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Maritimes Region

Framework Review for the Stock Assessment of the Offshore Whelk (*Buccinum undatum*) in the 4Vs and 4W Exploratory Fishery

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Exploration for Offshore Whelk in Nova Scotia began in 2004 and exploratory licences were issued to Louisbourg Seafoods Ltd. in 2010 for 4Vs and 4W North Atlantic Fisheries Organization (NAFO) Divisions and to Premium Seafoods Ltd. for 4W in 2012. At the request of Fisheries and Oceans Canada (DFO) Maritimes Region Resource Management, a monitoring framework was developed for the exploratory Offshore Whelk fishery in 2020 to provide advice on future monitoring and research. In 2021–22, Science advice was requested for the completion of a stock assessment and the development of indicators and reference points to determine stock status of Offshore Whelk.

Fishery dependent data from monitoring documents and industry-led detailed sampling were analysed to evaluate fishery trends, spatial distribution of the fishery, growth, maturity, prevalence of parasitism, and natural mortality. Based on these data a number of indicators were explored for monitoring the fishery using catch and length-based methods. Although several methods have been presented, catch-per-unit-effort (CPUE) was proposed as a proxy for biomass. Candidate limit reference points (LRPs) were estimated for all regularly fished areas (4W Middle Bank, 4Vs Area 1 and Area 2) based on a proxy for the unexploited biomass (B_0), the maximum annual mean CPUE (kg/trap). Candidate LRPs were defined as 20% and 30% of the B_0 proxy for all areas, although based on the risk of local depletion of Whelk, 30% was determined to be more appropriate as an LRP. Length-based indicators were recommended to use in addition to the catch-based indicator to monitor the number of juveniles in the catch but would require additional annual sampling of the length frequency of the catch.

This Research Document was presented at the May 17–18, 2022, regional peer review meeting on Framework Review for Stock Assessment of Offshore Whelk in 4Vs and 4W.

BACKGROUND

A monitoring framework was developed for the exploratory Waved Whelk (*Buccinum undatum*) fishery in Northwest Atlantic Fisheries Organization (NAFO) Divisions 4Vs and 4W in the Maritimes Region in February 2020 (DFO 2020a). The fishery data were analyzed and recommendations from Fisheries and Oceans Canada (DFO) Science were provided to licence holders for future research and monitoring to support an assessment framework. Recommendations made at the monitoring framework meeting (DFO 2020a) included ensuring accuracy of reported data, standardizing catch-per-unit-effort (CPUE) by soak time, improved reporting on species composition of the catch and bycatch, and continued sampling by industry to inform on life history and size structure of the Whelk population in 4Vs and 4W fishing areas.

In 2021, DFO Resource Management requested advice from DFO Science on the stock status of Whelk in order to assess the viability of a commercial fishery in Offshore 4Vs and 4W. This is the first stock assessment of the Waved Whelk exploratory fishery in 4Vs and 4W Offshore. There is currently no assessment framework in place to monitor the Offshore Whelk fishery and no formal science advice has been provided for this fishery since the monitoring framework in 2020 (DFO 2020a).

BIOLOGY OVERVIEW

The Waved or Common Whelk (*Buccinum undatum;* herein referred to as Whelk) is a carnivorous gastropod widely distributed throughout subtidal waters to depths of 1,400 m in the North Atlantic, occurring from western Greenland to New Jersey in North America, and from Svalbard to France in Europe (Mercier and Hamel 2008, Borsetti et al. 2018, Hollyman et al. 2018, Emmerson et al. 2020). Whelk inhabit a variety of substrates with densities ranging from 0.2 to 1.8 Whelk/m^2 (Jalbert et al.1989, Valentinsson et al.1999, Magnúsdóttir 2010).

Whelk are both a predator and a scavenger, with a flexible diet consisting of polychaetes, bivalves, echinoderms, crustaceans, and fish eggs (Himmelman and Hamel 1993, Evans et al. 1996). They detect their prey through waterborne odours and therefore Whelk's ability to detect prey is influenced by the strength and direction of the currents (Brulotte 2012). When prey or predators are present, Whelk can move at a rate of 2 to 15 cm/min over a distance of tens of metres (Himmelman 1988, Sainte-Marie 1991, Lapointe and Sainte-Marie 1992, Giguère et al. 2007), although dive surveys suggest Whelk are fairly sedentary (Magnúsdóttir 2010).

Whelk populations differ in length distribution, genetic structure, and size-at-maturity over small spatial scales (Haig et al. 2015). Evidence of these spatial variations, together with the absence of a larval phase and limited mobility of adults, suggests restricted mixing with neighboring populations and reduces the likelihood of rapid re-colonization in exploited areas (Brulotte 2012).

GROWTH RATES

In the Quebec Region, Whelk can reach a maximum size of 120–130 mm shell height with a lifespan of 11 to 15 years (DFO 1997, DFO 2009b, Brulotte 2012). In general, growth is expected to be fast for younger Whelk with slow overall growth as the Whelk ages (Shelmerdine et al. 2007). In a laboratory setting, growth of Whelk collected from the St. Lawrence Estuary was explored over a three-year period. For Whelk less than 50 mm, height increased by 9 mm annually and 2 mm annually for Whelk greater than 70 mm (Brulotte 2012). In field studies, *B. undatum* reached sizes of 45 to 50 mm shell height by their second year (Kideys 1996, Fahy et al. 1995). Temperature may impact growth rates, but can be explored using the width of periodically deposited calcified structures (Borsetti et al. 2021). Typically, growth increases with increasing water temperature for younger individuals; however, temperature may negatively impact growth on older individuals (Borsetti et al. 2021). The maximum size declines with increasing water temperature and generally Whelk are larger at higher latitudes despite slower overall growth rates (Emmerson et al. 2020).

SIZE AND AGE AT MATURITY

There are various methods to estimate the sexual maturity of Whelk including histological examination of gonads (Heude-Berthelin et al. 2011), microscopic analysis (Valentinsson et al. 1999), and visual inspection (Hollyman 2017). Differences in methodology could lead to differences in maturity estimates due to variation in the level of accuracy among methods (Borsetti et al. 2018). Typically, visual inspection based on the proportion of the gonad relative to the shell length is used to quickly determine male and female maturity.

Size-at-maturity differs among regions and between sexes. The size at which 50% of Whelk are sexually mature (L_{50}) can vary considerably between populations and over distances as small as 10 km (Haig et al. 2015). The L_{50} ranges from 49 to 76 mm for males and 60 to 81 mm for females in Quebec (Gendron 1992, Brulotte 2012); 54 to 72 mm for males and 52 to 72 mm for females in Sweden (Haig et al. 2015), and 45 to 64 mm for males and 53 to 65 mm for females on Banquereau on the Scotian Shelf (Ashfaq et al. 2019).

Environmental parameters have also been shown to influence size-at-maturity of Whelk. Whelk mature at smaller sizes in warmer water temperatures (McIntyre et al. 2015, Haig et al. 2015, Emmerson et al. 2018) and at shallower depths (< 10 m, Haig et al. 2015). Fishing pressure may also further reduce the size-at-maturity of Whelk (Heude-Berthelin et al. 2011). The discarding of individuals smaller than a minimum landing size (MLS) could ultimately favor smaller individuals with reduced growth (Fahy et al. 1995, Shelmerdine et al. 2007).

Multiple methods have been used to age Whelk. Age has typically been estimated by counting growth rings on the outer surface of the operculum; however, this method may not be precise, accurate, or reliable (Hollyman et al. 2018, Emmerson et al. 2020, Borsetti et al. 2021). Hollyman (2017) found that less than 20% of samples were clear enough to estimate age based on growth rings. An alternative method to estimate age and growth is using the statoliths which are calcareous sensory structures contained within the head of the Whelk that assists with balance, similar to otoliths in vertebrates (Borsetti et al. 2021).

In the St. Lawrence Estuary and the Scotian Shelf, Whelk mature at 5 to 6 years of age (Gendron 1991,1992, Ashfaq et al. 2019); however, maturation may differ geographically as seen in Welsh and Isle of Man populations (Emmerson et al. 2000).

PARASITISM

Whelk are susceptible to parasites, resulting in damage to the visceral mass. Whelk serve as an intermediate host for multiple species of trematode larvae including *Neophasis anarrhichae*, *Cercaria buccini*, *Zoogonoides viviparous*, and *Renicola* sp. (Ashfaq et al. 2019). A parasitized individual is identified by the presence of gray digestive gland and gonad (Tetreault et al. 2000). Many of these parasites, are more prevalent in larger, sexually mature individuals and can damage both digestive glands and gonads resulting in a wide range of problems including atrophy of the male penis and destruction of the female pallial oviduct (DFO 2009a). In a study on Banquereau in 2016, a quarter of Whelk in some areas were infected with parasites, with females typically more impacted than males (Ashfaq et al. 2019).

MORTALITY

An estimate of the natural mortality rate (*M*) is unknown for Whelk in the Maritimes Region; however, estimates exist from studies in United Kingdom (UK) populations. After death, the Whelk shell remains intact for an unknown amount of time similar to a fossil record (Laptikhovsky et al. 2016), allowing for a unique way to assess age at mortality. The *M* estimates in the UK using this method ranged from 0.63–0.85 (Laptikhovsky et al. 2016), similar to tag-recapture studies in the UK ($M = 0.6$; de Vooys and van der Meer 2010).

Predators of Whelk include sea stars, crabs, American Lobster, and fish (Thomas and Himmelman 1988, Shelmerdine et al. 2007). Sea urchins, isopods, and various crab species directly prey on Whelk eggs (Martel et al. 1986a, Dumont et al. 2008) with predation higher in more exposed areas compared to eggs deposited in crevices or under macroalgae (Dumont et al. 2008). Damage to egg masses can also increase susceptibility to breakage from wave action.

Mortality may occur indirectly from other commercial fisheries. Trawl gear can result in bycatch of a variety of non-target species which are either retained or discarded at sea, benthic habitat disruption, and can cause injury to species exposed to the gear path (Ramsay and Kaiser 1998). The impact of fishing gear is species dependent. In short-term studies, Whelk were resistant to trawl gear with greater than 98% survival (Fonds 1991, Fonds et al. 1992, Fonds 1994, Kaiser and Spencer 1995); however, exposed and injured invertebrates in the trawl path may be more susceptible to predation. In a study by Mensink et al. (2000), 60% of Whelk with moderate to severe shell damage died. For the Whelk trap fishery, Whelk can survive up to 10 days in a trap before it is hauled (Valentinsson et al. 1999, Wilcox 2023).

RECRUITMENT

The timing of reproduction of Whelk is unknown on the Scotian Shelf but is likely comparable to the timing in the Gulf of St. Lawrence. The onset of spawning is signaled by a noticeable increase in gonad size (Borsetti et al. 2020). Females gather in May to copulate and lay eggs two to three weeks later (Martel et al. 1986a, Gendron 1992, DFO 1997). Eggs are attached externally onto the substrate typically on vertical walls, boulders, or around kelp stipes (Martel et al. 1986a, Dumont et al. 2008). An egg mass can contain on average 140 egg capsules with each capsule containing approximately 2,700 eggs (Martel et al. 1986a, DFO 1997, Ashfaq et al. 2019) and often contain eggs of several females (Thatje et al. 2019). In Canada, it takes five to eight months for fully developed juveniles (2 to 3 mm in length) to emerge from the capsule (Martel et al. 1986a, DFO 1997); quicker development occurs in the UK (Brulotte 2012, Borsetti et al. 2020).

Egg laying and development of eggs are temperature dependent, typically only occurring between 2 to 10°C (Borsetti et al. 2020), with reduced survival of offspring at higher temperatures. Survival of eggs is typically less than 1.1% of those produced (Martel et al. 1986a, Valentinsson 2002). Fecundity is greater in larger sized Whelk (more eggs produced), but the quality of the eggs is independent of size (Thatje et al. 2019, McIntyre et al. 2015, Valentinsson 2002). Lower gonadal indices in larger Whelk compared to smaller individuals indicate that reproduction may not occur every year (Gendron 1992, Valentinsson 2002).

STOCK STRUCTURE

Genetic studies may be required to delineate between the genotypic and phenotypic variations observed in Whelk. Restriction-site associated deoxyribonucleic acid (RAD) sequencing has been used to resolve fine-scale population structure in several marine invertebrate species (Goodall et al. 2020). In one study in the UK, genetic differences were observed for Whelk populations separated by 20 to 30 km within the same bay (Pálsson et al. 2014). Genetic diversity varies by location with allelic richness much lower in Nova Scotia sub-populations compared to UK populations (Weetman et al. 2006). Similarities in shell morphology and thickness typically occur for populations closer together; however, variation may also be linked to environmental parameters and predation (Magnúsdóttir et al. 2017, Shelmerdine et al. 2007).

With the lack of genetic data, life history characteristics of Whelk could be used to estimate population structure (Weetman et al. 2006). Species with limited dispersal and with low fecundity may show isolated population structure, as is likely with Whelk (Weetman et al. 2006).

MOVEMENT

Marine predators and scavengers typically are highly mobile, using their acute chemosensory attributes to locate prey from indicators in the water (Himmelman 1988). The area around a food source or bait from a trap that can be detected by a predator is commonly referred to as the "area of attraction" and is influenced by a variety of factors including species, currents, substratum, and depth (Himmelman 1988, Sainte-Marie 1991). Tagging studies have been conducted to determine the size and shape of areas of attraction for Whelk, where Whelk are tagged and released along a known distance from a food source (McQuinn et al. 1988); however, area may be underestimated based on changes in Whelk behaviour and reduced movement from high current speeds (Himmelman 1988). In a study of Whelk in the Archipel de Mingan, Quebec, speed and direction of the currents were more important than season, bait, depth, substratum, and stress in determining the attraction area (McQuinn et al. 1988).

Waved Whelk may have limited movement. In a multi-year mark-recapture study in the UK, only one Whelk of the thousands released was recaptured outside of the 8 km^2 study area (Hancock 1963). Tag recapture studies estimated Whelk movement to range from 8.3 cm/min to 11.4 cm/min (Himmelman 1988) and distances travelled to reach baited traps have been observed for distances of 20 to 30 m (DFO 2009a). In the coastal Quebec fishery, Whelk were observed moving 15 cm/min to reach a food source or to avoid predation (DFO 2009b). Female Whelk reduce feeding during reproduction and are less attracted to baited traps during mating and egg laying (DFO 2021).

HABITAT

Whelk inhabit a variety of habitats with different environmental conditions throughout the North Atlantic. They can be found on boulders, cobbles, and mud substrates at depths greater than 100 m; however, they tend to aggregate in higher densities on soft bottom substrates at 15 to 30 m depth (DFO 2009b). Whelk are tolerant of a wide range of temperatures from 0˚C to 22˚C and salinities as low as 20 parts per thousand (ppt), although it is likely that optimal environmental conditions vary by sub-population (DFO 2009b, Thatje et al. 2019).

FISHERY OVERVIEW

Global expansion of the Whelk fishery began in the 1990s based on increasing market demand (Borsetti et al. 2018). In the northwest Atlantic, Whelk were traditionally landed as bycatch in the Maine lobster fishery, but a directed fishery began in 1996 based on an increase in market demand in Asia (Louisbourg Seafoods Ltd. 2011). The fishery continues to develop in Canada, specifically in Quebec, Newfoundland and Labrador, and most recently in Nova Scotia (Rawlings et al. 2009, Ashfaq et al. 2019). The longest established Whelk fishery in Canada began in the 1940s in the Gulf of St. Lawrence, and then expanded to the North Shore of Quebec in the early 1990s, and the Magdalen Islands in 2003 (DFO 2009b). The North Shore is an inshore fishery, and the feasibility of a deep water (73 to 182 m) fishery was explored in

2013; however, CPUE declined with increasing depth. In Newfoundland, the fishery is restricted to inshore vessels with a 50 mm MLS, and both effort and landings have varied since the beginning of the fishery (DFO 2021).

In 1995, a test fishery occurred in Lobster Bay, Nova Scotia using modified lobster gear at depths of 9 to 15 m. Catch rates varied among traps based on the aggregatory nature of the species and size distribution differed from previously studied Gulf of St. Lawrence and Bay of Fundy populations (Kenchington and Lundy 1996). A commercial fishery was explored on the Scotian Shelf but was not pursued further based on limited market, small size of Whelk, and value of the resource (Kenchington and Lundy 1996).

OFFSHORE NOVA SCOTIA EXPLORATORY WHELK FISHERY

The New and Emerging Fisheries Policy guides the development of new fisheries using a three-stage process. Stage I (Experimental) allows industry to investigate whether a species can be caught, what kind of gear is needed, and if markets exist. Stage II (Exploratory) allows industry to collect information to determine if a long-term fishery is possible. Stage III (Commercial) applies when the fishery is considered 'limited entry', and the commercial fishery begins on an indefinite basis. There are currently two active Offshore Exploratory Whelk Licence holders, one with access to 4Vs and 4W, and the second licence holder with access to 4W (Table 1).

Exploration for Offshore Whelk in Nova Scotia began in 2004 with an unsolicited proposal from Louisbourg Seafoods Ltd. They were issued an Experimental licence for NAFO Divisions 4Vs and 4W outside of 50 nautical miles. The Experimental licence was re-issued in 2009 and upgraded to an Exploratory licence in 2011. This single licence has since been split into two to allow fishing in both 4Vs and 4W NAFO Divisions. An additional Experimental licence was issued to Premium Seafoods Ltd. for Offshore 4W in 2011, this licence was upgraded to Exploratory in 2012.

Two Experimental licences were also issued for 4X and 5Z which were held jointly by the Group of 4 which consisted of Ocean Pride Fisheries (formerly Ocean Leader), Acadia First Nation, D'Eon Fisheries Ltd. (formerly D'Eon Seafoods) and Set N' Sail Fisheries (formerly Bonniessa Marie Fisheries). In February 2012, the Group of 4 was advised that there were potential gear conflicts with established fisheries and access to 5Z was removed from the licence. No licences have been issued since 2014; however, the development of camera surveys by licence holders was determined to demonstrate continued interest and maintain their eligibility to re-apply for the licence in the future.

The Offshore exploratory Whelk fishery occurs outside of 50 nautical miles in 4W and 4Vs with the exclusion of several conservation areas (Figure 1). The typical fishing season occurs between June and December and in addition to Waved Whelk (*Buccinum undatum)*, Stimpson's Whelk (*Colus stimpsoni*), and Moonsnail (*Euspira heros*) can be retained. The MLS for each area has been set based on current available data and only 5% of retained catch can be undersized Whelk. The exception to these size restrictions is when Whelk are collected for scientific purposes. Dockside monitoring is required to verify all catch prior to landing.

Table 1. Offshore Whelk exploratory licences and output controls for the Scotian Shelf.

