MIT2022-04 Bait retention as a driver to mitigation use in the surface longline fishery

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Front cover photo:

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Executive summary

We reviewed existing literature for methods to estimate bait loss caused by seabirds in New Zealand's commercial surface longline (SLL) fisheries and to model economic impact of bait loss. Further, we assessed whether data exists that could be used to estimate bait loss and economic impacts for the fisheries.

The methods ranged from observations of successful bait taking attempts, observations of secondary attacks on bait stealing seabirds (a conservative measure of successful bait taking attempts, since primary attacks are not always successful), or immediate retrieval of lines after setting to reduce other factors contributing to bait loss other than seabirds (e.g., predatory fish, disintegration, physical stresses from wave action, longline deployment and retrieval). However, depending on how bait loss is determined or defined, estimates can range by orders of magnitude. Moreover, visual determination of seabird depredation of bait leads to results with limited applicability to actual fishery operation (e.g., daylight observations are required, but most SLL fishing in New Zealand occurs during night).

As per legal requirements, SLL fishing vessels use some combination of seabird bycatch mitigation (e.g., using a combination of tori lines for the duration of all setting events, weighting lines, setting lines at night, or alternatively hookpod devices can be used as the sole bycatch mitigation method). We recommend implementing a case-control study to assess how different bycatch mitigation strategies affect bait loss. To ensure that bait loss due to seabird depredation is assessed, fishing practices need to be held constant between vessels with different bycatch mitigation measures. Alternatively, vessels with different fishing practices could alternate bycatch mitigation measures (e.g., switching bycatch mitigation measures half-way through the season) such that all assessed vessels were operating under different bycatch mitigation strategies.

To model economic consequences, we suggest collecting data on direct revenue for catch and costs of bycatch mitigation measures and other operational costs, because the scope of such work would be to incentivize fishers for the use of specific bycatch mitigation measures. Within New Zealand, commercial fishers can only sell fish to licensed fish receivers, and data on fish sold and prices for fish at the time of selling might be available through seafood industry owned databases. Alternatively, revenue and costs could be directly collected as part of a study dedicated to assessing bait loss.

1. Introduction

Seabird bycatch in commercial fisheries is a global conservation problem (Anderson et al. 2011). In longline fisheries, the risk of seabird bycatch is particularly high when bait is exposed near the surface of the water during setting and hauling (Brothers et al. 2010, Zhou et al. 2020). During bait exposure, seabirds often attempt to steal bait resulting in bait loss or accidental seabird bycatch (Brothers et al. 2010, Zhou et al. 2020). Both bait loss and bycatch (i.e., the bait is lost, and the bird also got caught on the hook) negatively affect the catch of targeted fish and causes a financial deficit to fishers. An economic analysis by Pierre & Clough (2021) of seabird bycatch reduction in surface longline (SLL) fisheries identified bait retention as an important factor affecting the economic consequences of seabird bycatch mitigation. However, real world data on bait loss rates, and its consequent economic impact, were lacking in the literature and hindered further development of the economic modelling of seabird bycatch mitigation use by Pierre & Clough (2021).

In New Zealand's longline fisheries, mandatory bycatch mitigation measures include using hook-shielding devices (hook pods) that were introduced in 2020, deploying a tori (streamer) line for the duration of all setting events, weighting lines, or setting lines at night (as per Fisheries (Seabird Mitigation Measures—Surface Longlines) Circular 2018). Meyer & MacKenzie (2022) assessed how different fishing practices (e.g., bycatch mitigation measures, line set up, etc.) and environmental factors (e.g., wind speed, sea surface temperature, etc.) influenced bycatch in New Zealand's SLL fisheries. They found that seabird captures were driven by factors such as moon phase, month of fishing, seabird species, sea surface temperature, the exact configuration of the tori line, and the number of turns during setting. However, most variables that potentially affect seabird bycatch were not recorded consistently or only very recently. Most of these sparsely collected attributes will be directly correlated with seabirds attempting to steal bait from hooks and therefore bait loss. Furthermore, direct records of bait loss in New Zealand's longline fisheries are currently absent.

In this project, we reviewed the existing literature to identify ways to collect and compile data on bait loss rates (and influencing factors) and economic consequences of bait loss to inform future economic assessments. We also assessed whether data exists that could be utilised to estimate bait loss and economic impacts in New Zealand's SLL fisheries.

Here, we define bait loss as the partial or complete removal of hooked bait from fishing gear by seabirds (following general definition of bait loss as per Muñoz-Lechuga et al. 2016, Donoghue et al. 2003), which also includes hooks with caught birds (i.e., the bait is not available to attract target fish species).

2. Methods

Scientific articles were sought using the Google Scholar search engine. The search terms were ‘bait depredation seabirds’, ‘bait loss seabirds’, ‘bait loss economic cost’. All identified articles were assessed as to whether they contain information on bait loss rates, economic effects of bait loss, and methods used to estimate bait loss. The literature review was predominantly limited to SLL fisheries.

The following data were assessed for their usefulness to inform the estimation of bait loss in New Zealand’s SLL fisheries:

- Protected Species Captures Database (PSCDB)
- Centralised Observer Database (COD)
- Catch effort data from the Enterprise Data Warehouse (EDW)
- Seabird necropsy reports
- Counts of seabirds around fishing vessels

The PSCDB contains groomed data that were collected by observers (stored in COD), reported by fishers (stored in EDW), and post-mortem identifications (Seabird necropsy reports; Abraham & Berkenbusch 2019). Observer data in the PSCDB includes information on fishing location, start of fishing, use of mitigation measure, and the capture of non-target species. Additional information regarding line weighting and other variables collected by observers but not included in the PSCDB can be derived from COD. In this report, we used the assessment by Meyer & MacKenzie (2022) that linked additional variables contained in COD to the PSCDB to identify factors that drive bycatch of seabirds in SLL fisheries. Permission to use the PSCDB and COD was granted by the Ministry for Primary Industries on 28/11/2022. Catch effort data from the EDW were not directly assessed because a groomed version of this dataset is contained in the PSCDB. Seabird necropsy reports were provided by Wildlife Management International Limited (WMIL) on 13/12/2022 and contain information on, for example, species, age, and stomach content (Bell, 2021). Counts of seabirds around fishing vessels were collected by fisheries observers and groomed data are described in Richard et al. (2020). This dataset is available on https://seabird-counts.dragonfly.co.nz/, but a non-anonymized version of the data were provided by Dragonfly Data Science on 08/12/2022. Data were collected on paper forms and electronic NOMAD devices. Only paper forms contained data collected in SLL fisheries. In this study, we assessed the number of records, in the supplied data set, that were observed during hauling, setting, and fishing.

The datasets were assessed for potential variables that could be used to determine bait loss and their overall suitability. No data grooming was carried out.

3. Results

From the literature search, 26 publications were initially found and assessed, of which 12 contained relevant information on bait loss or economic consequences of bait loss. The remaining 14 publications without explicit information on bait loss rates in SLL fisheries or economic consequences are listed in Appendix A. 11 studies contained information on bait loss, such as estimates and methods to determine bait loss. Each of these 11 studies were summarised (see section 3.1) and reported bait loss rates (expressed in lost baits per 1000 hooks), and additional information (e.g., whether bird-related bait loss was explicitly recorded) is summarized in Table 1. Furthermore, two publications provided information on fishery-related data that is needed to estimate the economic consequences of bait loss and are summarised in section 3.2

3.1 Bait loss

The following are summaries of bait loss related studies in pelagic longline fisheries, and Table 1 presents this information in a more condensed format.

