and operational conditions, paired t-tests were conducted to compare the rates of primary and secondary seabird attacks between unweighted and weighted branchlines during line setting. The use of adjacent segments as matched pairs served as a control to minimize variability unrelated to the treatment. Sink profiles with unweighted and weighted branch lines were derived using TDRs to estimate how far astern baited hooks reached specific depths. A two-way ANOVA was performed to compare mean sink times at three depths (2, 5, and 10 m) between unweighted and weighted branch lines.

The relationships between seabird bycatch rate (number per 1000 hooks) and 13 explanatory variables—latitude, longitude, vessel speed, weather, wind speed, wind direction, wave height, depth, temperature, BSL type, branchline weighting, month, and night setting ratio (NightSR)—were examined using a generalized linear model (GLM). The NightSR was defined as the proportion of hooks deployed at night within a given set, where NightSR = 0 indicates a fully daylight set and NightSR = 1 indicates a fully night set.

Bycatch rates for weighted and unweighted branchlines were calculated separately for each set. Night setting was defined as any setting activity occurring between the end of nautical twilight in the evening and before nautical dawn in the morning. Since commercial albacore vessels typically did not conduct full night sets, NightSR was used as a proxy to assess the influence of partial night setting on seabird bycatch. A negative binomial distribution was applied to the model to account for potential overdispersion in the bycatch data.

Generalized linear mixed models were used to investigate the effects of various mitigation measures on albacore catch rates. The fixed factors included latitude, longitude, day–night (if albacore was caught by daytime or nighttime setting hooks), branch line weighting, soak time, and BSL type. Albacore catch rates with weighted and unweighted hooks, by daytime or nighttime setting hooks, were calculated separately. In a typical set operation, the gear was deployed in multiple segments, usually 16 or 17. We defined soak time as the average operational duration of a single segment, measured in relation to the order of immersion. Specifically, soak time was calculated in reverse order of deployment, using the last segment as the reference point. The soak time of each segment represented the number of unit times that a segment remained submerged compared to the last segment. For example, in a set operation with 16 segments, fish catch records were obtained during the hauling operation using two observation shifts, each lasting four hours. During these shifts, we recorded catch data for segments 7, 8, 14, 15, and 16, with segment 16 being the last deployed. The corresponding soak times for these segments were 9, 8, 2, 1, and 0, respectively. Considering that the duration each segment remained in the water might affect the target catch, we incorporated soak time as a variable in the GLMM model to account for its potential impact. Fishing set and gear segments were regarded as random effects to account for overdispersion (Breslow, 1990).

3. Results

3.1. Trip information

Fishing sets were conducted from April 27 to August 17, 2013. Initially, vessels operated around 35°S and 15°E; however, because of severe weather in early June, they moved northward to approximately 30°S and then continued westward to approximately 5°W. The overall distribution of the fishing sets extended from approximately 35°S, 10°W to 35°S, 15°E (Fig. 2). A total of 103 fishing sets were conducted. The SC, DC, SE, and DE treatments were applied for 24, 22, 29, and 28 sets, respectively. A total of 48,382 hooks were observed to record seabird sightings and attack behaviors across the different treatments. During the study period, BSLs broke twice, and streamers tangled with BSLs five times; these instances were excluded from relevant analyses. Fig. 2 depicts the locations of the sets corresponding to different BSL treatments.

During the study period, the wind speed ranged from 0.6–3 knots (light air) to 21–26.9 knots (strong breeze). The wave height ranged from 0 to 4 m. The fishing sets typically began between 3 and 6 AM and lasted 6–6.5 h; after 0.5–1 h, hauling began. Setting 20 baskets required approximately 20 min, whereas hauling them required approximately 1 h. For most sets, the last 40 baskets remained in the water for 2 h, whereas some remained for 4 h. Two sets lasted for up to 17 h.

3.2. Seabird interactions

We observed 22 species of seabirds during setting and hauling (Table 2 and Table A1). The most frequently observed seabird species during the study were White-chinned Petrel and Great Shearwater. The most frequently observed seabird species—recorded on > 70 % of all sets—were the white-chinned petrel, spectacled petrel, cape petrel (*Daption capense*), black-browed albatross, and yellow-nosed albatross (Atlantic) (Fig. 3). Among the divers, the most abundant species were the white-chinned petrel, spectacled petrel, and great shearwater; on average, approximately 30 great shearwaters were noted per observation in regions located south of 35°S. Among the surface feeders, the most abundant species were the black-browed albatross and cape petrel. Our observations align with the

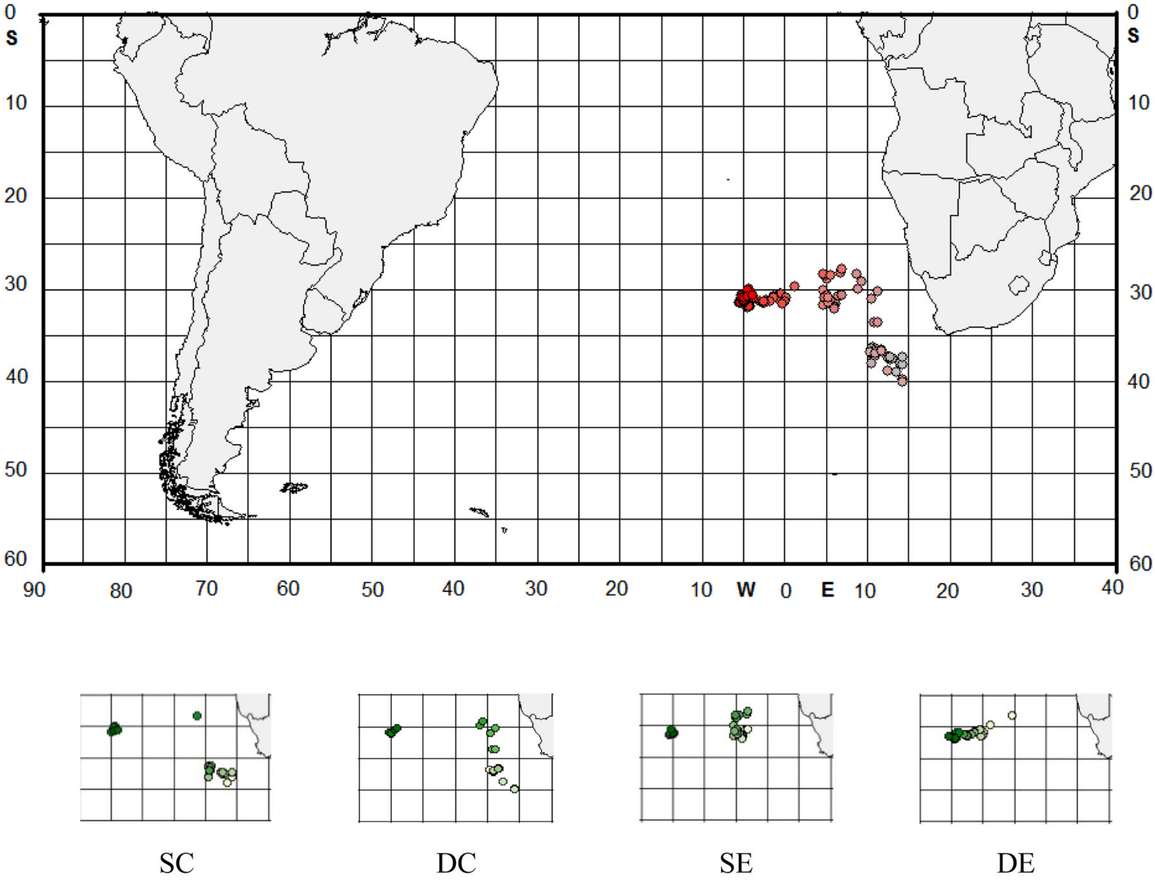

Fig. 2. Map of the study area and experimental design distributions. The color gradients indicate the experimental timeline, with light red and green representing the early stages and dark red and green indicating later stages. The four lower panels show the spatial distributions of different experimental configurations: SC, DC, SE, and DE.

