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Feasibility of tagging deepwater sharks in New Zealand

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EXECUTIVE SUMMARY

Finucci, B.[1] (2022). Feasibility of tagging deepwater sharks in New Zealand.

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Biological and ecological knowledge gaps for New Zealand sharks have been highlighted in recent regional risk assessments, conservation projects, and literature reviews. Data deficiency is particularly pronounced for deepwater species that are generally characterised with conservative life histories (low fecundity, late maturity, slow growth, low intrinsic rate of population increase) relative to shallower-dwelling species. Identified knowledge gaps for New Zealand sharks include validation of age and growth, population structure, movement and habitat use, and post-release survival. This information is important for understanding the vulnerability and resilience of species to fishing pressures and encouraging sustainable management, and it provides key inputs into current management tools such as spatially-explicit fisheries risk assessment frameworks.

Tagging studies are widely applied to investigate aspects of fish population dynamics, evolutionary ecology, life-history, and community ecology. For sharks, tagging studies have been particularly important for: delineating home ranges, nursery areas, habitat use, and stock identification; understanding growth, species movement, gear selectivity, and survival/mortality; and estimating relative abundance. To date, deepwater shark tagging studies have been limited to a handful of pilot studies. Nonetheless, these studies have provided valuable data on the application and effectiveness of available technology, as well as improving our knowledge on movement and connectivity, and survival.

In this review, the feasibility of a deepwater shark tagging programme in New Zealand waters was assessed. A tagging programme could aim to fill knowledge gaps in age and growth, movement and habitat use, and post-release survival for deepwater sharks with the greatest risk from commercial fishing. Sampling would most likely be opportunistic and rely on scientific observers on-board commercial fishing vessels during usual fishing operations. Tag releases from longline catches would likely have increased survival rates over trawl catches for deepwater species. Most deepwater shark catch has been reported from the ling (*Genypterus blacode*s) bottom longline fishery. Based on factors known to minimise capture stress and increase shark survival (e.g., tagging at night, depth of capture), the ling bottom longline fishery would be a suitable candidate for tagging deepwater sharks in New Zealand waters. Vessels greater than 30 m in length using manual baiting were found to consistently report deepwater shark catch; approximately half of the landings from the ling bottom longline fishery that were manually-baited reported at least one deepwater shark species in the period between 2000 and 2020. Furthermore, most of these landings (74%) occurred in the last five years.

Given the lack of data on deepwater shark movement and survival, any study initiated would be exploratory and should be treated as a pilot study. Options for this tagging study include conventional band recovery (mark-recapture), known fate (electronic tagging), or a combination of both. Such a study would provide some of the first insights in movement and post-release survival for select deepwater shark species into the South Pacific and beyond. Using telemetry (satellite tagging), a study could be completed in the short term (one or two years). A tagging study to better assess growth parameters, including age validation, would likely require several years of tagging and tagging returns to accumulate sufficient data. Species likely to be suitable for tagging include large-bodied species that are frequently reported from the ling bottom longline fishery, such as seal shark (*Dalatias licha*), leafscale gulper shark (*Centrophorus squamosus*), shovelnose dogfish (*Deania calcea*), and Plunket shark (*Scymnodon plunketi*).

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[1] National Institute of Water and Atmospheric Research (NIWA), New Zealand.

The success of a band-recovery (conventional) mark-recapture study depends on how likely tagged sharks are to be recaptured. This requires an understanding of survival and encounter probabilities, processes that are not known for deepwater sharks. To better quantify expected return rates and the potential tagging success of a mark-recapture study, it is recommended that an assessment of at-vessel mortality of deepwater sharks be conducted on commercial bottom longline fishing vessels to improve these knowledge gaps. A satellite telemetry study assessing post-release mortality and initial movement patterns would also provide insight into these probabilities. Coverage of the deepwater marine environment by observers and research surveys is sufficient to encounter tagged deepwater sharks around the South Island, Chatham Rise, and waters south of the New Zealand mainland, but is limited in northern New Zealand waters. Cooperation with all commercial vessels throughout the New Zealand Exclusive Economic Zone would likely improve the probability of recapturing tagged sharks.

1. INTRODUCTION

Deepwater sharks are generally characterised by conservative life histories (low fecundity, late maturity, slow growth, low intrinsic rate of population increase) relative to shallower-dwelling species (Kyne & Simpfendorfer 2010, Cotton & Grubbs 2015). A global review of life history traits for deepwater chondrichthyans found that increased maturity and longevity and decreased fecundity and breeding frequency was strongly associated with increasing depth (Rigby & Simpfendorfer 2015). Historical intensive deepwater fishing, combined with a lack of baseline data, stock assessments informing management plans, and conservative life histories, has resulted in localised population declines around the world with little-to-no evidence of stock recovery (Anderson & Ahmed 1993, Graham et al. 2001, ICES 2020). For example, the incredibly low productivity (singular fecundity, size at maturity reached at more than 80% of maximum observed length) of the Australian southern dogfish (*Centrophorus zeehaani*) was not realised until after the species had been subject to decades of exploitation (Graham & Daley 2011). It has now been estimated that for this species to recover from its current state (estimated at 8% B_0) to 20% B_0 will take approximately 63 years under current management arrangements (Daley et al. 2019). Recovery could be delayed by an additional 46 years with the reopening of regional fisheries (Daley et al. 2019). The potential vulnerability of these species highlights the need for monitoring, assessment, and management.

In New Zealand, nearly 80% of the 112 species of chondrichthyans (sharks, rays, and chimaeras) are found in the deep sea and about 20% are endemic to the region (Finucci et al. 2019a). At least 77 species, predominately deepwater chondrichthyans, have been reported as bycatch from commercial fisheries (Francis 2015). Some chondrichthyans (e.g., spiny dogfish, *Squalus acanthias*, Baxter's dogfish, *Etmopterus granulosus*, rough skate, *Zearaja nasuta*) were amongst the main non-target species recorded in New Zealand's offshore fisheries (Francis 2015, Anderson et al. 2017, Finucci et al. 2020). Biological and ecological knowledge gaps on New Zealand chondrichthyans have been highlighted in recent regional risk assessments, conservation projects, and literature reviews (Ford et al. 2015, Duffy et al. 2018, Ford et al. 2018, Finucci et al. 2019a). Data deficiency is particularly pronounced for deepwater species and knowledge gaps include validated age and growth, population structure, movement and habitat use, and post-release survival. This information is important for understanding the vulnerability and resilience of species to fishing pressures and encouraging sustainable management, and provides key inputs into current management tools such as the spatially-explicit fisheries risk assessment framework (SEFRA) (Large et al. 2019).

Tagging studies are widely applied to research aspects of fish population dynamics, evolutionary ecology, life-history, and community ecology (Bagley et al. 1994, Pine et al. 2003). Tagging studies have been particularly important for delineating home ranges, nursery areas, habitat use and stock identification, and for understanding growth, species movement, gear selectivity and survival/mortality, and estimating relative abundance (Kohler & Turner 2001, Latour 2005, Bouyoucos et al. 2020). Fish migration and movement patterns are key determinants in understanding stock structure and connectivity and overlap with fisheries interactions (Lédée et al. 2021). Monitoring marked individuals, or a group of marked individuals, over space and time can be a cost-effective and reliable means of studying fish populations and is an important tool for fisheries management (Brownie et al. 1985, Williams et al. 2002, Lédée et al. 2021).

This report was prepared as an output from the Fisheries New Zealand project SEA2020-24 'Feasibility study of the deepwater shark tagging programme' which had the following objectives.

Overall Objective

To study the feasibility of a deepwater shark tagging program, with the aim to fill knowledge gaps in age and growth, movement and habitat use, and post-release survival.

Specific Objectives

Develop a mark and recapture study setup, including both tagging strategy and recapture data analysis, for relevant shark species

This report presents the output in three sections. Section 2 provides a general overview of current knowledge on deepwater shark age and growth, movement and habitat use, and post-release survival. Section 3 discusses tagging study design and application. Section 4 assesses options for a deepwater shark tagging programme in New Zealand.

2. CURRENT KNOWLEDGE OF DEEPWATER SHARKS

2.1 Age and growth

The most common structure used for ageing coastal and pelagic elasmobranchs, the vertebral centra, is unsuitable for most deepwater species due to poor calcification of the vertebrae (Natanson et al. 2018b). Instead, attempts have been made to age deepwater sharks with their dorsal fin spines (Irvine et al. 2006). There are three main approaches to age determination using dorsal fin spines: 1) reading pigmented growth bands embedded within the enamel cap of the spine (Holden & Meadows 1962); 2) examining concentric growth bands visible in a transverse section of the spine, taken near the lumen (Clarke et al. 2002); and 3) reading growth bands on the stem (base) of the spine, usually revealed by staining and polishing the whole spine (Irvine et al. 2006). Variations of these three methods have been used to age chimaeras and squaliform sharks (for a review of species, see Natanson et al. 2018a, Finucci et al. 2021a). Although such methods have provided age estimates of greater than 70 years for some species (e.g., Clarke 2002), validation studies are lacking.

Interpretation of age estimates from fin spines is confounded by spine damage, discrepancies between internal and external band counts, and a lack of validation studies (Irvine et al. 2006). Validation for fin spine growth increments was examined in the black dogfish (*Centroscyllium fabricii*) from Greenland waters by comparing age estimates derived from fin spines with bomb radiocarbon dating (Hedeholm et al. 2021). Bomb radiocarbon dating is a widely adopted standard and was applied to eye lenses by Hedeholm et al. (2021), because radiometric methods applied to spine dentine material violated the 'closed system' assumption of radiometric dating (Cotton et al. 2014). Discrepancies were found between the two ageing methods, with fin spines yielding a maximum age estimate of 35 years whereas the bomb carbon age estimates exceeded 53 years, thus suggesting fin spines were unsuitable for ageing at least the oldest individuals of this species (Hedeholm et al. 2021). Bomb carbon dating has also shown that using growth zones for ageing sharks can underestimate true age and some shallow-water sharks have been found to be nearly twice as old as originally thought (Harry 2018). A recent study investigated the relationship between telomere length and body length (as a proxy for age) in *Etmopterus granulosus* with encouraging results (Nehmens et al. 2021). Near-infrared spectrometry has been used on skin samples of deepwater sharks to successfully predict age (Rigby et al. 2014). Although this technique offers the appeal of a non-lethal ageing method, the procedure relies on calibration from a sample set with known ages.

2.2 Movement and habitat use

Deepwater sharks are widely assumed to have broad, and often global, distributions due to the relative environmental homogeneity of the deep sea (Cotton et al. 2015b). It is assumed deepwater sharks are capable of long-distance movements given the general lack of genetic variation, long lifespans, and the tendency for species to segregate by sex and size class (Veríssimo et al. 2012, Cotton et al. 2015a, Finucci et al. 2018). However, recent tagging and genetics research suggests some populations are confined by geographical and oceanographic features and biological stocks exist over relatively small geographical areas (Cunha et al. 2012, Catarino et al. 2015, Catarino et al. 2017, Keggin 2017).

Movement ecology

Shark tagging studies were first introduced in the late 1920s and, for many shallow-water species, these studies have flourished into routine programmes gathering a wealth of information on species stock structure, distributions, movement and migration patterns, and behaviour (Kohler & Turner 2001). For example, the Cooperative Shark Tagging Program (CSTP) along the Atlantic and Gulf coasts of the

United States has tagged more than 295 000 sharks representing 52 species since it was first initiated in 1962 (Kohler & Turner 2018).

The earliest known telemetry study of a deepwater shark included a single gulper shark (*Centrophorus acus*[2]) tagged with an ultrasonic transmitter off Suruga Bay, Japan in 1986 (a second individual was tagged and presumed to have died) (Yano & Tanaka 1986). A literature review found that between 1986 and 2018 only 42 telemetry studies were carried out on deepwater fishes (teleost or chondrichthyan) (Edwards et al. 2019). Of these 42 studies, two involved acoustic telemetry of deepwater sharks (Portuguese dogfish (*Centroscymnus coelolepis*) and southern dogfish) (Bagley et al. 1994, Daley et al. 2015) and six involved satellite and archival telemetry of deepwater sharks (bluntnose sixgill shark (*Hexanchus griseus*), leafscale gulper shark (*Centrophorus squamosus*), Pacific sleeper shark (*Somniosus pacificus*), Greenland shark (*Somniosus microcephalus*), Cuban dogfish (*Squalus cubensis*), and Arctic skate (*Amblyraja hyperborea*)) (Hulbert et al. 2006, Peklova 2012, Williams et al. 2012, Rodríguez-Cabello & Sánchez 2014, Campana et al. 2015, Comfort & Weng 2015, Rodríguez-Cabello et al. 2016, Shipley et al. 2017a, Talwar et al. 2017, Rodríguez-Cabello et al. 2018, Coffey et al. 2020).

Satellite tagging has also been trialled for other deepwater species (*Centrophorus* spp., and bigeyed sixgill shark (*Hexanchus nakamurai*)), but these studies were unsuccessful in collecting data (Brooks et al. 2015, Hussey et al. 2018). All but one study was restricted to the Northern Hemisphere (the exception being work on *Centrophorus zeehani* off the Great Australia Bight in the Indian Ocean), and most studies have been conducted in the North Atlantic Ocean (Edwards et al. 2019).

Tagging studies have revealed some deepwater sharks (e.g., *H. griseus*) exhibit diel vertical migrations and can occupy relatively broad depth ranges and environmental conditions (Rodríguez-Cabello & Sánchez 2014, Comfort & Weng. 2015, Shipley et al. 2017a, Hussey et al. 2018, Coffey et al. 2020). For example, *H. griseus* was found to be capable of tolerating cold temperatures (5–7 °C) and low oxygen conditions (10–25% saturation) occurring within the local oxygen minimum zone without any reduction in activity levels (Coffey et al. 2020). Telemetry studies have indicated movement patterns are vastly different across species, even between related species. In the Northeast Atlantic, a study of five satellite-tagged *Centrophorus squamosus* reported the species was capable of long-distance migrations, with one individual traveling nearly 287 n. miles in 45 days, presumably following the continental slope at a mean depth of 900 m (Rodríguez-Cabello & Sánchez 2014). Two other individuals spent nearly four months travelling, reaching inferred speeds of 20 n. miles per day (Rodríguez-Cabello et al. 2016). In stark contrast, a study of congeneric gulper sharks (n = 71) off the coast of southern Australia reported that acoustically tagged *Centrophorus zeehaani* remained within a discrete area along the continental slope, with an average total movement range of less than 20 km (Daley et al. 2015). Off the Azores, preliminary results from fine-scale acoustic telemetry suggest seal shark (*Dalatias licha*) and *H. griseus* are highly resident and reside on island slopes and surrounding seamounts (L. Fauconnet, Instituto do Mar, pers. comm.).

Population genetics

Molecular genetic studies can provide important information for shark fisheries management and conservation applications, providing a better understanding of species identification, phylogeography, philopatry, and genetic effective population size (Dudgeon et al. 2012). For fisheries management, genetic techniques have been helpful for defining management units, and these techniques have already been used to better understand some of New Zealand's shallow-water species, including movement and population size estimates of the white shark (*Carcharodon carcharias*) population inhabiting New Zealand and Australia (Hillary et al. 2018, Davenport et al. 2021). Information on deepwater shark population genetics, however, is limited.

No study has examined genetic population structure or connectivity of a deepwater shark around New Zealand waters, although some studies have included samples from three frequently encountered species

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[2] Currently recognised as a synonym of *Centrophorus granulosus.*

(*Centrophorus squamosus*, *Etmopterus granulosus*, *Centroscymnus coelolepis*) in New Zealand (Straube et al. 2011, Veríssimo et al. 2011, Veríssimo et al. 2012, Straube et al. 2015). Outside New Zealand, genetic studies on deepwater sharks have shown variation in patterns of population differentiation despite species having comparable life history traits and overlapping sample sites (Veríssimo et al. 2011, Cunha et al. 2012, Veríssimo et al. 2012). Globally distributed species have shown the potential for high dispersal across ocean basins (Veríssimo et al. 2011, Veríssimo et al. 2012). Studies using nuclear microsatellite markers and mtDNA have found high levels of genetic homogeneity across the Atlantic Ocean, and low levels of genetic divergence between the Atlantic and Pacific oceans, suggesting some squaliform sharks have the ability to maintain some degree of genetic connectivity across ocean basins (Veríssimo et al. 2011, Veríssimo et al. 2012, Catarino et al. 2015, Keggin 2017). This broad level of connectivity, however, can be influenced by the movement of a small number of individuals over the course of one generation length (Wang 2004, Lowe & Allendorf 2010), which can be 25 years or more for deepwater sharks (Parker & Francis 2012). Population connectivity may also be restricted by differences in movement patterns between the sexes (sex-biased dispersal). Genetic evidence suggests female *Centrophorus squamosus* have long-term philopatry to New Zealand, meaning females may remain within the region (Veríssimo et al. 2012).

Other deepwater species display evidence of localized population structure. *Hexanchus griseus* has geographically distinct maternal lineages, indicating population structure along geographical ranges, with large-scale population subdivisions both between and within the Atlantic and Pacific oceans, and also at a smaller scale within the Mediterranean Sea (Vella & Vella 2017). Weak but significant genetic differentiation was reported between Chilean and New Zealand samples of *Etmopterus granulosus*, suggesting that gene flow may be limited across the South Pacific (Straube et al. 2011). The longnose velvet dogfish (*Centroselachus crepidater*) has been shown to exhibit Atlantic Ocean-Pacific Ocean differentiation and the possible existence of present-day gene flow barriers between the two ocean basins (Cunha et al. 2012, Keggin 2017). Fine-scale population differences were also reported in the Northeast Atlantic Ocean for both *Centroselachus crepidater* and shovelnose dogfish (*Deania calcea*) along two spatially similar sampling sites in the Rockall Trough (Hebrides North and South) and the Mid Atlantic Ridge, separated by approximately 2000 km (Keggin 2017). In comparison, the straight-line distance between the Chatham Islands and Auckland Islands is approximately 1500 km, highlighting that fine-scale population structure may also exist within New Zealand waters. Barriers to gene flow have been attributed to the influence of oceanographic currents (particularly their impact on prey distribution) (Cunha et al. 2012) and bathymetric features such as the shallow (300–900 m) Strait of Gibraltar, the shallow depth of which separates the Atlantic Ocean and Mediterranean Sea (Catarino et al. 2015, Gubili et al. 2016, Catarino et al. 2017). Of the global studies which have included New Zealand species widely distributed in the region, only samples from the Chatham Rise have been examined (Veríssimo et al. 2012, Keggin 2017).