Brothers (2017). A bait throwing device was tested on a Japanese fishing vessel that was operating in the Indian Ocean SBT fishing ground and the Freemantle Big Eye Tuna fishing ground (30º South 101º East) in 1992. Seabird bycatch and bait loss owing to seabird depredation was recorded, and results for SBT were presented. The author emphasises that the presented results are inconclusive at the time of writing, because '*the capability of the test machine to overcome these problems was well demonstrated its functions were by no means* *fully utilised during testing*' and the limited access to relevant data. Nevertheless, bait loss rates were presented for fishing trips with and without bait throwing device. No specifications were provided as to whether fishing trips without a bait throwing device used other bycatch mitigation measures (e.g., weighted hooks), or whether the focus is on pelagic or demersal longlining (though the targeted species imply that pelagic longlining has been assessed). Without a bait throwing device, 2.5 baits per 1000 hooks were taken by seabirds, and bait loss with a bait throwing device decreased to 1.4 baits per 1000hooks. Bird species that were captured included black-browed albatross (*Thalassarche melanophris*), grey-headed albatross (*Thalassarche chrysostoma*), royal albatross (*Diomedea epomophora*), giant petrel (*Macronectes* sp.) and flesh-footed shearwater (*Puffinus carneipes*).

Melvin et al. (2014). Combinations of three mitigation measures (weighted vs. unweighted branch lines set with two bird-scaring lines; hybrid lines with long and short streamers; during daytime and night-time) in a pelagic longline fishery in the South African Exclusive Economic Zone (EEZ) were tested regarding their efficacy in reducing seabird attacks on bait. Data were collected from two Japanese longline vessels in 2010 that primarily targeted bigeye tuna (*Thunnus obesus*), yellowfin tuna (*T. albacares*), albacore (*T. alalunga*), and swordfish (*Xiphias gladius*). Sets were described as typically beginning at 3am and ending by 8am. Half the vessel's branch lines were weighted, and the other half remained unweighted. To reduce bias due to environmental factors, vessels deployed opposite weighting configurations in any given day and alternated configurations day to day. Lines were hauled three hours after the set was completed (about 11am). Data on seabird attacks on baited hooks and seabird numbers were collected during daylight (i.e., some fishing occurred at night but was unobserved). Seabird attacks were classified into (1) primary attacks on baited hooks (mainly by diving birds: white-chinned petrel (*Procellaria aequinoctialis*); cape gannet (*Morus capensis*)), and (2) secondary attacks made by surface foragers (yellow-nosed albatross (*Thalassarche chlorohynchos/carteri*); black-browed albatross (*Thalassarche melanophrys*)) on seabirds that made initial primary attacks and observed during the setting of one gear segment (25–30 min). Secondary attacks can be interpreted as a conservative proxy for successful primary attacks (i.e., the bait was depredated by the seabird carrying out the primary attack, but not all primary attacks result in secondary attacks). Based on that definition, bait loss was 23.1 lost baits per 1000 hooks for unweighted lines and 3.3 lost baits per 1000 hooks for weighted lines (during day light). When including primary attacks (but note that not all of them were necessarily successful), bait loss was 40.2 and 9.8 lost baits per

1000 hooks for unweighted and weighted lines, respectively.

Brothers et al. (2010). 15-year study (1988 to 2003) to record seabird bycatch during line setting and hauling from the Indian Ocean, Southern Ocean, Coral Sea, and central Pacific Ocean. 25 species (albatrosses, petrels, and skuas) were caught, and approximately 6000 birds attempted to depredate bait from hooks. Data were collected from 11 longline vessels and 85% of sets occurred during daytime. 781 307 baited hooks were deployed of which 95% were observed being set and 67% were observed being hauled. Attempts of seabirds taking bait off a hook were classified as: (i) successful, where it takes the bait and does not get caught; (ii) unsuccessful, where it fails to take the bait and does not get caught; (iii) caught, when the seabird gets caught or hooked; (iv) possibly caught, when it appears to get caught but this is not entirely clear; and (v) unsure, when the outcome is uncertain. Each hook was observed for at least 30 seconds after setting (the authors describe that by then the hook was generally underwater and approximately 150 m astern), after which it was assumed that the baited hook was unlikely to be taken by a bird. When lightly weighted gear was used (baits could remain accessible to birds at 150 m astern), distant bird activity was observed using binoculars. If a caught bird means also that the bait is lost, an overall bait loss (across all regions and species) can be calculated by dividing the sum of successful bait depredation and caught bird by the total number of hooks deployed (numbers are presented in Table 2 of Brothers et al. (2010)). Seabirds that were possibly caught or unsure outcomes can also be included for more cautious estimates. Scaled to 1000 hooks, the bait loss estimates were: 2.738, 2.839, and 3.277 lost baits per 1000 hooks for observations of caught birds plus successful bait taking attempts, caught birds plus successful bait taking attempts and possibly caught birds, and caught birds plus successful bait taking attempts and possibly caught birds including unsure outcomes, respectively.

Gilman et al. (2003). An underwater setting chute was tested in the Hawaii pelagic longline tuna fishery in 2002. Setting was done with and without underwater setting chute in addition to normal tuna setting practices of using weighted branch lines and a main line shooter. Observers recorded unsuccessful bait depredation attempts by seabirds and contacts with gear near the bait. Further, bait retention was assessed for each haul, by checking the first 100 hooks for presence or absence of baits, which provides an overall estimate of bait loss (i.e., baits could have been lost for reasons other than depredation by seabirds). Average bait retention for control setting (i.e., without chute) was 69.5% and increased to 90.1% when the underwater setting chute was used. This would translate into a bait loss rate of 305 (i.e., (100%-69.5%)*1000) and 99 (i.e., (100%-90.1%)*1000) lost baits per 1000 hooks without and with underwater setting chute, respectively. This is much higher than, for example, reported bait loss in Brothers (1993), Brothers et al. (2010), Melvin et al. (2014), which explicitly recorded bait loss caused by birds. Here bait loss could also be due to mechanical action, loss to fish predating on bait without getting caught, and other non-seabird-related factors that cause the loss of baits from hooks. In addition to their results, Gilman et al. (2003) also provide estimates of bait loss due to seabird interactions (assuming that every seabird contact results in the removal of bait) and due to turbulence when setting gear (which is reduced when using the underwater setting chute). Bait loss due to seabirds was 4.8% and 0.15% without and with the underwater setting chute, respectively. Expressed in bait loss per 1000 hooks, these number would convert to 48 and 1.5 lost baits per 1000 hooks. But note that not all seabird interaction will necessarily result in bait loss (i.e., there will be unsuccessful bait removal attempts).

Kumar et al. (2015). The effect of bait species and baiting pattern on bait loss during longline fishing (depth range: 35–135 m) in Lakeshadweep Sea, India, was assessed between November 2009 to April 2011. Data were collected from 19 038 hooks and thus reflects rather small-scale fishing compared to large industrial fishing in other areas such as New Zealand. Fishing occurred mainly during dawn. Bait loss was defined as: less than 25% of the original bait size remained on the hook. Thus, this study provides a gross bait loss estimate and is not cause-specific (e.g., seabirds, loss due to mechanical actions, etc.). Bait loss was expressed in percentage of lost bait for different variable combinations (bait species, soak time, fishing depth). For example, across three different bait species, the bait loss ranged from 34 to 52%. The average bait loss across the three different bait species was 41.33% or 413 lost baits per 1000 hooks. The average across three different soak time was 55.06% or 550 lost baits per 1000 hooks and across three depths 48.87% or 488 lost baits per 1000 hooks.

Melvin & Walker (2008). Seabird interactions with pelagic longline vessels (Japanese vessel over 55 m length) in southern bluefin tuna in the New Zealand EEZ off the Fiordland coast in 2008 were observed. Observations were carried out during daytime. During observations, no line weighting (weights less than 45g) was used (a special permit was required); rather, tori lines were used during setting (with bait casting machine) and 3 to 4 m stout bamboo booms during hauling. Observers recorded the number of seabird attacks on sinking baits by species. Attacks were defined as ‘the taking a bait at or near the surface or a dive over where baits were sinking from the surface’ and were estimated ‘out to 100 m of the stern for the area inside the two tori lines and 5 m port of the port tori line’. During observation seabirds (e.g., Buller’s albatross (*Thalassarche bulleri*)) were attacking bait and other birds aggregated around primary bait attackers. Seabird attacks on baits usually occurred 20 to 50 m of the stern and no attacks occurred within the two deployed tori lines. Two separate observation periods with seabird attacks on bait were described: (1) two hours and 18 minutes of observations of seabird attacks during daytime (28 April) and (2) 101 minutes of observations of seabird attacks during daytime (29 April). During the first period, 11 attacks by Buller’s albatrosses were observed within the first 10 minutes. The authors assumed a set rate of one hook every eight seconds (i.e., 75 hooks in 10 minutes) and that every attack on bait was successful, resulting in 14.7% of bait being lost. The authors also describe that 11 birds killed in the section of line set during daylight, which comprised eight Buller’s albatross, one black-browed albatross, and two white-chinned petrels. In fact, these caught birds would need to be accounted for when calculating bait loss, but it is not clear from the authors description whether the eight caught Buller’s albatrosses were already included in the 11 attacks. In the second observation period, 19 bait attacks by Buller’s albatrosses occurred within 16 minutes, which would translate into 15.9% of lost bait (assuming all attacks were successful, and 120 baits were sets within 16 minutes). Converted into bait loss per 1000 hooks both estimates for bait loss are 147 and 159 lost baits per 1000 hooks, respectively.