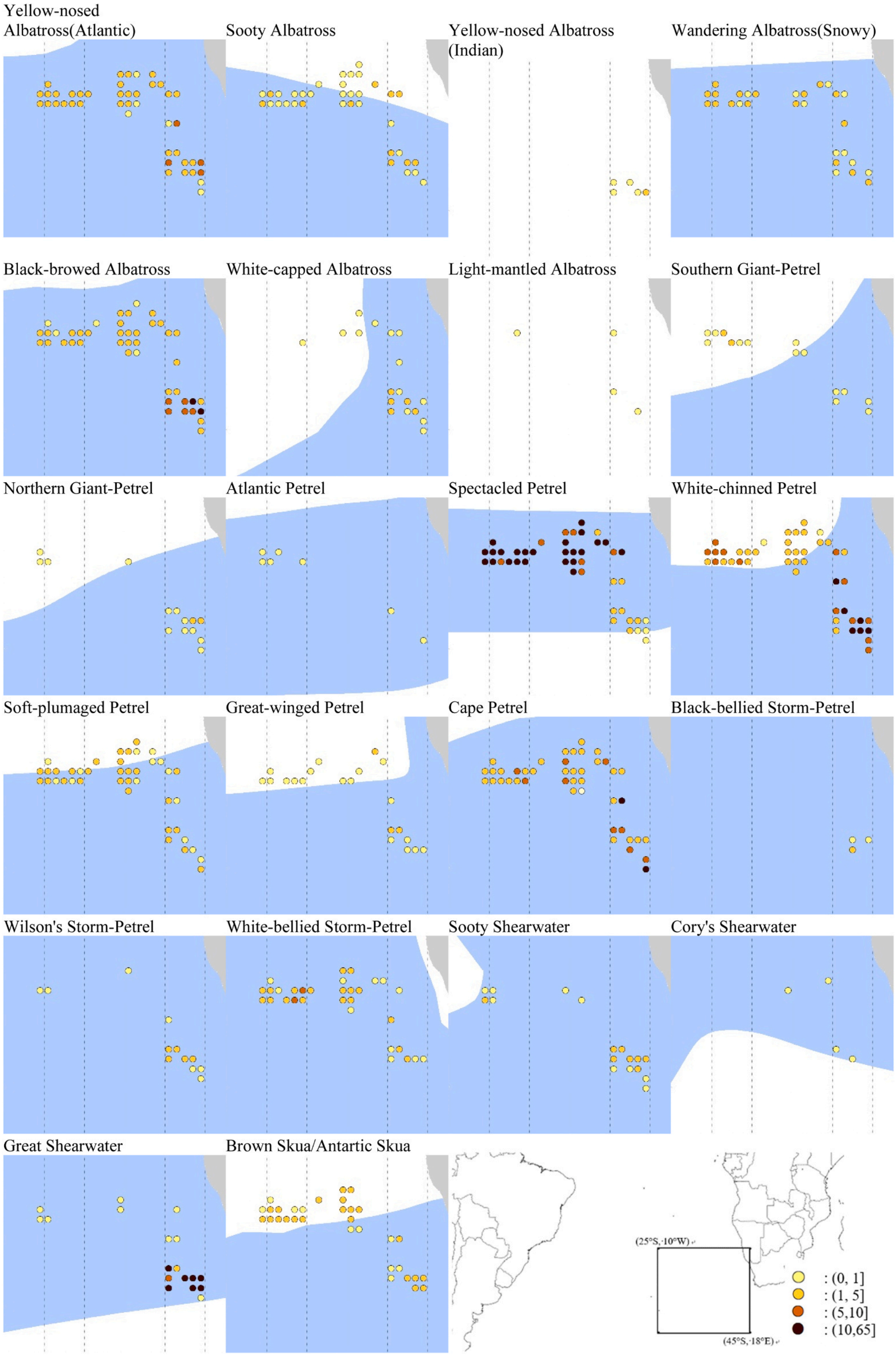

Fig. 3. Sighting locations and observed abundance of 22 seabird species during the experiment. Blue shading represents the species' distribution in the study area, as defined by the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. Colored points indicate the mean number of birds observed per observation. The right-bottom panel outlines the spatial extent of the study area covered by the other panels. The legend represents categories of birds observed per session: (0,1], (1,5], (5,10], and (10,65].

distributions reported by the International Union for Conservation of Nature (IUCN) for most species, except for the yellow-nosed albatross (Indian) (*Thalassarche chlororhynchos bassi*) and light-mantled albatross (*Phoebetria palpebrata*). The distribution map does not extend the yellow-nosed albatross (Indian) into the Atlantic Ocean, and the light-mantled albatross is typically found south of 45°S. Overall, the rate of seabird attacks on baited hooks was 2.2 times higher with unweighted branch lines than with weighted branch lines. The rates of primary and secondary attacks were the highest for great shearwaters (divers) and black-browed albatrosses (surface feeders), respectively. Primary attacks were made by sooty albatrosses (*Phoebetria fusca*), sooty shearwaters (*Puffinus griseus*), and southern giant-petrels (*Macronectes giganteus*) on unweighted branch lines but not on weighted branch lines. The numbers of attacks during hauling were similar between the unweighted and weighted branch lines (Table A1).

Data on seabird attacks from the center, port, and starboard sides of the vessel were combined to enable comparison of the distribution of attacks between divers and surface feeders. Overall, the rates of attacks—both primary attacks by divers and secondary attacks by surface feeders—on baited hooks were higher with unweighted branch lines, regardless of BSL type, than with weighted branch lines (Fig. 4). Primary attacks were made mostly by divers, whereas secondary attacks were made mostly by surface feeders.

3.3. Sink rate of baited hooks

A total of 194 TDR records were collected for the four configurations. The shallowest and deepest hooks in the fishing gear deployments were typically at depths near 100 or 200 m. No crew members were injured during the study, indicating that the