Habitat use

Prolonged monitoring programmes for shallow-water sharks have also allowed us to understand habitat associations and identify critical habitats for species, such as home ranges, nursery areas, and feeding grounds (Heupel et al. 2004, Reyier et al. 2014). Long-term monitoring has also shown these habitat associations can change over time (e.g., range expansion or reduction) in response to changes and/or modifications to the environment (Bangley et al. 2018).

Without the means to observe deepwater sharks in their natural settings over prolonged periods of time, inferences on habitat use are often made from catch composition of fisheries surveys. Deepwater sharks aggregate by size, sex, and/or developmental stage, and aggregations may be correlated with environmental factors such as depth, temperature, benthic characteristics, or biological factors such as prey availability, reproductive opportunity, or parturition (Wetherbee 2000, Marongiu et al. 2017, Finucci et al. 2018, Porcu et al. 2020). Segregation by sex and maturity stage is also common (Yano & Tanaka 1988, Wetherbee 1996, Clarke et al. 2001, Holt et al. 2013, Moura et al. 2014, Cotton et al. 2015a), which may dictate large migrations for mating or pupping. Small individuals of squaliform shark are known to occur in either shallower or deeper water than adults (e.g., Yano & Tanaka 1988, Irvine et al. 2012, Moura et al. 2014).

There are no confirmed nursery grounds for deepwater sharks, but some specific areas are suspected to be important for breeding purposes (Heupel et al. 2018). Juveniles are often consistently found in discrete locations (Veríssimo et al. 2011, Holt et al. 2013, Hussey et al. 2015, Heupel et al. 2018), whereas reproductively active or gravid females are very infrequently reported in catch data and often at specific locations; in New Zealand, this includes Puysegur (Veríssimo et al. 2012, Moura et al. 2014). For oviparous species, large clusters of egg cases and large numbers of juveniles have been identified in discrete locations on the shelf-break, along the outer shelf and upper slope, near cold seeps and hydrothermal vents, and on cold-water coral reef habitat (Treude et al. 2011, Henry et al. 2016, Hoff 2016, Salinas-de-León et al. 2018, Armstrong & Finucci unpublished).

2.3 At-vessel and post-release mortality

In a global review of capture and post-release mortality of sharks, there were no published, quantified data on at-vessel mortality (dead or dying when hauled on board) of deepwater sharks caught by commercial fishing vessels (Ellis et al. 2017). Since this review, one study has been published assessing mortality of some deepwater sharks caught on commercial longline vessels operating off Spain (Rodríguez-Cabello & Sánchez 2017). Here, at-vessel mortality was found to be lower than expected for *Centrophorus squamosus*, *Deania calcea*, and *Centroscymnus coelolepis* (< 10%), but when the number of dead individuals was combined with individuals assessed in poor condition, at-vessel mortality rose to nearly 20% for *Centrophorus squamosus* and 40% for both *Deania calcea* and *Centroscymnus coelolepis* (Rodríguez-Cabello & Sánchez 2017). Mortality is expected to be high in more tropical climates (Talwar et al. 2017). Deepwater sharks live at colder temperatures than those at the surface, and the amount of time exposed to warmer temperatures is thought to increase capture stress and ultimately lead to mortality (Talwar et al. 2017). In the Caribbean, at-vessel mortality for Owston's dogfish (*Centroscymnus owstonii*) captured by a research vessel was 80% (Brooks et al. 2015).

Information on post-release mortality of deepwater sharks is also incredibly limited. Of the one study assessing mortality from commercial vessels mentioned above, 33% of *Centrophorus squamosus* tagged with satellite tags and released in a healthy condition died within 5–10 weeks after release (Rodríguez-Cabello & Sánchez 2017). The few studies that have formally investigated stress response and post-release survival of deepwater sharks from research vessels indicated that surface temperature, depth of capture, and body size strongly influenced the fate of these animals (Brooks et al. 2015, Daley et al. 2015, Talwar et al. 2017). Large-bodied *Hexanchus griseus* have been captured from depths down to 1343 m with very high post-release survival (> 80%, D. Grubbs, Florida State University, pers. comm.) but smaller sharks captured from much shallower depths experience very high post-release mortality due to either predation or capture-induced stress (Brooks et al. 2015, Talwar et al. 2017). A 'post-release enclosure' was trialled in Exuma Sound, The Bahamas, to release satellite-tagged, small-bodied *Squalus cubensis* at specific depths in order to improve post-release survival (Shipley et al. 2017a). Although the sample size was small, movements of the sharks released with this method were recorded for the entirety of the tag deployment period. No quantitative data on this method have been provided yet. As an alternative to hauling sharks to the surface, attempts have been made to tag individuals at depth (Sigurdsson et al. 2006, Kristinsson et al. 2013). Band-powered spearguns were recently used to tag *H. griseus* at depths over 500 m (D. Grubbs, Florida State University, pers. comm.), and, in the Northeast Atlantic, miniature acoustic transponders wrapped in bait were ingested by *Centroscymnus coelolepis* at 1517–1650 m depth (Bagley et al. 1999), making this the deepest tracked shark to date.

3. TAGGING STUDY DESIGN AND APPLICATION IN NEW ZEALAND

Sharks are generally well suited subjects for tagging studies due to their tendency to aggregate and their relatively large size allowing them to carry tags successfully (Kohler & Turner 2001).

3.1 General tagging study designs

Tagging studies are well described within ecological literature (Amstrup et al. 2005, Pine et al. 2012, Krebs 2014). Tagging studies fall broadly into two categories, open and closed designs. Open designs allow for demographic (birth and deaths) and geographic (immigration or emigration) flow during the sampling period and allow adequate time or space for these processes to occur. In contrast, closed designs have no migratory flow. Unless immigration and emigration can be estimated, a closed population system is required to derive unbiased population estimates. Given the relatively mobile nature of sharks and current uncertainties regarding stock structure and movement patterns of deepwater sharks, it could be assumed that an open design is more suitable for deepwater sharks in New Zealand at this time.

For valid inference of results, open tagging studies should be designed to meet the following assumptions (Pine et al. 2012) because violations can lead to biases in results:

- marked individuals are representative of the population of interest, and the unmarked population parameters can be inferred from the marked population;
- markers do not affect the behaviour or fate of marked individuals;
- markers are not lost or misread;
- every marked animal alive in the population at the time of sampling has the same probability of capture;
- the fate of each marked animal is independent of the fate of other marked animals;
- resampling is instantaneous (sampling period is very short so that birth, death, immigration, and emigration do not occur during the resampling process).

These assumptions can be difficult to meet when working with threatened or elusive species, and in the marine environment, where sampling is mostly opportunistic (e.g., using commercial fisheries as part of its usual fishing operations where tagging is unlikely to occur across the entire population). Efforts have been made to minimise potential violations to these assumptions, such as the removal of known transient individuals (Hupman et al. 2018). This does, however, require prior knowledge about the ecology movement of the species population in question. The importance of meeting all the above mentioned assumptions is also dependent on the objective of the study. Although these assumptions are important to consider when estimating population size, not all assumptions are applicable (e.g., instantaneous resampling) when assessing other ecological questions (e.g., age validation).

All open design types require at least two sampling occasions, although more sampling occasions are generally recommended. In addition to the assumptions above, open designs also address the assumption that all individuals have the same probability of survival between sampling occasions. There are three types of open designs: band recovery (mark-recapture where the recapture process is terminal); known fate (electronic tagging with no recapture process); and live recapture (mark-recapture where the recapture process is not terminal). Live recapture design is not reported here, because this study design requires an estimation of encounter probability (i.e., the probability that an individual is alive and associated with the superpopulation at the time of study is detected).

3.1.1 Band-recovery (mark-recapture) design

Band (tag)-recovery designs differ from other designs as the recapture process is terminal. An example of a band-recovery design would include a conventional (non-electronic) tagging study, where any tagged shark that is recaptured is retained. Band-recovery designs allow for estimation of true survival probability and recovery probability (i.e., a marked shark is captured and reported) because the entire size range of the marked species can be included and often thousands of individuals are tagged. Here, precision of survival estimates (see Section 3.2) is affected by sample size, length of the study, expected survival rates, and encounter rates (band reporting). Precision is generally increased with a larger sample size, greater study duration, and increased encounter rate, which is typically higher for harvested/commercial species than it is for non-harvested/non-commercial species. If expected survival is higher, than a smaller sample size is needed because more individuals are available for recovery.

Shark studies using band-recovery design

Conventional mark identification tags have been applied widely for studying fish movements and have been used previously in New Zealand on coastal species (Hurst et al. 1999). Dart tags (spaghetti tags) are regularly applied in shark and other fish tagging programmes due to their ease of application and low cost, which provide the ability to tag large numbers of individuals (Latour 2005). Minimal training is required to apply the tags, and tags can be attached externally or internally, although externally is generally preferred to minimise handling time and the invasiveness of attachment (Figure 1). Because of the low cost of tags, individuals from any gear types and in all conditions (alive, injured, or moribund) can be marked. The use of conventional tags does require fishers and observers to recognise and return recaptured tags; as a result, tag returns are often tied with a financial reward to encourage return.

Figure 1: An example of a shark tagged with multiple tag types, including conventional tags (spaghetti tag in the dorsal musculature and roto-tag on the dorsal fin) and a pop-up satellite tag (Shipley et al. 2017b, reproduced with permission).

Conventional tags can provide broad overviews of long-term movements and have been used to delineate stock units and areas of importance to specific life history stages, including nursery areas. If sufficient young-of-the-year are tagged at an area of interest and later recaptured, nursery areas can be defined by quantifying the location of tag recoveries using minimum convex polygons (Bouyoucos et al. 2020). Such studies are often coupled and compared with acoustic telemetry and, thus, have been limited to species with inshore and accessible study sites (DeAngelis et al. 2008, Bouyoucos et al. 2020). If a representative sample (individuals of varying sizes and both sexes) from an area of interest is tagged, the location of recaptured individuals can provide inferences on habitat range, site fidelity, sex-biased dispersal, and stock identification (Kohler et al. 2002, Queiroz et al. 2005, Bird et al. 2020). For example, a skate tagging programme around the British Isles between 1959 and 2016 tagged 22 424 individual batoids, with returns from 3782 individuals (16.9% return rate, see Section 3.2 for additional information on return rates), and found that movement patterns varied considerably both within and across species and confirmed that current management areas corresponded to most, but not all, stocks (Bird et al. 2020).

Conventional tagging studies can also provide valuable insight into species life history and ecology that cannot otherwise be measured. For example, an elephantfish (*Callorhinchus milii*) was recaptured nearly 16 years after release (Coutin 1992), suggesting the actual longevity of the species was much greater than estimates provided with conventional age and growth methods (Francis 1997, Francis & Ó Maolagáin 2019). Only one band-recovery study on deepwater shark species of interest is known to the author (Rodríguez-Cabello & Sánchez 2017); at the time of the publication of the study, tag returns were low and were not reported. The low number of recaptures was attributed to several factors which likely discouraged reporting: a ban of target fishing in the region; a zero total allowable catch; and that tagging was completed in a Marine Protected Area where minimal fishing was allowed.

Band-recovery designs are frequently used for understanding shark growth parameters, specifically assessing age validation. By reporting date, location, and size (e.g., total length, disc width) of capture and recapture, growth can be obtained and used to estimate growth model parameters using standard growth models (e.g., von Bertalanffy, Gompertz, Schnute), alternative models (e.g., biphasic), or alternative approaches to model fitting (Braccini et al. 2007, Cailliet 2015, Smart & Grammer 2021). If recaptures are sufficient, parameter estimates can be made for separate sexes, over geographic areas, and comparisons can be made within and between species (Skomal & Natanson 2003, Cailliet 2015).

Band-recovery designs are often coupled with chemical marking (e.g., oxytetracycline) and return of the captured individual (or parts of) to validate age and growth estimates. These studies are considered some of the most powerful age and growth validation methods (Campana 2001, Cailliet & Goldman 2004). Even a small number of recaptures can improve and/or validate estimates that may otherwise underestimate or overestimate true age, which often occurs in shark ageing work (Harry 2018). A recent five year mark-recapture study of spiny dogfish (*Squalus acanthias*) in the Northwest Atlantic was able to validate band-pair deposition in dorsal-fin spines, concluding deposition was annual and that dorsal-fin spines can thus be used a viable means of accurately ageing this species (James et al. 2021). During the course of this study, 4306 individuals were tagged and 148 were recaptured (3.4% return rate). This method, however, can take several years to accumulate sufficient sample sizes from recaptured individuals and requires that appropriate fishing occurs in the area where the species is likely to occur (see Table 1 for an overview).

NIWA is currently involved with several band-recovery tagging projects in the Ross Sea, including one for Antarctic skate (*Amblyraja georgiana*) (B. Finucci, NIWA, unpublished). Although this work is ongoing, preliminary results have shown this species is likely long-lived (individuals have been recaptured after over 12 years from their initial release) and movement patterns are very localised.

3.1.2 Known-fate (electronic tagging) design

Known-fate designs include individuals marked with tags where the fate of the marked individual can be determined after marking. Post-release mortality studies using electronic tagging technologies (i.e., telemetry) are known-fate designs. Known-fate designs generally have smaller sample sizes than band-recovery designs due to the higher costs of equipment (e.g., electronic tags) (for a general comparison of the two methods, see Table 1). The high cost of equipment also means that the individuals tagged are selected (e.g., sharks assessed in good condition and likely to survive release, greater than one metre in length) to carry the tag (Brooks et al. 2015, Ellis et al. 2017). Data from electronic tags are transmitted via acoustics or satellite upon release and do not rely on the return of tags or the animal. However, if tags are found and returned, higher resolution data can generally be downloaded.

Table 1: Overview comparison of tagging study designs and their application.

	Tagging study design	
	Band recovery	Known fate
Tag type	Conventional	Satellite
Tag costs	Cheap (approx. $1 per tag)	Expensive (approx. $1,000–-$5,000 per tag)
Number of sharks to tag	Thousands	Tens
Sharks to tag	All sizes, all conditions	Sharks > 1 m in length and in good condition
Shark data collected	Species, size, sex, maturity stage, genetic sampling	Species, size, sex, maturity stage, genetic sampling
Time frame needed for reporting	Years	Months
Data collected from tags	Date, location, and depth of capture and recapture; survival if shark is recaptured	Date, location, depth of capture; temperature, depth, light levels throughout tag deployment; survival; additional biological information (e.g., speed) and environmental preferences (e.g., oxygen level preferences) can be inferred; factors affecting survival can be evaluated
Useful for understanding age and growth	Yes, with OTC injection	No*
Useful for understanding movement and habitat use	Yes – broad scale	Yes – broad scale spatial movement, fine scale use of water column
Useful for understanding population connectivity	Yes, genetic analyses should also be conducted	Yes, genetic analyses should also be conducted
Useful for understanding post-release mortality	Yes – long term	Yes – short term*

* If sharks are also tagged with conventional tags and injected with a chemical marker, then understanding aspects of ecology and biology could be useful here.

Shark studies using known-fate design

Sharks may be tagged using satellite tags or acoustic transmitters with passive acoustic monitoring. Movements inferred from conventional tagging studies have often been confirmed, and substantial knowledge added, using subsequent electronic tagging studies (Righton et al. 2007). Nearly all contemporary deepwater shark tagging studies have used satellite tags. Two contemporary studies have been carried out with acoustic transmitters, with relatively high rates of tag success (62 of 71 and 30 of 31 of tags transmitting (Daley et al. 2015, L. Fauconnet, Instituto do Mar, pers. comm.). While passive acoustic monitoring has the potential to track individuals in detail for prolonged periods of time, acoustic monitoring also requires the establishment, systematic maintenance, and retrieval of data from an acoustic array, an achievement unlikely to be successfully deployed in New Zealand given the associated costs of a large-scale array and the vastness of the New Zealand Exclusive Economic Zone (EEZ) (in comparison, off Australia, the study site was only 100 km long and 8–12 km wide, Daley et al. 2015). Thus, only those studies that employed satellite tags are reported here.

Satellite telemetry is well applied in shark research, specifically for coastal and pelagic species. In New Zealand, satellite tag studies have been successfully completed on species such as mako (*Isurus oxyrinchus*), porbeagle (*Lamna nasus*), smooth hammerhead (*Sphyrna zygaena*), and white shark (Duffy et al. 2012, Francis et al. 2015, Francis 2016, Francis et al. 2019), and ongoing work continues on school shark (*Galeorhinus galeus*), bronze whaler shark (*Carcharhinus brachyurus*), and manta rays (*Mobula birostris*) (E. Setyawan, University of Auckland, pers. comm., A. Burton, Massey University, pers. comm.). Satellite telemetry is regularly used to estimate short-term post-release mortality (e.g., Kaplan-Meier curves), and to understand factors that contribute to mortality and provide guidance on best practice for handling of sharks in commercial fisheries (Common Oceans (ABNJ) Tuna Project 2017, Ellis et al. 2017). Satellite telemetry is useful in providing fine-scale movement patterns (where the tag was deployed to where the tag starts transmitting data) and the collection of environmental data (e.g., depth, water temperature, changes in light levels) can be used to understand patterns and drivers of distribution (Francis et al. 2019). In recent years, these data have become increasingly useful in predicting where species are expected to be distributed with climate-driven ecological changes (Vedor et al. 2021) (see Table 1).