Licence Holder*	Area	2021/22 Total Allowable Catch (TAC)
Louisbourg	4Vs	700 mt (350 mt on Area 1)
Louisbourg	4W	250 mt
Premium	4W	250 mt

* active licences as of June 2021

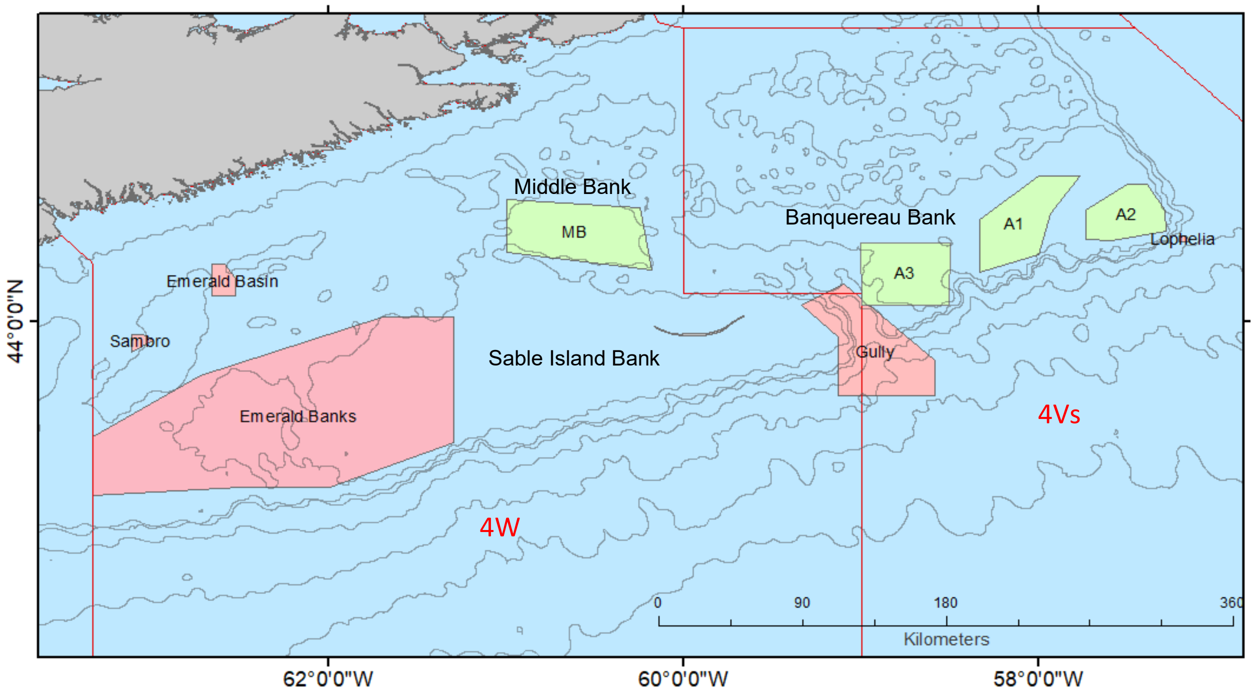


Figure 1. Map of offshore (outside of 50 nm) fishing areas in North Atlantic Fisheries Organization (NAFO) areas 4W and 4Vs. The closed areas are seen above shaded in pink. The main fishing areas in 4W (Middle Bank [MB]) and 4Vs (Areas 1–3) are shaded in green. The grey lines are contours and the red line identifies the NAFO boundaries. The major fishing banks are specified on the map (Banquereau in 4Vs; Middle and Sable Island Banks in 4W).

GEAR

Traps or pots are often considered a more beneficial gear than dredging because impacts on the benthic habitat are reduced. Modifications to the design of the trap can also lead to minimal bycatch (Logothesis and Beresoff 2004).

The exploratory Whelk fishery uses conical traps with a rigid circular opening of ≤ 127 mm diameter to minimize bycatch of decapods (Figure 2). Trap numbers are limited to 1,500 per licence holder and traps are typically deployed on a string approximately 20 fathoms (approximately 36 m) from one another (Louisbourg Seafoods Ltd. 2017). The Whelk pots are fitted with a cotton twine section capable of degrading over time to act as an escape mechanism and to prevent ghost fishing if traps are lost (Louisbourg Seafoods Ltd. 2017, Wilcox 2023).

SOAK TIME

Soak time is the period of time that the trap remains in the water. The Atlantic Fishery Regulations Section 115.2 currently prohibits any person from leaving fishing gear ‘soaking’ or unattended in the water for more than 72 consecutive hours to minimize loss of fishing gear, incidental mortality, the potential for gear conflict, and spoilage of catch (Department of Justice 1985). Currently, the soak time in the Whelk fishery varies but typically does not exceed the recommended timeframe unless inclement weather makes it difficult to retrieve traps (Louisbourg Seafoods Ltd. 2019). In Newfoundland, a study was conducted to examine the effects of soak time on Whelk catches. Traps that were left for 24 hours had 50% of the catch of traps left for 48 hours, and the average catch per trap declined for traps left for longer than 48 hours (CAFID 1996).

In the Maritimes Region, fishing reports prepared by industry showed similar results to the Newfoundland study, with the highest catches over short periods (approximately 72 hours) but declining catches for longer durations. These analyses showed that a soak time of two to five days resulted in the greatest CPUE (Louisbourg Seafoods Ltd. 2019) on Banquereau and CPUE reached its maximum at three days for Middle Bank (Premium Seafoods Group 2019).

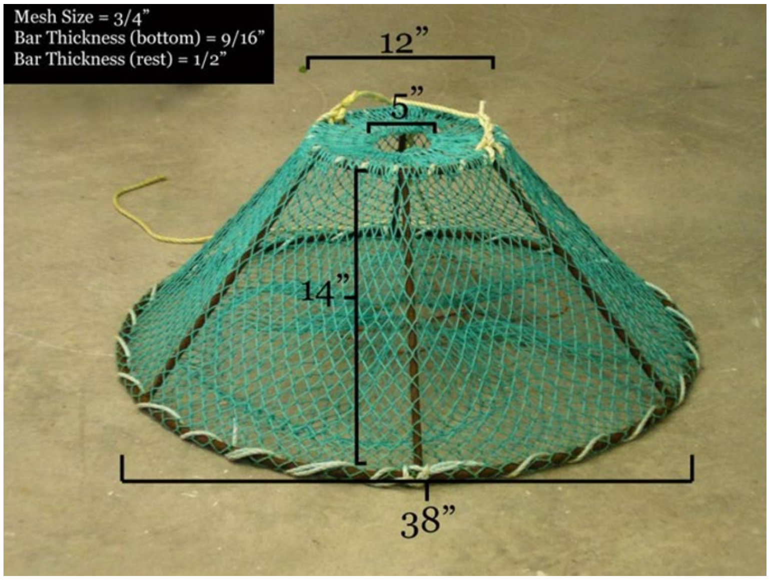


Figure 2. Conical Whelk trap. Source: (Louisbourg Seafoods Ltd. 2017).

BYCATCH AND DISCARDS

Bycatch may vary by season. For the Quebec Whelk fishery, fishing in early spring or late fall resulted in higher incidence of bycatch of vulnerable or juvenile commercially important species such as Snow Crab (*Chionoecetes opilio*; DFO 2009a).

In 4Vs, bycatch has been reported by industry as negligible and consisted mainly of Hermit Crab (Paguridae), Toad Crab (*Hyas* sp.), and Sculpin (*Myoxocephalus* sp.). More infrequently, sea stars (Asteroidea), sea urchins (*Strongylocentrotus* sp.), sand dollars (Clypeasteroida), and redfish (*Sebastes* sp.) have also been found in traps, and Whelk eggs have been observed attached to the gear. Poisonous Ten-ridged Whelk (*Neptunea decemcostata*) or SARA-listed (*Species at Risk Act*) species were not encountered. Stimpson's Whelk can be difficult to distinguish at sea and are therefore rarely reported separately. Recent investigations into the contribution of this species to the catch in 4Vs has been estimated to be less than 2%.

Onboard observer presence is by request and to date there has been only five trips of at-sea observations in the 4Vs region during the years of 2011, 2014, and 2015 (Table 2). Bycatch consisted mainly of crab species (e.g., snow, hermit, toad, and Rock Crab (*Cancer irroratus*)). Total discarded from any one string (approximately 50 traps per string) was < 25 kg, and typically, these higher bycatch rates corresponded with low Whelk landings (Wilcox 2023). Other species caught included squid (*Pterygioteuthis* sp.), sand dollars, sea urchins, sea stars, and sea ravens (*Hemitripterus americanus*) but all in very low quantities (< 5 kg discarded weight in any one string).

Prior to 2018, Whelk licence holders were only required to submit a single SARA log per season. In 2018, licence holders were required to submit a SARA log for each trip, along with the Whelk Monitoring Document (i.e., logbook). Based on the SARA logs submitted from the Whelk fishery, there were no interactions identified with any species at risk.

Table 2. Bycatch (kg) estimates from the Offshore Whelk fishery based on observed Whelk directed trips (n = 5). Estimated bycatch is based on a proportion of the observed catch applied to all landings for that year. There was no bycatch in the observed trip in 2015.

Species	2011	2014	Total
Sea Stars	81.3	0	81.3
Rock crab	406	0	406
Hermit crab	5,607	0	5,607
Squid	406	0	406
Sand Dollars	81.3	0	81.3
Sea Raven	0	18.1	18.1
Sea Urchin	163	0	163
Shorthorn Sculpin	81.3	0	81.3
Snow Crab	2,357	6.05	2,363
Toad Crab	650	6.05	656

CATCH MONITORING

Licence holders must submit a fishing and/or research plan prior to each season, comply with SARA monitoring during the fishing season, and must provide a report on the activities of the fishing season when completed.

All fishing activities are logged by trip using the Whelk Monitoring Document provided by DFO. This required documentation includes specific information regarding the licence holder and vessel, temporal and spatial fishing data (e.g., date set/hauled and position of trap), the number of traps (traps set/lost/hauled), the amount of catch (kept/discarded) for each species, and the number and weight of non-targeted species. All fishery catch is verified by dockside monitoring.

On an annual basis, both offshore licence holders develop and submit fishery plans to guide research and establish a timeline to gauge the progress of the fishery. Both licence holders have partnered with academic institutions to process samples and analyze life-history and size-frequency data that could inform assessments and management. A subset of Whelk is collected from fishing trips and several biological parameters are recorded including shell length, sex, sexual maturity, total weight, and shell characteristics (e.g., presence of epibionts or fractures). Other metrics such as tissue weight, shell weight, shell width, evidence of imposex, age, parasitism, and DNA analysis are also collected by industry when time allows. From these data, size frequency distributions, size- and age-at-maturity, sex ratios, growth curves, and population structure can be estimated.

FISHING HISTORY

NAFO Division 4Vs

In 2009, an experimental fishery commenced on Offshore Banquereau in NAFO Division 4Vs (Figure 3). After several successful commercial trips, the fishery evolved into an exploratory fishery in 2011. In 2012, after acquiring data on both catch and the biology of Whelk in the area, the 500 lb (226 kg) TAC was re-adjusted to levels that were more economical for the industry (350 mt TAC). From 2013 to 2015, landings were primarily from the area designated by industry as Area 1 (Figure 1). Further exploratory fishing outside of Area 1 was limited due to gear conflicts with the Arctic Surfclam (*Mactromeris polynyma*) fleet. In 2018, the TAC was increased from 350 to 700 mt, with a 350 mt cap on Area 1. Exploratory fishing outside of Area 1 has been successful since 2018. Fishing started earlier in the summer of 2018 and traps were modified to include weights. A third vessel was added to the fleet in 2019.

NAFO Division 4W

In 2011, an experimental fishery was conducted in the Middle Bank and Sable Island Bank areas (Figure 4). In 2012, the quantities observed in the surveys were deemed sufficient to warrant expansion to an exploratory fishery with a TAC set at 350 mt for each licence holder. The 2012 landings; however, were low compared to other commercially viable areas. From 2013 to 2016, surveys yielded very few Whelk with notably patchy distributions. In 2017, a joint venture between both licence holders resulted in a discovery of a section of Middle Bank which contained much higher densities of Whelk. DFO has encouraged further exploration outside of Middle Bank to determine if more harvestable aggregations occur elsewhere in 4W. In 2018, the minimum size was adjusted to 67 mm based on information derived from research at Cape Breton University (CBU) and the TAC was reduced to 250 mt per licence holder. In 2019, the TAC was not fully caught due to weather and mechanical issues with the boats and effort continued to be concentrated on Middle Bank in both 2019 and 2020.

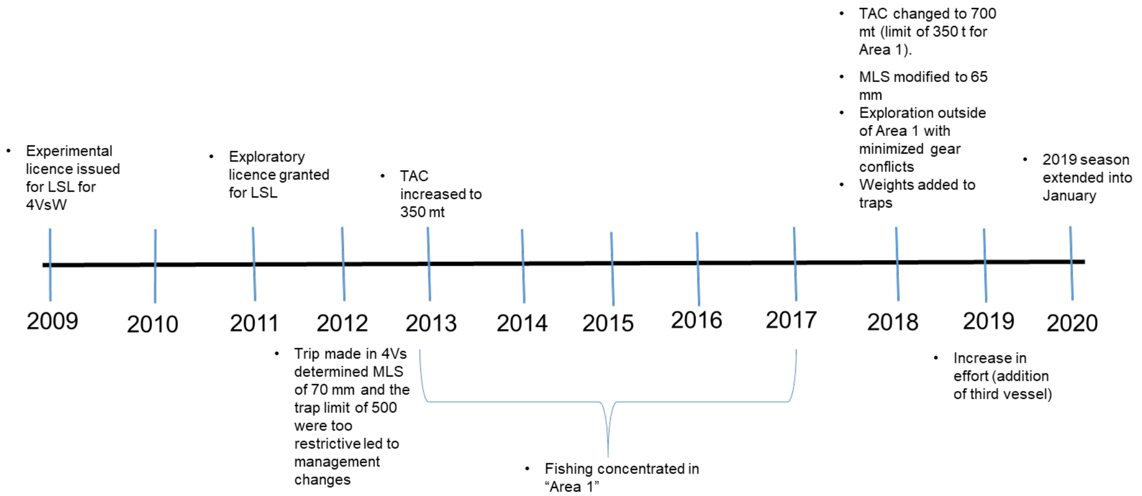


*Figure 3. Timeline of changes to the 4Vs offshore Whelk (*B. undatum*) fishery.*

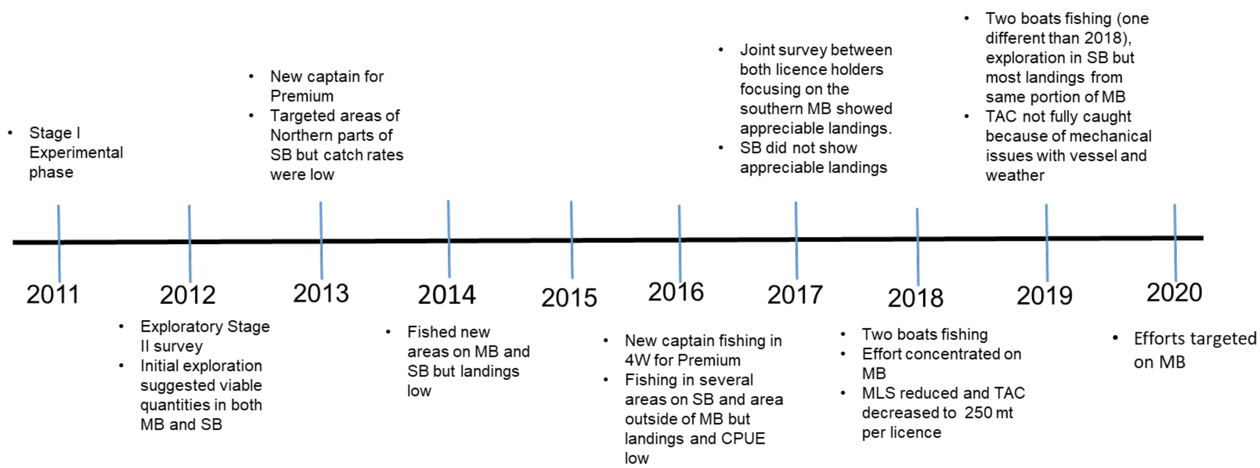


*Figure 4. Timeline of changes to the 4W offshore Whelk (*B. undatum*) fishery on Middle Bank (MB) and Sable Island Bank (SB).*

ANALYSIS

FISHERY INDEPENDENT DATA SOURCES

The distribution of harvestable densities of Whelk is generally not well known, even in the areas currently fished. There are currently no independent surveys to assess the Whelk population in the Maritimes Region; however, there are sources of data collected from surveys led by DFO.

The DFO Maritimes Ecosystem Research Vessel Survey is conducted on the Scotian Shelf every summer. Whelk are not well captured with the Ecosystem Survey trawl gear; however, catch patterns over time are considered representative of the general species distribution (Figure 5). The DFO Maritimes Snow Crab Survey occurs annually using a modified small mesh trawl gear. Whelk are commonly caught as bycatch in the Snow Crab Survey and although not specifically geared toward Whelk, survey data may provide some insight on distribution in the Offshore area.

Based on the distribution of Whelk found in the DFO Ecosystem Survey, harvestable densities may exist over the remainder of Banquereau (Figure 5). Whelk collected from this survey were categorized as Waved Whelk, Whelks, and Buccinidae, and were summed per tow from 2010 to 2020. Earlier in the time series, the DFO Ecosystem Survey did not identify most invertebrates to species level; therefore, higher level taxonomy was assumed to be *Buccinum undatum*. Whelk egg distribution was consistent with the spatial distribution of adults in the DFO Ecosystem Survey (Figure 6). A similar spatial distribution occurred from the DFO Maritimes Snow Crab Survey, where the largest abundances were found on Banquereau and Middle Bank in 4Vs and 4W (Figure 7). The Snow Crab Survey did not identify Whelk to species level and, therefore, interpretation of spatial data should be done cautiously since multiple species of Whelk are known to be captured.

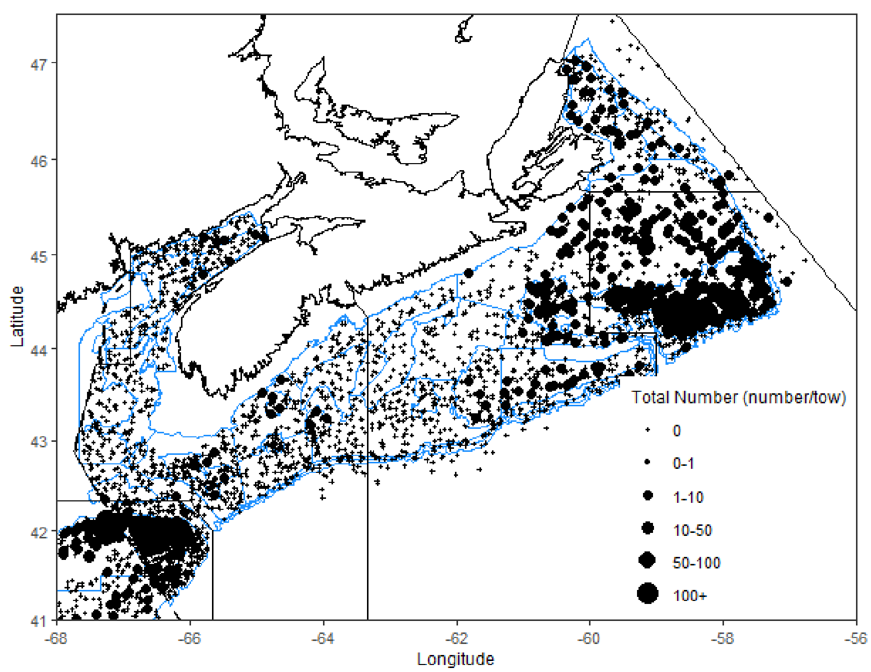


Figure 5. Number of Waved Whelk caught on the Maritimes Ecosystem Research Vessel Survey (number/tow) from 2010 to 2020 (species codes Buccinidae, Waved Whelk, Whelk). The + symbol indicates no Whelk were found in that tow and the black closed circles indicate the presence of Whelk with increasing size associated with higher abundances. The blue lines indicate the Maritimes Ecosystem Research Vessel Survey strata and the black lines are the NAFO Division boundaries.