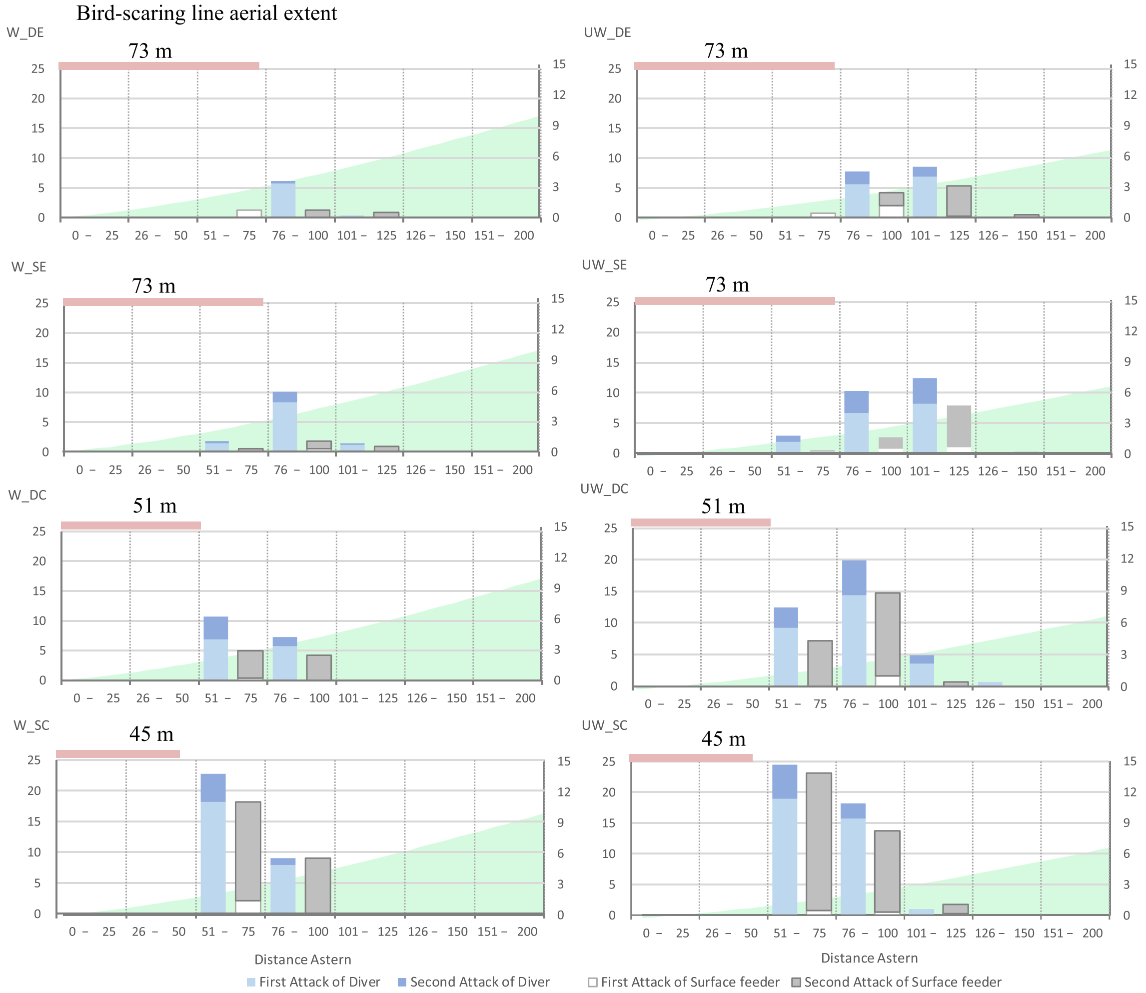

Fig. 4. Seabird attack rates (attacks per 1000 hooks) by diving and surface-foraging seabirds under different branch line and bird-scaring line configurations. The left column of panels represents weighted branch lines, while the right column represents unweighted branch lines. From top to bottom, the four rows correspond to different bird-scaring line configurations: DE, SE, DC, and SC. Light blue bars indicate primary attacks by diving seabirds, while dark blue bars represent secondary attacks by diving seabirds. Similarly, white bars show primary attacks by surface-foraging seabirds, and gray bars indicate secondary attacks by surface-foraging seabirds. The green shaded area represents the depth of baited hooks relative to the astern distance from the vessel. The right y-axis shows the sinking depth of baited hooks, while the left y-axis represents the number of seabird attacks. The orange bar denotes the aerial extent of the bird-scaring line.

experimental weighted branch lines were safe for use.

The influence of gear configuration on sink rates was considered in relation to the structural arrangement of the longline system. Each basket contained 12 hooks, with buoys positioned at both ends. This setup resulted in a catenary-shaped suspension of the mainline between floats, causing hooks at different positions to reach varying depths after deployment. Given this configuration, we aimed to evaluate whether shallow and deep hooks exhibited different sink rates at various depths, based on their relative positions within the gear structure. For the weighted branch lines, baited hooks sank to a depth of 5 m (sink rate is 0.18 m/s) within 100 m astern of the vessel. When the aerial coverage was short (~50 m), that is, for the DC and SC treatments cases, seabird attacks occurred within 51–100 m astern. In the DE and SE treatments, where the aerial extent of the streamer line was longer (~73 m), the baited hook reached a depth of approximately 3 m (sink rate ≈ 0.13 m/s) at the terminus of the streamer line. Seabird attacks were concentrated within 76–100 m astern and extended beyond 125 m. For the unweighted branch lines, baited hooks sank to a depth of 5 m (sink rate is 0.13 m/s) within 100 m astern of the vessel. When the aerial coverage was short (~50 m), seabird attacks were occurred within 51–125 m astern. When the aerial coverage was longer (~73 m), the baited hook reached a depth of approximately 3 m (sink rate ≈ 0.10 m/s) at the terminus of the streamer line. Seabird attacks concentrated within 76–125 m astern, and extended beyond to 150 m.

The difference in sink rate caused the baited hooks on the weighted branch lines to reach their given depth at a distance closer to the vessel than the hooks on the unweighted branch lines. Both types of branch lines sank to a depth of 10 m, well beyond the aerial coverage of the BSLs. For the unweighted branch lines, the hooks reached a depth of 6 m at around 200 m from the vessel. By contrast, for the weighted branch lines, the hooks reached a depth of 9 m at the same distance (Fig. 4). ANOVA revealed that the time required for sinking hooks to depths of 2, 5, and 10 m did not differ significantly between the shallow and deep hooks. When the data for the shallow and deep hooks in the baskets were combined, the weighted branch lines were determined to sink considerably faster than the unweighted branch lines did to all benchmark depths (Fig. 5). During the initial stage of sinking, that is, within the first 10 m, the weighted hooks sank faster than the unweighted hooks did. At deeper depths, the sink rate was influenced by the entire gear configuration, including the main line and assembled hooks. At depths of 2, 5, and 10 m, the sink rates of the baited hooks were 31.3 %, 26.7 %, and 25.3 % faster, with the weighted branch lines than with the unweighted branch lines.

3.4. Seabird bycatch

During the observation period in which seabird abundance and attack behaviors were recorded, 46 seabirds were caught on the corresponding unweighted branch lines and 18 on the corresponding weighted branch lines. These bycatch numbers align with the observed attack rates and are summarized by species in Table 2, allowing for a direct comparison among species-specific abundance, attack behavior, and bycatch incidence. Although attacks by white-capped albatrosses (*Thalassarche cauta*), cape petrels, and brown skuas were observed, no bycatch was recorded for these species. A total of 316 seabirds were recorded as bycaught from 103 fishing sets, based on data collected during the retrieval of all hooks. Of these, 298 seabirds were caught during setting operations and recovered dead, 4 were caught alive during hauling, and 14 were caught alive by trolling lines. This resulted in a total observed bycatch rate of 0.75 birds per 1000 hooks (Table 1). Specifically, for daytime setting operations with BSLs and unweighted branchlines, a total of 292 274 seabirds were caught, corresponding to a catch rate of 1.2 birds per 1000 hooks. For 293 nighttime setting operations with

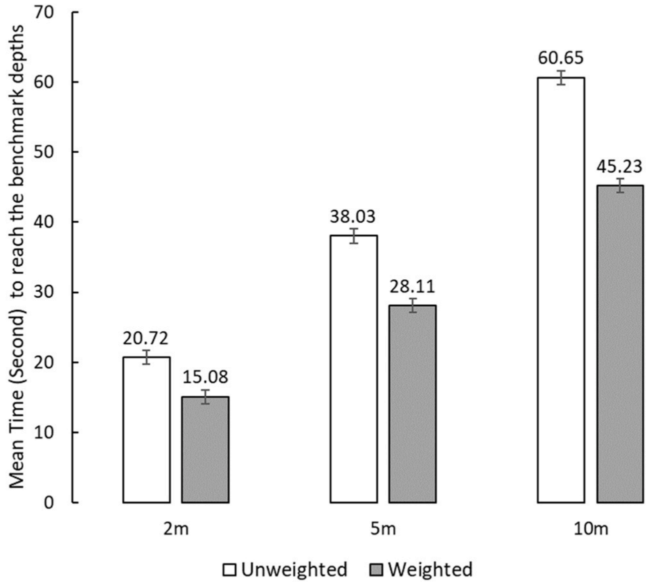

Fig. 5. Mean sinking time of baited hooks to reach 2 m, 5 m, and 10 m benchmark depths with unweighted and weighted branch lines. Sinking time is measured in seconds. Statistical comparisons were conducted using Two-way ANOVA (depth × branchline type). Error bars represent 95 % confidence intervals.