Very few satellite telemetry studies have been conducted on deepwater species and these could all be described as pilot studies (Table 2). However, with recent advances in technology, interest in tagging deepwater sharks is growing. There are four manufacturers for pop-up satellite archival tags that are regularly used for telemetry studies: Wildlife Computers (WC), Microwave Telemetry, Lotek, and Desert Star (Table 2). WC is the most commonly used manufacturer for shark-tagging studies and has been used previously by NIWA and for most studies on deepwater species (Francis et al. (2019), see Table 3). One study used Lotek tags, and this study had a considerably higher failure rate than the other studies, with only two of 16 tags reporting data. All other deepwater studies have had relatively low tag failure rates (generally one tag), with additional tags detaching prematurely. WC tags are equipped with an integrated 1800 m tag release device (RD1800) to reduce the chance of crushing. This can induce premature tag release, as reported for one individual by Rodríguez-Cabello & Sánchez (2014), but this may not be an issue in New Zealand given the known depth ranges of species (Anderson et al. 1998). Tag attachments are often custom-tailored to maximise the success of deployments. WC survival tags (sPATs) are considered mid-range in price (approximately $2,000 USD per tag, which includes Argos satellite fees) and provide data resolution of approximately 0.5 m for depth and 0.05 °C for temperature. Length of deployment can be customised, but tags are generally deployed for two or three months. More expensive tags, WC miniPATs and Microwave X-Tags, have similar features but can record data for longer periods of time (up to 24 and 12 months, respectively) and provide much finer resolution of environmental data (e.g., WC miniPATs record depth and temperature profiles at 15-s intervals instead of daily minimums and maximums as recorded by WC sPATs) (Figure 2). Cheaper tag options (Desert Star, SEA-TAG LOT) lack depth sensors, are not normally equipped with an emergency release (extra costs), are considerably larger in size (which may induce more hydrodynamic drag), and are not generally recommended.

Table 2: Review of deepwater shark satellite tag studies. Adapted from (Edwards et al. 2019). BLL is bottom longline.

Species	Ocean basin	Gear type	Depth of capture (m)	Soak time (hrs)	Sample size (tag datasets used/tags deployed)	Tag type and attachment	Tracking duration (day)	Tag depth range reported (m)	Data reported	Tag failures/ Premature releases	Reference
Amblyraja hyperborea	Arctic	Commercial and research BLL	800–1100	12	7/9	WC miniPAT; fin (wing) mount	40–300	500–1300	Temp, depth; activity levels, speed inferred	2/4	Peklova (2012)
Somniosus microcephalus	NW Atlantic	Research BLL, through ice	NA	NA	14/15	WC Mk-10 PAT; Dart	35–334	0–1816	Temp, depth, seasonality, diel movement; speed inferred	1/4	Campana et al. (2015)
Hexanchus griseus	N Pacific	Research BLL	300–350 (night); 500–600 (day)	12–14	4/6	WC miniPAT and VCAT; NA	53–97	250 - > 700	Temp; depth; light, diel movement; oxygen, speed inferred	1/0	Comfort & Weng (2015)
Centrophorus spp., *H. griseus*, and *H. nakamurai*	NW Atlantic	Research BLL	473–1024	4	0/16	Lotek LAT-1400 PSAT; NA	NA	472–1024	Post-release mortality	12/2	Brooks et al. (2015)
Centrophorus squamosus, Deania calcea, Centroscymnus coelolepis	NE Atlantic	Commercial BLL	1044–1220	2–3	11/16	WC miniPAT; Dorsal anchor	45–121	500–1500	Post-release mortality, temp, depth, diel movement; distance, speed inferred	1/2	Rodríguez-Cabello & Sánchez (2014), Rodríguez-Cabello et al. (2016)
Squalus cubensis	NW Atlantic	Research BLL	500–750	4	7/8	Microwave X-Tags PSAT; Monofilament bridle	5–14	304–904	Post-release mortality, temp, depth, diel movement	1/NA	Shipley et al. (2017a)
Somniosus microcephalus	Arctic	Research BLL	NA	12–24	5/5	4 mrPAT + 1 WC miniPAT pershark; Novel fin attachment plate	34–45	NA	Distance travelled	0/0	Hussey et al. (2018)
C. squamosus	NE Atlantic	Commercial BLL	882–1368	NA	NA	WC miniPAT; NA	NA	NA	NA	NA	Fauconnet et al. (pers. comm.)

Table 3: Comparison of available satellite tags. (Continued on next page)

Brand	Wildlife Computers	Wildlife Computers	Microwave Telemetry	Lotek	Desert Star
Model	sPAT	miniPAT	High rate x-tag	PSATLIFE	SEA-TAG LOT
Price ($US)	2,000	3,950	4,000	1,950, on sale as of June 2021	900
Discount ($US)	None	3,750 (50–99 units); 3,550 (100+ units)	Discounts for 10+	1,755 for 50–99 units, 1,658 for > 100 units	799 for 50+, 499 for 999+
Duration	30, 45, 60 days, or when conditions indicating no movement are met	Up to 2 years but durations > 9 months are rarely achieved	Up to 12 months	14, 28, 53, 85 days	User-determined. Can be set at the factory or by user but the latter requires 'starter kit' of PC, docking station, and software
Argos fees included	Y	N	N	N	Y (1 month post-release)
Tether included	Y (3 anchor options)	Y	N	Y	N
Auto deploy	Y	Y	Y	Y	Y
Weight in air (g)	60	60	40	87	42
Length (mm)	124	124	121	131	178
Inferred mortality	Depth > 1700 m; tag at constant depth > 24 hr; no light change	User responsibility from raw data provided	User responsibility from raw data provided	User responsibility from raw data provided	Low temp gradient for specified number of days (shark dead on sea floor or floating at the surface), low temp exposure (shark in water colder than expected), period of darkness (in deep water/under an obstruction / caught and in a hold)
Emergency release	Depth > 1700 m; tag at constant depth > 24 hr	Depth > 1800 m; tag at constant depth > specified time (customisable)	> 1250 m, 4 days at constant depth (customisable)	3 days constant depth (customisable). No max depth release but rated to 2000 m	Constant depth (based on temp gradient); minimum temp for specified time (e.g., < 10 °C for 30 mins)

Table 3: continued.

Brand	Wildlife Computers	Wildlife Computers	Microwave Telemetry	Lotek	Desert Star
Model	sPAT	miniPAT	High rate x-tag	PSATLIFE	SEA-TAG LOT
Data available	Daily min/max depth, min/max temp, light change (yes/no). Time series depth data at 10 min intervals to determine fate of animal	Geolocation, depth, and temp time series and histograms (customisable)	Time series of depth, light and temperature at 15–60 min intervals, depending on deployment duration	Time series of depth and temperature at 5 mins. Daily min/max depth, min/max temp, light, geolocation processed on-board	Geolocations, light, min/max/mean temperature, max temp rate. Reason for release. No depth.
Other	If returned, full high-res archived data can be downloaded. A benthic sPAT (can measure activity and inactivity) is also available and can go to 2000 m.	If returned, full high-res archived data can be downloaded. Pinger for radio tracking of tag after pop-up but unlikely to be useful in large open spaces (range ~ 2 km). Time cost in fitting tracks. GPE3 track in WC Portal low cost; UKFSST fitting high cost.	If returned, full high-res archived data can be downloaded		Solar powered (no battery), average transmission duration 5 months. Mortalities in deepwater may not report if sink rate exceeds min temp response rate and mortality rate will be biased low. SEATAG-3D records depth and transmits time series; emergency release at 1850 m. ~$2,000 per unit. 210 mm long x 60 g weight

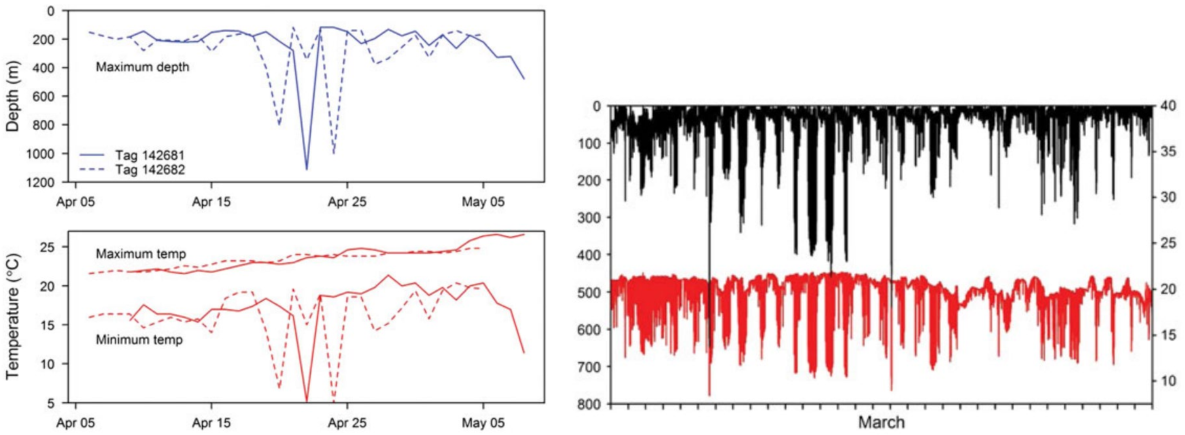


Figure 2: Examples of data resolution from a Wildlife Computers survival pop-up archival tag (sPAT) and miniPAT (from Francis & Jones 2017).

3.2 Sample size

The number of tagged individuals for a study differs depending on research aims. Even sample sizes of one individual have shown to lead to significant discoveries and may reveal aspects of behaviour that would otherwise be impossible to obtain, such as migrations. A sample size of one may also provide proof of concept for novel equipment or methods. A single basking shark (*Cetorhinus maximus*) demonstrated that marine animals could be monitored by satellite tags (Priede 1984), and another individual showed the species was capable of transatlantic migrations (Gore et al. 2008). Small sample sizes (<10 individuals) allow for insight into individual variability in movement patterns (e.g., diving behaviour, home ranges), and these sample sizes can be considered appropriate when studying rare or highly threatened species. Small sample sizes can also be useful for the ‘exploration phase’ of study and minimise potential losses if new methods or technologies fail to work. Larger samples sizes (>100) can offer insight into age- and sex-specific behaviours, and the largest studies to date (>1000) have be used to quantify habitat use over large spatial scales and estimated susceptibility to interactions with humans (Sequeira et al. 2019).

Mark-recapture experiments, specifically band-recovery designs, require that recapture rates are high enough to derive precise estimates of population parameters, such as survival rates. There is therefore a need to release enough tags into the population to ensure a sufficient number of recaptures. The tag recapture rate (*return rate*) is dependent on two probability processes: the probability of surviving and returning to the sampling area (*survival probability*) and the probability of being encountered, conditional on being alive and in the sample (*encounter probability*):

$$\textit{Return rate} = \textit{survival probability} \times \textit{encounter probability}$$

Estimating a return rate requires an *a priori* understanding of survival probability and encounter probability. If a band-recovery design is implemented to estimate survival rates, a general estimation approach outlined by Brownie et al. (1985) can be followed to determine an initial sample size. Here, banding and recovery data are modelled as functions of survival rate (the probability that a banded individual at the time of banding in year i is still alive at the time of banding in year i+1) and band recovery rate (the probability that a banded individual at the time of banding in year i is recovered during year i). To investigate the relationship between tagging sample size and precision of estimated mean and annual survival rates, the program BAND2 (available online at https://www.mbr-pwrc.usgs.gov/software.html, Wilson et al. 1989) can be used to calculate the necessary sample size to achieve desirable coefficient of variation (CV) of the survival estimate. A CV of 0.20 (or 20%) is considered reasonable for ecological work (Krebs 2014).

Tag loss and recapture rates must be considered when determining sample sizes. In conventional shark tagging studies, reported recapture rates are generally less than 5% (Kohler & Turner 2001). There are some exceptions; for example, between 2001 and 2004 a mark-recapture study for blue shark (*Prionace glauca*) reported a recapture rate of 20% (Queiroz et al. 2005). There are many factors that influence tag return rates, including natural mortality of tagged fish, tagging induced mortality (including capture-induced mortality), fishing pressure, emigration out of the tagging and/or fishing area, changes in the susceptibility to capture over time, non-reporting of recaptured tags, and tag shedding or loss (Francis 1989, Simpfendorfer et al. 2004, Latour 2005). Tag shedding rates vary across and within species, and can also vary by tag type, capture gear, and tagging position (Kohler & Turner 2001, Dicken et al. 2006). To reduce tag loss, sharks are often tagged with multiple tags and can be tagged with more than one type of tag. Individuals that are double-tagged can have recapture rates twice as high as those with a single tag (Björnsson et al. 2011).

In satellite telemetry studies, some of the aforementioned factors affecting tag return rates are not applicable (e.g., fishing pressure, non-reporting, emigration, susceptibility to capture over time). However, tag failure and premature release are also important factors to consider for electronic tags. For the most commonly used satellite tags (Wildlife Computers and Microwave Telemetry) tag failure is generally less than 10% (Hammerschlag et al. 2011, Common Oceans (ABNJ) Tuna Project 2017). In deepwater tagging studies, tag failure appears to be higher, affecting up to 36% of tags deployed per study (Edwards et al. 2019). However, this rate also includes the use of new tag technologies where higher failures rates are expected during trial periods. Premature tag release can exceed 50% and may be attributed to anchor or tether failure or tag predation (Hays et al. 2007, Hammerschlag et al. 2011, Edwards et al. 2019). However, premature release is generally not considered a significant problem for shorter deployments (a couple of months) because tags can be designed to last for up to three years. This lifespan is rarely attained; the minimum number of days an individual is tracked averages approximately one month, and most tag loss occurs 6–12 months after tagging (Hammerschlag et al. 2011, Common Oceans (ABNJ) Tuna Project 2017).

3.3 Other considerations

3.3.1 Genetic sampling

Contemporary studies of population structure have focused on genetic techniques to provide insight into broad connectivity between populations that occurs over multiple generations. While the lower costs, reduced risk, and larger sampling ability associated with these genetic techniques is appealing, the use of genetics alone does not consider population structure relevant to ecology or fisheries (i.e., over months or years) observed by other means of sampling. Broad levels of connectivity can be influenced by the movement of a limited number of reproductive individuals, and this type of connectivity is unlikely to be relevant for fisheries management if the majority of a population remains resident. Recent studies have suggested pairing genetic approaches with methods that inform movement on ecological timescales can be most beneficial for management decisions (Kerr et al. 2017, Lédée et al. 2021).

A genetic study assessing population structure could be completed in conjunction with a tagging study by taking a genetic sample (e.g., fin clip) at the time of capture. Next-generation sequencing technologies are increasingly used to resolve fine-scale population structure through the assessment of single point mutations (i.e., single nucleotide polymorphisms, SNPs) across whole genomes and multiple individuals (Green et al. 2019, Davenport et al. 2021). SNPs have been used to estimate the breeding population size of *Carcharodon carcharias* in the South Pacific (Davenport et al. 2021) and are currently being used to discriminate stocks of *Callorhinchus milii* across New Zealand-Australia (B. Finucci, NIWA, unpublished). Close-kin mark-recapture, an extension of traditional mark-recapture approaches by examining the genetic relatedness between parent and offspring, has also been explored in some fish and shark species (Hillary et al. 2018). This method, however, is reliant on sufficient recaptures of related individuals and uses the relatively costly application of whole mitogenome sequencing.

3.3.2 Factors contributing to mortality

If at-vessel mortality and subsequent release mortality is found to be high, there may be a need to further understand the factors contributing to mortality and devise handling techniques that will improve survival. Because sharks lack swim bladders, the external effects of barotrauma (i.e., experiencing reduced pressure while brought to the surface) are less evident than in teleosts. However, deepwater sharks have enlarged livers which assist with hydrostatic buoyancy and can be sensitive to pressure changes (Pethybridge et al. 2010). Some species also have positive buoyancy (e.g., *Hexanchus griseus*), and their ability to submerge to deeper waters after release may be impacted when the individual is injured or stressed (Rodríguez-Cabello & Sánchez 2017). This could further expose the shark to predation and warmer surface temperatures (Brooks et al. 2015). Gas embolism (presence of gas bubbles in tissues) is also suspected to affect long-term shark survival, but this has not be investigated further (García et al. 2015).

4. OPTIONS FOR NEW ZEALAND

4.1 Species of interest

In a qualitative risk assessment of New Zealand chondrichthyans (Ford et al. 2015, Ford et al. 2018), most non-Quota Management System (QMS) sharks considered to be at the greatest risk from fishing were deepwater species. The risk from commercial fishing to these species (Table 4) was assessed as higher than that for any protected shark and was equal to, or higher, than any shark within the QMS (with the exception of *Centroscymnus owstonii*). These species were assessed as Not Threatened under the New Zealand Threat Classification System (NZTCS) (Duffy et al. 2018). Under the IUCN Red List of Threatened Species categories and criteria, all species are globally assessed as Near Threatened (NT) or threatened (Vulnerable, Endangered, Critically Endangered) (IUCN 2020).

Currently telemetry technology has been found to be suitable for fish of at least 1 m in length (Brooks et al. 2015, Ellis et al. 2017). Thus, *Etmopterus granulosus* would be too small for a telemetry study at this time but may still be suitable for conventional tagging.

Table 4: Non-QMS deepwater sharks having the greatest risk in the qualitative risk assessment, ordered by declining risk according to the most recent qualitative risk assessment (Ford et al. 2018).

Species	Species code	Maximum size (cm)	NZTCS Conservation status	IUCN status (global)
*Scymnodon plunketi**	PLS	150	Not Threatened	Vulnerable (VU)
Etmopterus granulosus	ETB	96	Not Threatened	Least Concern (LC)
Dalatias licha	BSH	153	Not Threatened	Vulnerable (VU)
Deania calcea	SND	126	Not Threatened	Near Threatened (NT)
Centrophorus squamosus	CSQ	145	Not Threatened	Endangered (EN)
Centroselachus crepidater	CYP	103	Not Threatened	Near Threatened (NT)
Centroscymnus owstonii	CYO	133	Not Threatened	Vulnerable (VU)

* *Scymnodon plunketi* has now been synonymised with *S. macracanthus*, see (Vaz 2021).

Additional large-bodied deepwater sharks for assessment have been suggested in Table 5. Although these species have been identified as species with low risk to fishing, the biology of these species is poorly known in New Zealand waters, but they are thought to have life histories that make them highly vulnerable to fishing activities (e.g., high longevity) (Ford et al. 2015).

Table 5: New Zealand non-QMS deepwater chondrichthyans having low risk in the qualitative risk assessment, but with data deficient issues.