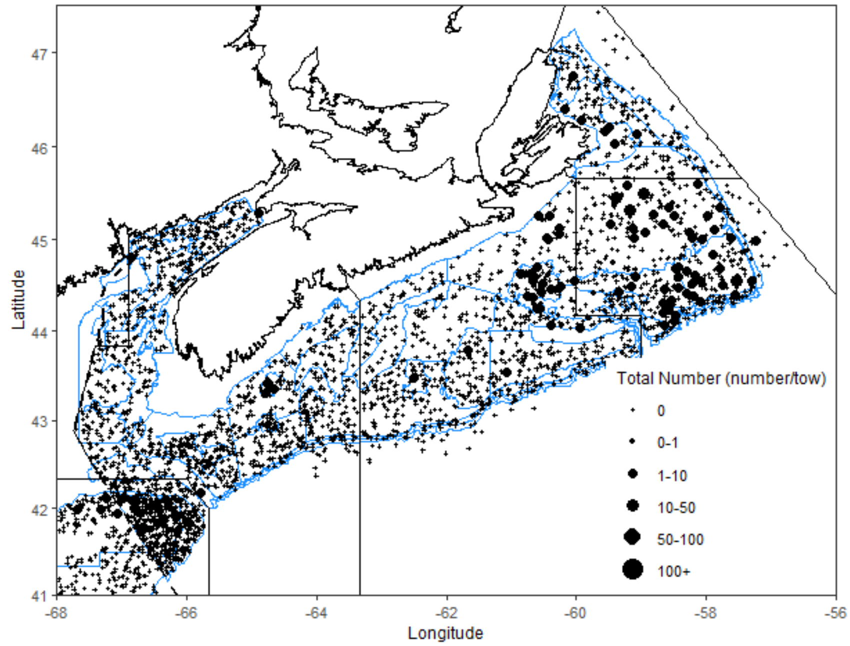


Figure 6. Number of Whelk eggs caught on the Maritimes Ecosystem Research Vessel Survey (number/tow) from 2010 to 2020 (species code 1510). The + symbol indicates no Whelk eggs were found in that tow and the black closed circles indicate the presence of Whelk eggs with increasing size associated with higher abundances. The blue lines indicate the Maritimes Ecosystem Research Vessel Survey strata and the black lines are the NAFO Division boundaries.

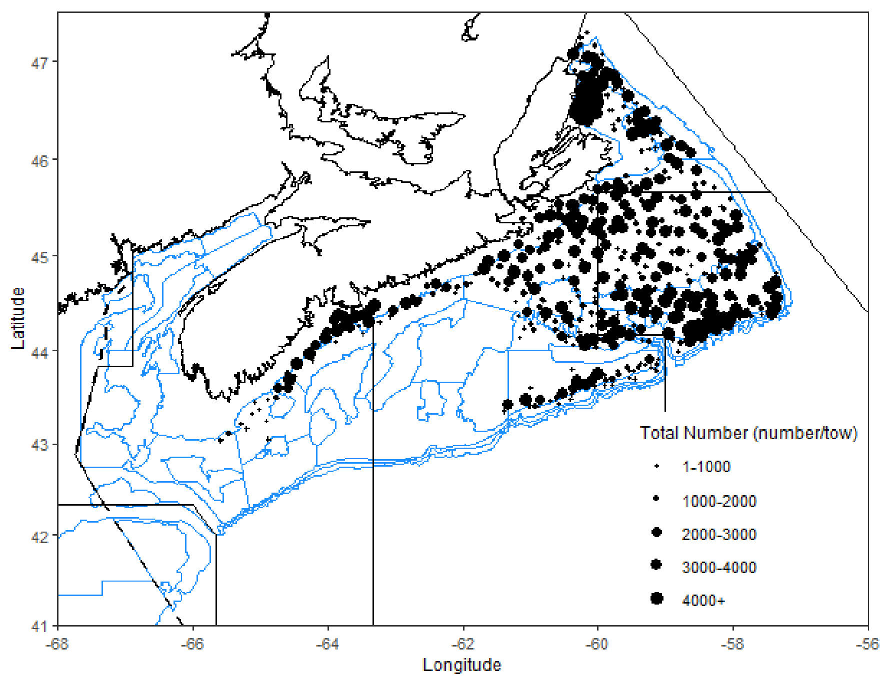


Figure 7. Number of Whelk caught in the DFO Maritimes Snow Crab Survey (number/tow) from 2002 to 2020. Species composition may include more than Waved Whelk. The black closed circles indicate the presence of Whelk with increasing size associated with higher abundances. Tows without Whelk present are not depicted in the figure. The blue lines indicate the DFO Maritimes Ecosystem Research Vessel Survey and the black lines are the NAFO Division boundaries.

FISHERY DEPENDENT DATA SOURCES

Commercial Fishery

Landings and Effort

Landings of Whelk have generally increased in Offshore 4Vs since the beginning of the experimental fishery in 2009 (Figure 8). The industry has explored a variety of bank habitat, and have consistently found harvestable densities of Whelk in 4Vs. In 2018, they found greater densities in 4W. The highest total landings of Whelk were 676 mt in 4Vs in 2020, and 211 mt in 4W in 2018 (Figure 8). In recent years, landings were spread out across Banquereau in 4Vs concentrating in three main areas (Area 1, Area 2, Area 3, Figure 1, Figure 9). In 2019, landings in 4W were concentrated on the southern portion of Middle Bank and further exploration occurred on Sable Island Bank. In most years, including 2020, landings were primarily from Middle Bank (Figure 9).

There are currently no reported landings of Moonsnail in the Whelk fishery. Stimpson's Whelk were identified in the 2019 landings, but no numbers were provided and the report indicated that Stimpson's Whelk represented less than 2% of the catch (Louisbourg Seafoods Ltd. 2019). As indicated in the Whelk monitoring framework (DFO 2020a), efforts should be made to quantify the number of Stimpson's Whelk in the catch moving forward.

Whelk fishing occurred from July to November in 4W (Figure 10a) and extended to December in 4Vs (Figure 10b). Over the last three years, most of the landings and effort occurred in August to October in both fishing areas.

Figure 8. Exploratory Offshore Whelk fishery landings (mt) in NAFO Divisions 4W and 4Vs. Blue horizontal lines indicate TAC for 4W and pink horizontal lines indicate TAC for 4Vs.

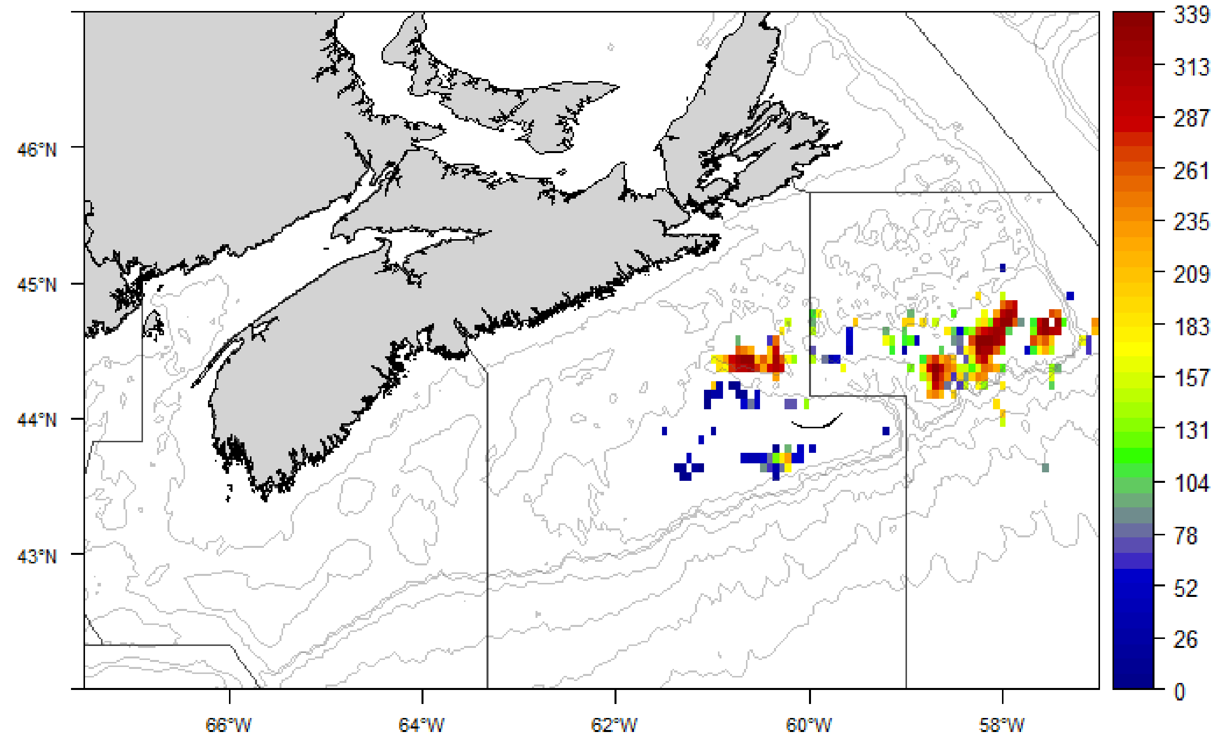
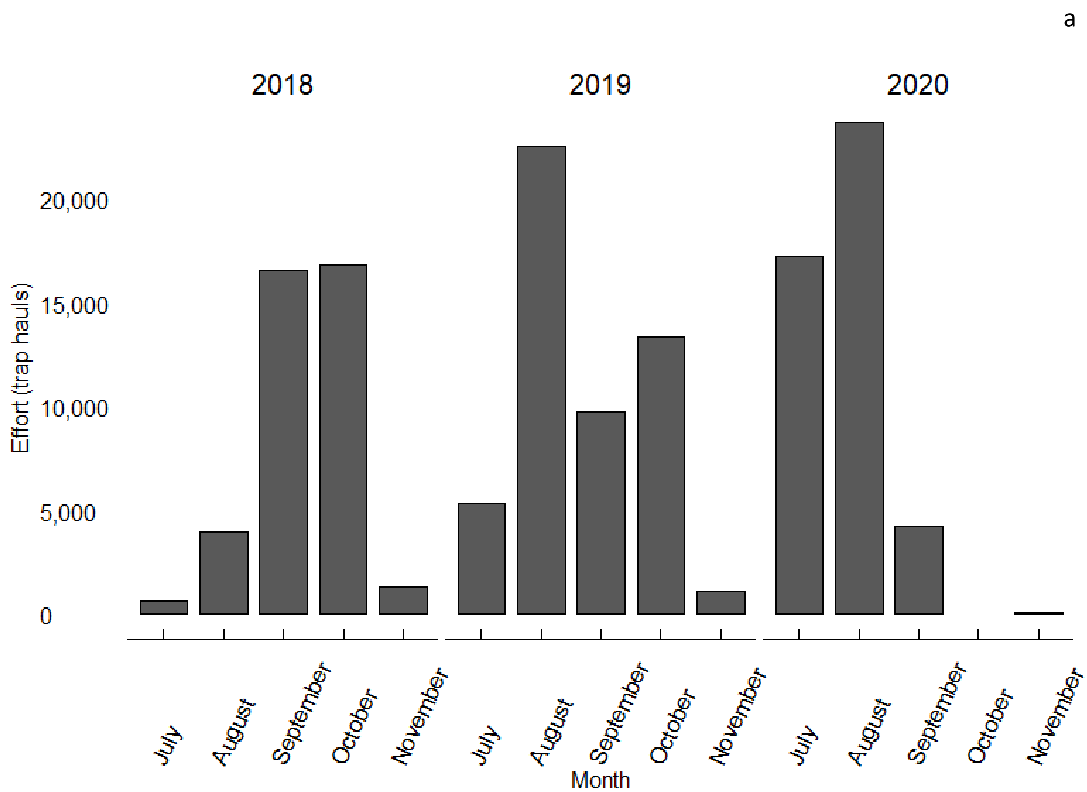


Figure 9. Spatial footprint of the total landings (mt; using a 5-minute grid) of the exploratory Offshore Whelk fishery in 4W and 4Vs from 2009 to 2020. The grey lines are depth contours and the black lines are the NAFO Division boundaries.



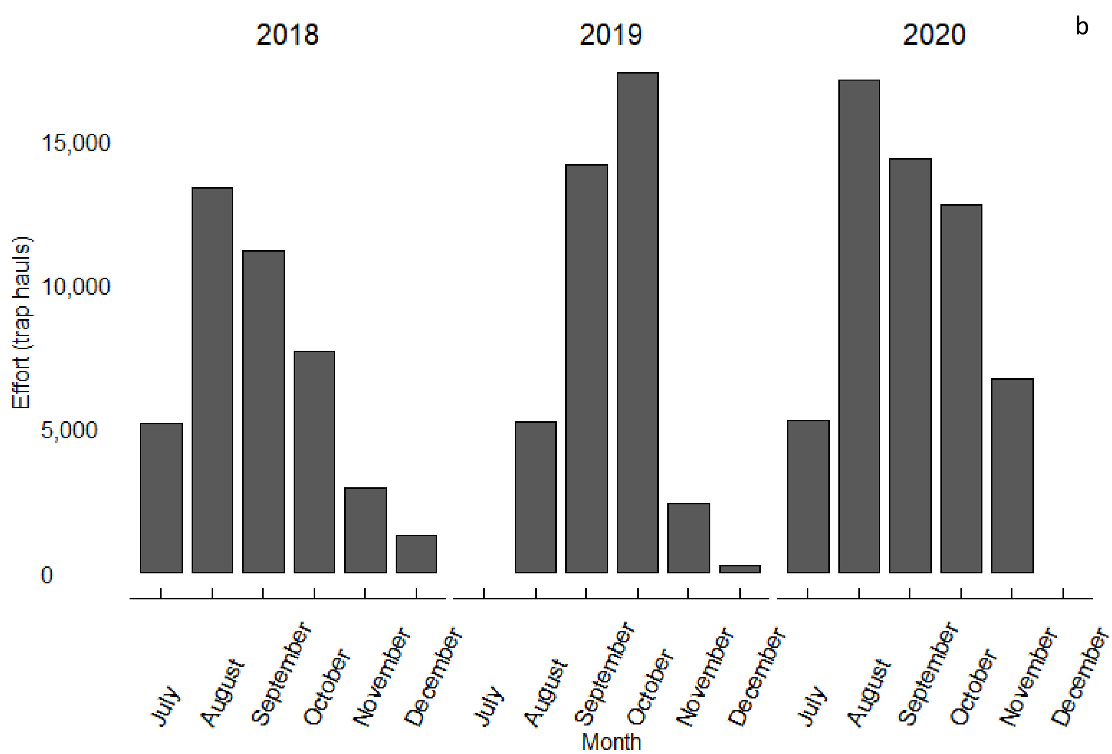


Figure 10. Monthly effort (number of traps hauled) for 4W (a) and 4Vs (b) from the exploratory Offshore Whelk fishery from 2018 to 2020.

Effort in the Whelk fishery is based on the number of traps hauled. For cases where effort information was not recorded, industry representatives provided copies of the Whelk Monitoring Document to identify missing information. In some sets (*n* = 1,219), effort could not be determined, and this information was excluded from effort and catch rate calculations. In general, effort has increased since 2015 in 4Vs with efforts doubling in 2018, driven by an increase in TAC from 350 to 700 mt and the addition of a third vessel to the Whelk fleet in 2019 (Figure 11). Spatially, effort has expanded further east (Area 2) and west (Area 3) in recent years on Banquereau, with reduced effort in Area 1 (Figure 1, Figure 12). In 4W, effort was minimal from 2012 to 2017 but increased substantially in 2018 with the addition of a second vessel to the fleet (Figure 11). In 4W, effort has been centrally localized, with very high effort on southern Middle Bank (Figure 12). This could be cause for some concern as this is double the effort required to capture the same amount in 4Vs (Figure 13, Figure 14).

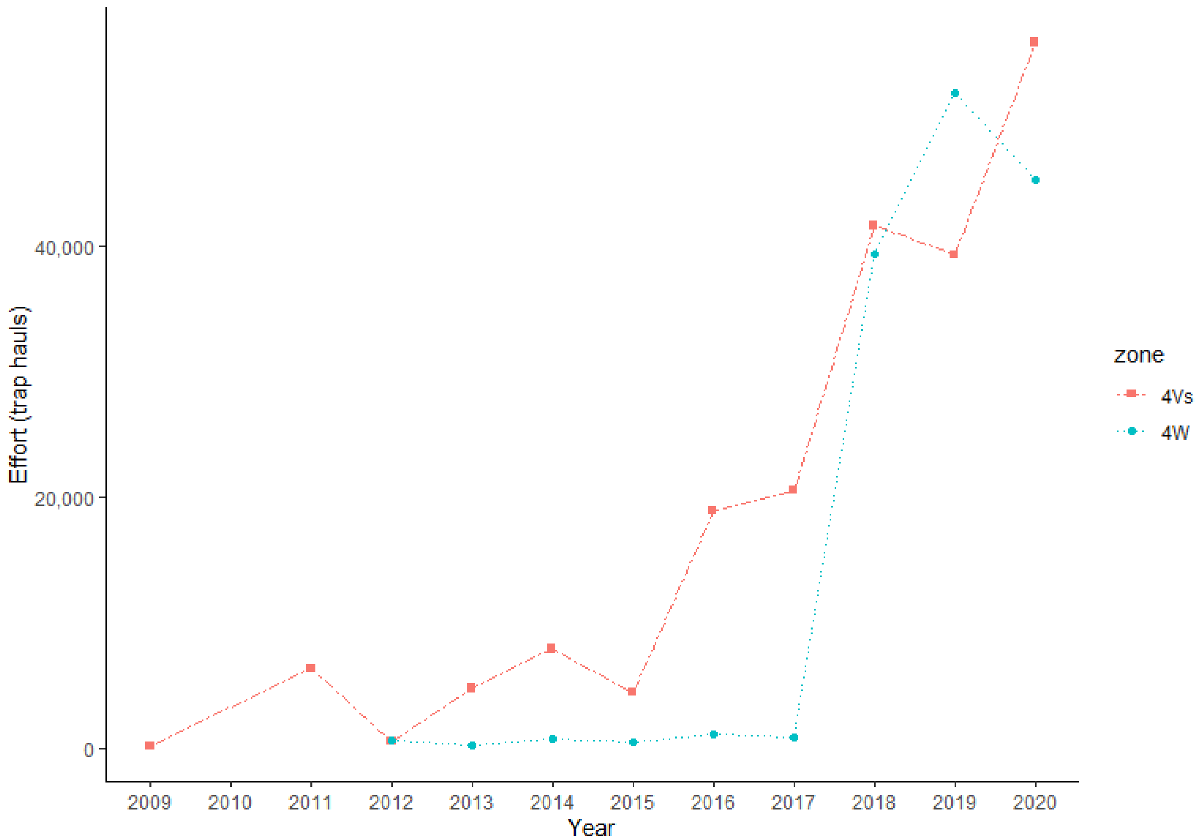


Figure 11. Exploratory Offshore Whelk fishery effort (number of traps hauled) in NAFO Divisions 4W and 4Vs.