Sato et al. (2013). Fishing trips of a commercial pelagic longline vessel operating in the western North Pacific off the coast of northeastern Japan were observed from 6 December 2010 to 10 January 2011. The effect of paired tori lines vs. single tori lines on seabirds attacking bait was studied. Lines were set in the afternoon (completed two hours after sunset) and hauled again at midnight. Target fishing depth was 40 to 70 m, and an average of 4000 hooks were used in each operation. Tuna hooks were set using a line shooter for the mainline and bait (whole mackerel (*Scomber japonicus*) and squid (*Todarodes pacificus*)) casting was done by fishers. Observations of seabird behavior began with line setting until dusk, with 15 minutes dedicated to recording seabird attacks. Seabird attacks were categorized into primary (direct attempt to steal bait - only dives and underwater plunges over baited hooks considered) and secondary attacks (charging bait brought to surface by bird making the primary attack). 16 740 hooks were observed during bait attack observations, and 88% and

2% of primary attacks attributed to Laysan albatrosses (*Phoebastria immutabilis*) and black-footed albatrosses (*Phoebastria nigripes*), respectively, 6% could not be determined to species level, and 4% by black-legged kittiwakes (*Rissa tridactyla*). With single tori lines, the mean number of albatross attacks was 25.69 attacks per 1000 hooks, which reduced to 12.29 attacks per 1000 hooks with paired tori lines. Mean secondary attacks were 13.61 attacks per 1000 hooks and 5.98 attacks per 1000 hooks with single tori lines and paired tori lines, respectively. As per Melvin et al. (2014), secondary attacks can be considered a conservative proxy of successful bait depredation attempts by seabirds, whereas all primary attacks might not be successful.

Brothers (1991). Data on seabird bycatch and interactions were recorded in longline fisheries off Tasmania's SW coasts in 1988. During setting (either fully or partially observed) and hauling (on most days), observations from the open deck were made of albatross counts (at 30-min intervals during setting) 500 m behind and 250 each side astern the vessel. When possible, hook stealing attempts were recorded as successful, unsuccessful, bird caught, bird not caught, or unknown. Four vessels were observed, of which one used streamer lines during some fishing trips. The report provides the number of bait stealing attempts (similarly to primary attacks described by Melvin et al. (2014)) per 1000 hooks. For vessels without streamer lines, bait taking ranged from 6.4 to 12.1 attempts per 1000 hooks. For the vessel with streamer lines (used on some fishing trips), there were 12.3 attempts per 1000 hooks (note that streamer lines were not used on all fishing trips, hence this number includes attempts during fishing trips with and without streamer line). Further, the number of baits taken were reported for one vessel, although how successful bait taking attempts were determined was not further described. Without streamer line the total number of baits taken between 0 to 200 m distance from stern was 29.2 baits lost per 1000 hooks, which reduced to 8.6 baits lost per 1000 hooks when streamer lines were used. Wind conditions were also described as having affected successful bait taking, where bait loss due to seabirds was 8.98 and 32.24 lost baits per 1000 hooks during favorable (light winds that resulted in high bait casting efficiency) and unfavorable wind conditions (strong winds negatively affecting bait casting efficiency and thus exposing bait to seabirds), respectively.

Løkkeborg (1998). A commercial longliner operating on the fishing grounds off the coast of mid-Norway (64º03’–65º50’N; fishing depth 172–455 m, year: 1996) was observed to determine bait loss caused by seabirds. Two different bycatch mitigation measures were used:

(1) a setting funnel, and (2) a seabird scaring device (tori lines), plus a control without bycatch mitigation measures. To reduce the number of factors causing bait loss by seabirds, longlines were immediately retrieved after casting and before sinking to the seabed. The authors note that between 5–20% of bait will be lost when setting with an automatic baiter which needs to be considered. Bait loss was provided in percentage of hooks without bait or with remnants and reported for two different baits (mackerel and squid). The percentage bait loss of mackerel was 19.5%, 22.7%, and 13.1% (or 195, 227 and 131 lost baits per 1000 hooks) for fishing without bycatch mitigation, fishing with a setting funnel, and fishing with a seabird scaring device, respectively. The corresponding squid bait loss was 21.1%, 26.0%, and 17.2% (or 211, 260, and 172 lost baits per 1000 hooks), respectively. Thus, tori lines were the most effective at preventing bait loss, while the setting funnel increased bait loss compared to the control of no mitigation measures.

Løkkeborg & Robertson (2002). Similar study as in Løkkeborg (1998), but with higher fishing effort. As in Løkkeborg (1998), lines were retrieved immediately after setting. Four fleets with the following bycatch mitigation measure configurations were studied: (1) control without bycatch mitigation, (2) bird-scaring streamer line, (3) a line shooter and (4) bird-scaring streamer and line shooter combined. Bait loss was recorded via video. For mackerel bait, reported bait loss was 14.5%, 2.1%, 12.7%, and 4.2% (or 145, 21, 127, and 42 lost baits per 1000 hooks) for fishing without bycatch mitigation, bird scaring line, line shooter, and both mitigation measures combined, respectively. For squid bait, bait loss was 1.6%, 0.9%, 3.7%, and 10.6% (or 16, 9, 37, and 106 lost baits per 1000 hooks), respectively. Bird scaring lines were the most effective at reducing bait loss for both bait types.

Sànchez & Belda (2003). Small vessel demersal and pelagic longlining was observed around the Columbretes Islands (39º54’ N, 0º41’ E, Mediterranean Sea, Spain) in 1998. 24 pelagic longliners were studied that targeted swordfish (*Xiphias gladius*), and setting occurred between 11 am and 8 pm. Hauling took place during the morning of the following day. Observers recorded the number of hooks set, the number of bait-taking attempts by seabirds (actively went into the water after the bait), the success of these attempts, and the number of bycaught seabirds. It is not clear from the authors description, whether bait-taking attempts were observed during setting, fishing, hauling, or all combined. For pelagic fisheries, 40 088 hooks were set, 74 successful bird taking attempts (415 attempts in total), and 10 seabird mortalities were reported, resulting in 2.095 lost bait per 1000 hooks.

Table 1: Available information on bait loss rate from the scientific literature (scholar Google search terms: "bait depredation seabirds", "bait loss seabirds", "bait loss economic cost"). NS: not specified; 1°: primary attacks; 2°: secondary attacks. Table continued over next 8 pages.

Bait loss rate (lost baits / 1000 hooks)	Bird-caused bait loss (B) or overall loss rate (O)	Successful depredation observed? (Y/N)	Fishing depth (m)	Setting speed (kts)/ setting rate (sec/hook)	Observation method	Fishery	Year	Bycatch mitigation	Observed seabird species	Reference
2.5	B	Y	NS	NS/5.7	NS	Indian Ocean Southern bluefin tuna*	1992	Without bait throwing device (other mitigation NS)	Black-browed albatross, Grey-headed albatross, Royal albatross, Giant petrel and Flesh-footed shearwater**	Brothers (2017)
1.4				NS/5.7				With bait throwing device (other mitigation NS)		
3.3 (2° attacks) 9.8 (1° attacks)***	B	Y (2° attacks) N (successful 1° attacks cannot be confirmed)	50–200	9.8/NS	Observer-recorded seabird attacks (1° and 2°) during daylight	South African Exclusive Economic Zone (EEZ) Bigeye tuna, yellowfin tuna, albacore, swordfish	2010	With line weighting and tori lines, data collected during daylight	White-chinned petrel, cape gannet	Melvin et al. (2014)
23.1 (2° attacks) 40.2 (1° attacks)***								Without line weighting but with tori lines		

Table 1: continued.