Species	Species code	Maximum size (cm)	NZTCS Conservation status	IUCN status (global)
Hexanchus griseus	HEX	550	Not Threatened	Near Threatened (NT)
Somniosus antarcticus	SOP	600	Not Threatened	Least Concern (LC)
Somniosus longus	SOM	150	Data Deficient	Data Deficient (DD)

4.2 Fisheries and surveys of interest

Deepwater sharks are caught predominately as non-target catch in bottom trawl and longline commercial fisheries (Francis 2015, Anderson et al. 2017, Anderson et al. 2019, Finucci et al. 2019b, Finucci et al. 2020). They are also frequently caught in some research trawl surveys, particularly those on Chatham Rise, in the Sub-Antarctic, and off the west coast South Island (O'Driscoll et al. 2011, Bagley et al. 2013, O'Driscoll & Ballara 2019). Although the distribution of commercial catches (Francis 2015, Finucci et al. 2021a) and the catch composition from research surveys (e.g. size, sex) (Finucci et al. 2018) have been well documented, the at-vessel condition and the fate of discarded catch is largely unknown.

Commercial capture of these deepwater sharks would be relatively opportunistic, because they are bycatch species, and tagging and reporting of sharks would be reliant on collaboration with fishers. For a conventional tagging study where resources and skills required to tag individuals are relatively low (see Section 3.1.1 on band-recovery design), all live discarded catch could be tagged from commercial (via the scientific observer programme) and research vessels. This could result in relatively large numbers of sharks tagged over a broad spatial and temporal scale and from a range of depths and habitat types.

In contrast, for a satellite tagging study where resources (i.e., the number of tags) available is likely to restricted (and expensive), sharks should be tagged from activities where 1) at-vessel survival is high (with minimal injuries) and 2) post-release mortality is also likely to be low. Although not qualitatively or quantitatively evaluated in New Zealand, it could be assumed that sharks are in relatively better condition from a longline set than a trawl tow, where sharks must also endure physical damage e.g., impalement or crushing injuries (Ellis et al. 2017). Overseas, deepwater sharks have been successfully tagged and recaptured after being caught at depths beyond 1100 m in commercial bottom longline fisheries (Rodríguez-Cabello et al. 2016, Rodríguez-Cabello & Sánchez 2017).

4.2.1 Commercial and observer fisheries data analysis

Observer data collected aboard commercial fishing vessels were extracted from the Fisheries New Zealand Observer Programme database (*cod*) for all observed bottom longline events (one event defined as one set) targeting any species from 2000 to 2020 (calendar year). Surface longline fisheries were not assessed here. *Centroscymnus owstonii* (CYO) used to be reported frequently in these fisheries, but these records have greatly reduced (< 5 annually) since Japanese-flagged vessels fishing off the west coast South Island ceased their activities in 2015 (Griggs et al. 2018). Data were groomed for missing and erroneous information (e.g., no position data) and where data could not be adjusted, sets were removed from analysis. Vessel class (autoline or manual baiting) was determined using criteria given by Finucci et al. (2020).

Some reporting categories were amalgamated for this analysis. For deepwater shark catches, the generic code, Deepwater Dogfish (DWD) also includes any catch reported under other generic codes (CEN, ODO, and OSD); the code for *Etmopterus granulosus* (ETB) also includes *Etmopterus* spp. (ETM); the code for *Scymnodon plunketi* (PLS) also includes *Scymnodon macracanthus* (SCM); the code for *Deania calcea* (SND) also includes *Deania hystricosa* (SNR); and the code for *Somniosus rostratus* (SOM) was combined with *Somniosus microcephalus* (SMI, not a valid species in New Zealand) and *Somniosus* *pacificus* (SOP) for a generic sleeper shark (*Somniosus* spp.) category. For bottom longline fisheries, the hāpuku & bass (*Polyprion oxygeneios*, *P. americanus*, HPB) fishery included any records where the target fishery was hāpuku (HAP), bass (BAS), or both (HPB).

Comparison of observed catches with research trawl survey catches

To assess the catch composition of deepwater sharks caught in the commercial longline fisheries, a high level comparison was made with the research trawl survey data. Research trawl surveys have collected information relating to deepwater sharks throughout New Zealand waters dating back to the 1980s (Clark & King 1989, O'Driscoll et al. 2011, Bagley et al. 2013). Species identification is considered reliable since the introduction of identification guides (McMillan et al. 2011, McMillan et al. 2019) and additional information, including length, sex, and maturity are also available. Thus, the research trawl survey data are useful to evaluate alongside the distribution of deepwater shark catch records from the ling (*Genypterus* blacodes, LIN) longline fishery. These data sources were not directly comparable in a comparison of trawl and longline surveys off the Rockall Trough in the Northeast Atlantic Ocean which showed that longline gears were more selective to larger deepwater sharks, and it was suggested the absence of large individuals from trawl catch indicated that larger individuals may be able to outswim towed gear (Clarke et al. 2005). However, deepwater sharks are well documented to aggregate and segregate spatially and by depth according to size, sex, and life history stage (Moura et al. 2014). By assessing where research trawl surveys have recorded large sharks (> 1 m total length), this could provide an indication that longline vessels fishing in the same locations are also catching large sharks.

Here, trawl survey catch data from 2000 to 2020 were extracted from the Fisheries New Zealand *trawl* database where the deepwater shark species of interest were recorded and measured to be at least 1 m in total length. Species catch (summed greenweight in kilograms) was plotted as a smoothed 2-dimensional kernel density estimation (i.e., estimation of probability density) for both observer records in the ling bottom longline fishery and research trawl surveys for a visual comparison of where species were most often reported.

4.2.2 Characterisation of observer and trawl suvey data

Observed longline fisheries (all target species)

Since 2000, 77 species of cartilaginous fishes were reported by observers in the bottom longline fisheries. Of the species of interest mentioned in Section 4.1, the most reported observed species (by weight and record) were *Deania calcea* (SND), *Dalatias licha* (BSH), and sharks reported in a generic category (DWD) (Table 6, Table 7). Large quantities of *Centrophorus squamosus* (CSQ), *Scymnodon plunketi* (PLS), and *Etmopterus granulosus* (ETB) were also reported. *Somniosus* spp. (SOM) was not reported in most years; the largest number of SOM records (16) occurred in 2011.

Deepwater sharks were primarily caught in observed bottom longline fisheries targeting ling (Figure 3). Small amounts of catch are also reported by longline fisheries targeting bluenose (*Hyperoglyphe antarctica*, BNS), HPB, ribaldo (*Mora moro*, RIB), school shark (*Galeorhinus galeus*, SCH), Patagonian toothfish on Macquarie Ridge (*Dissostichus eleginoides*, PTO), and snapper (*Chrysophrys auratus*, SNA). Very few records (< 5) were reported from red gurnard (*Chelidonichthys kumu*, GUR), tarakihi (*Nemadactylus macropterus* & *N. rex*, TAR), and Antarctic toothfish (*Dissostichus mawsoni*, ATO) target sets, and they were not considered further. Most catch of SOM, as well as a small proportion of ETB, were reported in PTO target fisheries.

In observer records, deepwater shark species of interest were consistently recorded each year in LIN target sets (20–76% of sets), with an average of ~50% of sets in the past five years reporting at least one species of interest (Figure 4). Reporting of a deepwater shark was high in RIB target fisheries (0–100% of sets, mean=76%), but the number of sets were low and observed catches were reported in a small number of years. For other fisheries, the average number of sets where a deepwater shark was reported was generally low: PTO (0–74%, mean=35%), BNS (0–54%, mean=17%), HPB (0–39%, mean=7%), SCH (0–52%, mean=6%), and SNA (<5%, mean=<1%).

Where the fate of deepwater shark catch was recorded by observers, most catch was either released alive (43%) or discarded (33%) (Figure 5). BSH and DWD reported catch made up the largest proportion of released alive and discarded catch. Half the catch of BSH, DWD, and ETB was reported to be released alive. Most CYO (81%), CYP (86%), and HEX (55%) were discarded (which included one observer authorised discard and seven Schedule 6 discard records). Retained catch accounted for 21% of records, with large amounts of SOM (55%), PLS (48%), SND (37%), and CSQ (36%) retained (including categories for mealed, dressed, or retained for liver). A small proportion of deepwater catch was lost (3%), which was largely SND and PLS.

Since most deepwater shark catch was observed in the ling longline fishery, the following sections will report on observer-reported catch in the ling bottom longline fishery.

Table 6: Annual number of observer records from bottom longline fisheries for select deepwater sharks from 2000 to 2020. Species codes: *Dalatias licha* (BSH), *Centrophorus squamosus* (CSQ), *Centroscymnus owstonii* (CYO), *Centroselachus crepidater* (CYP), generic Deepwater Dogfish (DWD), *Etmopterus granulosus* (ETB), *Hexanchus griseus* (HEX), *Scymnodon plunketi* (PLS), *Deania calcea* (SND), and sleeper sharks (*Somniosus* spp.).

Year	BSH	CSQ	CYO	CYP	DWD	ETB	HEX	PLS	SND	SOM
2000	83	0	0	3	158	175	0	29	161	0
2001	217	0	0	0	279	198	0	0	163	1
2002	243	0	0	0	211	127	68	0	207	0
2003	215	46	0	6	307	212	29	47	207	1
2004	46	0	0	0	168	10	2	2	50	0
2005	176	0	2	0	119	115	52	0	282	0
2006	293	70	0	0	193	0	3	2	375	0
2007	116	16	3	4	131	19	1	9	198	0
2008	60	2	0	0	85	10	18	0	76	0
2009	76	21	0	0	241	3	12	1	47	0
2010	185	45	2	0	102	21	1	21	105	0
2011	4	3	0	0	25	74	0	44	0	16
2012	89	38	0	3	115	18	0	22	15	1
2013	8	0	1	1	8	0	10	2	4	0
2014	194	44	0	6	93	52	10	73	172	1
2015	10	9	1	8	17	28	22	18	15	0
2016	54	41	0	3	174	16	22	115	190	0
2017	89	139	23	11	161	62	32	113	175	5
2018	117	95	37	42	163	71	18	59	119	2
2019	57	24	1	0	55	24	13	7	89	0
2020	16	49	0	0	150	4	29	73	53	0

Table 7: Annual observer recorded greenweight (t) from bottom longline fisheries for select deepwater sharks from 2000 to 2020. Species codes: *Dalatias licha* (BSH), *Centrophorus squamosus* (CSQ), *Centroscymnus owstonii* (CYO), *Centroselachus crepidater* (CYP), generic Deepwater Dogfish (DWD), *Etmopterus granulosus* (ETB), *Hexanchus griseus* (HEX), *Scymnodon plunketi* (PLS), *Deania calcea* (SND), and sleeper sharks (*Somniosus* spp.).

Year	BSH	CSQ	CYO	CYP	DWD	ETB	HEX	PLS	SND	SOM
2000	3.1	–	–	0.1	34.8	19.3	–	2.3	7.1	–
2001	10.5	–	–	–	26.8	29.2	–	–	20.7	<0.1
2002	8.0	–	–	–	9.1	7.1	1.2	–	5.9	–
2003	28.8	3.1	–	0.1	19.2	8.3	0.6	1.5	20.3	<0.1
2004	1.2	–	–	–	4.7	1.8	0.1	0.1	1.4	–
2005	5.6	–	<0.1	–	14.6	0.3	1.1	–	13.9	–
2006	16.1	20.6	–	–	1.2	–	0.1	0.1	52.9	–
2007	8.2	1.6	<0.1	0.6	4.3	3.1	<0.1	1.1	19.0	–
2008	1.4	<0.1	–	–	1.9	0.2	0.4	–	2.6	–
2009	1.4	1.8	–	–	30.5	0.1	1.0	<0.1	2.3	–
2010	8.4	6.4	<0.1	–	5.2	0.2	<0.1	2.4	13.6	–
2011	0.1	<0.1	–	–	2.4	4.8	–	3.0	–	0.5
2012	2.4	2.4	–	<0.1	4.2	1.2	–	0.5	0.7	<0.1
2013	<0.1	–	<0.1	<0.1	3.4	–	0.8	0.1	1.0	–
2014	6.5	1.3	–	0.1	5.3	4.8	0.1	7.7	7.1	<0.1
2015	0.9	0.1	<0.1	0.1	0.1	0.1	0.4	0.5	0.9	–
2016	1.6	0.8	–	<0.1	1.3	0.2	0.3	2.8	26.7	–
2017	2.7	33.4	1.0	<0.1	9.0	3.4	0.9	6.0	24.5	0.1
2018	4.1	5.8	2.4	1.1	2.5	2.6	0.2	1.7	16.2	0.4
2019	3.9	1.0	<0.1	–	4.3	2.2	0.3	0.2	7.3	–
2020	0.3	0.9	–	–	2.6	0.9	0.6	1.4	3.0	–

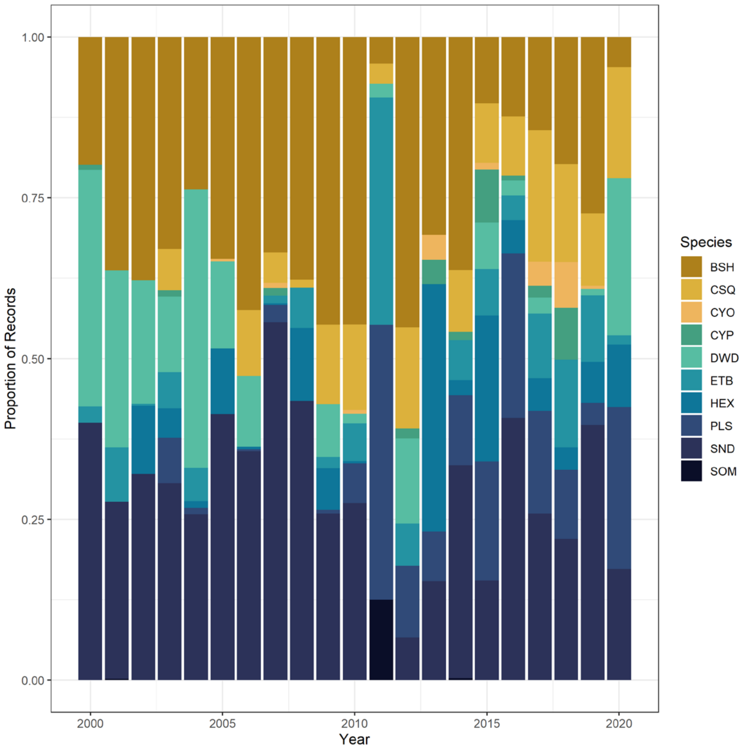


Figure 3: Annual deepwater shark species composition for all observed bottom longline fisheries from 2000 to 2020. Species codes: *Dalatias licha* (BSH), *Centrophorus squamosus* (CSQ), *Centroscymnus owstonii* (CYO), *Centroselachus crepidater* (CYP), generic Deepwater Dogfish (DWD), *Etmopterus granulosus* (ETB), *Hexanchus griseus* (HEX), *Scymnodon plunketi* (PLS), *Deania calcea* (SND), and sleeper sharks (*Somniosus* spp.).

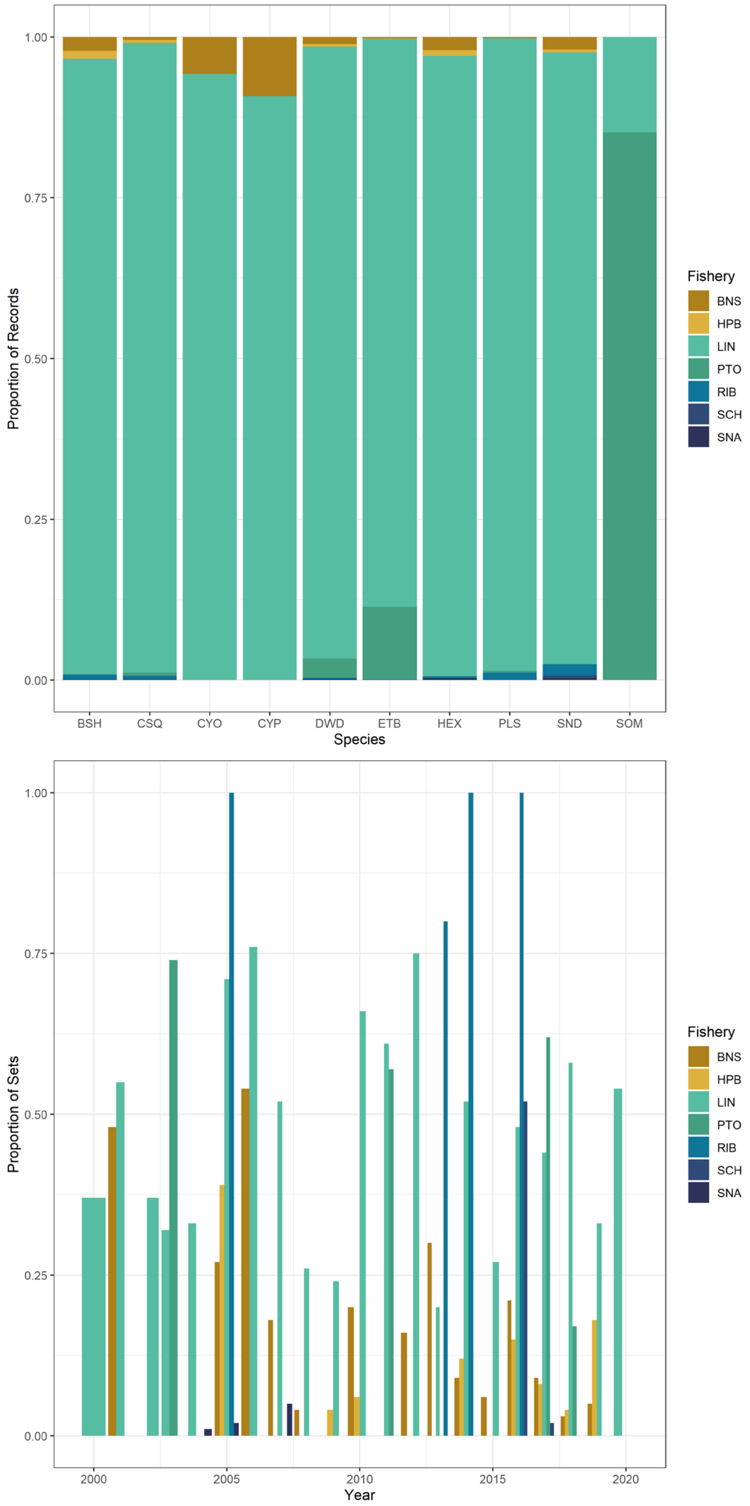


Figure 4: **Proportion of deepwater shark catch colour-coded by bottom longline target fishery (top) and proportion of observed bottom longline sets annually where at least one of the deepwater shark species of interest was recorded (bottom) from 2000 to 2020. Target fishery codes: bluenose (BNS), hāpuku & bass (HPB), ling (LIN), Patagonian toothfish (PTO), ribaldo (RIB), school shark (SCH), and snapper (SNA). Species codes: *Dalatias licha* (BSH), *Centrophorus squamosus* (CSQ), *Centroscymnus owstonii* (CYO), *Centroselachus crepidater* (CYP), generic Deepwater Dogfish (DWD), *Etmopterus granulosus* (ETB), *Hexanchus griseus* (HEX), *Scymnodon plunketi* (PLS), *Deania calcea* (SND), and sleeper sharks (*Somniosus* spp.).**