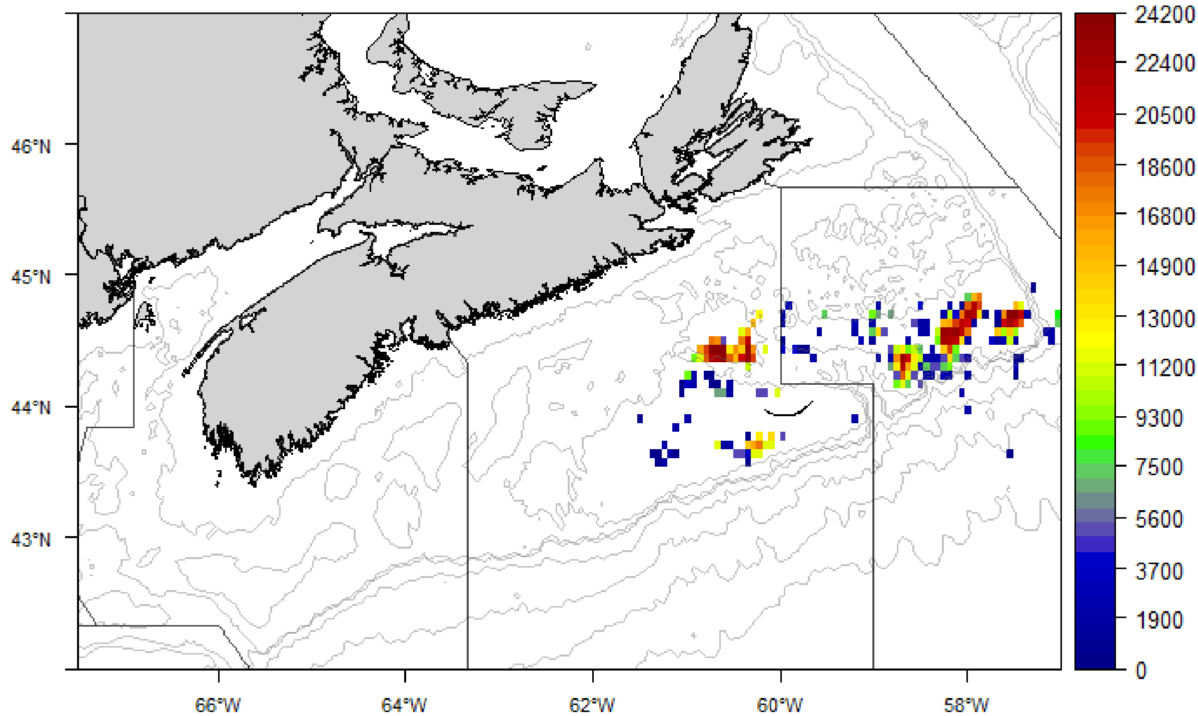


Figure 12. Spatial footprint of the effort (traps hauled using a 5 min grid) of the exploratory Offshore Whelk fishery in 4W and 4Vs from 2009 to 2020. Sets with no effort data were assumed to be 50 traps to explore spatial extent. The grey lines are depth contours and the black lines are the NAFO Division boundaries.

Catch Rates and Soak Time

Catch rates have been presented as catch per trap hauled; however, the soak time of the trap can ultimately impact this indicator and was a consideration for reporting catch rates identified in the Whelk monitoring framework (DFO 2020a). Studies on soak time of Whelk for 4Vs and 4W fishing areas, indicate that catch increases up to 48 to 72 hours, and then reaches saturation where no more catch is observed (Louisbourg Seafoods Ltd. 2019, Premium Seafoods 2019). This relationship was further explored using fishery data to determine if catch rates should be adjusted for soak time.

On the Whelk Monitoring Document, soak time in days is a required entry, although often this is not recorded or is less accurate since it is recorded at the trip level rather than for each set. For the current analysis, soak time was estimated using the date hauled and date set entries and for sets where traps were set and hauled on the same day, a 12-hour soak time was assumed.

Both non-standardized and standardized (including soak time) CPUE are included in Figures 13 and 14 for comparison. CPUE on the Scotian Shelf was greater on Banquereau compared to Middle and Sable Island Banks (Figure 15). For the 2009–2020 time series in 4Vs, non-standardized CPUE estimates increased since 2012 with CPUE stabilizing at 12 to 17 kg/trap over the last 8 years (Figure 13). In comparison, when soak time is considered, annual CPUE estimates peaked in 2015 and stabilized at a lower CPUE of approximately 10 kg/trap after 2016. For the 2012–2020 time series in 4W, CPUE was low overall and standardized CPUE estimates peaked in 2015 at approximately 4 kg/trap per day, declined in 2016 after a change in captain of the vessel, and stabilized at 3.5 to 4 kg/trap per day after 2017. Catch rates estimated from non-standardized CPUE were closer to 5 kg/trap and peaked in 2017 (Figure 13,

Figure 14). Spatially, CPUE estimates in 4W are higher on Middle Bank compared to catch on Sable Island Bank (Figure 15).

No clear relationship between CPUE and soak time (number of days in the water) was observed, potentially due to the high variability in the data (Figure 16). CPUE is standardized in the inshore Quebec Whelk fishery using a linear model with month as a factor at the set and trip level. Similar methods were explored for 4Vs and 4W. At the set level, the regression assumptions of the linear model were not met using raw and $\log_{10}$ transformed CPUE (see Figure A1). When CPUE was combined at the trip level, the regression assumptions were met but the relationship between CPUE and soak time was not significant. Similar results were observed when CPUE was analyzed for each fishing area (4W and 4Vs) and on a smaller spatial scale (e.g., A1 in 4Vs; see Figure A2). Based on these analyses there is no evidence to suggest that the inclusion of soak time influences CPUE and the exclusion of soak time simplifies the calculation of the catch rate indicator. Soak time on a finer scale (e.g., number of hours) may result in less variable data and should continue to be recorded and assessed for future monitoring of the fishery. All other reference in the document to CPUE is using the non-standardized CPUE to ensure comparability among sets.

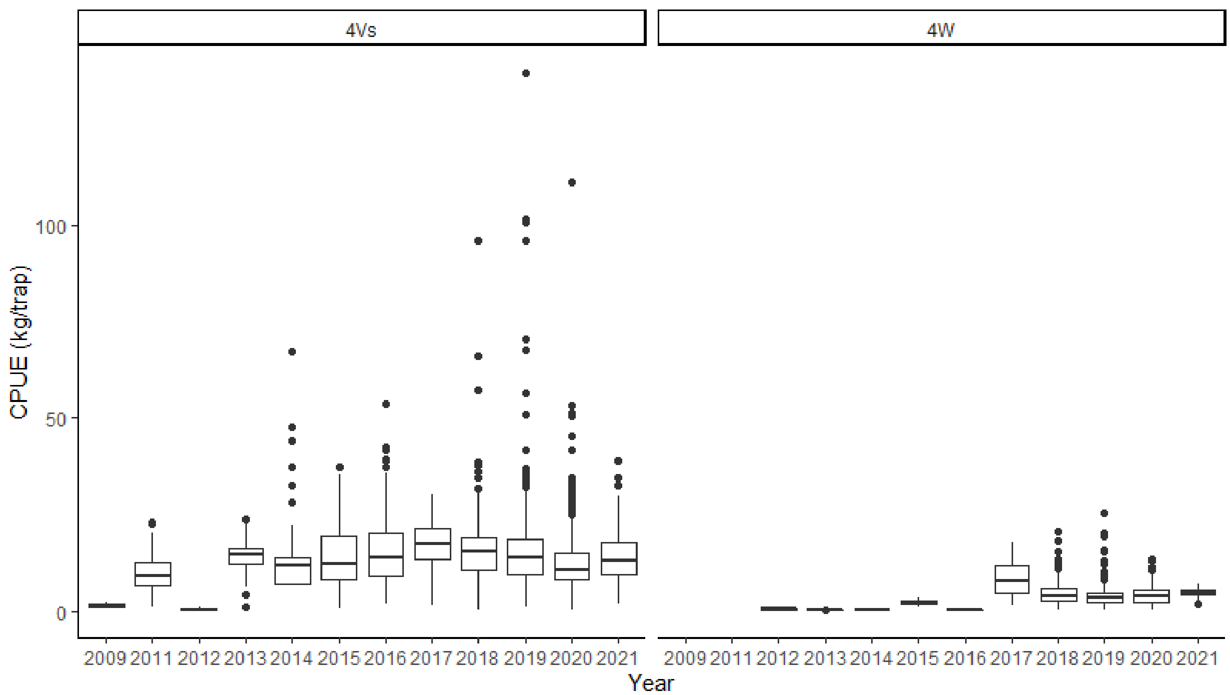


Figure 13. Boxplots of non-standardized catch-per-unit-effort (CPUE: kilograms per trap) in NAFO Divisions 4Vs (left) and 4W (right) for the exploratory Offshore Whelk fishery. The horizontal line in the boxplot represents the median value while the box depicts the interquartile range. Values that are 1.5 times the interquartile range are plotted as single solid black circles.

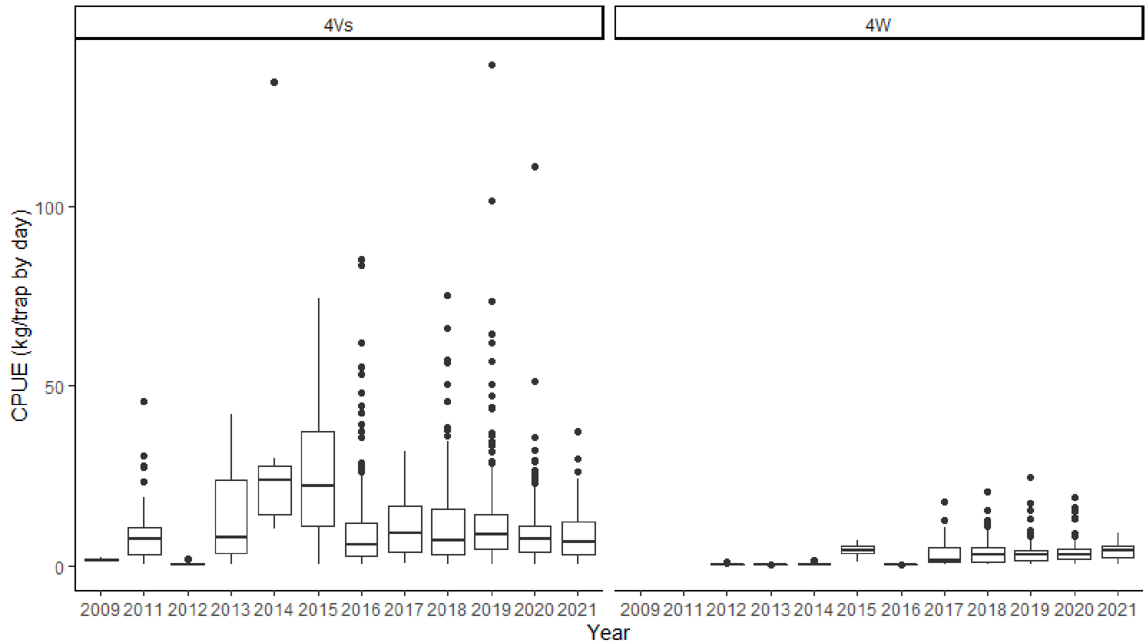


Figure 14. Boxplots of standardized catch-per-unit-effort (CPUE: kilograms/trap per day) in NAFO Divisions 4Vs (left) and 4W (right) for the exploratory Offshore Whelk fishery. The horizontal line in the boxplot represents the median value while the box depicts the interquartile range. Values that are 1.5 times the interquartile range are plotted as single solid black circles.

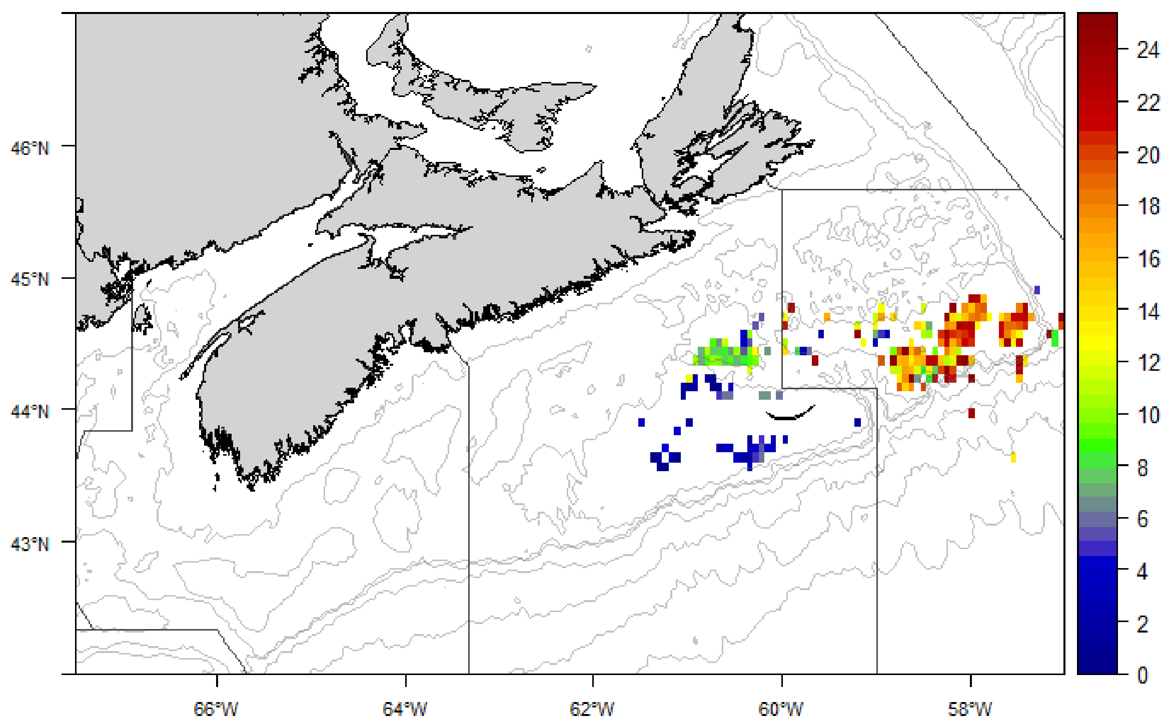


Figure 15. Spatial distribution of fishery mean catch-per-unit-effort (landings per trap haul using a 5-minute grid) of the exploratory Offshore Whelk fishery in 4W and 4Vs from 2009–2020. The grey lines are depth contours and the black lines are the NAFO Division boundaries.

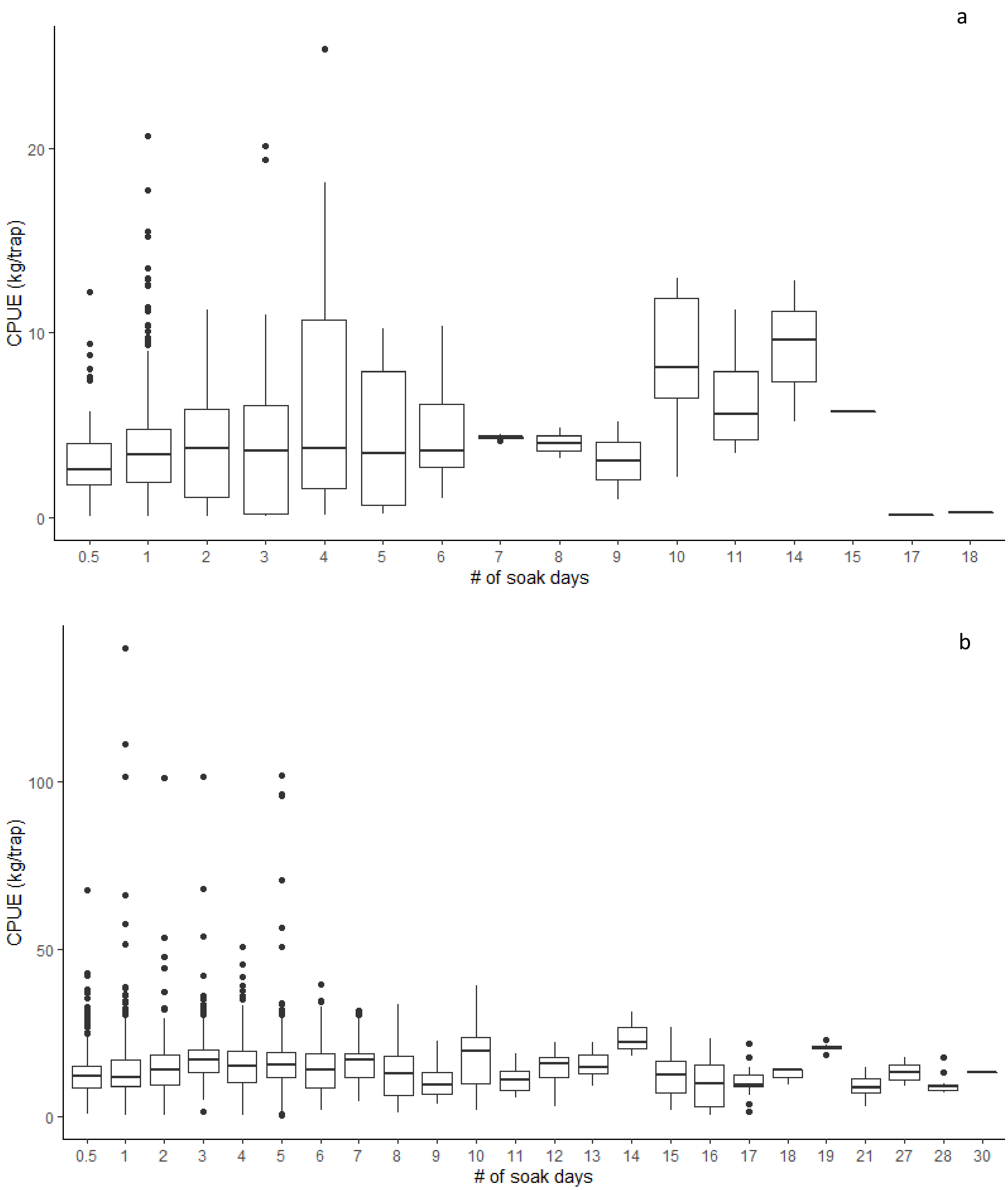


Figure 16. Boxplots of catch-per-unit-effort by number of soak days of the trap from the Offshore Whelk fishery in 4W (a) and 4Vs (b). The horizontal line in the boxplot represents the median value while the box depicts the interquartile range. Values that are 1.5 times the interquartile range are plotted as single solid black circles.