BSLs and unweighted branchlines, 6 seabirds were caught, with a catch rate of 0.04 birds per 1000 hooks. Additionally, for daytime settings with weighted branchlines, 18 seabirds were caught, resulting in a catch rate of 0.75 birds per 1000 hooks. No weighted branchlines were deployed during nighttime settings. The seabird species caught during hauling included the great shearwater (*Puffinus gravis*), black-browed albatross, and spectacled petrel. Besides, trolling lines were used by the crew during the haul as a recreational activity, separate from the main fishery operation. Seabirds caught by trolling lines were released alive. Fig. 6 presents the bycatch rates for six species, which accounted for $>$ 98 % of all seabird mortalities. Black-browed albatrosses exhibited the highest bycatch rate (2.90 birds/1000 hooks) in the SC treatment with unweighted branch lines. For all BSL types, the bycatch rates for the six seabird species were lower with weighted branch lines than with unweighted branch lines. The rates of seabird bycatch for all species, except for white-chinned petrels and spectacled petrels, were the lowest for the DE treatment, followed by the SE, DC, and SC treatments.

GLMs were used to identify the correlations of seabird bycatch with 13 variables, such as latitude, wave height, and temperature. Seven GLMs were constructed: one for each of the six species and one for all species combined (Tables A2–A8). Initially, a univariate GLM was constructed for the number of seabird bycatch. Significant variables ($p < 0.05$) from the univariate model were used to develop a multivariate GLM. The analysis results for all species combined (Table A2) indicated that seabird bycatch was significantly, negatively correlated with both weighted branch lines and temperature ($p < 0.001$ and $p = 0.0046$, respectively). The number of seabird bycatch was significantly lower in May than in April ($p = 0.013$); however, the other months exhibited no significant differences. Notably, NightSR and BSL type exerted no significant effect on bycatch rate. In the seabird bycatch analysis, although the GLM model included only 13 variables, some of these variables contained multiple categories, resulting in a total of 29 actual variables. For each species, we had 202 observed data points, yielding a variable-to-sample ratio of approximately 1:7. While this is slightly below the commonly suggested ratio of 1:10, it is still considered acceptable for model estimation.

Table 3 presents the significant variables across the seven GLM models. The results confirmed the significant, negative correlations of seabird bycatch with weighted branch lines and temperature. For sooty albatrosses, an inverse correlation was noted between bycatch rate and wave height; larger waves were significantly associated with lower bycatch rates.

On average, approximately 35 % of all hooks were set at night for each set. A total of 296 bycatch instances occurred during daytime, whereas only 6 occurred at night. All birds caught at night were white-chinned petrels; three of these were caught on nights bracketing the full moon. Overall speaking, the seabird bycatch rate was 23.83 times higher during daytime (1.101 birds/1000 hooks) than nighttime (0.046 birds/1000 hooks). The bycatch rate for white-chinned petrels was 5.8 times higher during daytime (0.29 birds/1000 hooks) than during nighttime (0.05 birds/1000 hooks).

Table 1

Summary statistics of metrics to evaluate the effect of unweighted and weighted branch lines and nighttime vs. daytime setting on seabirds and target fishes.

Metric	Whole trip	
Total hooks in the trip	394,972 hooks	
Birds caught	316	
During Setting	298	
During hauling	4	
By trolling	14	
	Unweighted branch lines	**Weighted branch lines**
Total Hooks	370,962	24,010
Bird caught		
During Day	274	18
During Night	6	N/A
Albacore caught	9399	391
Bird bycatch rate (bird/1000 hooks)		
By daytime setting	1.20	0.75
By nighttime setting	0.04	N/A
Albacore catch rate (no./1000 hooks)	25.34	16.28
By daytime setting	30.41	18.22
By nighttime setting	28.79	N/A
Number of hooks observed in setting	**24,372**	**24,010**
Primary attacks times	365	184
Diver birds	336	169
Surface feeder	29	15
Secondary attacks	401	162
Diver birds	110	41
Surface feeder	291	121
Attack rate (attack/1000 hooks)	31.4	14.4
Sink rate (m/s to 10 m)	0.24	0.3
Astern distance to 10 m depth (m)	273	206

Note: N/A = not applicable.

Table 2

Mean seabird sighting and standard error (SE), sets present, attack rates and numbers of seabird bycatch during observed period during the set with unweighted and weighted branch lines, stratified by species and foraging guild. The bold and significance levels relate to and W and UW are pooled across BSL designs and numbers.

Guild	Common name (Scientific name)	IUCN Status	Sighting during UW					Sighting during W				
Diver bird			Sightings (SE)	1st Attack per 1000 hooks	2nd Attack per 1000 hooks	Attend sets	No. of bycatch	Sightings (SE)	1st Attack per 1000 hooks	2nd Attack per 1000 hooks	Attend sets	No. of bycatch
	White-chinned Petrel (Procellaria aequinoctialis)	VU	5.27(0.54)	**3.53 (0.78)**	1.39(0.37)	99	13	5.02(0.52)	**2.01(0.45)***	0.90(0.34)	99	3
	Spectacled Petrel (Procellaria conspicillata)	VU	10.71 (0.79)	**6.95(1.05)**	**3.06(0.68)**	92	3	9.55(0.69)	**2.56(0.47)*****	**0.57(0.21)*****	95	
	Great Shearwater (*Puffinus gravis*)	LC	16.39 (2.94)	**35.48(6.19)**	7.71(2.66)	28	9	17.70 (3.82)	**17.57(3.38)****	3.39(1.84)	27	7
	Sooty Shearwater (*Puffinus griseus*)	NT	1.64(0.75)	0.79(0.79)		14		1.71(0.27)			15	1
	Cory's Shearwater (*Calonectris diomedea*)	LC	1.00(0.00)			1		1.00(0.00)			1	
Surface feeder												
	Cape Petrel (Daption capense)	LC	3.57(0.28)			84		3.75(0.29)	0.13(0.09)		85	
	Yellow-nosed Albatross, Atlantic *(Thalassarche chlororhynchos chlororhynchos)*	EN	3.24(0.33)		**9.40(1.80)**	77	7	2.94(0.28)	0.07(0.07)	**2.94(0.76)*****	78	
	Black-browed Albatross *(Thalassarche melanophris melanophris)*	LC	3.38(0.38)	1.37(0.41)	**11.16(1.93)**	74	11	3.27(0.50)	0.62(0.31)	**5.14(1.17)*****	78	7
	Soft-plumaged Petrel (*Pterodroma mollis*)	LC	1.20(0.07)			61		1.28(0.07)			53	
	White-bellied Storm-Petrel (*Fregetta grallaria*)	LC	3.43(0.47)			42		3.56(0.50)			41	
	Brown Skua/Antartic Skua (*Catharacta antarctica*)	LC	1.51(0.13)	0.71(0.28)	**1.38(0.59)**	41		1.62(0.16)	0.43(0.24)	**0.16(0.16)***	39	
	Sooty Albatross (*Phoebetria fusca*)	EN	1.18(0.07)	0.40(0.40)	0.82(0.49)	28	2	1.26(0.09)		0.14(0.14)	39	
	Wandering Albatross, Snowy (*Diomedea exulans exulans*)	VU	1.17(0.08)		1.13(0.57)	24		1.18(0.09)		0.20(0.19)	28	
	Southern Giant-Petrel (*Macronectes giganteus*)	LC	1.17(0.11)	0.43(0.43)	1.30(0.68)	12		1.09(0.09)		1.01(0.65)	11	
	Wilson's Storm-Petrel (*Oceanites oceanicus*)	LC	2.44(0.88)			9		2.25(0.51)			12	
	Great-winged Petrel (*Pterodroma macroptera*)	LC	1.22(0.15)			9		1.13(0.13)			8	
	Northern Giant-Petrel (*Macronectes halli*)	LC	1.00(0.00)		0.74(0.80)	6	1	1.33(0.33)			3	
	White-capped Albatross (*Thalassarche cauta*)	NT	1.50(0.50)		3.82(2.62)	4		1.20(0.20)		1.11(1.01)	5	
	Atlantic Petrel (*Pterodroma incerta*)	EN	1.00(0.22)			3		1.00(0.00)			3	
	Yellow-nosed Albatross, Indian *(Thalassarche chlororhynchos bassi)*	EN	1.00(0.00)			2		1.00(0.00)			2	
	Light-mantled Albatross (*Phoebetria palpebrata*)	NT	1.00(0.00)			1		1.00(0.00)			2	
	Black-bellied Storm-Petrel (*Fregetta tropica*)	LC	1.00(0.00)			1		2.00(0.00)			1	