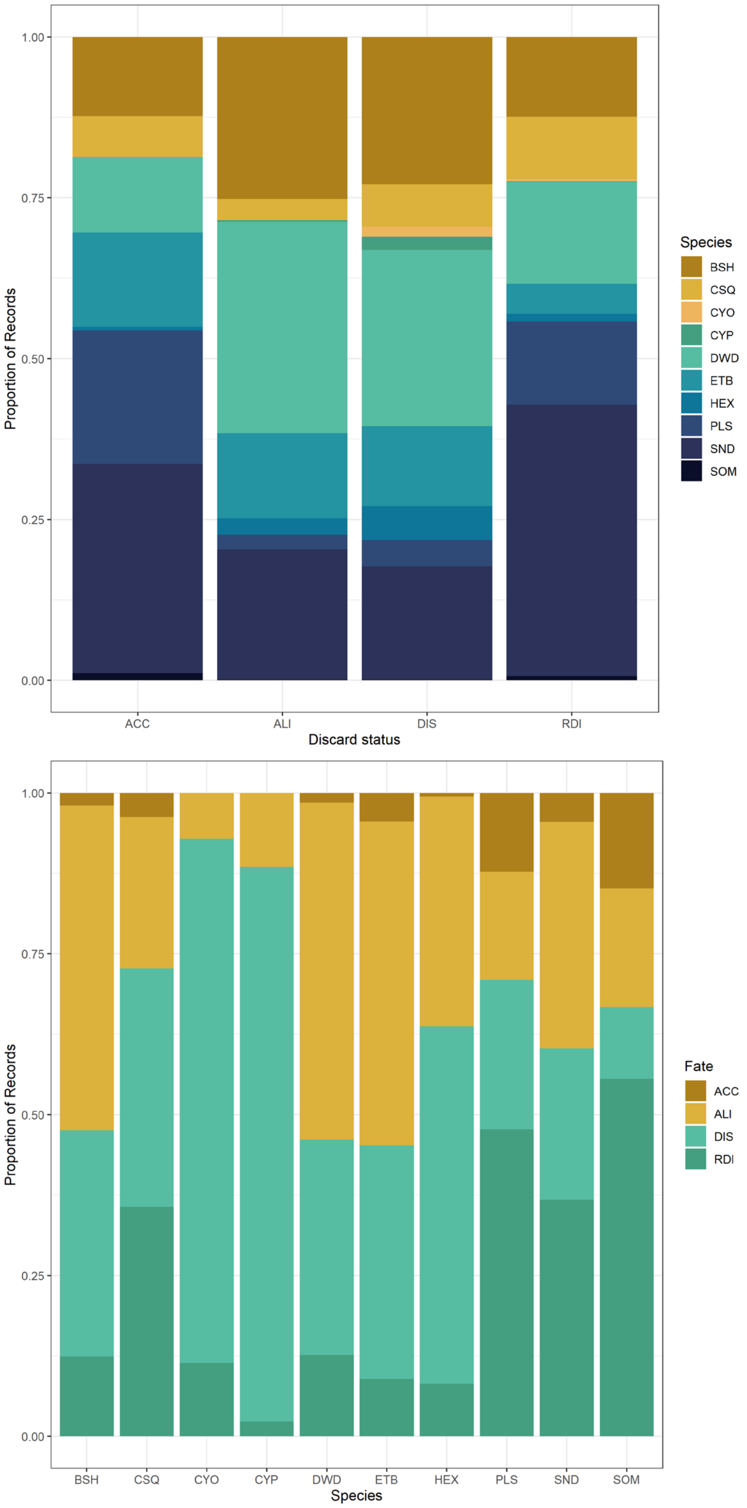


Figure 5: Fate of deepwater shark catch as reported for all observed bottom longline fisheries from 2000 to 2020 by fate code (top) and by species (bottom). Fate codes: Lost (ACC), Released alive (ALI), Discarded (DIS), and Retained (RDI). Species codes: *Dalatias licha* (BSH), *Centrophorus squamosus* (CSQ), *Centroscymnus owstonii* (CYO), *Centroselachus crepidater* (CYP), generic Deepwater Dogfish (DWD), *Etmopterus granulosus* (ETB), *Hexanchus griseus* (HEX), *Scymnodon plunketi* (PLS), *Deania calcea* (SND), and sleeper sharks (*Somniosus* spp.).

Observed ling bottom longline fishery

From 2000 to 2020, 34 vessels in the ling bottom longline fishery reported deepwater shark catch, and 20 of these vessels had reported deepwater shark catch in the last five years. Most observed deepwater shark catch in the ling bottom longline fishery in recent years consisted of SND and PLS (approximately 20–40% each) (Figure 6). BSH made up a large component (up to ~50%) of the recorded catch in earlier years, but this reduced (< 25%) from 2015. CSQ (15–20%) made up an increasing proportion of the recorded catch from 2015. CYO, CYP, and SOM were very infrequently recorded and made up very little of the catch. Most deepwater shark catch was reported as released alive or discarded, with the exception of the following species where a considerable proportion of catch was retained: CSQ (36%), PLS (48%), and SND (37%).

Biological measurements (e.g., length, sex) were not recorded, so it is not possible to determine the size composition of deepwater sharks caught in the fishery. By assessing the mean individual weight (kilograms) of sharks caught on a set (total weight divided by the number of sharks), it appears that a range of sizes of each species was caught in the fishery (Figure 7). This, however, assumes each shark captured on a set was the same size and may not be indicative of the true catch composition. Additionally, the mean weight for some species exceeded 15 kg (e.g., ETB, SND), as shown in Figure 7, and these are unlikely to be accurate given reported maximum length for these species (see Section 4.1). For some species, including BSH and PLS, estimated mean individual weight peaked between 7 and 10 kg, indicating larger individuals (> 1 m total length) may have been captured in this fishery and would likely be large enough to be suitable for satellite tagging purposes. Most sharks recorded under the DWD were likely to be small (< 5 kg) based on the frequency of the mean individual weight (Figure 7).

Comparing autoline and manual baiting vessels, both method types had a similar distribution by vessel length, with most sets deployed by vessels approximately 45 m in length (Figure 8). Vessels using manual baiting and greater than 30 m in length reported deepwater shark catch in all sets. Autolining vessels deployed many more hooks than manual vessels (most sets deployed ~5000 hooks vs. < 2000 hooks). The frequency of soak times between the two methods was similar, with most sets having a soak time of between 10 and 15 hours. Autolining vessels also frequently had a soak time of approximately 5 hours. The spatial extent of observed fishing effort differed between the two methods (Figure 9). Vessels using autolines were distributed throughout much of the New Zealand EEZ, including Chatham Rise, Puysegur, Campbell Plateau, and Bounty Plateau. The distribution of effort for manual baiting vessels was largely restricted to inshore waters, with effort on the western Chatham Rise, West Coast South Island, and Puysegur.

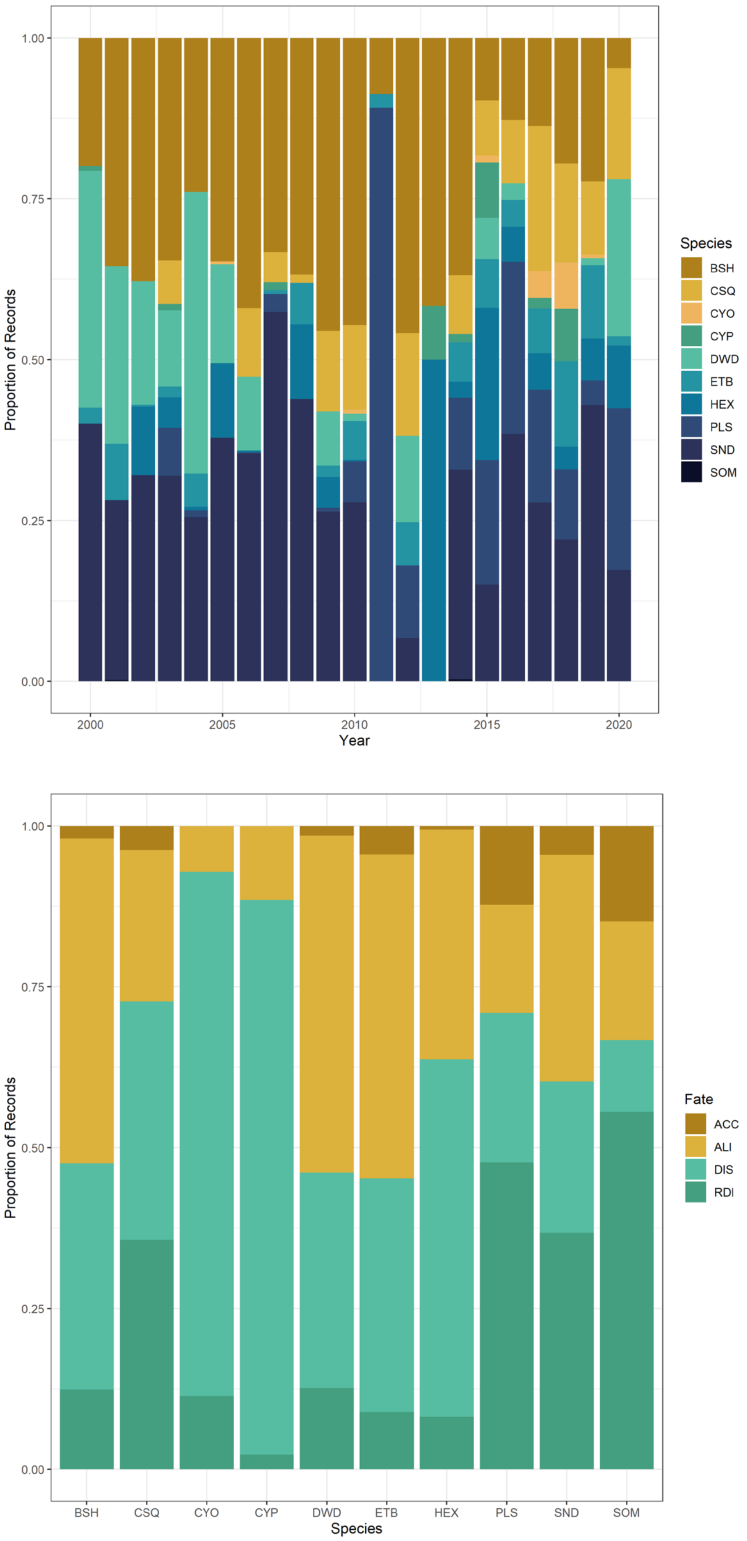


Figure 6: Annual deepwater shark species composition (top) and fate of deepwater shark catch (bottom) as recorded by observers for the ling bottom longline fishery from 2000 to 2020. Fate codes: Lost (ACC), Released alive (ALI), Discarded (DIS), and Retained (RDI). Species codes: *Dalatias licha* (BSH), *Centrophorus squamosus* (CSQ), *Centroscymnus owstonii* (CYO), *Centroselachus crepidater* (CYP), generic Deepwater Dogfish (DWD), *Etmopterus granulosus* (ETB), *Hexanchus griseus* (HEX), *Scymnodon plunketi* (PLS), *Deania calcea* (SND) and sleeper sharks (*Somniosus* spp.).

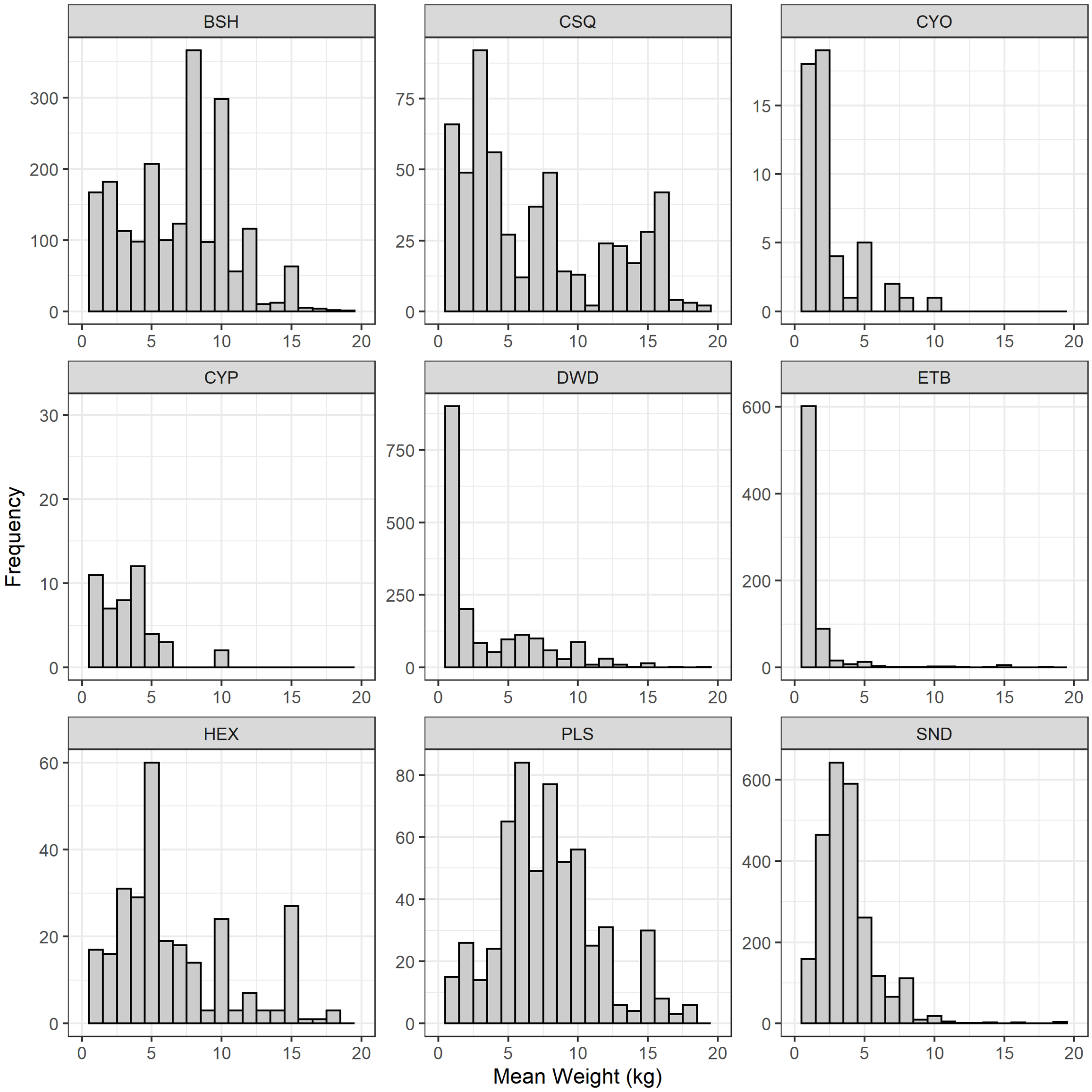


Figure 7: Estimated mean individual weight (kg, total weight divided by the number of sharks per set) of deepwater sharks caught in ling bottom longline fishery as recorded by observers from 2000 to 2020. Records of fish > 20 kg (n=74) not shown here. Species codes: *Dalatias licha* (BSH), *Centrophorus squamosus* (CSQ), *Centroscymnus owstonii* (CYO), *Centroselachus crepidater* (CYP), generic Deepwater Dogfish (DWD), *Etmopterus granulosus* (ETB), *Hexanchus griseus* (HEX), *Scymnodon plunketi* (PLS), and *Deania calcea* (SND).