Detailed Sampling

Additional data have been collected from industry throughout the exploratory fishery in both 4W and 4Vs based on subsamples of unsorted catch. Data on size, sex, maturity, age, and parasitism were provided by industry for the inclusion in this framework, although some of the observed parameters varied throughout the time series. For Whelk, fine-scale spatial differences in size and maturity have been observed in the 4Vs fishing area (Ashfaq et al. 2019). Therefore, all analyses based on the data were divided up by three main areas for 4Vs (Figure 1). For 4W, spatial data were provided for 2019 and 2020 samples; however, ages were only available for 2019 and low sample sizes prohibited examining finer spatial scales. More data would be necessary to assess 4W by smaller defined fishing areas in the future.

In 4W, sex ratios varied by year, with males captured more often than females in the catch since 2018 (Figure 17). In 4Vs, the sex ratio was consistent among years (Figure 18a) and areas (Figure 18b), with more females observed in 2020. Females are thought to reduce feeding during the reproduction period; however, based on the timing of the fishery and the detailed sampling, the sex ratios in the traps during May and June, when females are assumed to be laying eggs, could not be explored.

Length (shell height)-weight relationships were plotted to assess outliers in the data. A total of 12 outliers were removed from further analyses, based on Studentized residuals of magnitude greater than 4. Length-weight relationships varied by year and area (Figure 19). In 4W, Whelk of similar shell length were lighter than individuals in 4Vs potentially because of thicker shells being more prominent in 4Vs areas (Figure 19e).

Size distributions by shell length and shell weight were similar by year in 4W. Smaller sized Whelk were captured more frequently in 2012 and 2018. In 2019 and 2020, lengths of the detailed samples generally ranged from 50 to 90 mm (Figure 20a). Weights were typically more variable and size frequency did not vary by sex (Figure 20b). For 4Vs, size distribution of the catch appears related to the area sampled. In 2018, smaller individuals were captured in Area 2, and Area 3 have larger Whelk than both Area 1 and Area 2 (Figure 21a; Figure 21b). Shell length and weight distributions did not differ by sex (Figure 21c). The proportion of the catch in the trap below MLS was high for both fishing areas and across years, likely because collection occurred prior to sorting onboard (Figure 20, Figure 21).

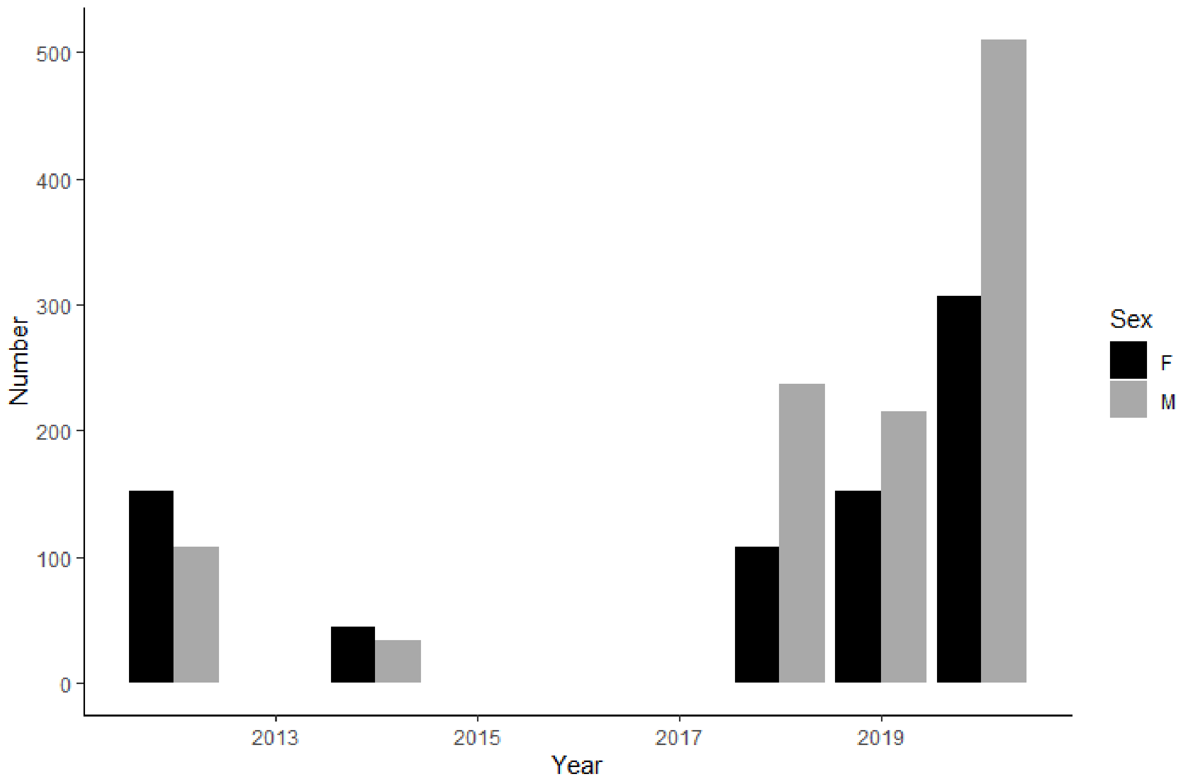


Figure 17. Sex ratios of the detailed sampling from the Whelk fishery by year in 4W fishing areas.

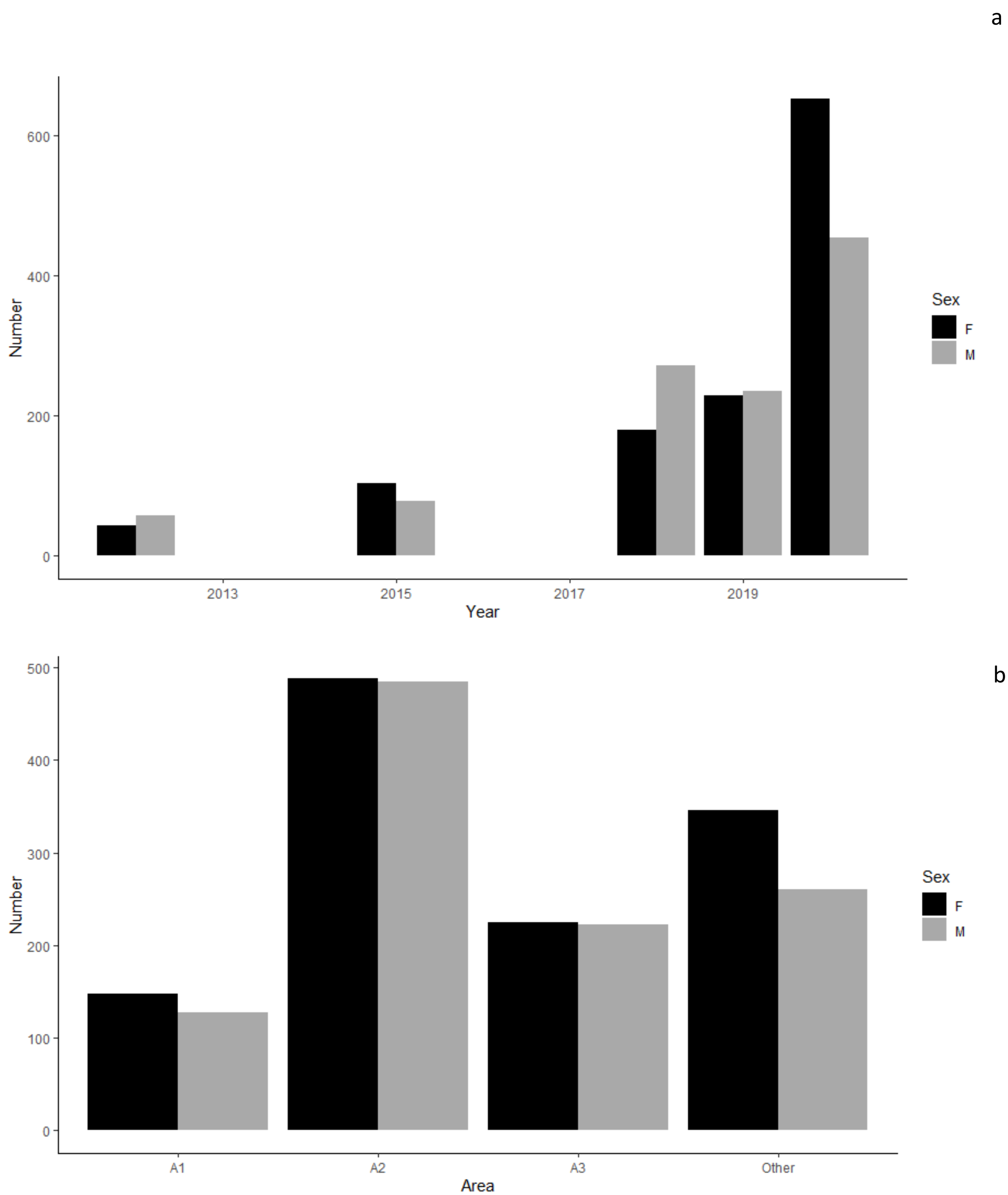


Figure 18. Sex ratios of the detailed sampling of the catch from the Whelk fishery by year (a) and area (b) in 4Vs fishing areas.

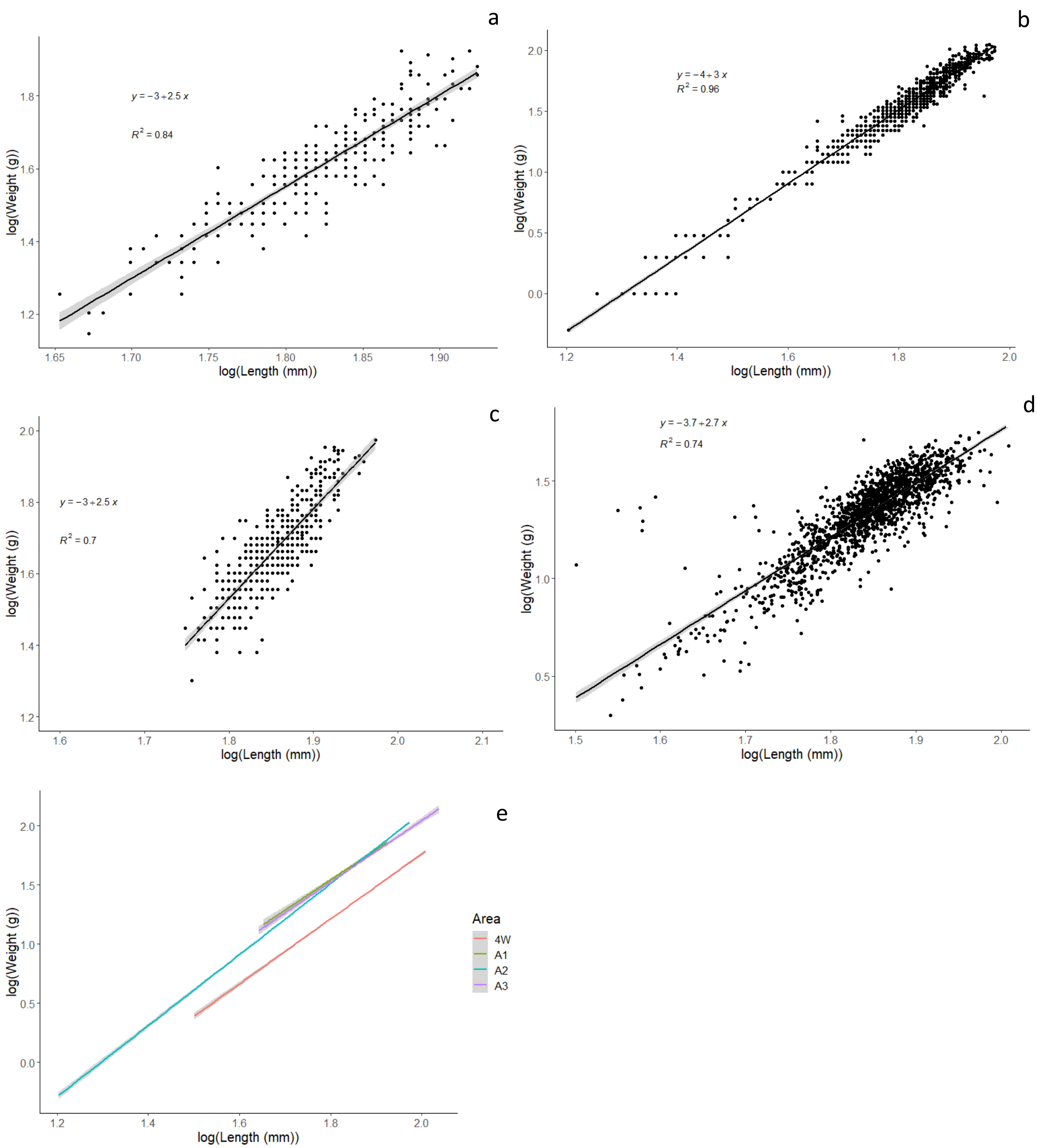


Figure 19. Length-weight relationships for detailed samples taken in Area 1 (a), Area 2 (b),and Area 3 (c) in 4Vs and all of fishing area 4W (d). The fitted regression lines are depicted in panel e to compare among areas.

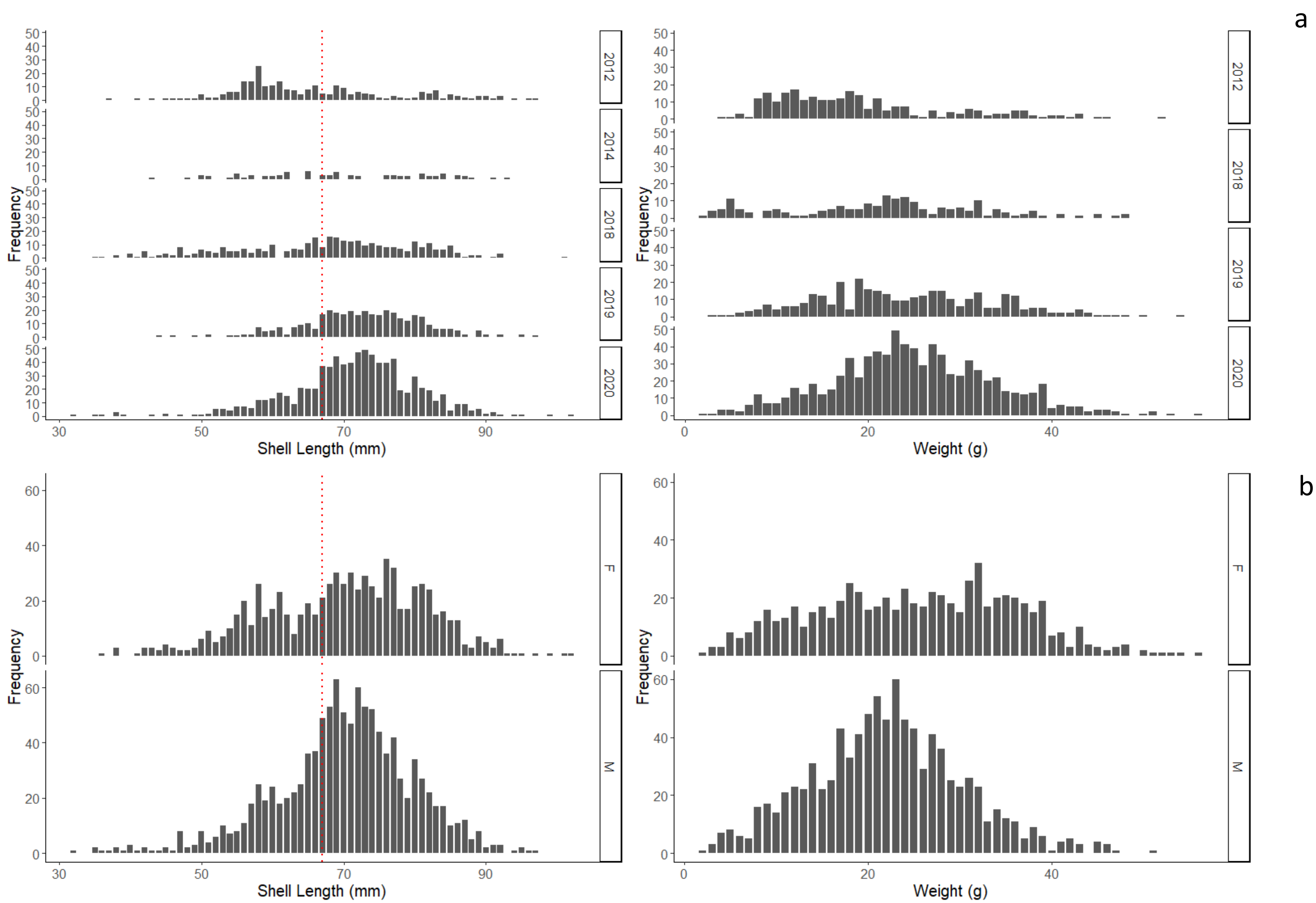


Figure 20. Shell length (left) and shell weight (right) frequencies by year (a) and sex (b) of the detailed sampling from the Whelk fishery in 4W. The red dotted vertical line represents the minimum landing size (MLS) at 67 mm.