Note: Status is shown by IUCN criteria, where LC: Least Concern, NT: Near Threatened, VU: Vulnerable, EN: Endangered, see details inwww.birdlife.org/datazone/speies/search https://iucn.org/resources/publication/iucn-red-list-categories-and-criteria-version-31 (IUCN, 2001). *:P < 0.05, **:P < 0.01, ***:P < 0.001

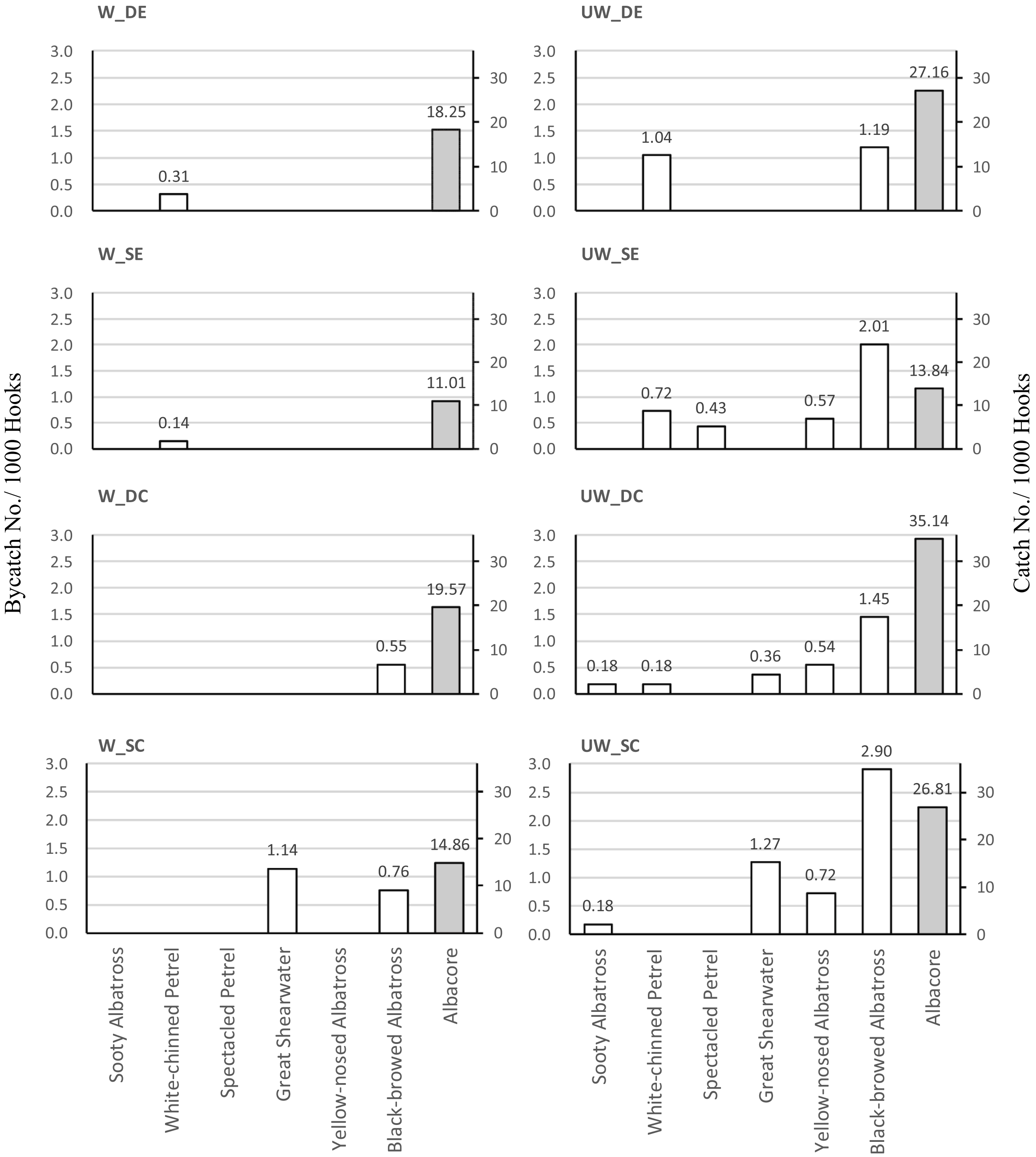

Fig. 6. Bycatch rates for six seabird species and albacore catch rate under different branch line and bird-scaring line configurations. The left column of panels represents weighted branch lines, while the right column represents unweighted branch lines. From top to bottom, the four rows correspond to different bird-scaring line configurations: DE, SE, DC, and SC. This graph illustrates the bycatch rates for six seabird species alongside the albacore catch rate, under different branch line and bird-scaring line configurations. The left y-axis denotes seabird bycatch rates, while the right y-axis indicates the albacore catch rate, providing an overview of the effect on both seabirds and the target species.

3.5. Albacore catch rate

During the retrieval process, our observers worked in two shifts per day, each lasting four hours. During these shifts, they recorded the specific basket in which the albacore catch occurred, allowing us to determine whether the catch was made using a weighted or unweighted branch line. Fig. 6 compare the fish catch rates across the different treatments. The mean catch rate of albacore was determined to be 11.01–35.14 fish per 1000 hooks for all treatments.

In the initial GLMM model, we considered six main variables: latitude, longitude, weight, soak time, BSL type, and setting time (day/night), along with all pairwise interaction terms and two random variables. The results indicated that the interaction between

Table 3
Significant variables identified by the generalized linear model for total seabird and each species.

	Total	Great Shearwater	Spectacled Petrel	Sooty Albatross	Yellow-nosed Albatross (Atlantic)	White-chinned Petrel	Black-browed Albatross
Lat			0.341*				
Lon		0.800**					
Wave							
Small swell				−4.587***			
Moderate swell				−4.339***			
Temperature	−0.432**	−0.574**			−1.091*		
Branch lines	−2.762***	−2.165***				−3.309***	−2.139***
Month	−2.032*						
NightSR			3.642**				

Note: *:P < 0.05, **:P < 0.01, ***:P < 0.001

setting time and soak time, as well as the interaction between BSL type and soak time, were statistically significant. This finding suggests that the effects of the variables vary under different settings, highlighting the need for subgroup analyses. The results of the subgroup analysis by setting time are summarized in Table 4. The day group contained 618 observations, including 527 unweighted and 91 weighted branch lines. fish catch rates showed a statistically significant increasing trend toward the north and west (Table 4a).

Table 4
Table of fixed effects from the generalized linear mixed model (GLMM) fitted to albacore catch rates per segment, based on data collected during 103 hauling operations by two observation shifts, each lasting four hours.

(a) GLMM analysis results for albacore catch rates in the daytime setting subgroup.