Bait loss rate (lost baits / 1000 hooks)	Bird-caused bait loss (B) or overall loss rate (O)	Successful depredation observed? (Y/N)	Fishing depth (m)	Setting speed (kts)/ setting rate (sec/hook)	Observation method	Fishery	Year	Bycatch mitigation	Observed seabird species	Reference
2.738 (caught birds + successful bait loss) 2.839 (previous + possibly caught birds) 3.277 (previous + unk. outcome)	B	Y	NS	NS/6	Observer-recorded seabird interactions during first 30 sec. of setting/hauling during daylight: (i) successful, (ii) unsuccessful, (iii) caught, (iv) possibly (v) unsure	Indian Ocean, Southern Ocean, Coral Sea, central Pacific Ocean	1988–2003	Various mitigation measures but not further described	Albatrosses, petrels, and skuas	Brothers et al. (2010)

Table 1: continued.

Bait loss rate (lost baits / 1000 hooks)	Bird-caused bait loss (B) or overall loss rate (O)	Successful depredation observed? (Y/N)	Fishing depth (m)	Setting speed (kts)/ setting rate (sec/hook)	Observation method	Fishery	Year	Bycatch mitigation	Observed seabird species	Reference
99 (due to all factors) 48 (due to bird interactions) ****	O and B	Y	NS	NS	Observer-recorded unsuccessful bait depredation attempts by seabirds and contacts with gear near the bait. Bait retention was assessed for each haul by checking first 100 hooks for presence/absence of bait (caught fish or seabirds considered bait loss)	Hawaii pelagic longline tuna	2002	Underwater setting chute + normal tuna setting practices of weighted branch lines and main line shooter	Black-footed and Laysan albatrosses	Gilman et al. (2003)
305 (due to all factors) 1.5 (due to bird interactions) ****								Without underwater setting chute + normal setting practices of weighted branch lines and main line shooter		

Table 1: continued.

Bait loss rate (lost baits / 1000 hooks)	Bird-caused bait loss (B) or overall loss rate (O)	Successful depredation observed? (Y/N)	Fishing depth (m)	Setting speed (kts)/ setting rate (sec/hook)	Observation method	Fishery	Year	Bycatch mitigation	Observed seabird species	Reference
413–550	O	N	35–135	NS	Bait condition on hauling: Bait remaining if >25% of original bait size remaining; Bait lost if <25% of original bait size remaining	Lakeshadweep Sea, India pelagic (small-scale) longline	2009–2011	NS	NS	Kumar et al. (2015)
147–159 (bait loss) *****	B	N	2–129	10.6/7	Observer-recorded seabird attacks on sinking baits during daylight	Pelagic Japanese longline vessels New Zealand EEZ, Fiordland coast Southern bluefin tuna	2008	Tori lines, bait casting machine, bamboo booms during hauling; no line weighting	Buller's albatross	Melvin & Walker (2008)

Table 1: continued.

Bait loss rate (lost baits / 1000 hooks)	Bird-caused bait loss (B) or overall loss rate (O)	Successful depredation observed? (Y/N)	Fishing depth (m)	Setting speed (kts)/ setting rate (sec/hook)	Observation method	Fishery	Year	Bycatch mitigation	Observed seabird species	Reference
13.61 (2° attacks) 25.69 (1° attacks)***	B	Y (2° attacks) N (successful 1° attacks cannot be confirmed)	40–70	9/NS	Observer-recorded seabird behaviour during line setting until dusk. 15 min. recording of seabird attacks. 1° - direct attempt to steal bait (dives, underwater plunges over baited hooks) 2° - charging bait on surface by bird making 1° attack	western North Pacific off northeastern Japan coast	Dec. 2010 – Jan. 2011	Single tori lines	Laysan albatrosses, black-footed albatrosses 6% could not be determined to species level 4% by black-legged kittiwakes	Sato et al. (2013)
5.98 (2° attacks) 12.29 (1° attacks)***								Paired tori lines		

Table 1: continued.

Bait loss rate (lost baits / 1000 hooks)	Bird-caused bait loss (B) or overall loss rate (O)	Successful depredation observed? (Y/N)	Fishing depth (m)	Setting speed (kts)/ setting rate (sec/hook)	Observation method	Fishery	Year	Bycatch mitigation	Observed seabird species	Reference
29.2 (without tori line) 8.6 (with tori line) 8.98 (favorable wind conditions) 32.24 (unfavorable wind conditions) 6.4–12.3 (across all observed vessels)	B	Y (observed successful bird taking attempts) N (observed bird taking attempts)	60–150	NS/7.3	Observer-recorded counts of albatrosses behind and astern the vessels and hook stealing attempts from open deck at 3-min intervals Successful, unsuccessful, bird caught, bird not caught, or unknown	300 km SW of Tasmania	1988	Streamer line on 1 out of 4 vessels	NS	Brothers (1991)

Table 1: continued.

Bait loss rate (lost baits / 1000 hooks)	Bird-caused bait loss (B) or overall loss rate (O)	Successful depredation observed? (Y/N)	Fishing depth (m)	Setting speed (kts)/ setting rate (sec/hook)	Observation method	Fishery	Year	Bycatch mitigation	Observed seabird species	Reference
131–172 (seabird scarer) 227–260 (setting funnel) 195–211 (no measure)	B	Y (lines retrieved immediately after setting to reduce bait loss due to other factors than seabirds)	172–455	7–8/NS	NS	Coast of mid-Norway (64º03’–65º50’N)	1996	Fleet with setting funnel Fleet with seabird scaring device (streamer) Control fleet without bycatch mitigation	NS	Løkkeborg (1998)
42–106 (bird scaring line and line shooter) 31–127 (shooter) 9–21 (bird scaring line) 16–145 (no measure)	B	Y (lines retrieved immediately after setting to reduce bait loss due to other factors than seabirds)	174–512	6.5–8.0/NS	NS	Coast of Ålesund (mid-Norway)	1999	NS	Northern fulmars	Løkkeborg & Robertson (2002)

Table 1: continued.

Bait loss rate (lost baits / 1000 hooks)	Bird-caused bait loss (B) or overall loss rate (O)	Successful depredation observed? (Y/N)	Fishing depth (m)	Setting speed (kts)/ setting rate (sec/hook)	Observation method	Fishery	Year	Bycatch mitigation	Observed seabird species	Reference
2.095 (only pelagic)	B	Y (lines retrieved immediately after setting to reduce bait loss due to other factors than seabirds)	NS	NS	Count of empty hooks due to seabirds immediately after setting lines without anchors	Pelagic longlines targeting swordfish Bottom longlines targeting hake or red common sea bream, red sea bream, and toothed bream Columbretes Islands, Mediterranean Sea, Spain (39º54’ N, 0º41’ E)	1998	NS	NS for pelagic longliners.	Sànchez & Belda (2003)

* Not clearly described whether bottom or SLL vessels were studied.

** These were captured species; depredating species not explicitly described.

*** 1° attacks on baited hooks and 2° attacks made by surface foragers on seabirds that made initial 1° attack (see main text)

**** Overall bait loss rate (i.e., also caused by other reasons that depredation by seabirds) and assumed seabird-related bait loss when assuming that all seabird interactions with gear result in bait loss (but note that other studies show that not all depredation attempts are successful).

*****Seabird captures not included (i.e., downward biased)

3.2 Economic costs

Brothers (2017). Further to estimated bait loss (see section 3.1), the authors quantified the economic effects of bait loss when comparing longlining with and without bait throwing device. The assumptions made were daily operating cost of longline vessel of $10 000, 200 operating days per year, 0.33% average hooking rate of southern bluefin tuna (SBT), an average SBT weight of 62.8kg, and an average SBT price per kg of $50 (currency not specified). Without bait throwing devices (bait loss rate of 2.5 baits per 1000 hooks), there would be a $15 543 deficiency due to bait loss (i.e., lost fish). With bait throwing devices, the fishing fleet might be able to increase fishing effort as it would allow line setting at a higher rate. Using the bait throwing device (bait loss rate of 1.5 baits per hook), but maintaining current fishing effort, the economic loss would reduce to $8704 and $12 403 if fishing effort increased. On some days, bait loss can be unusually high with higher economic impacts.