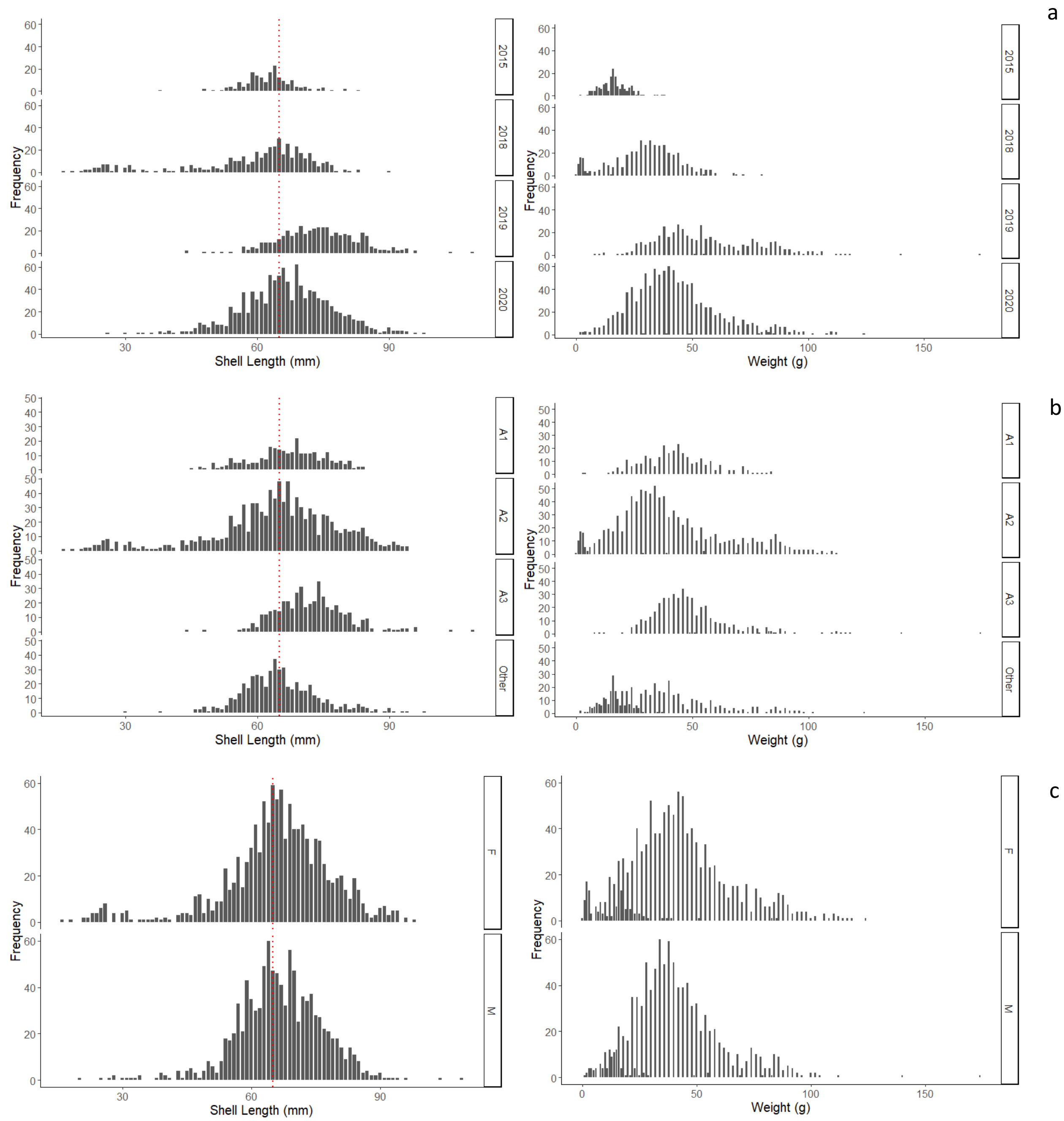


Figure 21. Shell length (left) and weight (right) frequencies of the detailed sampling from the Whelk fishery in 4Vs by year (a), area (b), and sex (c). The red vertical dotted line represents a minimum landing size (MLS) of 65 mm shell length.

Length-at-Age

Estimated ages from the detailed sampling conducted by industry ranged from 2 to 12 years old in 4W and from 2 to 16 years old in 4Vs (Figure 22, Figure 23). In 4W, the average age from the fishery was 6. The age of the catch was younger in 2012, with older and larger Whelk caught in more recent years (Figure 22). No age data were available for 2020. Limited data were available in 4Vs for 2012 and 2015 (*n* = 1 to 2 trips). In 2018, smaller and younger individuals were sampled and older individuals were captured in 2020 (Figure 23a). The average age of the catch was 8.5 years. When examined by area, Area 2 had younger Whelk in the catch (Figure 23b).

Length-at-age data were collected in 4W in 2012, 2018 and 2019 and in 4Vs in 2012, 2015, and 2018–2020. A Gompertz growth model has been used to describe growth in UK Whelk populations, assuming a sigmoidal curve with slow initial growth (Hollyman et al. 2018, Emmerson et al. 2020); however, length and age data are typically limited on juvenile Whelk. This makes it difficult to fit the lower end of the growth curve, so multiple studies have used the von Bertalanffy growth model to fit Whelk data (Fahy et al. 1995, Kideys 1996, Shelmerdine et al. 2007, Heude-Berthelin et al. 2011, Borsetti et al. 2021). A study on comparisons of von Bertalanffy and Gompertz growth models on US Whelk indicated that the von Bertalanffy typically fit the data better (Borsetti et al. 2021). Therefore, a von Bertalanffy growth equation was fit to the growth data as:

$$L = L_{inf} * (1-\exp(-k*(a-t_0)))$$

where a is the age, L_{inf} is the asymptotic size, k is the growth coefficient, and t_0 is the theoretical age at a length of 0. For both fishing areas, the t_0 parameter was not significant (p-value > 0.05) so it was removed from the model.

The growth curve was estimated using limited data after age 8 for 4W. Based on noted changes in size at small spatial scales, growth of Whelk in 4Vs was separated out by location fished. Areas were assigned to defined fishing Areas 1 to 3 and all data outside of these locations were defined as “Other” (Figure 1). Spatial data were limited in 4W so all areas were combined. Growth parameters are summarized in Table 3. For 4W, k was slightly higher than all areas in 4Vs and L_{inf} was higher than all areas in 4Vs except Area 2 (Table 3, Figure 24). The fitted growth curve was similar in 4Vs for Areas 1, 3 and “Other” areas but differed for Area 2 which exhibited slower growth up to age 8 and then faster growth for older (11+) ages (Figure 24).

Table 3. Von Bertalanffy growth parameters based on industry detailed samples from the exploratory Whelk fishery using shell length and age data collected from 2012, 2018, and 2019 in 4W and 2012, 2015, and 2018–2020 in 4Vs. The t_0 parameter fit was not significant for all areas and was removed from the growth equation. “4Vs All” is for the entire fishing area. The 95% confidence intervals are provided in parentheses. L_{inf} = asymptotic size, k = growth coefficient

Parameter	4W	4Vs-Area 1	4Vs-Area 2	4Vs-Area 3	4Vs-Other	4Vs- All
L_{inf} (mm)	83.9 (81.1–86.7)	72.6 (69.2–75.9)	89.3 (85.5–93.0)	78.9 (75.3–82.5)	73.5 (71.7–75.4)	80.3 (78.7–81.8)
k	0.31 (0.28–0.34)	0.28 (0.22–0.33)	0.16 (0.15–0.18)	0.25 (0.20–0.30)	0.30 (0.27–0.33)	0.22 (0.21–0.23)

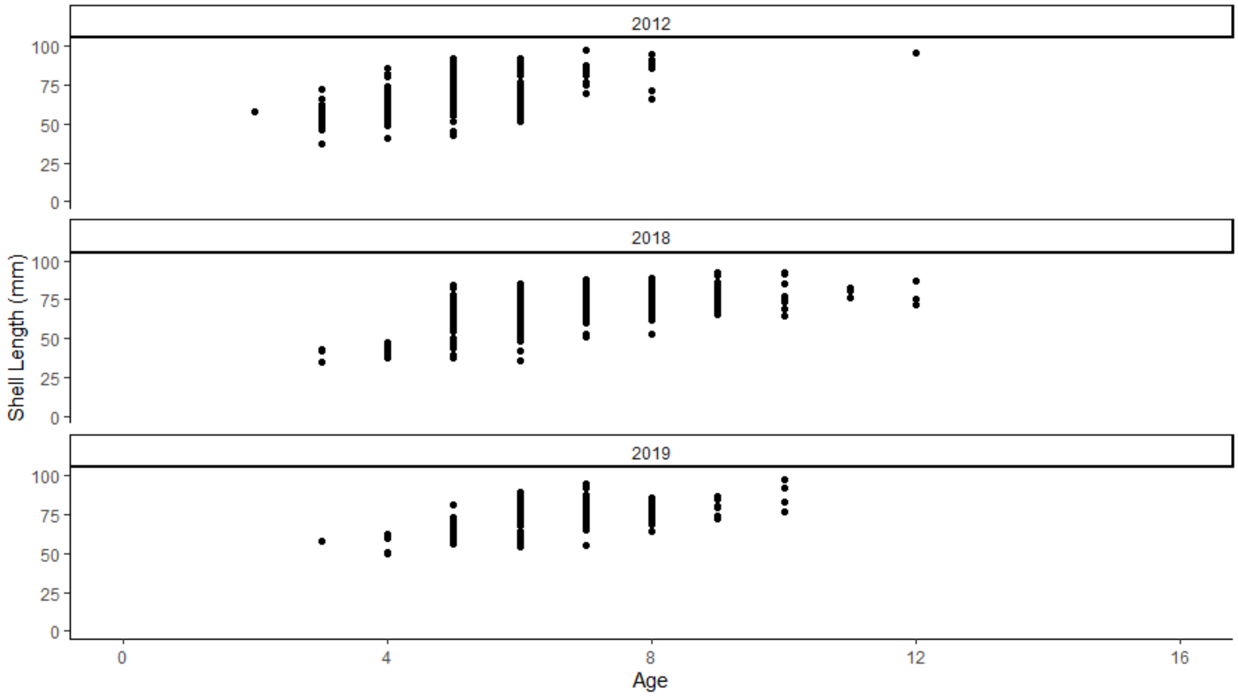


Figure 22. Length-at-age of the detailed samples from the catch from the Whelk fishery in 4W. No ageing was completed in 2020.

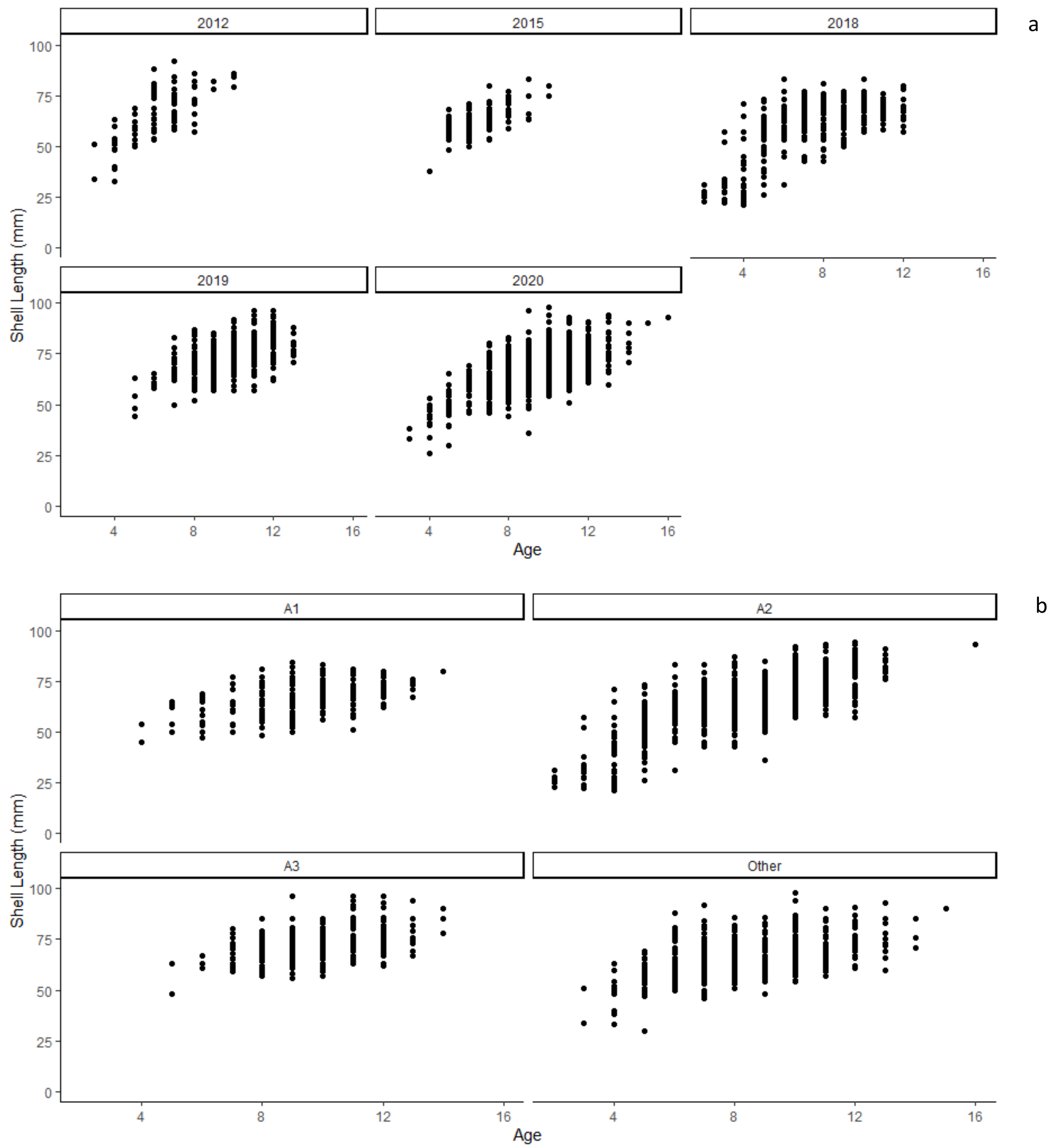


Figure 23. Length-at-age of the detailed samples from the catch from the Whelk fishery in 4Vs by year (a) and area (b). The “Other” category includes all data outside of the current defined fishing areas (Areas 1 to 3).

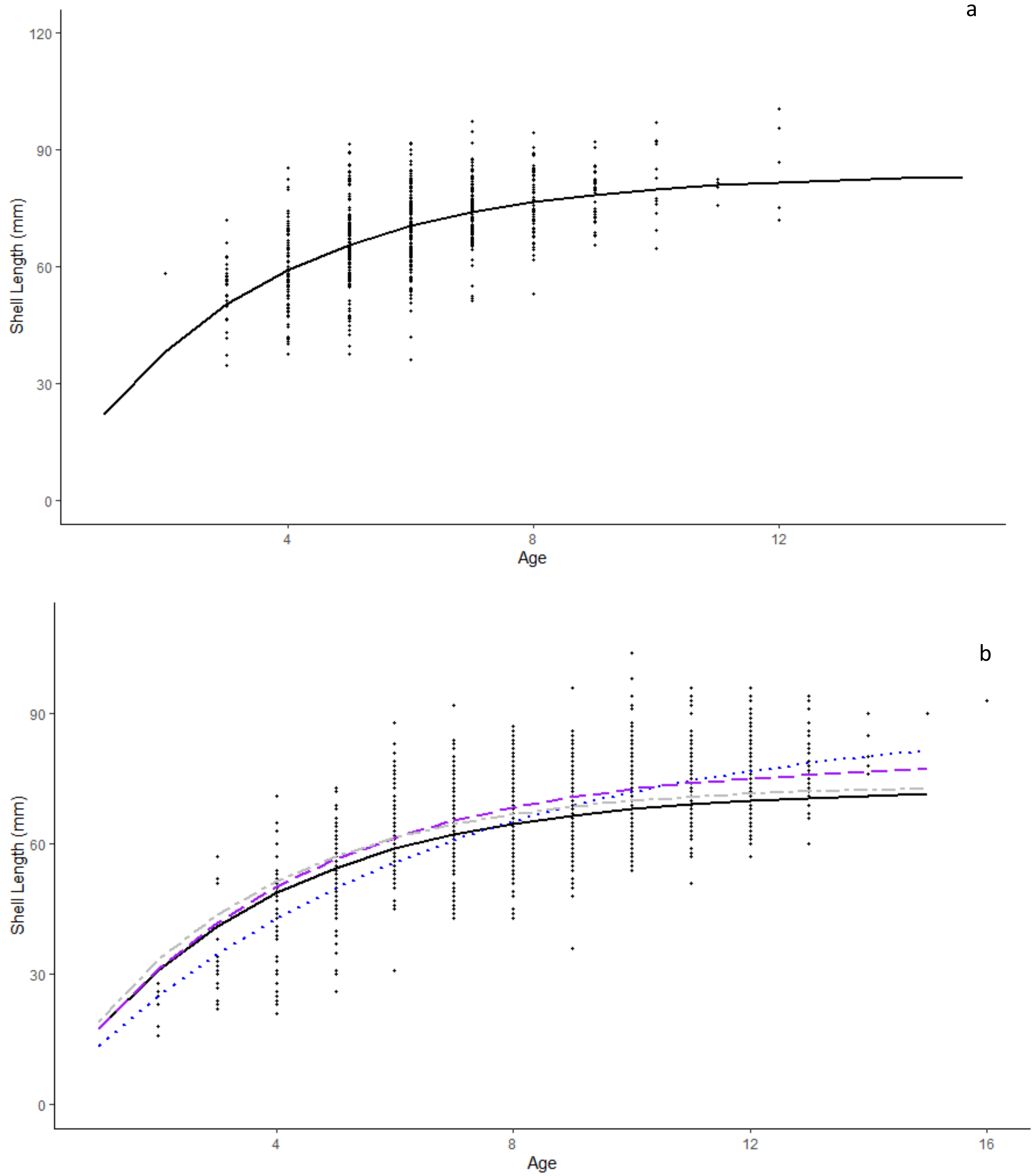


Figure 24. Von Bertalanffy growth curve based on detailed sampling of the catch from the Whelk fishery in 4W (a) and 4Vs (b) fishing areas. For 4W, only 2012, 2018, and 2019 data were used. For 4Vs the lines are based on different areas for Area 1 (solid black), Area 2 (dotted blue), Area 3 (dashed purple) and all other areas (dashed grey). The solid circles represent length-at-age data for each sample.

Maturity

Maturity from detailed samples was estimated by external examination of the Whelk gonads. For males, a Whelk was considered mature when the gonad exceeded 50% of the body cavity (Ashfaq et al. 2019) and females were classified as mature based on the thickness of the gonad (> 4 mm) or having a gonado-somatic index (GSI) of ≥ 6%. Length- and age-at-maturity were estimated using binary logistic regression models. Individuals with parasites were removed from the analysis. For 4W, length at 50% maturity (L_{50}) was estimated to be 63.8 mm shell length (Table 4, Figure 25), consistent with the study by Ashfaq et al. (2019). When separated out by sex in 4W, the L_{50} was 63.4 mm shell length for males and 64.6 mm for females. For 4Vs, length- and age-at-maturity were estimated separately by area. L_{50} estimates were similar for all areas in 4Vs, ranging from 55.3 mm to 58.5 mm shell length (Figure 26, Table 4). The L_{50} was more variable for the “Other” area which included all other fishing locations outside of the three main fishing areas. When separated out by sex in 4Vs, the L_{50} was 52.4 mm for males and 57.6 mm for females in Area 1, 53.3 mm for males and 60.7 mm for females in Area 2, and 59.2 mm for males and 58.1 for females in Area 3. Age at 50% maturity (A_{50}) was estimated to be 5.5 to 6.5 years for all areas (Figure 27, Table 4).

Table 4. Length (mm) and age (years) at 50% (L_{50} and A_{50}) and 90% (L_{90} and A_{90}) maturity of Whelk by area in 4W and 4Vs. The “Other” category includes measurements from all other areas outside of the three identified fishing areas.