Variable	coefficient (95 % CI)	*P* value
Intercept	−0.079 (−1.128, 0.970)	0.882
Latitude	−0.097 (−0.130, −0.064)	< 0.001
Longitude	−0.043 (−0.058, −0.029)	< 0.001
Weight	−0.321 (−0.514, −0.128)	0.001
Soak time	0.068 (0.046, 0.091)	< 0.001
BSL		
DE	reference	
DC	0.168 (−0.052, 0.388)	0.134
SE	−0.122 (−0.316, 0.072)	0.219
SC	−0.132 (−0.369, 0.106)	0.277

(b) GLMM analysis results for albacore catch rate in the nighttime setting subgroup

Variable	coefficient (95 % CI)	*P* value
Intercept	0.182 (−2.376, 2.740)	0.889
Latitude	−0.102 (−0.184, −0.021)	0.014
Longitude	−0.056 (−0.094, −0.018)	0.004
Soak time	−0.041 (−0.109, 0.027)	0.241
BSL		
DE	reference	
DC	0.233 (−0.689, 1.154)	0.621
SE	0.339 (−0.083, 0.761)	0.115
SC	0.389 (−0.154, 0.931)	0.160

(c) GLMM analysis results for albacore catch rate by BSL types

	DE (n = 196)		**DC** (n = 144)	
Variable	coefficient (95 % CI)	*P* value	coefficient (95 % CI)	*P* value
Intercept	−4.841 (−11.430, 1.749)	0.150	1.371 (−0.134, 2.876)	0.074
Latitude	−0.255 (−0.472, −0.039)	0.021	−0.058 (−0.105, −0.011)	0.016
Longitude	−0.007 (−0.083, 0.069)	0.861	−0.033 (−0.056, −0.010)	0.004
DayNight	−0.474 (−0.838, −0.110)	0.011	−0.558 (−1.342, 0.227)	0.163
Weight	−0.279 (−0.640, 0.082)	0.129	−0.291 (−0.674, 0.093)	0.137
Soak time	0.049 (0.010, 0.088)	0.013	0.057 (0.014, 0.100)	0.009
	SE (n = 234)		**SC** (n = 165)	
Variable	coefficient (95 % CI)	*P* value	coefficient (95 % CI)	*P* value
Intercept	1.127 (−1.538, 3.793)	0.407	−2.845 (−6.077, 0.386)	0.084
Latitude	−0.055 (−0.142, 0.032)	0.213	−0.181 (−0.282, −0.080)	< 0.001
Longitude	−0.050 (−0.074, −0.026)	< 0.001	−0.075 (−0.123, −0.028)	0.002
DayNight	−0.051 (−0.361, 0.258)	0.746	−0.008 (−0.409, 0.394)	0.971
Weight	−0.414 (−0.805, −0.023)	0.038	−0.508 (−0.893, −0.122)	0.010
Soak time	0.059 (0.019, 0.099)	0.004	0.058 (0.010, 0.106)	0.019

During daytime, fish catch rate was 32.1 % lower with weighted branch lines than with unweighted branch lines ($p = 0.001$). Furthermore, for one unit increase in soak time, fish catch rate increased by 6.8 % ($p < 0.001$). Regarding BSL type, the results indicated no significant difference in albacore catch rate.

The night group contained 121 observations, all of which were unweighted. Because the night data did not include outcomes pertaining to weighted branch lines, the analysis for this subset focused on latitude, longitude, soak time and BSL type. Except for the soak time variable, the relationships between albacore catch rates and the explanatory variables closely resembled those in the daytime group. Regarding soak time, the result indicated no significant difference in fish catch rate (Table 4b).

The results of the subgroup analysis by BSL type are summarized in Table 4c. For the subgroup analysis by BSL type, the number of observations for each type was as follows: DE (196), DC (144), SE (234), and SC (165). Soak time significantly influenced the outcomes of all BSL treatments (DE: $p = 0.013$, DC: $p = 0.009$, SE: $p < 0.004$, and SC: $p = 0.019$). However, setting time (day/night) significantly influenced the outcomes of only the DE treatment ($p = 0.011$), whereas weight significantly influenced the outcomes of only the SE and SC treatments (SE: $p = 0.038$ and SC: $p = 0.010$). For the fish catch rate analysis, the variable-to-sample ratio in all subgroups was far greater than 1:10, indicating that there was no concern about having too few samples or too many variables.

4. Discussion

4.1. Seabird sighting and bycatch

Observation of seabirds attending fishing vessels provides valuable insights into seabird distribution and helps with determining the overlap between fisheries and seabird habitats. Between 2002 and 2016, 28 seabird species were documented across pelagic longline fleets in the South Atlantic Ocean and southwestern Indian Ocean (Jiménez et al., 2020). We observed 60 % of these species and recorded six additional species, namely, Wilson's storm-petrel (*Oceanites oceanicus*), white-capped albatross, white-bellied storm-petrel, black-bellied storm-petrel, Atlantic petrel (*Pterodroma incerta*), and soft-plumaged petrel (*Pterodroma mollis*). Notably, the Atlantic petrel is classified as an endangered species; this indicates that the fisheries operations in these regions pose potential conservation risks, despite no attack behavior being observed in the present study.

Between 2018 and 2020, albatrosses constituted 70 % of all seabirds caught as bycatch in the Pacific Ocean albacore longline fishery (Gilman et al., 2023). In the Uruguayan pelagic longline fleet in the southwest Atlantic Ocean, albatrosses constituted > 90 % of all seabirds caught as bycatch ($n = 598$) (Jimenez et al., 2010). In contrast, albatrosses comprised only 35 % of the seabird bycatch in the albacore longline fishery (operating in the southeastern Atlantic Ocean) assessed in our study. However, these figures may not be directly comparable due to differences in several factors, including the implementation of mitigation measures, the number of vessels sampled, and the temporal coverage of the data. Data corresponding to the period of 2001–2014 indicated that the seabird bycatch in the pelagic longline fleet in the Atlantic Ocean predominantly comprised Atlantic black-browed albatrosses, great shearwaters, and white-chinned petrels (Jimenez et al., 2010; Seco Pon et al., 2007; Tamini et al., 2015; Tuck et al., 2011). A similar trend was observed in our study; the bycatch primarily comprised white-chinned petrels, great shearwaters, black-browed albatrosses, spectacled petrels, yellow-nosed albatrosses (Atlantic), and sooty albatrosses.

White-chinned and spectacled petrels are prevalent in the Southern Ocean. Because of their cathemeral activity and aggressive feeding behavior, these seabirds face major threats from longline fisheries. The rate of bycatch is the highest for white-chinned petrels because they are particularly difficult to deter from baited hooks and highly susceptible to incidental capture (Phillips et al., 2006; Ryan et al., 2012). In the present study, white-chinned petrels attended the fishing vessel in 96 % of the sets, resulting in a bycatch rate of 0.181–1.042. Notably, all birds caught at night were white-chinned petrels. The distribution of these petrels in our study extended 5° farther north than that recorded by the IUCN; however, their sightings were less abundant north of 32°S. Therefore, the IUCN should consider expanding the distribution range of white-chinned petrels to reflect their broader presence.

The spectacled petrel, similar to the white-chinned petrel, is a medium-sized procellariiform abundant in waters around 30°S. In this study, the extent of abundance and the rate of attack were higher for spectacled petrels than for white-chinned petrels. However, the bycatch rate was lower for spectacled petrels than for white-chinned petrels. This finding is consistent with those of studies indicating a lower bycatch rate for spectacled petrels than for white-chinned petrels (Bugoni et al., 2008; Jimenez et al., 2010). The relatively low bycatch rate for spectacled petrels may be attributable to their feeding behaviors, such as pulling and dragging bait rather than swallowing it directly. The spectacled petrel is classified as a critically endangered species because of its small population size and high susceptibility to bycatch in longline fisheries (Ryan et al., 2006).

In our study, 100 % of great shearwaters and 62.5 % of black-browed albatrosses were caught in April and May in areas located south of 35°S, where these species were abundant. Great shearwaters exhibit distinct spatiotemporal distribution patterns and aggressive bait-attacking behaviors (Jimenez et al., 2011). Once great shearwaters attended our fishing vessel, they became the predominant bycatch species, with bycatch rates ranging from 0.362 to 1.268, corresponding to their high attack rates. Black-browed albatrosses are commonly caught as incidental bycatch during commercial fishing operations (Robertson et al., 2014). In this study, the bycatch rate for black-browed albatrosses ranged from 0.554 to 2.899 birds per 1000 hooks - among the highest rates ever recorded, underscoring the urgent need for effective mitigation in this fishery.