Kühn (2016). This study assessed the frequency and quantity of bait in the stomachs of northern fulmars caught in longline fisheries on the Faroe Islands. Potential economic loss per fishing trip was calculated as:

$$\text{Potential loss (\$, per trip)} = ((x*a)*b)*y \tag{1}$$

where x is the number of birds around a vessel, y is fishing efficiency (i.e., % of hooks that catch a fish), a is the average number of bait found in bird stomachs, and b is the average price per fish. The parameters x and y where unknown and the authors modelled different scenarios, and b was obtained from literature and market research. Parameter a was calculated from data on the frequency and quantity of bait in stomachs of bycaught northern fulmars on the Faroe Islands determined since 2004. For catch and market values, the author converted kg catch and value per kg fish into individual-based metrics, because bait loss is modelled on a per hook basis. The average price per fish per species was calculated as:

$$\text{Av. Price per fish} = \text{average mass per fish (kg)} * \text{average price per kg fish} \tag{2}$$

Parameter b, the average price per fish for all species combined was calculated as the sum of all species-specific *Av. Price per fish* multiplied by the proportion of species-specific catch in longline fisheries on the Faroe Islands.

3.3 Data

3.3.1 Protected Species Captures Database (PSCDB)

The PSCDB comprises three tables, catch_effort_t, observer_effort_t, and all_captures_t. catch_effort_t, contains groomed data on all fishing events reported by fishers. In observer_effort_t, groomed fisheries data reported by fisheries observers are stored, and some variables overlap with those reported by fishers. The table all_captures_t, contains all the protected species captures reported by fisheries observers. Variables for all three tables are described in Appendix B.

Variables to directly estimate bait loss are absent in the PSCDB. However, estimated greenweight of catch (variable 'catch' in the PSCDB table catch_effort_t; see Table B-1) is directly correlated to the amount of available bait and hence affected by bait loss, provided other correlated factors are accounted for or kept constant. Further, the presence of tori lines is recorded in the table observer_effort_t (Table B-2). For small-vessel (< 45 m vessel length) SLL fisheries (domestic vessels, except for some Australian vessels in 2006–07), 8% of set hooks were observed by fisheries observers for the 2006–07 to 2019–20 fishing years combined. That means differences in catch (i.e., as a proxy for bait loss) between fishing events with and without tori lines can only be assessed (when using the PSCDB) for a small fraction of domestic small-vessel SLL fishing effort in New Zealand. In addition, observed fishing events are not representing the full spatial distribution of domestic small-vessel SLL fishing effort. Figure 1A shows the spatial fishing intensity of domestic (including some Australian vessels in 2006–07) small-vessel SLL between the 2006–07 to 2019–20 fishing years. Small-vessel SLL fishing predominantly occurred from the west to east coast of the North Island and off the west coast of the South Island. Most of that fishing activity occurred further inshore with approximately 22 000 to 160 000 hooks set within each 0.2° grid cell (Figure 1A). Further offshore, fishing effort per grid cell ranged between approximately 400 to 3000 hooks set. Moreover, some fishing occurred off the east coast of the lower South Island and fishing effort per grid cell ranged approximately between 3000 to 8000 hooks set (Figure 1A). Figure 1B shows the proportion of observed fishing effort (total number of hooks) in each grid cell. While some fishing areas further offshore were well observed (close to 100% observer coverage per grid cell), areas closer to the coast received a lower observer coverage and some areas (especially, east coast of the lower South Islands) were mostly unobserved. Therefore, small-vessel SLL fishing activity and correlated variables might not be fully represented in the observer data.

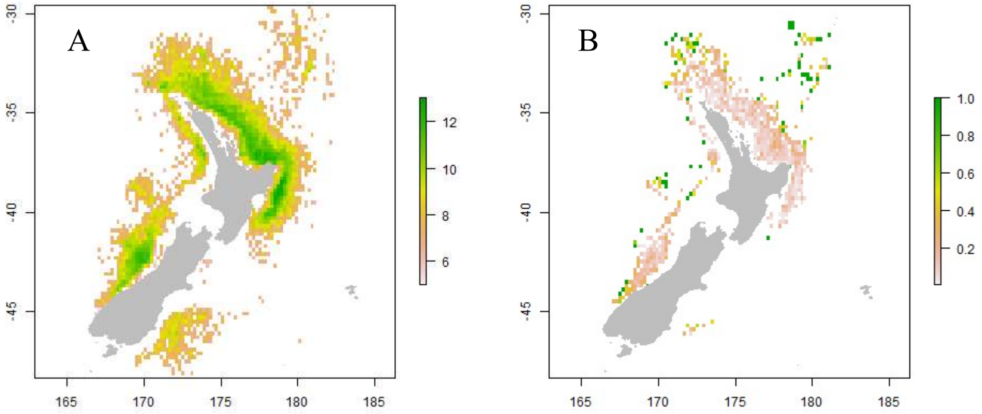

Figure 1: Spatial distribution of total and observed small-vessel surface-longline fishing activity for domestic and Australian vessels (91 events in the 2006–07 fishing year) between the 2006–07 and 2019–20 fishing years: (A) total fishing effort (number of hooks set) on log-scale per grid cell, (B) proportion of observed fishing effort per grid cell (grid cells without any observed fishing activityare blank). The resolution is 0.2° grid cells.

Bait loss and thus catch will be influenced by bycatch mitigation measures (e.g., tori lines). However, other environmental variables can affect seabird behavior and fish catch, which could mask the effect of bycatch mitigation strategies on catch and bait loss. For example, seabird feeding behavior can be influence by moon phase (Bull 2007, Cruz et al. 2013, Petersen et al. 2009, Pinet eta al. 2011, Zhou et al. 2020). Figure 2 shows that, in some fishing years (e.g., 2008–09, 2017–18 to 2019–20), the average moon phase was substantially different between fishing events with and without deployed tori lines (shown for fishing activity in fishery management area 1; top of North Island). Meyer & MacKenzie (2022), showed that moon phase is one of the main predictors of seabird bycatch in New Zealand’s surface longline fisheries (other factors were fishing year, area within New Zealand, presence/absence of a vessel freezer, and start month of fishing).