Area	L_{50} (mm)	L_{90} (mm)	A_{50} (years)	A_{90} (years)
4W	63.8	80.5	5.5	8.9
4Vs-A1	55.3	68.0	6.5	10.6
4Vs-A2	57.2	71.8	6.5	11.4
4Vs-A3	58.5	68.0	6.0	9.3
4Vs-Other	56.8	69.2	5.5	11.4

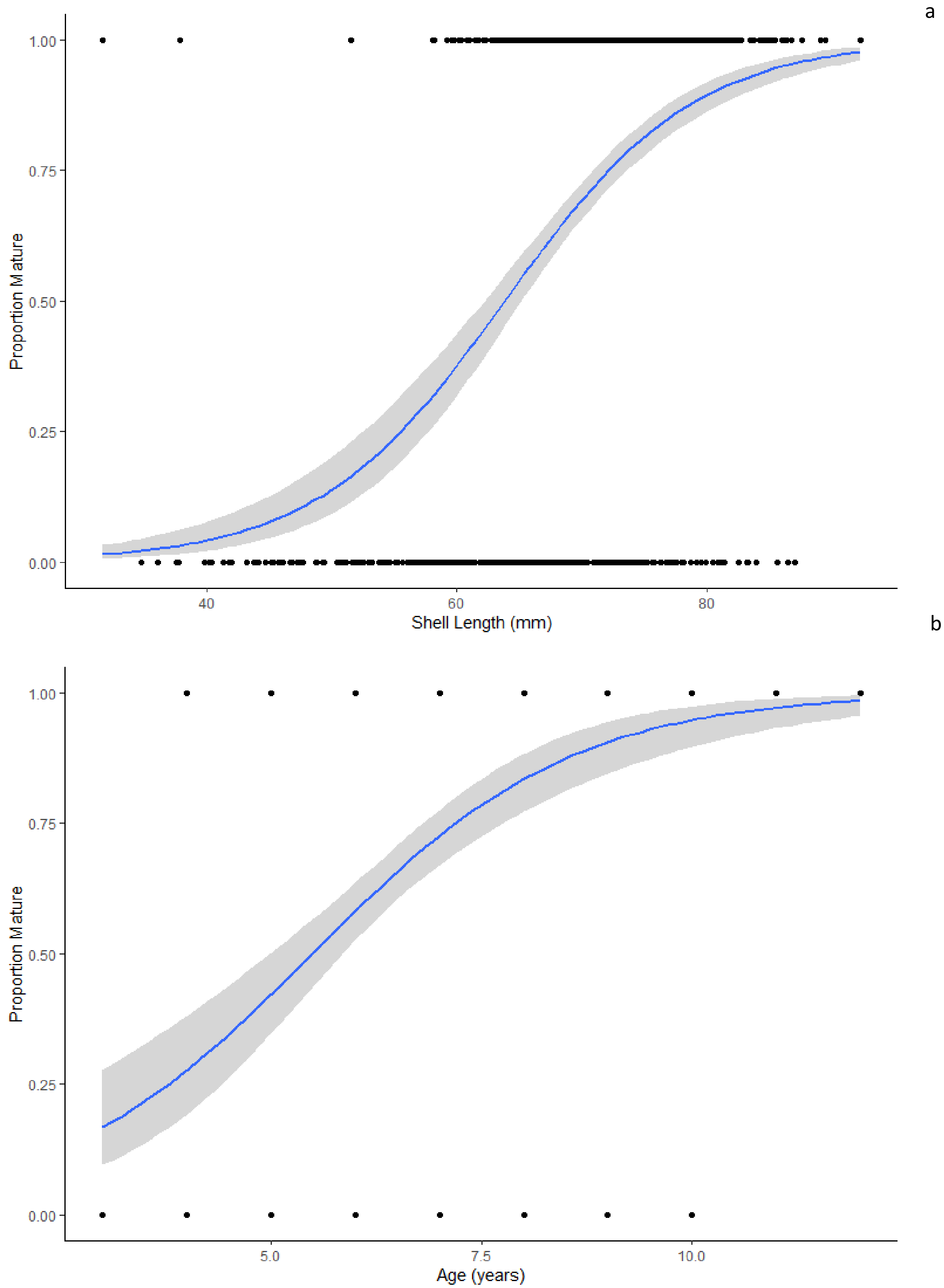


Figure 25. Maturity-at-length (a) and -age (b) curves estimated from binary logistic regression models using data from detailed sampling of the catch from the Whelk fishery in 4W. The shaded grey region is the 95% confidence interval.

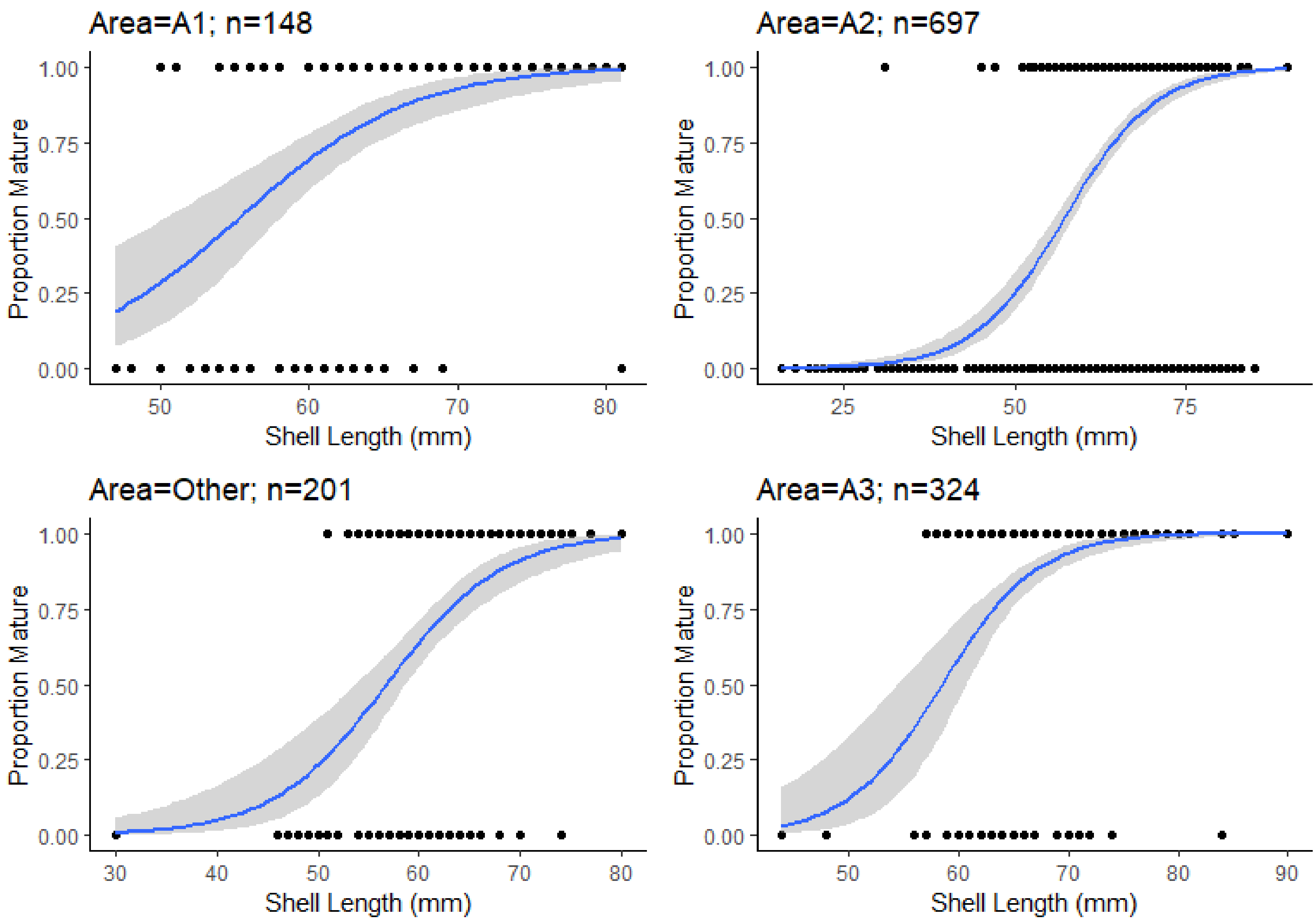


Figure 26. Maturity-at-length curves estimated from binary logistic regression models using data from detailed sampling of the catch from the Whelk fishery in 4Vs by area fished. The shaded grey region is the 95% confidence interval and the sample size is indicated by "n". The "Other" area includes all areas outside of Areas 1 to 3.

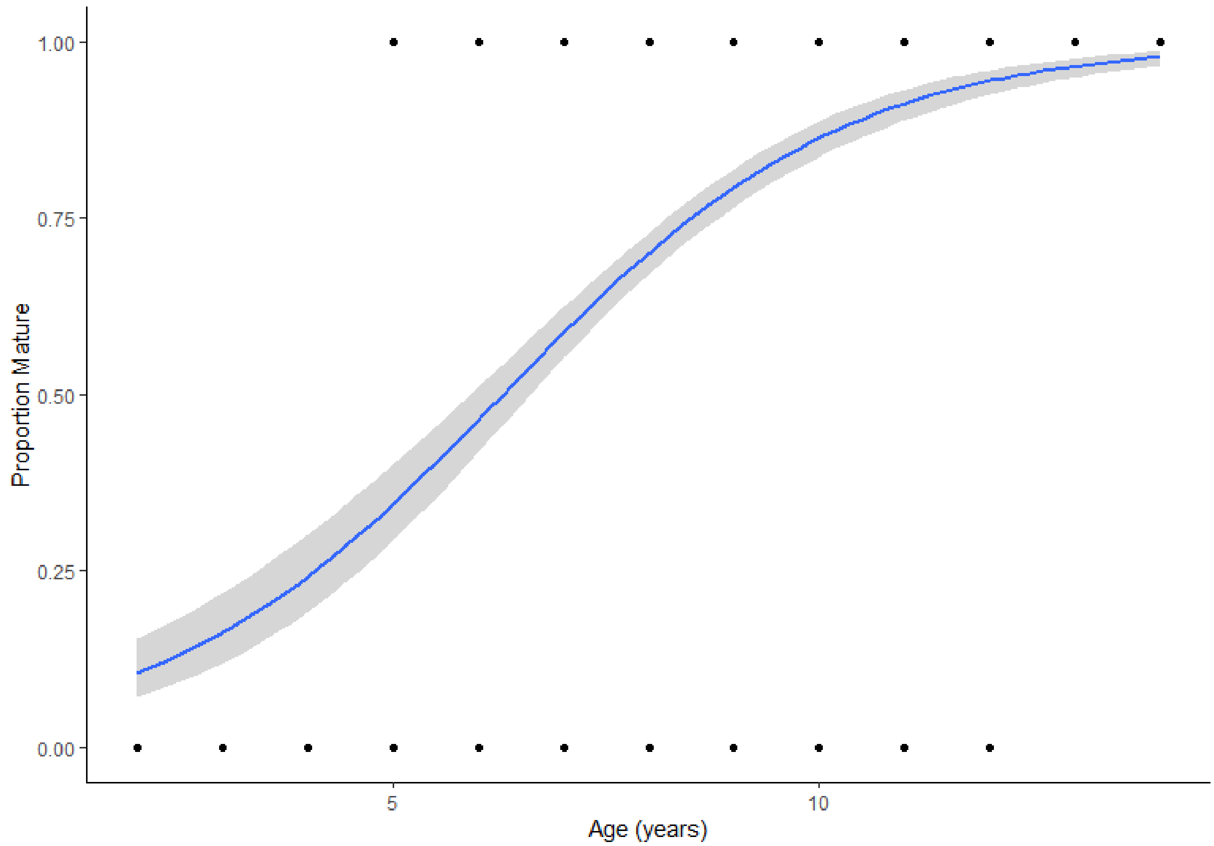


Figure 27. Maturity-at-age curve estimated from a binary logistic regression model using data from detailed sampling of the catch from the Whelk fishery in 4Vs. The grey shading is the 95% confidence interval.

Parasitism

As part of the detailed sampling, the presence or absence of parasites were recorded for both 4W and 4Vs. In 4Vs, 69% of the 856 detailed samples examined had parasites and prevalence did not differ by fishing area (Figure 28). For 4W, parasites were present in 14% of 1,716 samples. No coordinates were provided for the detailed samples in 4W so spatial analysis could not be explored.

Natural Mortality Rate

Two methods of estimating *M* based on life history traits (Then et al. 2015) were applied for Whelk. The first is based on maximum age (t_{max}):

$$M = 4.899\ t_{max}^{-0.916}$$

The second is based on the von Bertalanffy growth parameters (k and L_{inf}):

$$M = 4.118k^{0.73}L_{inf}^{-0.33}$$

M estimates ranged from 0.44 to 0.50 using the maximum age method and 0.25 to 0.40 using the growth parameter method (Table 5). These estimates are lower than the *M* estimates ranging from 0.6 to 0.85 from studies in the UK (de Vooys and van der Meer 2010; Laptikhovsky et al. 2016).

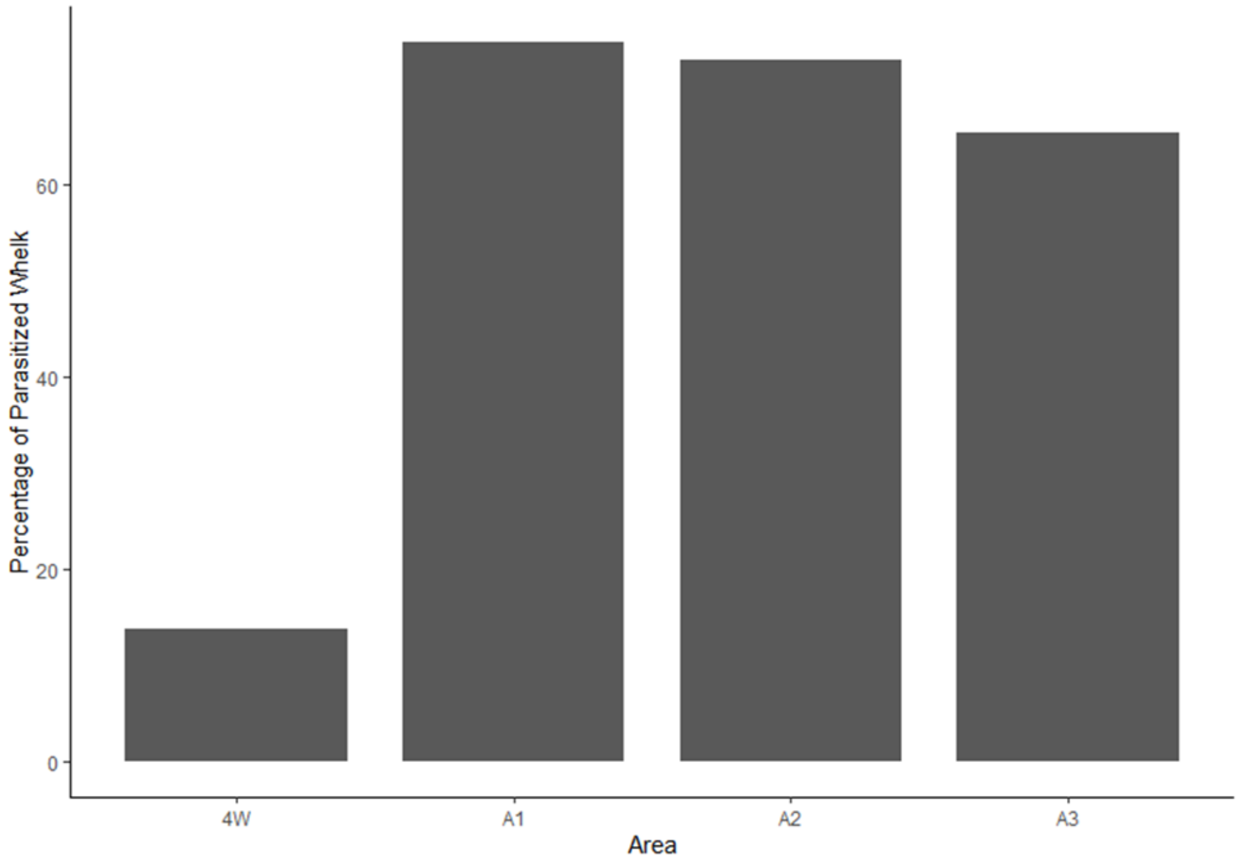


Figure 28. The percentage of parasites by fishing area based on detailed samples taken by industry for 4Vs fishing areas (A1–A3) and for 4W.

Table 5. Summary of natural mortality rate (M) estimates for Whelk in 4W and 4Vs using methods in Then et al. (2015).

Area	M (Maximum Age Method)	M (Growth Method)
4W	0.50	0.40
4Vs	0.44	0.32
4Vs-Area 1	0.47	0.39
4Vs-Area 2	0.47	0.25

INDICATORS FOR MONITORING FISHERIES

DFO has implemented a Precautionary Approach (PA) framework for the management of commercial fisheries. This PA policy manages threats of serious or irreversible harm of fisheries where there is scientific uncertainty (DFO 2009c), and encourages the development of a harvest strategy that aims to keep the removal rate moderate when the stock status is healthy, promote rebuilding when stock status is low, and ensure a low risk of serious or irreversible harm (DFO 2009c). The provisional harvest strategy in DFO's PA policy includes a Removal Reference (i.e., a harvest rate) for three stock status zones delineated by a Limit Reference Point (LRP) and an Upper Stock Reference Point (USR). The LRP is defined as the stock level below which productivity is sufficiently impaired to cause serious harm, but above a level where risk of extinction becomes a concern (DFO 2009c). Indicators for stock status are evaluated based on three zones relative to the reference points, the critical zone (below the LRP), the cautious zone (between the LRP and the USR) and the healthy zone (above the USR).

Multiple indicators of stock status and methods of estimation are evaluated here for monitoring the Whelk fishery. Indicators and candidate LRPs were estimated for each Offshore Whelk fishing area in the Maritimes Region that is regularly fished, consisting of 4W Middle Bank, and two areas in 4Vs (Area 1 and Area 2).

Catch-Based Indicators

Catch-based indicators that rely on commercial fishery data are commonly used to assess data-limited fisheries. Catch rates can be used as an indicator of biomass to monitor fishing areas; however, concerns over the sole use of fishery dependent data to monitor stock status are warranted. Catch rates are a measure of landings and effort. Effort varies by fishery but may include a time period (e.g., duration of tow, soak time), be related to the gear used (e.g., per trap, number of hooks) or include area fished (e.g., swept area of a trawl). Fishery dependent indicators such as CPUE may be impacted by changes in fishing behavior and experience, annual and seasonal variability, technological advances, and changes in environmental conditions (DFO 2009b).

Management measures used in parallel with catch rate indicators can limit the risk of overharvesting. For example, in the Quebec Whelk fishery, conservation measures have been implemented since the beginning of the fishery including the development of defined fishing areas and the introduction of a TAC, MLS, and a truncated fishing season (DFO 2009b).