In this study, longitude, latitude, temperature, and month were used as spatial-temporal predictors related to seabird distribution patterns. Our GLM analysis indicated that the bycatch rates for great shearwaters, yellow-nosed albatrosses (Atlantic), and spectacled petrels were significantly associated with these environmental and temporal predictors, which likely reflect seabird abundance. The distributions of sighted seabirds belonging to these species (Fig. 2) provided a reasonable explanation for this association. For instance, the higher numbers of great shearwaters sighted in areas with eastern longitude and low temperatures explained their higher bycatch rates in these regions. The GLM analysis further suggested that the use of weighted branch lines effectively reduced the bycatch of species such as the white-chinned petrel and black-browed albatross, which exhibited aggressive bait-attacking behaviors.

4.2. *Attack behavior*

Of the six primary seabird species caught as bycatch, three belonged to the diving guild, exhibiting both primary and secondary attack behaviors, whereas the other three (albatrosses) belonged to the surface-feeding guild, exhibiting secondary attack behaviors. Among the seabird species caught in this study, the great shearwater was the most aggressive and competitive one. Their foraging behavior, supported by their ability to dive to depths of up to 18.9 m (Ronconi et al., 2010), provides them with a competitive advantage over other species, such as the white-chinned petrel, which typically dives to 5 or 6 m but can reach depths of up to 13 m (Berrow et al., 2000; Huin, 1994). This diving ability likely contributed to great shearwaters being the most prevalent bycatch species in our study when they were part of the attending seabird assemblage, consistent with their high attack rates and competitive behavior. Although black-browed albatrosses are generally regarded as surface feeders, they can dive to depths of up to 2.5 m (Anderson and Mcardle, 2002) and exhibit primary attack behaviors.

Our findings support the hypothesis that different seabird assemblages exhibit different levels of hierarchical and competitive behaviors at both species and individual levels (Jimenez et al., 2011). High-resolution data on seabird–vessel interactions and bycatch rates are essential for understanding the species-specific effects of fisheries on seabirds (Votier et al., 2023). These effects vary depending on the seabird genus. Strong associations were observed between seabird abundance, attack behaviors, and bycatch rates. In general, attack rates were proportional to species sightings; however, certain species, such as the great shearwater and black-browed albatross, exhibited disproportionately high levels of aggression. Conversely, species such as the cape petrel were less aggressive than others. Furthermore, the risk of bycatch varied by species: white-chinned petrels were more likely than others to be caught, whereas spectacled petrels were less likely (despite making frequent attacks) than others to be caught. These findings suggest that species-specific behavioral traits significantly influence bycatch rates, highlighting the complex dynamics between seabird aggression and fishing operations (Bentley et al., 2021).

4.3. *Effectiveness of mitigation measures*

The effectiveness of various BSL-based mitigation measures in reducing bycatch rates is influenced by factors such as deployment, gear configuration, and fishing operations (Jiménez et al., 2020; Melvin et al., 2014; Sato et al., 2012). In our study, no seabird attacks occurred in areas covered by BSLs. Notably, the fishing crew of the study vessel often customized the BSLs by using materials available onboard; this introduced variability in the streamer length. Although the experimental design (RFMO-recommended; ICCAT Recommendation 11–09) was found to be more effective than the conventional design in altering the distribution and frequency of seabird attack behaviors, it did not result in a statistically significant reduction in seabird bycatch. In this study, the effectiveness of bird-scaring lines (BSLs) appeared to be primarily influenced by the length of the mainline: the conventional mainlines were approximately 65 m long, whereas the experimental mainlines were 125 m long. It is important to note that none of the BSLs deployed in this study achieved the ICCAT-recommended 100 m aerial extent. This deviation from the guidelines likely limited the effectiveness of the BSLs and may explain the lack of significant differences in bycatch rates among BSL treatments. Beyond the limited aerial coverage, baited hooks remained at depths accessible to seabirds. Therefore, variations in BSL aerial extent may have shifted the spatial location of potential seabird attacks—either closer to or farther from the stern—rather than substantially reducing the overall accessibility of baited hooks. These results underscore the importance of adhering to standardized mitigation guidelines to ensure effective bycatch reduction.

In our study, seabird attacks rarely occurred in the astern area when baited hooks had sunk deeper than 5 m. When hooks were still shallower than 5 m, attacks were concentrated in the astern area not covered by BSLs. Therefore, bycatch mitigation measures for seabird assemblages in the southeastern Atlantic should focus on protecting the astern area, particularly when baited hooks are within the upper 5 m of the water column.

Regardless of branch line weighting, the sink rates in this study were slower than those reported by Melvin et al. (2014). During normal fishing operations, the unweighted hooks reached a mean depth of 5.57 m within 30 s, whereas the weighted hooks reached a mean depth of 13.44 m in the same period. By contrast, the weighted branch lines reached a mean depth of 10 m within 40 s, with a sink rate of 0.3 m/s; this finding aligns with that of a study conducted in waters surrounding New Zealand (Anderson and Mcardle, 2002). Our use of weighted branch lines increased the sink rate by up to 32 % at shallower depths, effectively reducing the risk of seabird bycatch.

Night setting is a widely used and effective measure for mitigating seabird bycatch (Gilman et al., 2023; Løkkeborg, 2008). Its effectiveness is attributable to the fact that many seabirds are most active around dawn and dusk (BirdLife International Global Seabird Programme, 2009). Melvin et al. (2014) combined multiple mitigation measures and found that seabird bycatch rates were > 13 times higher during daytime (0.378 birds per 1000 hooks) than during nighttime (0.028 birds per 1000 hooks). In a subsequent study, Melvin et al. (2014) demonstrated that the bycatch rate for white-chinned petrels was 4.6 times higher during daytime (2.00 birds per 1000 hooks) than during nighttime (0.439 birds per 1000 hooks). We found that the bycatch rate for all bird species was much higher during the daytime than during nighttime. These results highlight the effectiveness of night setting as a bycatch mitigation measure, also for species such as the white-chinned petrel, which are active at night. However, while NightSR was not a significant variable in explaining seabird bycatch rates—except for the spectacled petrel—this does not imply that night setting is ineffective as a mitigation measure. In our study, NightSR represents the proportion of hooks set at night during each fishing operation, rather than soak time. The average

NightSR was 0.35 (SD = 0.19), indicating a relatively consistent fishing pattern in which about one-third of hooks were deployed at night. This limited variation may explain the lack of a statistically significant association with bycatch rates. Moreover, our data showed that only 6 seabirds were caught on hooks set at night, compared to 292 caught on hooks set during the day. This finding suggests that modest levels of night setting may not be sufficient to substantially reduce seabird bycatch, and that a more comprehensive implementation—i.e., setting all hooks at night—may be required to achieve meaningful mitigation. Besides, in our study, 18 incidents of seabird bycatch were recorded during hauling. All seabirds were released alive. Our findings indicate a need for the development of mitigation measures that specifically target the hauling process to enhance the overall effectiveness of bycatch mitigation (Gilman et al., 2014).

Comparing our study's findings with previous research on seabird bycatch rates in similar fisheries. Huang et al. (2009) provides estimates of seabird incidental catch by pelagic longline fisheries in the South Atlantic Ocean. This study analyzed data from fishery observers over a five-year period, covering 61 trips and 6181 observed sets, with over 20 million hooks deployed. It reported seabird bycatch rates ranging from 0.026 to 0.063 birds per thousand hooks, with hotspots identified at 20°–40°S/10°W–15°E and 35°–45°S/45°–55°W.

Compared to these findings, our study observed similar species compositions in the southeastern Atlantic Ocean. However, a key distinction is that our sample vessel operated within the bycatch hotspot identified in Huang et al. (2009), resulting in significantly higher seabird bycatch rates. Moreover, the vessel used conventional, self-made bird-scaring lines (BSLs), which were commonly employed by the fleet prior to the implementation of standardized BSL regulations in 2008. These results demonstrate the importance of adhering to internationally recommended mitigation standards, such as those outlined by ICCAT and ACAP, rather than relying on locally adapted or convenient practices.