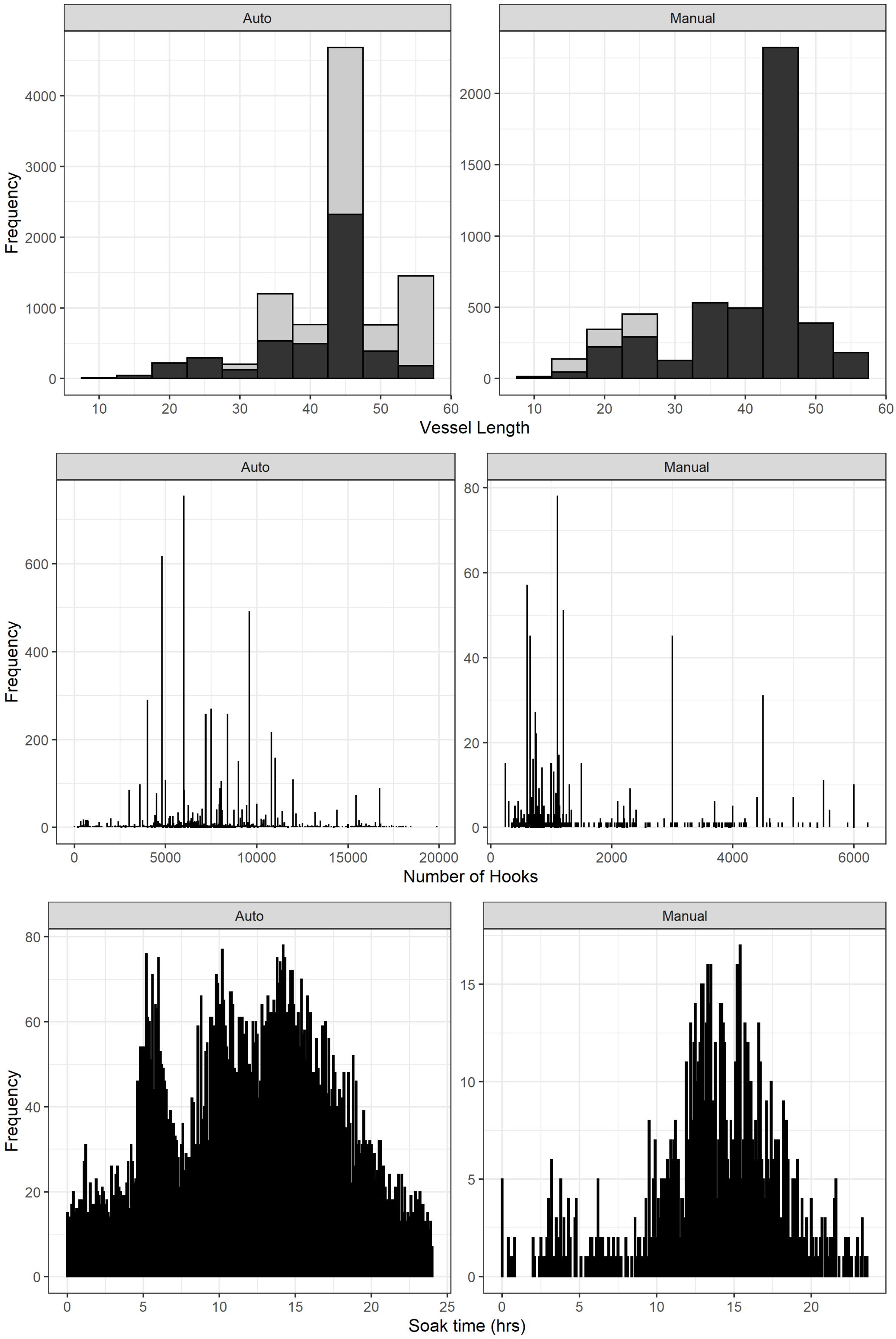


Figure 8: Comparison of data for observed autoline and manual baiting vessels in the ling bottom longline fishery from 2000 to 2020. Top: Frequency of bottom longline sets deployed by vessel length (m) for all sets (light grey bars) and sets where deepwater sharks were recorded (dark grey bars). Centre: Frequency of the number of hooks per set. Bottom: Frequency of sets deployed by soak time.

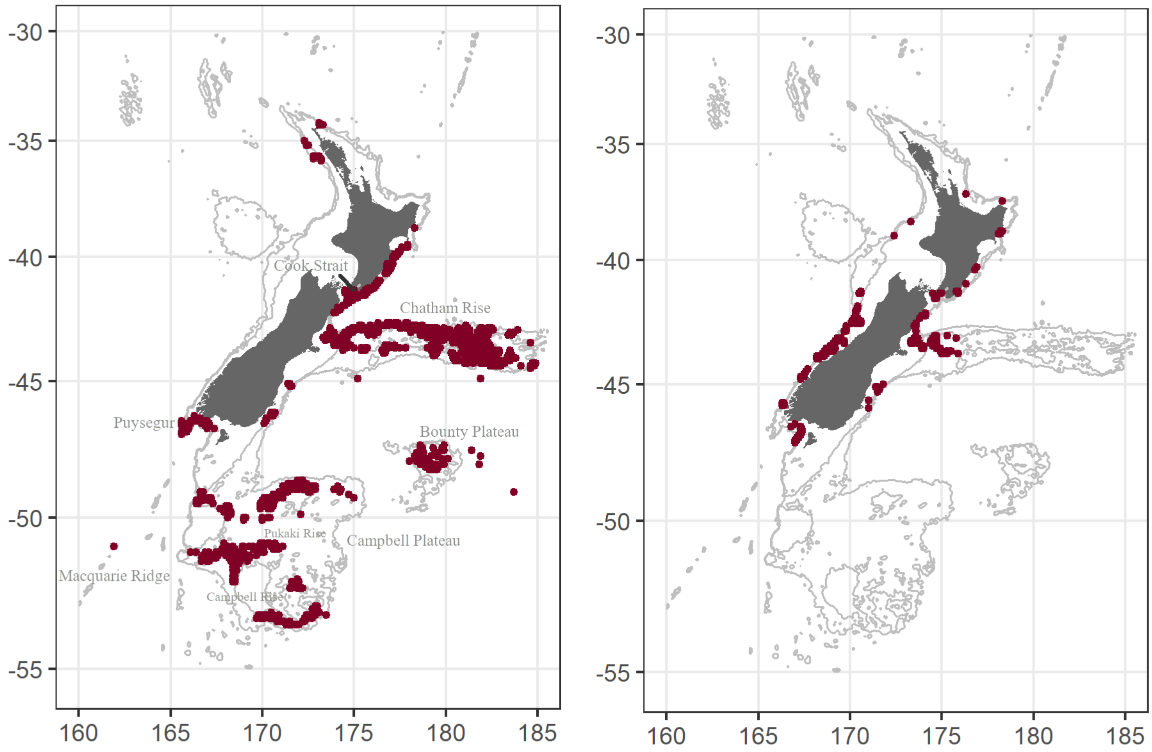


Figure 9: The distribution of observed effort in the ling bottom longline fishery for autoliners (left) and manual baiting vessels (right) from 2000 to 2020.

Most sets in the ling bottom longline fishery were deployed between August and November, and in the evening and early morning (from 18:00 to 06:00 hours NZST) (Figure 10). Sets where deepwater sharks were most frequently recorded occurred in late spring (October and November) and set start times were during the evening hours, particularly from 20:00 to 02:00 NZST (Figure 10). The soak time of most sets exceeded 10 hours and peaked at around 15 hours (Figure 11). The frequency of sets in which deepwater sharks were recorded followed a similar pattern. The mean depth of sets occurred around 400 m and again between depths of 500 and 600 m (Figure 11). Most sets where deepwater sharks were recorded were between 400 and 600 m (Figure 11, Figure 12). Mean depth of capture peaked between 500 and 600 m for most species (BSH, CSQ, CYO, ETB, SND, and PLS). For HEX and CYP, peak depth of capture occurred around 400 m, and the peak catch recorded for DWD was bimodal, with most catches occurring at a mean depth of approximately 450 m, and again at 550 m.

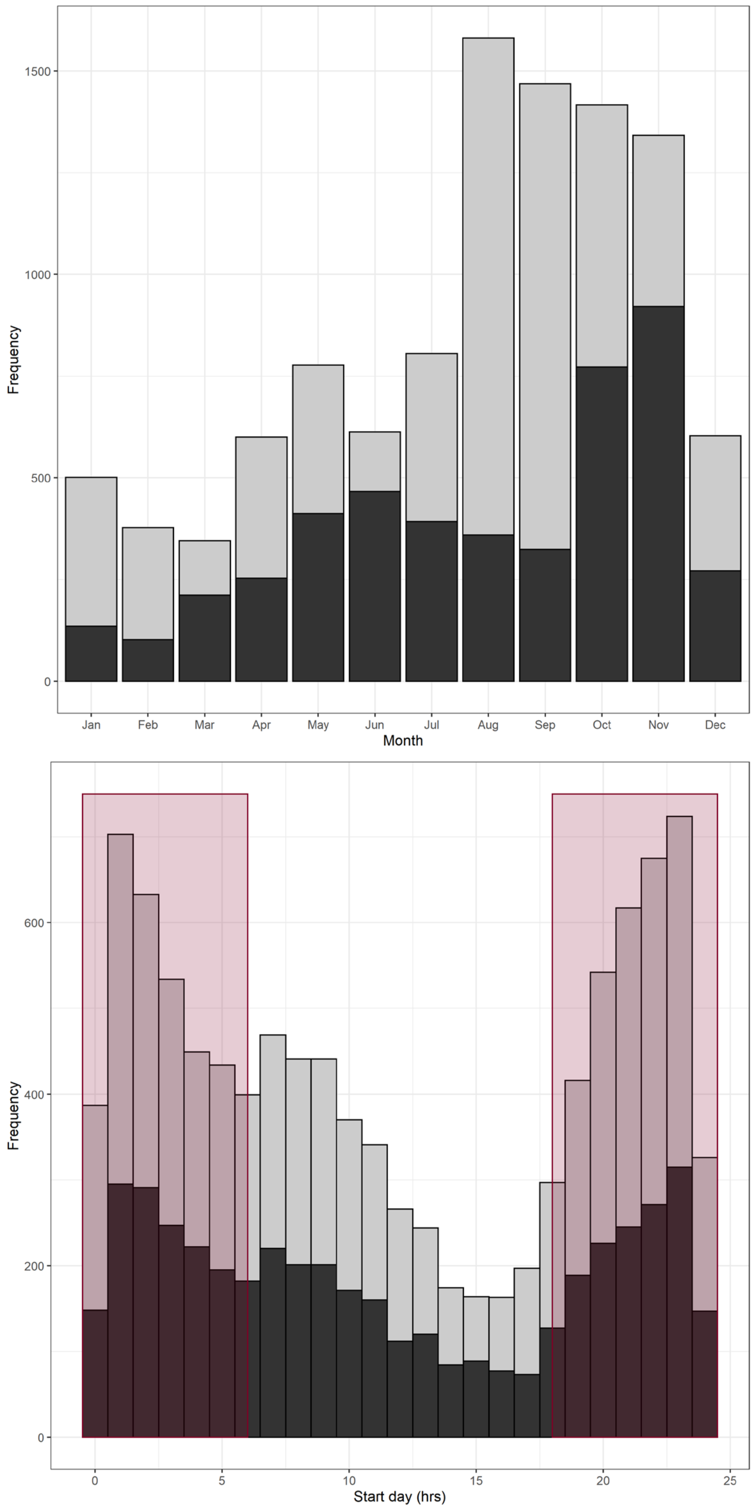


Figure 10: Frequency of bottom longline sets deployed by month (top) and by time of day (event start time, hrs, bottom) for all observed sets in the ling bottom longline fishery (light grey bars) and sets where deepwater sharks were recorded by observers (dark grey bars) from 2000 to 2020. Red blocks indicate night hours, when deepwater shark survival is likely to be higher (Brooks et al. 2015).

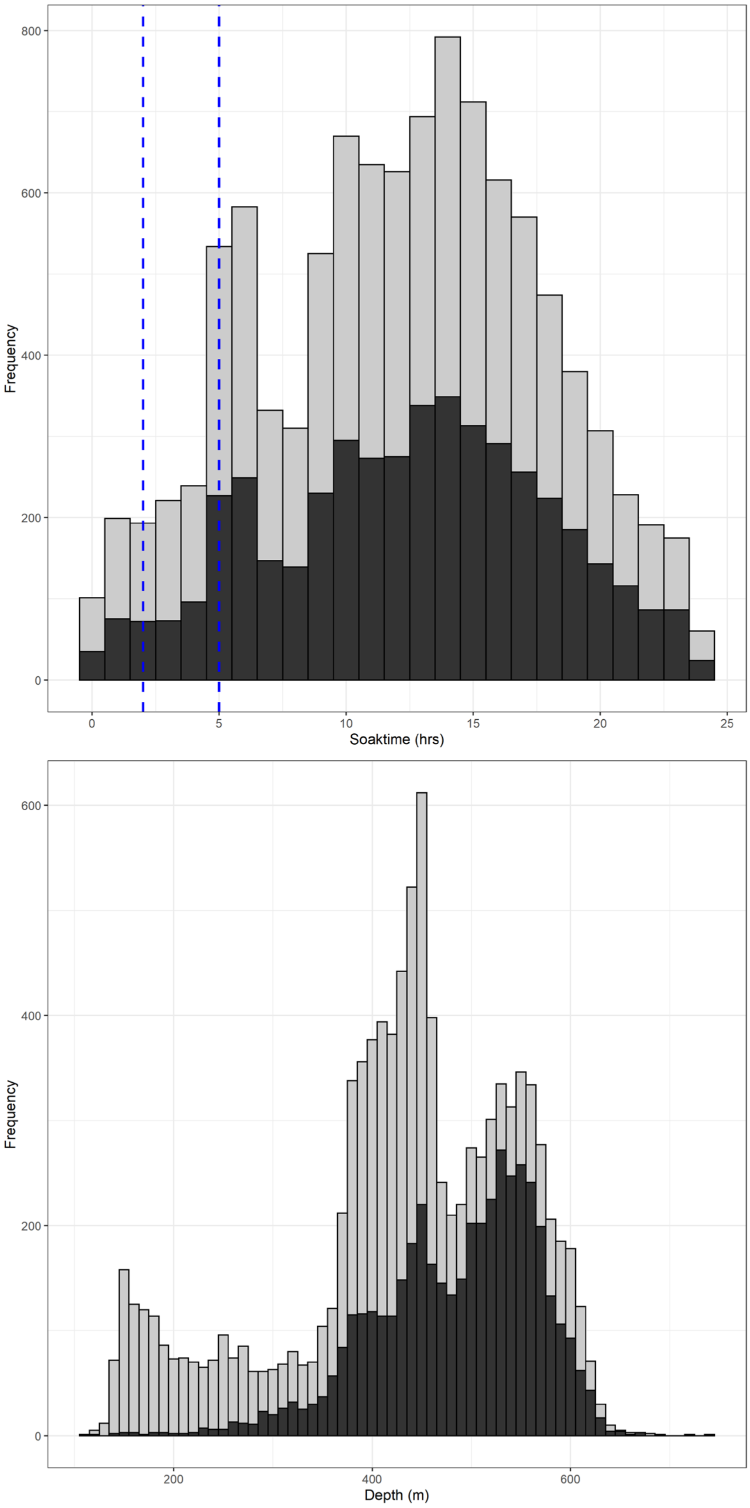


Figure 11: Frequency of bottom longline sets deployed by soak time (hrs, top) and mean depth (bottom) for all observed sets in the ling bottom longline fishery (light grey bars) and sets where deepwater sharks were recorded by observers (dark grey bars) from 2000 to 2020. Blue lines highlight soak time (2 to 5 hrs) where deepwater shark survival is likely to be higher (Brooks et al. 2015, Rodríguez-Cabello & Sanchez 2017).

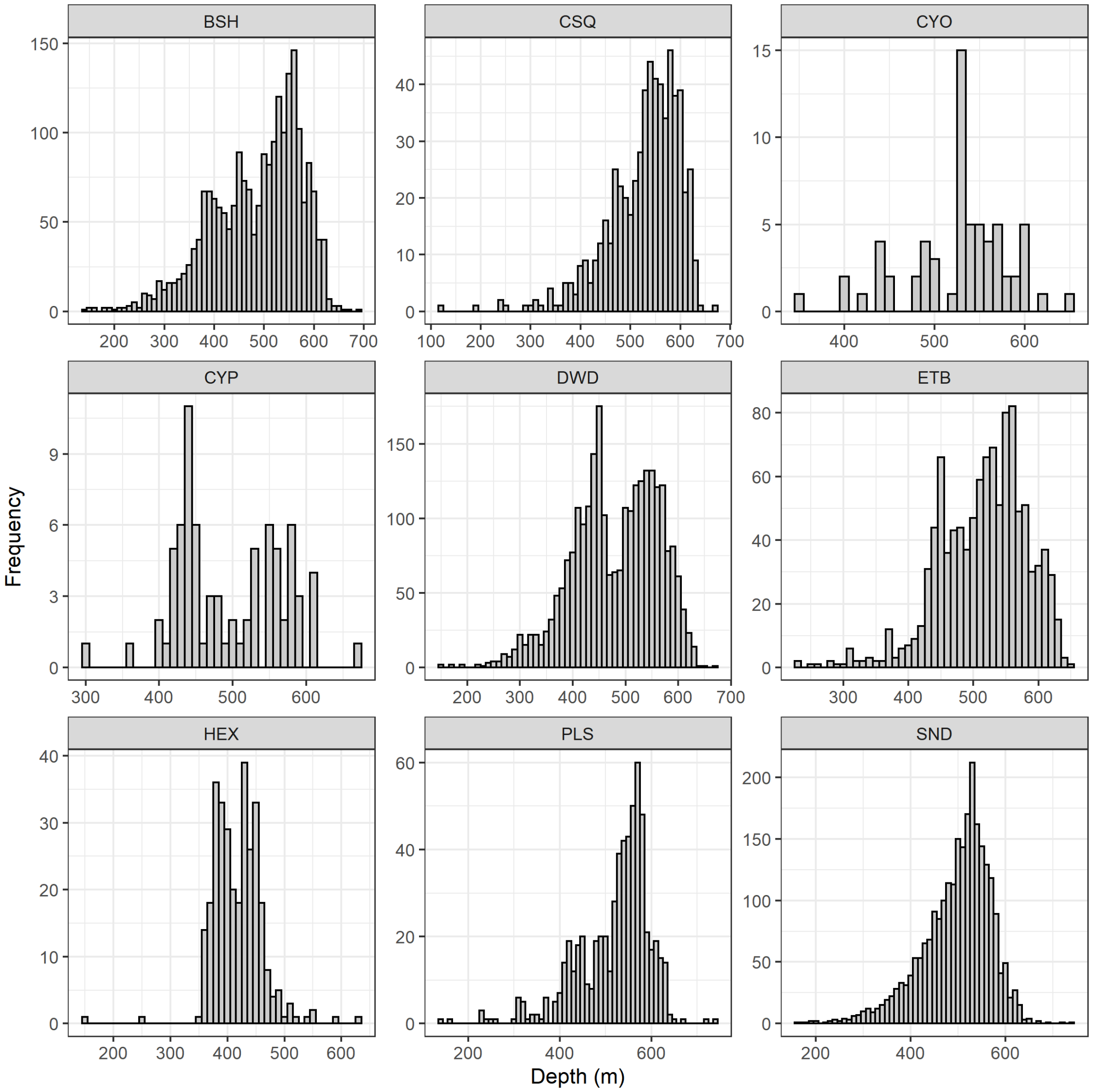


Figure 12: Mean depth of capture (m) of deepwater sharks caught in ling bottom longline fishery as recorded by observers from 2000 to 2020. Records of fish > 20 kg (n=74) not shown. Species codes: *Dalatias licha* (BSH), *Centrophorus squamosus* (CSQ), *Centroscymnus owstonii* (CYO), *Centroselachus crepidater* (CYP), generic Deepwater Dogfish (DWD), *Etmopterus granulosus* (ETB), *Hexanchus griseus* (HEX), *Scymnodon plunketi* (PLS), and *Deania calcea* (SND).