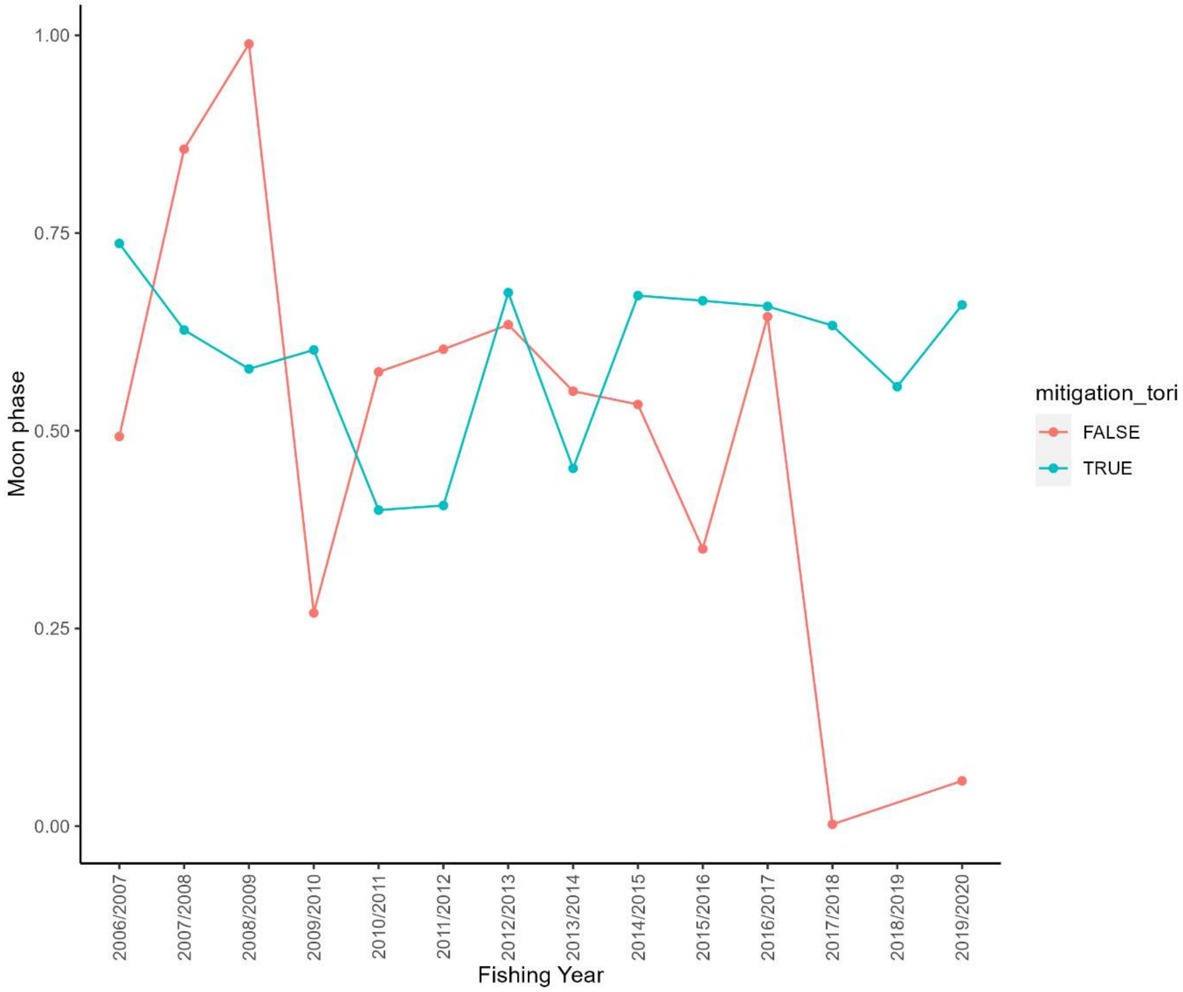

Figure 2: Average moon phase (fractional illumination of the moon's surface) per fishing year for vessel with (TRUE) and without (FALSE) tori line (mitigation_tori) in small-vessel surface-longline fishing (domestic and Australian flagged vessels) in fishery management area 1.

3.3.2 Centralised Observer Database (COD)

The PSCDB contains only a few variables (e.g., presence/absence of tori lines, moon phase, time of the day) to assess how bycatch mitigation measures could affect bait loss or total catch. Additional variables related to bycatch (e.g., vessel speed, sea surface temperature, etc.) are stored in the COD, and their suitability to identify other effects on seabird bycatch was assessed in Meyer & MacKenzie (2022). Seabird bycatch was correlated with gear configuration variables (e.g., seabird captures decreased if the tori line was properly set over the bait entry point, attachment height of the tori line influencing its spatial extent reduced seabird captures) and fishing practice (e.g., reduction in seabird bycatch with increasing number of night hours during fishing) (Meyer & MacKenzie 2022). Other variables influencing seabird bycatch were the distance to shore (decreased bycatch with increased distance), number of turns during setting (increased bycatch with increased number of turns), and sea surface temperature (increased bycatch with increased sea surface temperature). Hence, variables are contained in the COD that could also be correlated with bait loss. However, Meyer & MacKenzie (2022) found several issues with the existing data sets that might have biased the estimate effects of assessed variables on bycatch. Current data collection protocols allow for subjectivity during data collection (e.g., deck lighting which could attract birds is recorded as to whether there existed unnecessary deck lighting). Moreover, scarce observations for bycatch mitigation measures (e.g., whether tori line was over bait entry point) limit to assess their potential to reduce bycatch (Meyer & MacKenzie 2022). The assessment of catch weight and/or bait loss would also be affected by the data sparseness and data collection subjectivity.

3.3.3 Catch effort data from the Enterprise Data Warehouse (EDW)

See comments made in section 3.3.1.

3.3.4 Seabird necropsy reports

Information on stomach contents of caught seabirds were obtained from necropsy report by WMIL (Bell, 2021). For SLL fishing between the 2010–11 and 2020–21 fishing years, there were 375 records of necropsied seabirds. Of these, only 18 records (5%) contained the term ‘bait’ in the column ‘stomach content’. In other words, there is insufficient information in existing necropsy reports to assess bait loss (e.g., as done in Kühn (2016); see section 3.2) in SLL fisheries based on stomach contents of caught seabirds.

3.3.5 Counts of seabirds around fishing vessels

Data on the number of seabirds around fishing vessels could be used as an indicator of how much bait could be taken (as done in Kühn (2016); see section 3.2). A summary of the data by species and location is available at https://seabird-counts.dragonfly.co.nz/. Here, we focused on the number of observations done during hauling, setting, and fishing. Table 2 shows that the number of records ranged between 320 and 2425 observations between the 2007–08 and 2017–18 fishing years (collected on paper forms). However, during that time period between 85 and 100% of observations were done during hauling (see discussion for implications regarding bait loss estimation).

Utilising the dataset on counts of seabirds around fishing vessels would require linking observed fishing events with those recorded in the PSCDB and/or COD, which is done by matching vessel key, date, station number, and trip number between the different datasets. However, in this dataset, station number was sometimes recorded as a sequential number instead of the actual station number and some counts are not synchronized to fishing events (personal communication with Yvan Richard, Dragonfly Data Science). Hence, linking this dataset to the PSCDB or COD is not feasible.

Table 2: Number of observations in "Count of all seabirds around observed vessels" dataset between the 2007–08 and 2017–18 fishing years based on paper forms.

	Number of observations				
Fishing year	Hauling	Setting	Fishing	Unspecified	Total
2007–08	481	21			502
2008–09	1007	20			1027
2009–10	1048	1	20		1069
2010–11	1635			23	1658
2011–12	1536	16		45	1597
2012–13	1120			21	1141
2013–14	320				320

Table 2: continued.

	Number of observations				
Fishing year	Hauling	Fishing year	Hauling	Fishing year	Hauling
2014–15	516			89	605
2015–16	2036				2036
2016–17	2118	8		5	2131
2017–18	2421	4			2425

4. Discussion and recommendations

4.1 Discussion

The studies assessed in this literature review highlight potential methodologies to estimate bait loss due to depredation by seabirds in New Zealand’s commercial SLL fisheries. The applied methods ranged from observations of successful bait taking attempts, observations of secondary attacks on bait-stealing seabirds (as a conservative measure of successful bait taking attempts, because primary attacks on bait are not always successful) or setting lines and then retrieving them immediately for bait counting to reduce factors other than seabirds that could have caused bait loss (e.g., predatory fish species, disintegration, and physical stresses from wave action, longline deployment and retrieval).

Unless accounting for factors other than seabird depredation, gross bait loss rate is not a good proxy for seabird-related bait loss. For example, the study by Gilman et al. (2003) reports a large discrepancy between overall bait loss (305 lost baits per 1000 hooks) and hypothetical bait loss based on seabird interactions (1.5 baits were lost per 1000 hooks, when assuming that every seabird contact with fishing gear results in the removal of bait). However, quantifying seabird interactions with fishing gear or alternatively primary attacks on bait might still result in overestimated bait loss. For example, Melvin et al. (2014) quantified both primary attacks (i.e., bait taking attempts, which might not always be successful) and secondary attacks (i.e., bait stealing attempts on successful primary attackers). Bait loss based on primary attacks was almost twice as high compared to bait loss based only on secondary attacks (Melvin et al. 2014). Using secondary attacks would provide a conservative measure but might underestimate actual bait loss as it seems unlikely that every successful primary attack would result in secondary attacks. Hence, actual seabird-caused bait loss cannot be accurately quantified via quantifying seabird interactions, primary attackers, or secondary attackers.