In interpreting the effectiveness of mitigation measures, it is important to acknowledge that none of the BSLs used in this study achieved the ICCAT-recommended aerial extent of 100 m for vessels longer than 35 m. Furthermore, the proportion of hooks set during nighttime was insufficient to qualify as "night setting" under ICCAT definitions. These deviations from international guidelines should be made explicit, as they may have limited the overall effectiveness of mitigation measures and contributed to the absence of statistically significant differences among BSL treatments. Thus, while the study provides valuable behavioral insights, the results must be interpreted within the context of these limitations.

4.4. *Effect on target catch*

The challenge of balancing a reduction in seabird bycatch with maintenance of target catch rates complicates fisheries management. Several studies have highlighted the intricacy of this problem and obtained mixed results regarding the effectiveness and implications of bycatch mitigation measures. Gilman et al. (2023) analyzed data from the electronic monitoring system of a pelagic longline fishery in the Pacific Ocean and found that the combination of nighttime setting and deep fishing effectively reduced the risk of seabird bycatch without significantly affecting the target catch rate. These findings align with those of a study indicating no negative effect of mitigation measures on target species (Løkkeborg and Robertson, 2002) and those of another study indicating elevated catch rates and reduced bait loss under similar conditions (Løkkeborg, 2003). Many studies have indicated that some mitigation measures exert no or even positive effects on target species catch (Avery et al., 2017).

Melvin et al. (2014) reported that the use of weighted branch lines had no statistically significant effect on the overall catch rate of target species. While the mean catch rate of albacore was lower in the treatment group, this difference was not tested statistically, as albacore was not a target species and was caught in low numbers. Gilman et al. (2022) highlighted potential trade-offs associated with seabird bycatch mitigation. In the US North Pacific tuna longline fishery, the use of weighted hooks led to a 53 % reduction in target species catch, despite sink rates increasing. Similarly, we observed a significant reduction in albacore catch when weighted branch lines were used. From the fishers' perspective, this reduction is primarily attributable to reduced bait mobility, which limits the bait's ability to attract fish.

Our findings underscore the need for a careful evaluation of the effects of mitigation measures on target species. Although such measures can effectively reduce seabird bycatch, their potential negative effect on target species catch cannot be overlooked. The variability in the findings regarding treatment outcomes suggests that the effects of mitigation measures vary depending on factors such as gear configuration, target species, and fishing location, indicating a need for well-designed, nuanced, and adaptable mitigation measures. Our results indicate that soak time significantly influenced albacore catch rates in the daytime setting subgroup, but not in the nighttime subgroup. This implies that beyond a soak time of four hours, its effect on catch rates becomes negligible. These insights may inform the optimization of future experimental designs.

Interviews were conducted with the fishing crew after the experiment of this study. In general, the crew members were eager to reduce seabird bycatch, partly to avoid the labor and bait loss associated with managing bycatch. However, they were concerned about the potential negative effects of mitigation measures on target species such as albacore. Although reducing seabird bycatch might help minimize bait loss, fishers contemplating adopting mitigation measures prioritized their economic implications, particularly their effects on target species catch. This highlights the importance of developing measures that balance the goal of seabird conservation with the economic viability of fishing operations.

5. Conclusion

Our findings suggest that the use of weighted branch lines and appropriate BSLs significantly reduced seabird bycatch in longline fisheries. The present study demonstrated that the use of weighted branch lines was associated with 77 %, 36 %, and 61 % reductions in the bycatch rates for white-chinned petrels, black-browed albatrosses, and all seabirds, respectively, confirming the effectiveness of this measure. To optimize bycatch reduction efforts, fishing operations must also consider the diving capabilities of seabirds and the aerial coverage of BSLs.

Night setting effectively reduced seabird bycatch per unit effort, although exceptions exist for certain species, such as the northern fulmar (Melvin et al., 2019; Sánchez and Belda, 2003). In the present study, approximately one-third of all setting operations occurred at night, resulting in a bycatch rate considerably lower than that during daytime operations. However, many fisheries found it difficult to complete an entire set at night (Melvin et al., 2014; Orbesen et al., 2017). Notably, night setting was typically combined with other mitigation measures to further reduce seabird bycatch.

Until now, after RFMOs adopted regulations seeking to achieve reductions in levels of seabird bycatch, numerous measures for mitigating seabird bycatch have been tested and implemented across fisheries. In the present study, we examined the impact of fishing operations using only bird-scaring lines and the benefits derived from the additional use of a second mitigation measure alongside bird-scaring line on pelagic albacore longline vessels. Our findings not only confirmed the effectiveness of the combined measures but also clarified the behavior of various seabird species in the southern Atlantic Ocean. We further analyzed the temporal variations in seabird assemblages associated with the study fishery and evaluated their foraging interactions.

Despite mitigation measures success, a concern emerged during hauling operations: trolling lines used to catch albacore carried a risk of seabird bycatch. Thus, mitigation measures tailored to hauling operations must be developed to minimize seabird bycatch during this phase.

Although mitigation measures hold promise in reducing seabird bycatch, their potential negative effect on target species catch must be addressed. Continual evaluation and adaptation are necessary to strike a balance between reducing seabird bycatch and maintaining target catch rates. Fishers' concerns, particularly those regarding economic viability and catch efficiency, must be addressed to facilitate the long-term implementation of mitigation measures.

We could not proactively determine the fishing days and operational areas for the commercial fishing vessel considered in this study because of uncertainties in actual catch conditions and weather. Moreover, the captain's concerns about the effect of weighted branch lines on albacore catch imposed limitations on the experimental design, further complicating subsequent statistical analyses. Furthermore, fishers expressed reluctance to modify the BSL design to increase aerial coverage, such as extending the mainline or attaching a float at the end to increase drag. They were concerned that the increased tension might cause the tori pole or the BSL mainline to break, disrupting fishing operations. Additionally, maintaining vessel speed to counteract the increased drag could raise fuel consumption, which was also considered unacceptable.

CRediT authorship contribution statement

Huan-Chang Liao: Project administration, Investigation. **Hsiang-Wen Huang:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Yu-Min Yeh:** Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Shu-Chun Chen:** Writing – review & editing, Methodology, Formal analysis. **Ting-Chun Kuo:** Writing – review & editing, Funding acquisition.

Ethical Statement

This study was conducted in accordance with institutional and national guidelines for the ethical treatment of animals. All data on seabird bycatch and behavior were collected through on-board observations aboard a commercial Taiwanese albacore longline fishing vessel, with the full cooperation of the fishing crew. Observers did not intentionally capture or harm seabirds for research purposes. However, when seabirds were incidentally caught during fishing operations, trained observers followed standard handling protocols to recover and identify dead specimens and to release any live birds in a manner that minimized further stress or injury. All procedures were non-invasive and aligned with ethical practices for wildlife research at sea. Data collection was carried out under appropriate permits, and no additional animal experimentation requiring institutional animal care and use committee (IACUC) approval was involved.

Declaration of generative AI and AI-assisted technologies in the writing process

ChatGPT was used to improve the readability and language of the manuscript. After manuscript preparation, the authors reviewed and edited the content to ensure accuracy. The authors agree to take full responsibility for the content of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is dedicated to the memory of Yu-Huai Wang, whose contribution of time–depth recorders and professional support was instrumental to this study. We are also deeply grateful to all the fieldworkers who participated in the data collection. Special thanks go to the staff at the Data Science Statistical Cooperation Center, Academia Sinica, for their assistance with statistical analyses. We also appreciate the constructive comments and feedback provided by three anonymous reviewers, as well as by Dr. Stephanie Prince, Mr. Alan Munro, and Mr. Scott Pursner. This manuscript was edited by Wallace Academic Editing.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2025.e03752.

Data availability

Data will be made available on request.

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