Observer record comparison with research trawl survey data

Observers reported that deepwater sharks were caught in the ling longline fishery throughout New Zealand waters (Figure 13, Figure 14). The distribution of observed catch varied by species, and there are some areas where density of observed catch was highest for one or more species: Puysegur (BSH, CSQ, DWD, ETB, SND); Cook Strait (BSH); East Coast South Island (CSQ, CYO, PLS); and southeastern Chatham Rise (CYO, CYP, DWD, ETB, PLS). High density observed catches also occurred on Pukaki Rise for ETB, around Chatham Islands for HEX, and on Campbell Rise for PLS. Observed catches of SOM were restricted primarily to the Macquarie Ridge, where relatively high density observed catches of ETB (this may be the congener *Etmopterus viator*, Straube et al. 2012) were also recorded (Figure 14).

There were some similarities in the distribution of research trawl survey catch compared with that of the observed catch described above. As such, these locations would likely be the most suitable to target for tagging deepwater sharks. Specifically, for BSH, Puysegur and northern Chatham Rise were both areas of high density catches in observed longline and research trawl catch. These areas were also important for CSQ and SND. Campbell Plateau and southeastern Chatham Rise also had high density catches (observed longline and research trawl) for CSQ and SND, respectively. Northwest Chatham Rise was an area of interest for PLS.

For other species (CYO, CYP, HEX), the distribution of catches was different between the two sources of data. Observed catches showed high density for CYO and CYP northwest and southeast Chatham Rise, but high density trawl catches for CYO was largely along the northern Chatham Rise. CYP trawl catches were sparse, with few records of individuals exceeding 1 m in length. Catch reported under ETB, DWD, and SOM were not compared here, because ETB did not exceed 1 m in length (and thus, there were no research trawl records in this data set), the DWD code was not used in trawl surveys, and there were no records of SOM from trawl surveys during the time period selected.

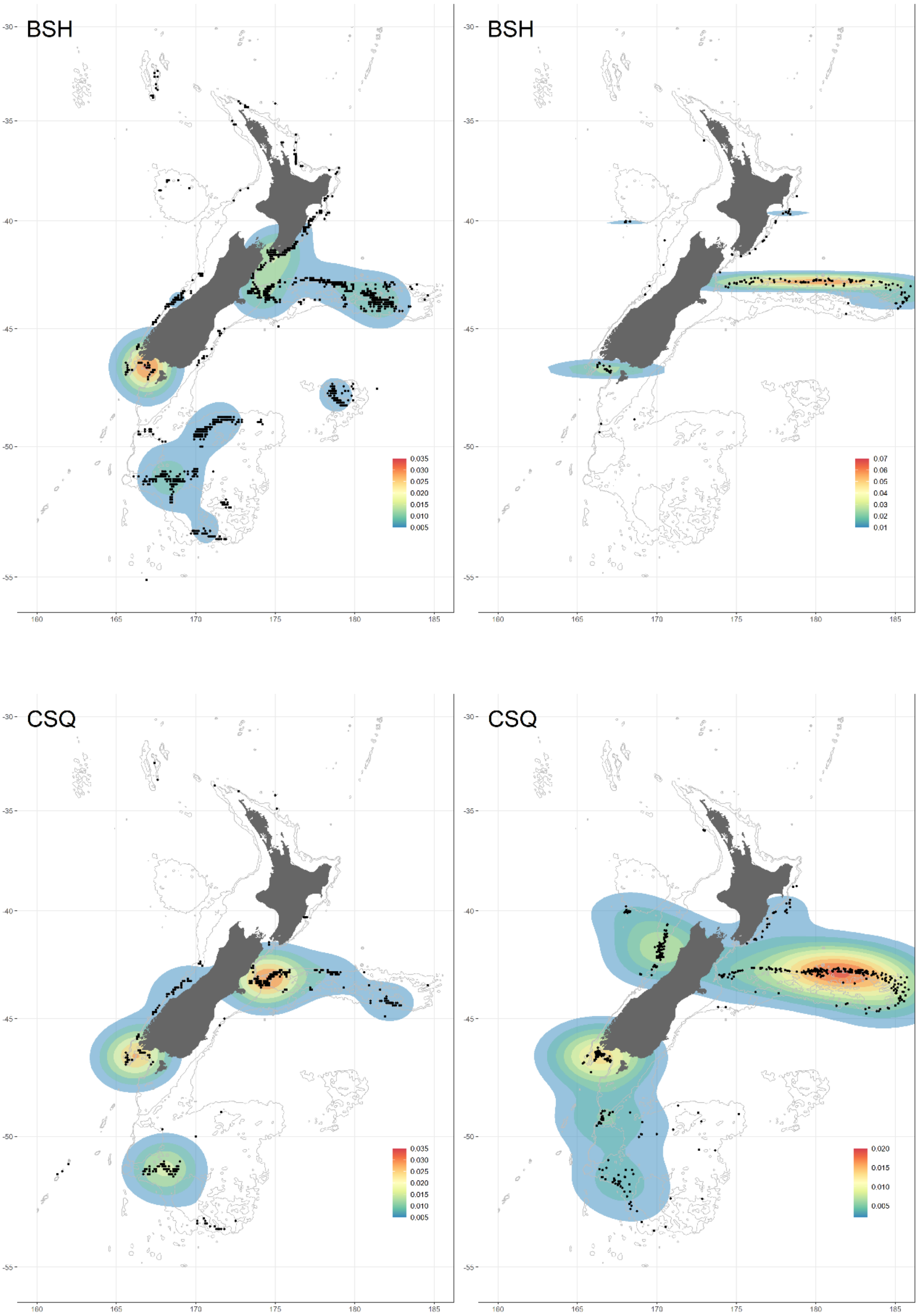


Figure 13: Distribution of deepwater shark catch (black dots) and 2-dimensional density estimation of catches (by greenweight, kg) from observer records from the ling bottom longline fishery (left) and research trawl surveys (right), from 2000 to 2020. Codes are defined in the Figure 12 caption. (Continued on next 3 pages)

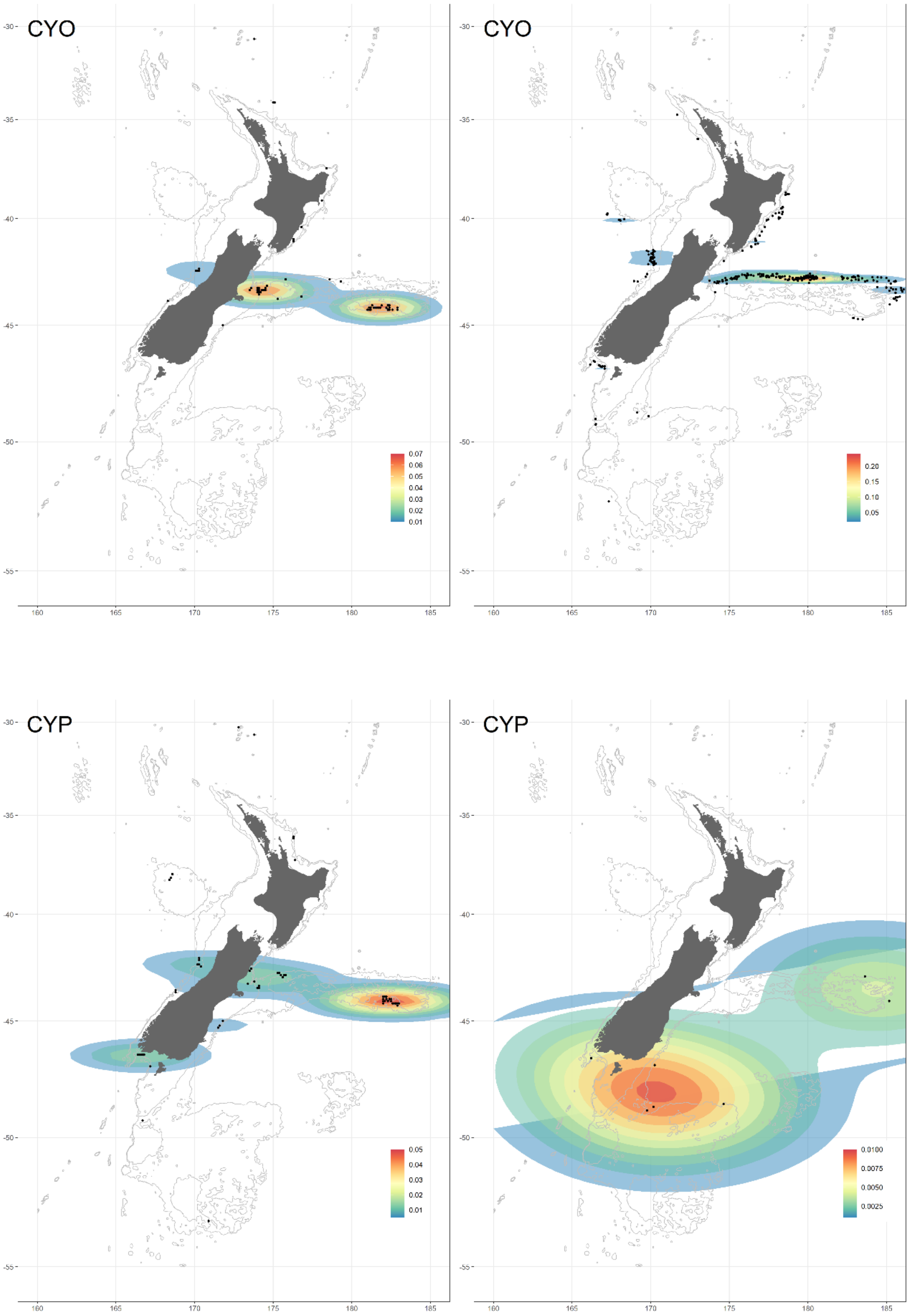
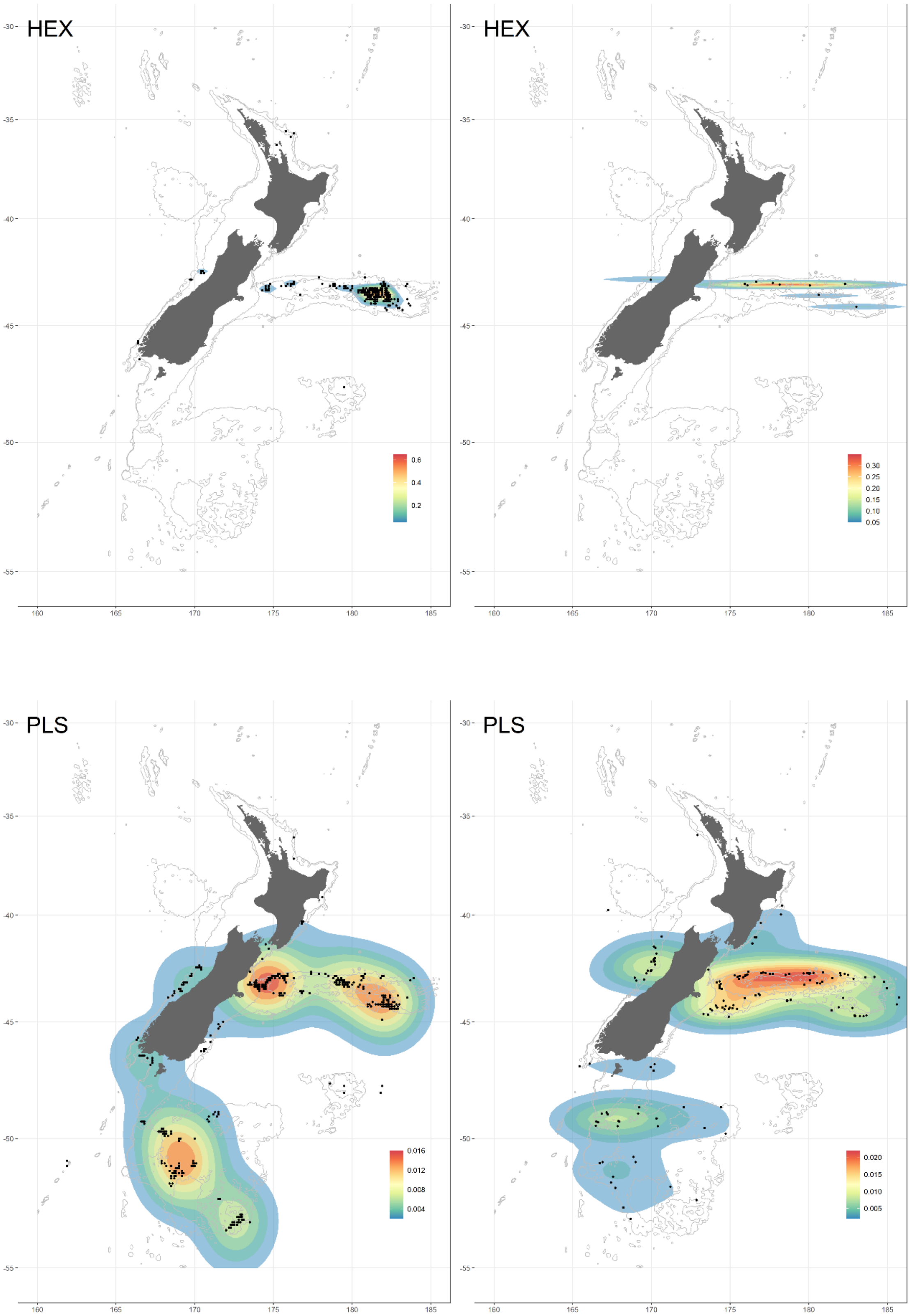


Figure 13: continued.



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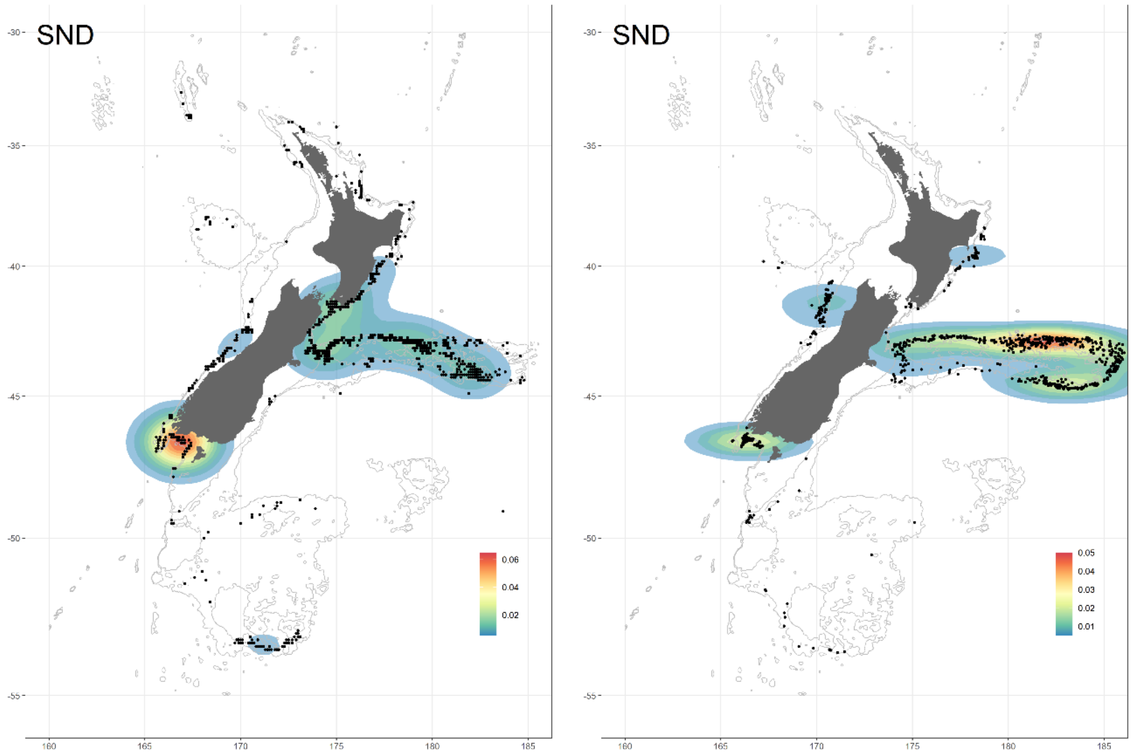

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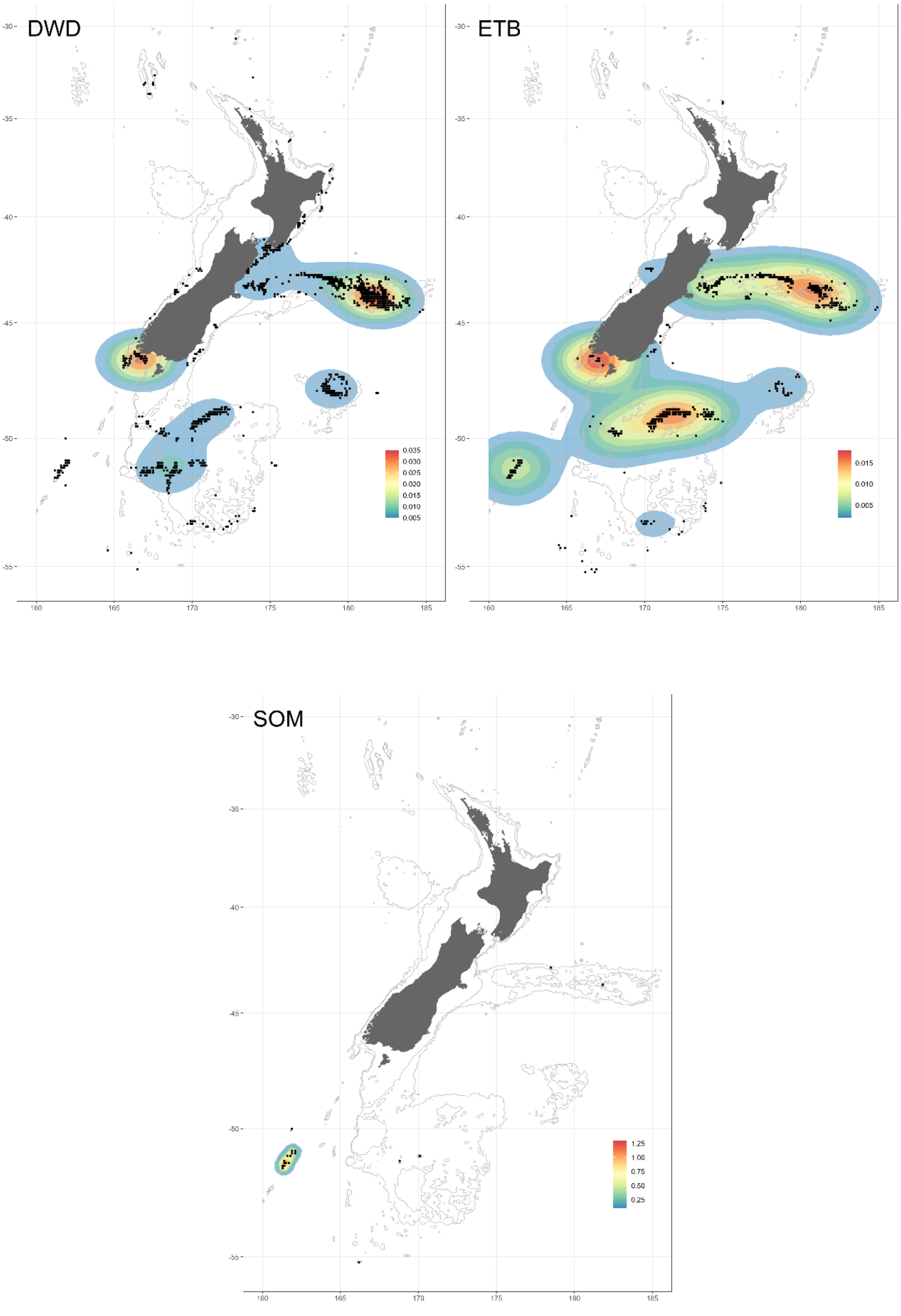


Figure 14: Distribution of deepwater shark catch (black dots) and 2-dimensional density estimation of catches (by greenweight, kg) from observer records in the ling bottom longline fishery from 2000 to 2020. No records for DWD and SOM exist in research trawl surveys and there were none for ETB where individuals exceeded 1 m total length.