There exist several problems with direct observations of bait stealing attempts by seabirds. Observations need to be done during daylight, which means that seabird-caused bait loss can only be estimated for one portion of the fishing event. However, recent SLL fishing in New Zealand occurs mostly during night hours (Meyer & MacKenzie 2022). Further, it might be difficult to visually determine successful bait taking attempts, and the evaluated studies have not assessed the potential false positive and false negative rates.

Most studies assessed here showed that bycatch mitigation measures can reduce bait stealing by birds and hence bait loss. Further, Brothers (2017) showed that, in their specific case study, economic deficiency due to bait loss can be almost halved when bycatch mitigation is deployed. Directly quantifying bait loss due to seabird depredation would require intensive data collection (overall bait loss, seabird-related bait loss, other factors causing bait loss and this under different scenarios, such as variable weather conditions during fishing, different bycatch mitigation measures, etc.) with clearly defined data collection protocols to reduce subjectivity when counting bird stealing attempts (and whether these are successful). Based on that, overall bait loss and what proportion is caused by depredating seabirds could be directly estimated. However, removing all seabird interaction might not be feasible with existing or even future bycatch mitigation methods.

Simply knowing total seabird-related bait loss is not answering the question by how much bait loss is reduced through specific bycatch mitigation strategies (the main incentive for fishers) and would be a rather expensive task. Moreover, the data available for New Zealand's commercial SLL fisheries assessed here provide some information that could potentially be used to model bait loss, but inconsistent or only very recent recording of relevant variables and linking issues between datasets limit the suitability of these datasets for such analysis. In addition, some of the collected data are not fit-for-purpose, such as the 'Counts of seabirds around fishing vessels' data where most observations were done during hauling, although most seabird depredation is likely to occur during setting and bait taken during hauling is not causing a financial deficit (i.e., fishing has finished). To understand the difference in bait loss based on different bycatch mitigation strategies, a case-control study would be more suitable. Vessels without any, or a widely applied, seabird bycatch mitigation measure would serve as a control case, which includes gross bait loss caused by all possible factors, including seabird depredation (either total seabird depredation when no bycatch mitigation measure is deployed or minimum seabird depredation with basic bycatch mitigation). For example, Ward & Myer (2007) analyzed survey data from pelagic longline data in the 1950s to understand factors influencing bait loss (depredation was not explicitly modelled) and found that bait loss was influenced by hook depth, bait species, local tuna abundance, and timing of longline operations. Importantly, fishing gear and techniques were held constant throughout the study period, reducing the number of factors that can vary and thus the required sample size. Bait status and hook status were recorded during retrieval. Some predictor variables were estimated from survey records (e.g., soak time was based on time of retrieval and start and end times of longline deployment).

In Ward & Myer (2007), bait loss was modelled using generalized estimating equations (Liang & Zeger 1986) to account for dependency within daily observations across fishing events and also for correlations between 'observations for hooks that were close together along the longline and lower correlation for hooks that are further apart'. Nevertheless, Ward & Myer (2007) highlight that extrapolating results derived from data collected during the 1950s to the present is not recommended, because of changes in fishing practices over time. Further, the specific seabird assemblage (e.g., the proportion of diving birds) in the study area will be important factors of bait loss. The same principle would apply to extrapolating bait loss rates from other studies outside New Zealand to commercial SLL fishing within New Zealand. Hence, collecting data on bait loss and drivers of bait loss should be explicitly collected for focal fisheries within New Zealand.

Not many of the reviewed studies modelled the economic consequences of bait loss caused by seabirds. The direct economic consequences will change each season depending on the value of targeted species and operational costs. Thus, economic models on bait loss would require regular updating to account for changes in economic inputs. Economic modelling also needs to consider how fishing practices would change because of implemented management measures. For example, Brothers (2017) studied the bait loss rate and economic consequences when using a bait throwing device. While the use of a bait throwing device can reduce bird interactions with bait and hence bait loss, the economic outcomes are also affected by changes in fishing practice when the mitigation measures allow for increased fishing effort (which would also result in higher economic losses across all baited hooks).

The results presented by Brothers (2017) are only indicative of economic consequences due to bait loss, because the authors highlighted that their results are inconclusive due to limited data access and study design. Kühn (2016) demonstrated an approach to model economic consequences due to seabird-caused bait loss using information on the number of seabirds around vessels, fishing efficiency, number of baits found in bird stomachs, and average price per fish. However, the required data are either not available for New Zealand's SLL fisheries, not without bias, or based on potentially invalid assumptions. The number of seabirds around vessel data collected for New Zealand fisheries were mainly collected during hauling, and any depredation post-fishing has no effect on fish caught. Further, data of seabird counts around vessels would require more specific information on the birds' location (e.g., whether they occurred close to hooks or lines, in proximity of the vessels, etc.) because this might influence the chance of birds stealing bait. Kühn (2016) adjusts the number of seabirds around vessel by using a multiplier to reflect the average number of baits found in bird stomachs. Data on stomach contents have been collected for seabirds caught in New Zealand's commercial fisheries, but information on bait in seabird stomachs was scarce (see section 3.3.4). Prices of fish or export values are difficult to obtain and to our knowledge data on target species-specific export values are not available from governmental agencies (data were not available on request to Ministry for Primary Industries). Further, export values are also likely to vary by fish condition (e.g., body condition, whether fish was fresh or frozen, etc.) and be affected by logistic factors (e.g., recent season were badly affected by limited airfreight capacity to Japan) (Richard Wells, personal communication) – information that might be difficult to obtain. Lastly, fishing efficiency (or catch per unit effort) itself is already inherently biased by seabird-caused bait loss, unless data on fishing efficiency where no seabird depredation occurred would be available.

4.2 Recommendations

For an in-depth analysis of bait loss caused by seabirds, existing data collecting protocols (e.g., observer programme and electronic monitoring) would require extensive updating. Instructions for observations of bait taking attempts (and whether these were successful) would be required and should include the timing when observations are carried out (e.g., observing hooks until these are fully submerged) and the observed area (e.g., bait-taking attempts until 150 m astern the vessel). Secondary attacks on primary attackers (e.g., as done in Melvin et al. 2014) should be collected to further generate a conservative estimate of bait loss, because it might not always be possible to distinguish successful and unsuccessful bait-taking attempts. Further, additional variables affecting seabird depredation (e.g., moon phase, time of the day, etc.) need to be consistently recorded and a random sample of all SLL fishing activity would be required to avoid bias in estimated bait loss. Almost all studies assessed here, failed to report the accuracy (e.g., standard error) of their estimates bait loss (in some cases statistical tests were reported). Any analysis of bait loss or seabird depredation in New Zealand's SLL fisheries would require reporting of standard statistics to evaluate the robustness of derived conclusion (e.g., difference in bait loss between fishing with different bycatch mitigation measures).

The analysis of stomach contents can provide further insights into the amount of seabird depredation. However, currently these data are only recorded as to whether bait or contents (e.g., discards) were present in seabird stomachs. Therefore, necropsies protocols could be adjusted to determine bait content to species level. Further, necropsy data only reveal how many baits can be found in bycaught seabirds and are not a random sample of all seabirds that interact with fishing gear. Data on stomach contents of non-bycaught birds would therefore be required to obtain an unbiased assessment of bait loss due to seabird depredation.

Whilst extending data collecting protocols and necropsies would help improving our understanding of the mechanistics of bait loss, it might be logistically challenging to instruct observers to collect data on bait loss in addition to other compulsory tasks during the observer programme. Further, the observation of bait taking attempts and analysis of necropsies only serve as an approximation of the true bait loss caused by seabirds, because it seems logistically impossible to observe all seabird depredation and whether it being successful (or only during a very limited scenario that is not representative of actual fishing practices). Rather, we recommend collecting data on changes in catch per unit effort, which amongst other factors, is influenced by bait loss, and is ultimately the relevant end point to commercial fishers (i.e., lost bait is causing financial deficit due to reduced catch). For example, a case-control study design would allow assessing how catch per unit effort changes with different seabird bycatch mitigation strategies. As per legal requirement, SLL vessels in New Zealand use tori lines combined with night fishing and line weighting (and more recently hookpod devices (a capsule encasing the point and barb of baited hooks) can be used as an alternative bycatch mitigation measure. That means, alternative bycatch mitigation measures (and their effect on bait loss) can only be assessed in New Zealand, if they are combined with hookpod devices or the three other mitigation measures. To test bycatch mitigation measures that exclude any of those being legally required in New Zealand, alternative collaboration with fisheries that have less stringent rules around bycatch mitigation would be required. However, care needs to be taken that any studied international fishery would be relevant for fishing within New Zealand (e.g., using similar fishing practice etc.). To ensure that bait loss due to seabird depredation is assessed, fishing practices need to be held constant between vessels with different bycatch mitigation measure. The disadvantage of that approach, however, would be that not all relevant fishing practices would be reflected in the bait loss estimates. Alternatively, vessels with different fishing practices could alternate bycatch mitigation measures (e.g., switching bycatch mitigation measures half-way through the season) such that all assessed vessels were operating under different bycatch mitigation strategies. Importantly, the selection of studied vessels should be based on a random sampling design, and not based on logistic factors (e.g., better communication with specific fisheries, length of fishing trip etc.) to avoid bias in estimated bait loss.