4.3 Is the ling longline fishery suitable for tagging deepwater sharks?

To minimise capture-induced stress associated with considerable changes in ambient temperature and light availability, it is recommended that deepwater sharks are tagged at night (Brooks et al. 2015). The amount of time spent on a line will also affect survival. For smaller species (< 2 m total length), it has been recommended that soak times should not exceed 3–4 hours (Rodríguez-Cabello & Sánchez 2014, Brooks et al. 2015, Ellis et al. 2017, Rodríguez-Cabello & Sánchez 2017). Rodríguez-Cabello & Sánchez (2017) found that most sharks assessed in good condition were caught and brought on-board within a 5-hour window, whereas 75% of sharks in poor condition, or dead, were landed after 5 hours. Longer soak times (12 hours) have been used in studies where skates and larger-bodied sharks (> 3 m total length, e.g., hexanchids, some somniosids) have been tagged.

Based on these factors (and assuming dedicated tagging voyages are not possible), the ling bottom longline fishery would be a suitable candidate for tagging deepwater sharks. Fishing effort occurs year-round, allowing for sampling to take place during all seasons. Most longline sets are set in the evening and early morning (from 18:00 to 06:00) (Figure 10), which is also when most deepwater shark catch is reported. Deepwater sharks were caught at depth ranges shallower than the depth ranges of previous deepwater shark tagging studies (600 m vs. 1000 m or more, see Section 3.1), and targeted fisheries generally do not fish beyond 1000 m (Dunn & Ballara 2019). This may indicate high at-vessel survival for deepwater sharks in the ling bottom longline fishery. However, soak time is generally longer (> 5 hours) than what is recommended in the literature. Vessels greater than 30 m in length and using manual baiting consistently reported deepwater shark catch. These vessels also used fewer hooks, which would reduce the amount of time deploying and hauling back a set, and this may minimise stress and increase survival for sharks caught on a line. Thus, manual liners would be preferred over autoliners.

Assessing only observed vessels using manual baiting, there were a total of 18 vessels, 43 trips, and 951 sets deployed from 2000 to 2020. Of these, 16 vessels (89%), 39 trips (90%), and 434 sets (46%) reported at least one deepwater shark species. Most sets (n=319, 74%) were deployed in the last five years (2015–2020). The highest density catches of deepwater sharks for these sets occurred off Puysegur and East Coast South Island (Figure 15). Therefore, tagging effort should be focused on these locations.

According to observer records, species most likely to be encountered in the ling bottom longline fishery are SND, PLS, CSQ, and BSH. These are all species that could be tagged with both conventional and satellite tags. A considerable amount of SND, PLS, and CSQ catch has been retained, and financial compensation for fishers may be required to encourage release of catch. HEX may also be a suitable candidate for tagging in this fishery if tagging effort is considered around the Chatham Islands.

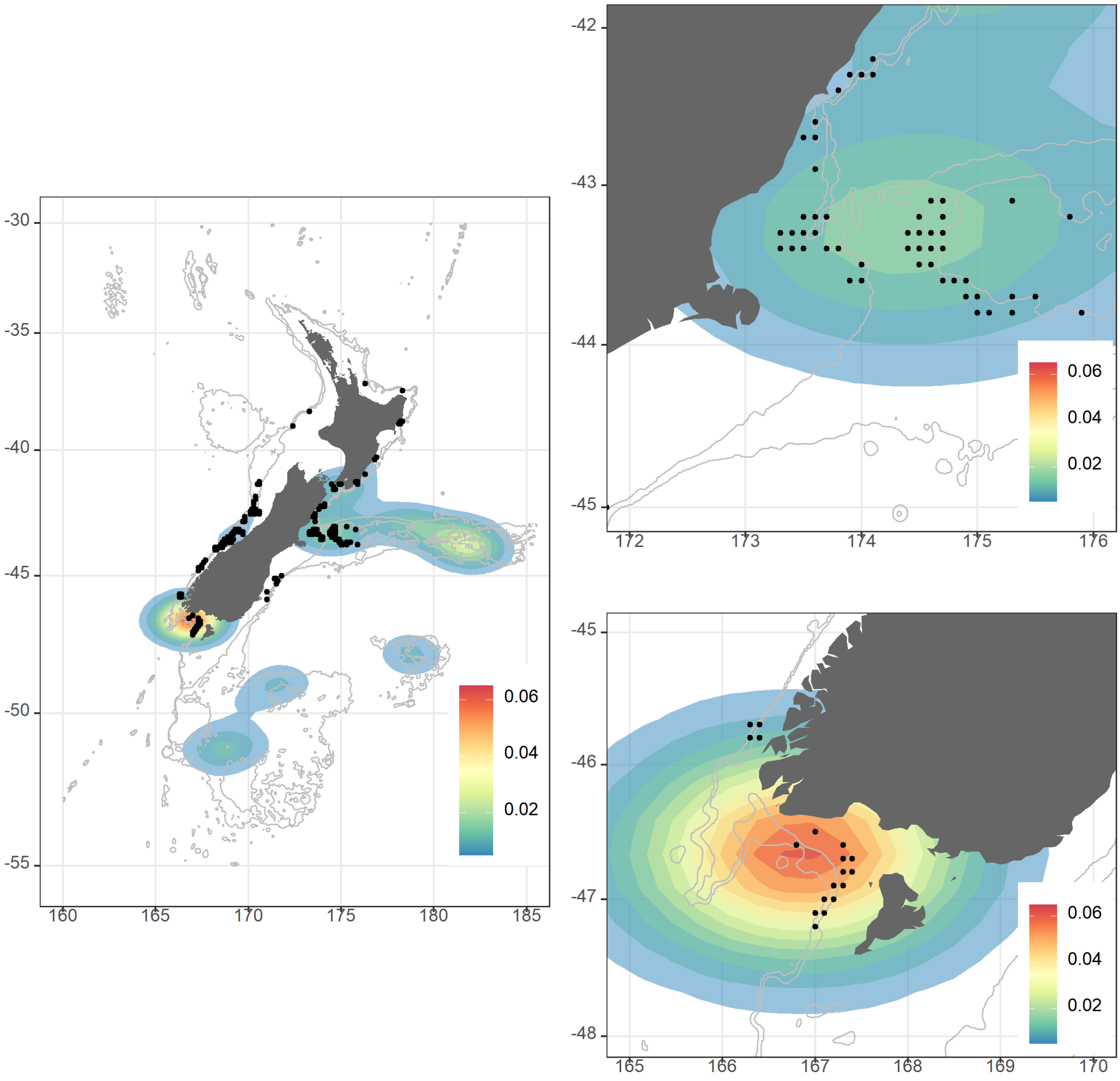


Figure 15: Observed commercial sets in the ling bottom longline fishery using manual baiting where deepwater shark catch was reported (black dots) and 2-dimensional density estimation of catches (by greenweight, kg) from 2000 to 2020 for the New Zealand Exclusive Economic Zone (EEZ), and East Coast South Island (above) and near Puysegur (below).

5. DISCUSSION

Information on tagging studies for deepwater sharks is limited and largely dependent on a handful of pilot studies. Nonetheless, these pilot studies have provided valuable data on the application and effectiveness of available technology, as well as improving our knowledge on movement and connectivity, and survival. Understanding movement patterns, population structure, and fisheries interactions is necessary to successfully manage exploited species and address conservation concerns for threatened species.

The ling bottom longline fishery was identified as a suitable candidate for tagging deepwater sharks in New Zealand waters. Given the lack of information on deepwater shark movement and survival, pilot studies could be initiated and could include a band-recovery design, known-fate design, or a combination of both. These studies would provide some of the first insights in movement and post-release survival for select deepwater shark species in the South Pacific and beyond. Using telemetry, a study could be completed in the short term (one or two years). A mark-recapture study to better assess growth parameters, including age validation, would likely require several years of tagging and tagging returns to accumulate sufficient data.

To better quantify expected return rates and the potential tagging success of a tagging study, some research gaps have been identified below.

5.1 Recapture probability

The success of a band-recovery (conventional) mark-recapture study depends on how likely tagged sharks will be recaptured. Estimating this return rate requires some understanding of an individual's probability of surviving and returning to the sampling area, and its probability of being encountered. For deepwater sharks in New Zealand, these probability processes are not known, but they are likely to be relatively low based on other shark studies (Section 3.2). Survival probability could be qualitatively assessed using at-vessel mortality as a proxy for survival or quantitatively evaluated with a post-release mortality satellite telemetry study.

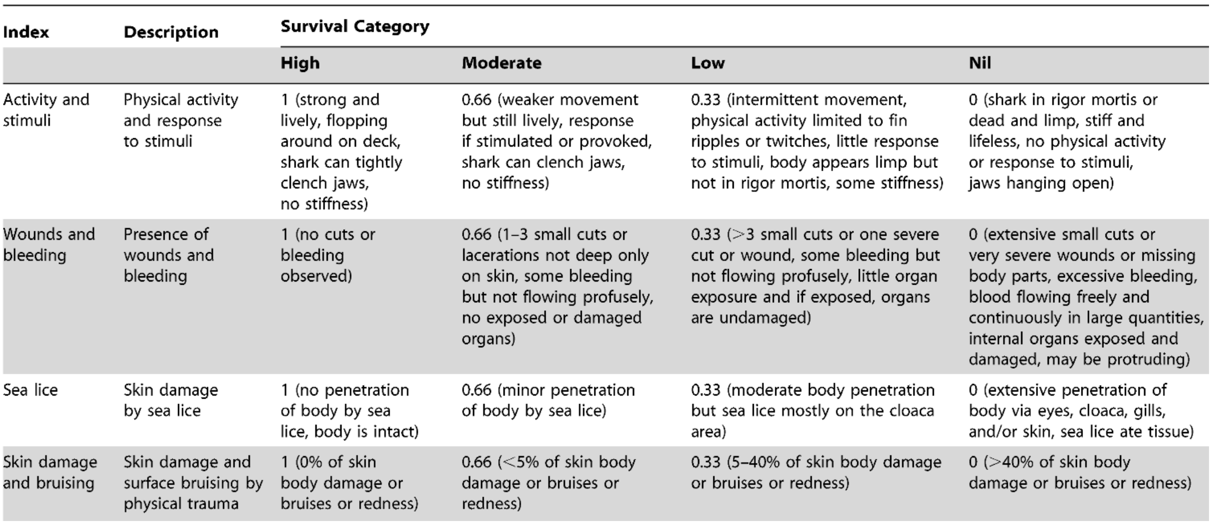
Encounter probability will largely be reliant on the spatial and temporal distribution of fishing effort in New Zealand waters. Bottom trawl fisheries contacted 7.2% of the seabed in the New Zealand Territorial Sea and EEZ between 2008 and 2018 (annual average of 2.2%), and the largest swept areas were at depths between 400 and 800 m (Fisheries New Zealand 2020). The extent of bottom longline fisheries in New Zealand has not been quantified, but much of the commercial effort associated with the ling fishery occurs on the Chatham Rise, across the Sub-Antarctic, and off the west coast South Island (Finucci et al. 2020). Observer coverage of these fisheries is generally well spread across fisheries in the Chatham Rise and Sub-Antarctic areas, but overall coverage of the commercial effort of primary offshore fisheries likely to capture deepwater sharks is approximately 20–40%, and coverage of the smaller fisheries in northern New Zealand waters is limited (Anderson et al. 2017, Anderson et al. 2019, Finucci et al. 2020). Although each fishery has seasonal components to effort (e.g., June–September for hoki, Anderson et al. 2019), deepwater fishing occurs year round. Research trawl surveys also regularly occur on the Chatham Rise (biennially in January), across the Sub-Antarctic (biennially in November–December), and in recent years, off the west coast South Island (triennially in July–August).

Coverage of the deepwater marine environment by observers and research surveys is likely to be sufficient to encounter tagged deepwater sharks around the South Island, the Chatham Rise, and waters south of the New Zealand mainland. To increase encounter probability in these areas, cooperation from commercial vessels without observers would also be needed. In addition, fishing and surveying effort is largely absent from much of New Zealand's northern waters. If these species move northward to these areas, re-encounter is unlikely. The possibility of such movement patterns could become apparent with outcomes from a future satellite telemetry study.

5.2 Improved sampling of ling bottom longline fishery for biological data and at-vessel mortality

Deepwater telemetry studies, particularly those aimed at understanding movement, are reliant on the ability of a target species to withstand extreme changes in ambient pressure, light, and temperature during transport from occupied depths to the surface and back (Brooks et al. 2015, Ellis et al. 2017). Physiological responses to these extreme changes upon capture vary greatly by species, and mortality (both at-vessel and post-release) varies considerably across regions, ocean basins, and fisheries and has been linked to environmental stresses and operational variables (e.g., gear type, handling, soak time) (Ellis et al. 2017, Musyl & Gilman 2019).

Given the lack of information on at-vessel mortality of deepwater sharks generally, and within New Zealand, it is recommended that an assessment of at-vessel mortality be conducted on commercial bottom longline fishing vessels. At-vessel mortality can be estimated by assessing shark condition using measures such as levels of activity, wounds, and bruising and is also useful in qualitatively estimating post-release survival (see Figure 16, Braccini et al. 2012, Rodríguez-Cabello & Sánchez 2017). This will provide initial information on the availability of sharks that can be tagged, and how many can be expected to survive post-release. This should not replace a quantitative evaluation of post-release survival, however, because it has been found that factors, such as post-release swimming, are not useful predictors of survival (Francis & Jones 2017, Raoult et al. 2019). One-third of satellite tagged *Centrophorus squamosus* released in a "healthy condition" were reported to die in the short term (Rodríguez-Cabello & Sánchez 2014, Rodríguez-Cabello et al. 2016). In addition to assessing shark condition, efforts can also be made to record biological data (e.g., sex, total length) of deepwater sharks on commercial longline vessels, particularly in the ling longline fishery. This information will provide insight into gear selectivity and will assist in determining where large sharks suitable for satellite tagging are located.



Index	Description	Survival Category			
		High	Moderate	Low	Nil
Activity and stimuli	Physical activity and response to stimuli	1 (strong and lively, flopping around on deck, shark can tightly clench jaws, no stiffness)	0.66 (weaker movement but still lively, response if stimulated or provoked, shark can clench jaws, no stiffness)	0.33 (intermittent movement, physical activity limited to fin ripples or twitches, little response to stimuli, body appears limp but not in rigor mortis, some stiffness)	0 (shark in rigor mortis or dead and limp, stiff and lifeless, no physical activity or response to stimuli, jaws hanging open)
Wounds and bleeding	Presence of wounds and bleeding	1 (no cuts or bleeding observed)	0.66 (1–3 small cuts or lacerations not deep only on skin, some bleeding but not flowing profusely, no exposed or damaged organs)	0.33 (>3 small cuts or one severe cut or wound, some bleeding but not flowing profusely, little organ exposure and if exposed, organs are undamaged)	0 (extensive small cuts or very severe wounds or missing body parts, excessive bleeding, blood flowing freely and continuously in large quantities, internal organs exposed and damaged, may be protruding)
Sea lice	Skin damage by sea lice	1 (no penetration of body by sea lice, body is intact)	0.66 (minor penetration of body by sea lice)	0.33 (moderate body penetration but sea lice mostly on the cloaca area)	0 (extensive penetration of body via eyes, cloaca, gills, and/or skin, sea lice ate tissue)
Skin damage and bruising	Skin damage and surface bruising by physical trauma	1 (0% of skin body damage or bruises or redness)	0.66 (<5% of skin body damage or bruises or redness)	0.33 (5–40% of skin body damage or bruises or redness)	0 (>40% of skin body damage or bruises or redness)

Figure 16: Indices and scoring criteria used to estimate post-capture survival of chondrichthyans in Australian gillnet fisheries (Braccini et al. 2012, reproduced with permission).

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