To model economic consequences of bait loss, a complex set of information would be required (e.g., export values on how these vary annually, by fish conditions, by logistic factor, etc.). We suggest collecting data on direct revenue for catch and costs of bycatch mitigation measure and other operational costs, because the scope of such work would be to incentivize fishers for the use of specific bycatch mitigation measures. Within New Zealand, commercial fishers can only sell fish to licensed fish receivers, and data on fish sold and prices for fish at the time of selling might be available through seafood industry owned databases such as FishServe (https://www.fishserve.co.nz/). Alternatively, revenue and costs could be directly collected as part of a study dedicated to assessing bait loss (see previous paragraph).

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Appendix

Appendix A

Table A-1: Assessed references without relevant information to infer bait loss in surface-longline fisheries caused by seabird depredation.

Reference	Notes
Gilman et al. (2007)	No bait loss information provided.
Muñoz-Lechuga et al. (2016)	Describes depredation by fish.
Gandini, P., & Frere, E. (2012)	Inconclusive presentation of results.
Gilman et al. (2022)	No bait loss information provided.
He (1996)	Bottom-longline.
Jahncke et al. (2001)	No bait loss information provided.
Melvin et al. (2013)	Same fishery as studied in Melvin et al. (2014) but data collected in 2009. Focus was on seabird bycatch, but primary and secondary attacks were also recorded. However, data are not presented in way allowing to calculate bait loss rates.
Robertson & Ashworth (2012)	Only describing the development of an underwater bait setter device (similar to a hook pod).
Ward & Myers (2007)	Analysis on factors affecting bait loss but no direct bait loss rates presented.
Ward et al. (2004)	More looking at catch rates to infer factors affecting bait loss in relation to soak time.
Zhou & Brothers (2021)	No relevant data presented.
Kumar et al. (2016)	No bait loss presented.
Løkkeborg (2001)	Bottom-longline.
Løkkeborg (2003)	Bottom-longline.

Appendix B

Table B-1: Description of the catch_effort_t table in Protected Species Database (descriptions were originally developed by Dragonfly Data Science (https://www.dragonfly.co.nz/)). Table continues over next page.

Column	Description
method	Method of the fishing
effort_num	Number of fishing events in each record
total_hook_num	Total number of hooks set
total_net_length	Total length of net (m)
gear	Code describing the fishing gear
fishing_duration	Total time spent fishing (hours, derived from the start and end times)
form_type	Code indicating the form type that the effort was reported on
dcf_key	DCF key of the form
event_key	Primary key indicating the event. Combination of CE source identifier and fishing event keys.
fishery	Code derived from the target species and the fishing method, used to define a target fishery for protected species reporting
target	Target species
stats_area	Statistical area of the fishing
fishing_year	Fishing year, based on an October 1st start
start_date	Start date of the fishing, from start_datetime
start_time	Start time of the fishing event, from start_datetime
start_datetime	Start datetime of the fishing event
end_date	End time of the fishing event, from end_datetime
end_time	End time of the fishing event, from end_datetime
end_datetime (	End datetime of the fishing event
trawl_area	Area of the fishing event (based on the start point). Area defined in `shapes.custom_trawl`
area	Area of the fishing event (based on the start point). Area defined in `shapes.summary_areas`
fma_area	FMA of the fishing event (based on the start point). Area defined in `shapes.custom_fma`
start_point	Start point of the fishing event
end_point	End point of the fishing event
next_event_key	Next fishing event
prev_event_key	Previous fishing event
catch	Estimated greenweight of the catch (kg)
vessel_key	Vessel key of the fishing
vessel_class	class of the vessel, used for modelling (S: small, L: large, A: all; the split between S and L is at 28 m for Trawl, 34 m for BLL, and 45 m for SLL; all other methods have a class of A).
vessel_size	size-class of the vessel (in metre ranges), may also be 'U' for unknown
vessel_reg_type	Registration of the vessel (C: Charter, D: Domestic)

Table B-1 continued.

Column	Description
vessel_nation	Nationality of the vessel registration
vessel_length	Length of the vessel (m)
vessel_freezer	Flag indicating whether the vessel has a freezer
vessel_meal	Flag indicating whether the vessel has a meal plant
trawl_proctype	Processing type of trawl vessels. Trawl vessels are either \`small\` (< 28m), \`meal\`, \`nomeal\`, or \`fresher\`
distance_to_shore	distance to shore of the fishing (m)
night_hours	Number of hours of the fishing that were at night
moon_phase	Fractional illumination of the moon's surface
start_solar_altitude	Solar altitude (degrees) at the start of the fishing
end_solar_altitude	Solar altitude (degrees) at the end of the fishing
client_key	Client key associated with the fishing event

Table B-2: Description of the observer_effort_t table in Protected Species Database (descriptions were originally developed by Dragonfly Data Science (https://www.dragonfly.co.nz/)). Blank cells for descriptions are already covered in Table B-1. Table continues over next page.

Column	Description
id	Unique id of each row
trip_number	Observer trip number
station_number	Observer station number
event_key	Link to the fishing effort associated with the fishing (not the COD event key)
effort_num	
total_hook_num	
total_net_length	
vessel_key	
vessel_class	
vessel_size	
target	
fishery	
method	
area	
fma_area	
area_name	Readable name of the summary area
start_date	
start_time	
start_datetime	
end_date	
end_time	
end_datetime	
fishing_year	
start_point geometry	
end_point geometry	

Table B-2 continued.

Column	Description
stats_area	Statistical area
in_eez	flag indicating whether the fishing was within the outer boundary of the EEZ [Always true in this table]
excluded	Whether this event was excluded from protected species bycatch estimation [Always null in this table]
mitigation_sled	Flag indicating whether a SLED was used
mitigation_none	Flag indicating whether no mitigation was used
mitigation_tori	Flag indicating whether tori lines were used
mitigation_baffler	Flag indicating whether bafflers were used
mitigation_warp_scarer	Flag indicating whether warp scarers were used
mitigation_other	Flag indicating whether other mitigation was used

Table B-3: Description of the all_captures_t table in Protected Species Database (descriptions were originally developed by Dragonfly Data Science (https://www.dragonfly.co.nz/)). Blank cells for descriptions are already covered in Table B-1. Table continues over next page.

Column	Description
trip_number	
station_number	
vessel_key	
vessel_class	
vessel_size	
vessel_length	Length of the vessel (m)
event_key	
method	
Area	
start_datetime	
end_datetime	
start_date	
end_date	
fishing_year	
start_point	
start_point_j	Start point of the fishing, jittered randomly to meet MPI data confidentiality requirements
target	
fishery	
specimen_number	Specimen number
caught_time	Caught time
observer_species	Species as recorded by the observer

Table B-3 continued.

Column	Description
species	Species following necropsy and other identifications

model_species	Species as used in model estimation, including imputation and other corrections
alive	Alive status code
injuries	Injury status code
autopsied	Whether the specimen was necropsied
photo_id	Species recorded in photographs
capture_method	Capture method code
sex_code	Sex code
age_code	Age code
original_station	Original station number
remarks	Collated observer remarks
updates	Record indicating changes that were made to the COD record
cid	Identifier used to track captures when COD is updated

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