B_0 proxy

Virgin biomass or unexploited biomass (B_0) is the biomass of a stock that has not yet been fished, and a proportion of B_0 is commonly used as a candidate LRP (e.g., Mace 1994, Sainsbury 2008). In data-limited fisheries, CPUE can be used as a proxy for biomass under the assumption that the two metrics are proportional to each other (DFO 2015). If information exists on resource conditions prior to or shortly after the onset of fishing, some inferences about B_0 may be possible (Gabriel and Mace 1999).

For each fishing area, the maximum annual mean CPUE in the time series was used as a proxy for B_0 and was the basis for estimating candidate LRPs. The maximum annual mean CPUE in the time series was used rather than the CPUE from the first year of fishing, based on the assumption that catch rates in early exploratory years of the fishery are not a true representation of potential catch rates (e.g., Kleisner et al. 2013).

Candidate LRPs were estimated using 20% and 30% of the B_0 proxy. The basis for establishing 20% of B_0 was reached by assuming a low to medium productivity and defining B_{MSY} as 40% of B_0, a generally accepted 'default' proxy for B_{MSY}, and setting the candidate LRP as 50% of B_{MSY} (Ministry of Fisheries 2011). Based on the uncertainties for the stock (e.g., stock structure, impacts of low population size) and to provide a buffer from new fishing pressures and ecosystem changes, a more conservative 30% B_0 proxy was also considered based on the Sainsbury (2008) guidance for setting reference points.

For both 4W and 4Vs, catch rates were estimated separately for the major fishing areas to account for known variation in life history traits among areas and observed differences in catch rates in 4W. For the 2014–2020 time series in 4W Middle Bank, the maximum mean annual CPUE (7.91 kg/trap) was observed in 2017 and was used as the proxy for B_0. Low CPUE values occurred during the first few years of exploration of the 4W area; however, CPUE stabilized from 2018 onward (Figure 29). The candidate LRPs based on the 20% and 30% B_0 proxies were 1.58 kg/trap and 2.37 kg/trap, respectively (Figure 30). CPUE in 2020 was above both candidate LRPs.

For 4Vs, the majority of fishing occurred in Area 1, with recent exploration extending to other fishing areas. For the 2011–2020 time series in 4Vs Area 1, the mean annual CPUE estimates have declined since 2017 (17.4 kg/trap), and have fluctuated between 12 to 15 kg/trap for most of the time series (Figure 31) but remained above the candidate LRPs (3.48 kg/trap, 5.22 kg/trap, Figure 32). Exploration in 4Vs Area 2 began in 2018 and CPUE has declined from a maximum annual mean of 17.0 kg/trap to 13.3 kg/trap in 2020. Based on a maximum annual mean CPUE in 2018, the candidate LRPs would be 3.40 and 5.09 kg/trap respectively for 20% and 30% B_0 proxies (Figure 33). Additional data would be required to set reference points for Area 3, which currently has only been fished for two years.

Based on the skewed distribution of the data, sensitivities were run for all areas using the maximum annual median value of the time series instead of the annual mean. The results did not differ substantially from the mean values for CPUE so were not included in this document.

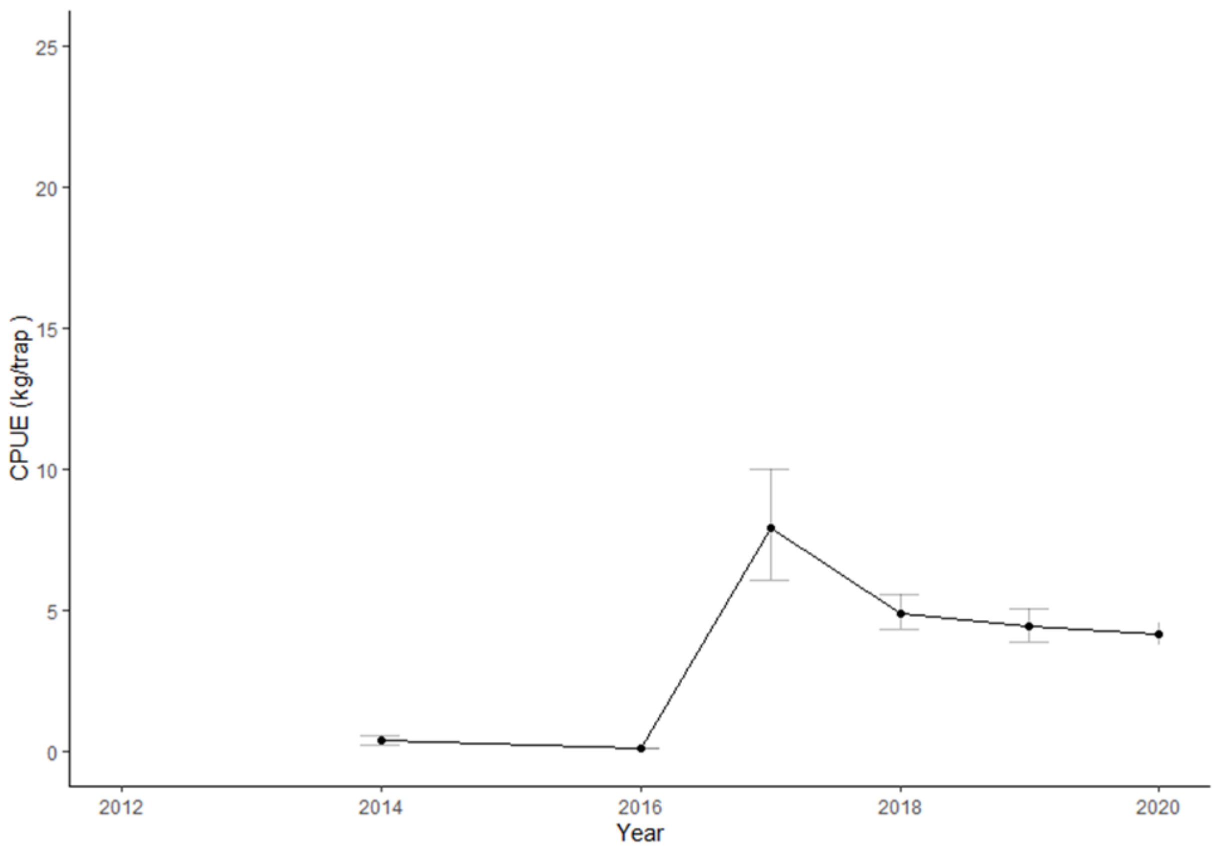


Figure 29. Mean catch-per-unit-effort (CPUE: kg/trap) for the Offshore Whelk fishery for 4W Middle Bank. The error bars represent the 95% confidence intervals for the annual mean CPUE.

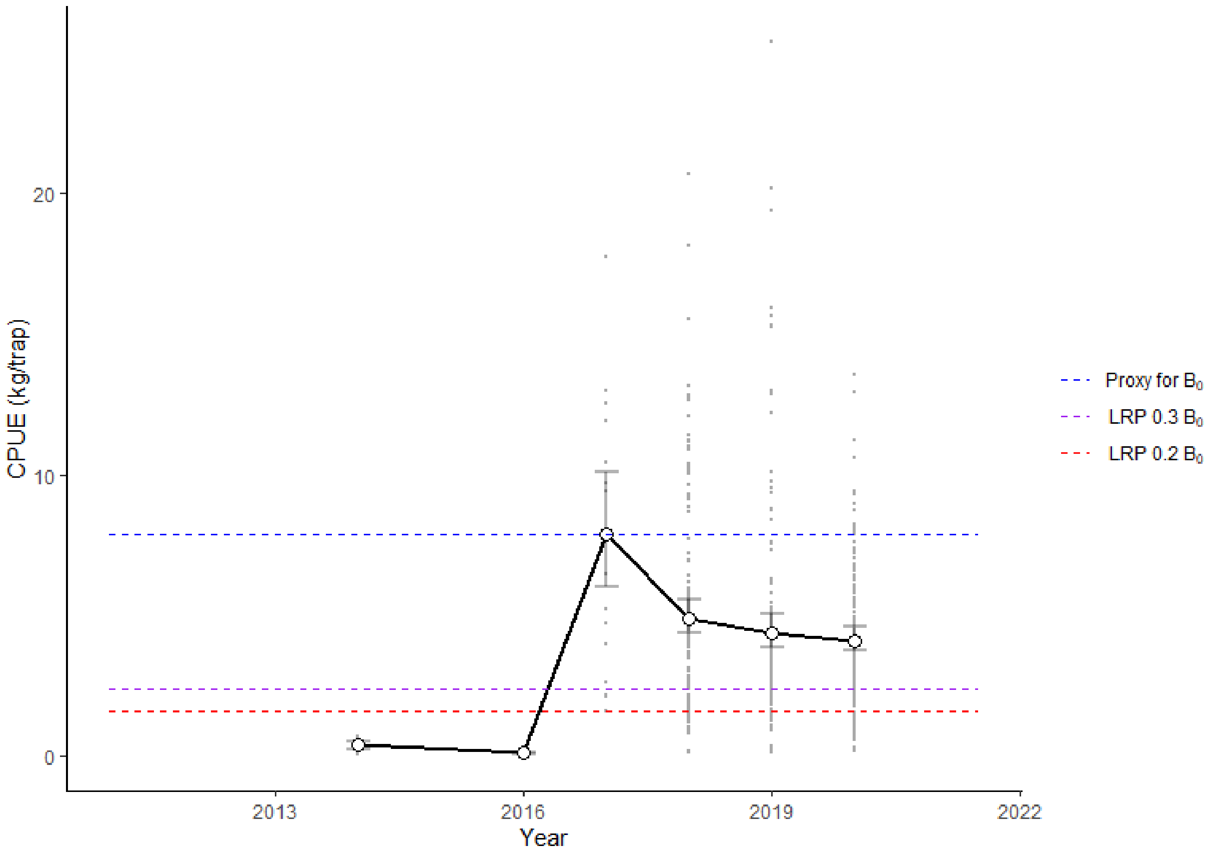


Figure 30. Mean catch-per-unit-effort (CPUE: kg/trap, open circles) for the offshore Whelk fishery for 4W Middle Bank. The error bars represent the 95% confidence intervals for the annual mean CPUE. The solid grey circles are the individual CPUE per set in each year. The blue line is a proxy for B_0 based on the maximum mean value in the time series, the red line is 20% of the B_0 proxy and the purple line is 30% of the B_0 proxy.

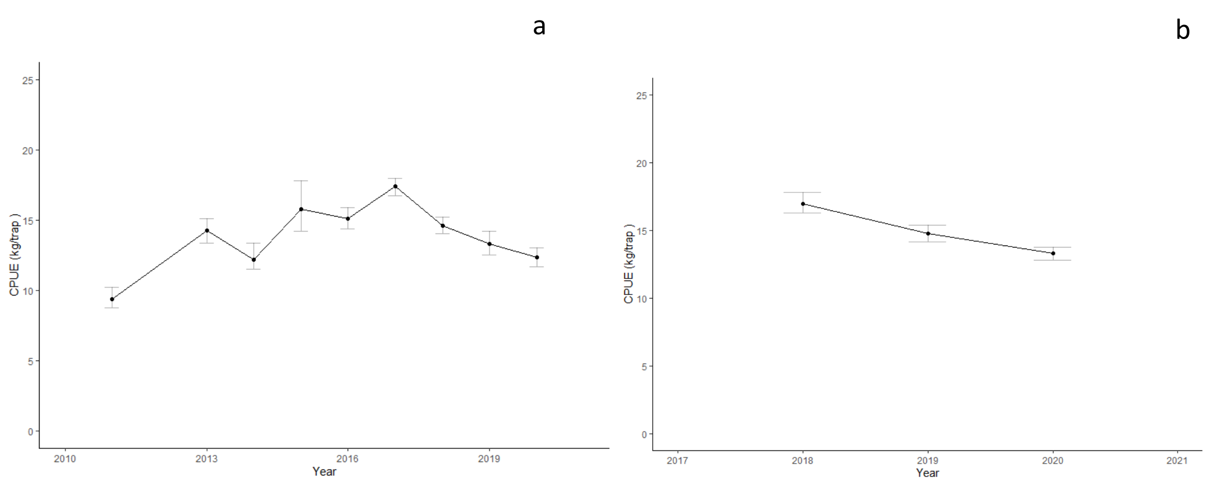


Figure 31. Mean catch-per-unit-effort (kg/trap) for the Offshore Whelk fishery in fishing Area 1 (a) and Area 2 (b) in 4Vs. The error bars represent the 95% confidence intervals for the annual mean CPUE.

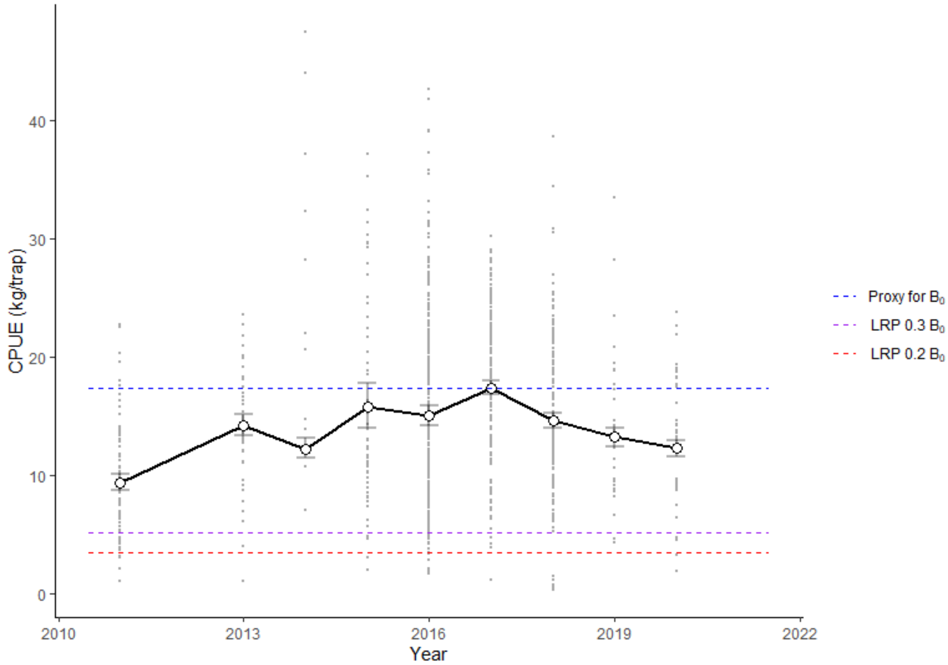


Figure 32. Mean annual catch-per-unit-effort (CPUE: kg/trap, open circles) for the Offshore Whelk fishery in fishing Area 1 in 4Vs. The error bars represent the 95% confidence interval of the annual mean CPUE. The solid grey circles are the individual CPUE per set in each year. The blue line is a proxy for B_0 based on the 2017 mean value in the time series, the red line is 20% of the B_0 proxy and the purple line is 30% of the B_0 proxy.

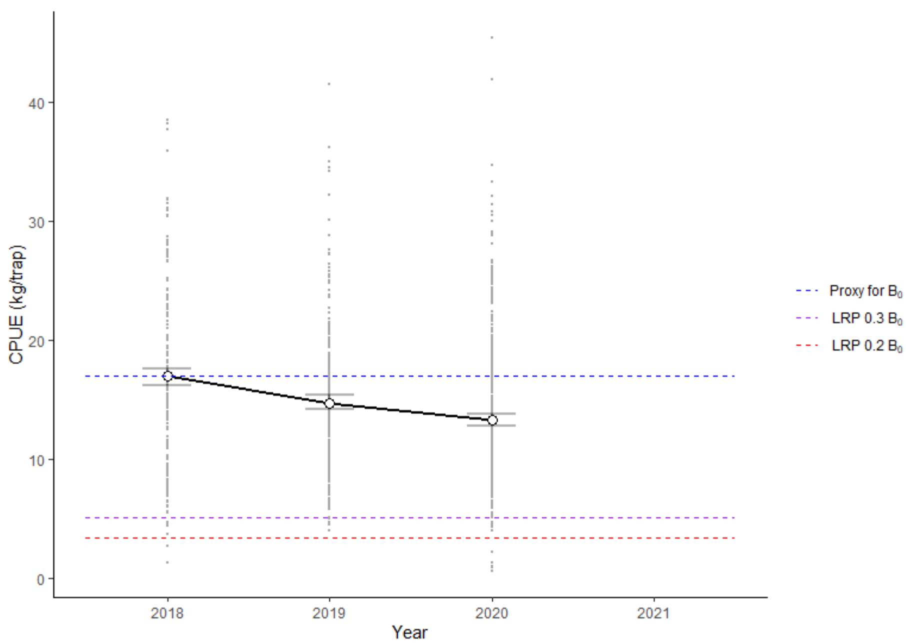


Figure 33. Mean catch-per-unit-effort (CPUE: kg/trap, open circles) for the Offshore Whelk fishery in fishing Area 2 in 4Vs. The error bars represent the 95% confidence interval of the annual mean CPUE. The solid grey circles are the individual CPUE per set in each year. The blue line is a proxy for B_0 based on the maximum mean value in the time series, the red line is 20% of the B_0 proxy and the purple line is 30% of the B_0 proxy.

Surplus Production Models

Surplus production or biomass dynamics models capture the combined effects of recruitment, growth, and natural mortality in a single parameter *r*, the intrinsic rate of population growth. In these models, fishing mortality (*F*) is the ratio of catch to exploitable biomass and relies on the theory that the predicted surplus production depends on population size. Production models require a minimum of a times series of CPUE and total catch. These models can be criticized for being overly simple since they do not account for size-structure, varying recruitment, or changes in selectivity (DFO 2015); however, they may be the best available approach when data are limited. Using these models, maximum sustainable yield (MSY) reference points can be estimated.

SPiCT

SPiCT (Surplus Production Model in Continuous Time) is based on a biomass dynamics model that internally estimates *F* and biomass (*B*) at MSY as part of the model fitting (ICES 2018). A SPiCT model was fit for both 4W and 4Vs using the "spict" package (Pederson and Berg 2021) in R (R Core Team 2022). The model was run for 4Vs and 4W using inputs for catch, effort and CPUE combined for the entire area since TAC is not based on specific fishing areas. For 4W, data were used from 2013 to 2020 in order for the model to converge. For 4Vs, data from 2016 to 2020 were used based on consistency in effort during this time period. Sensitivities were run within the model using the *check.ini.function* to confirm the model converged with different initial values. For 4Vs, 8 of 10 sensitivities converged with the data inputs and for 5 of 10 sensitivities for 4W. Model outputs for 4W suggest high variability and that the population of Whelk are in a depleted state before the start of the fishery (Figure A3) and thus this method is unlikely reflecting the true population. Model outputs from 4Vs, suggest that biomass is declining and fishing mortality in 2020 was above F_{MSY} (Figure A4).

Even though the SPiCT models converged, production models like SPiCT generally work best when there is a lot of contrast (of effort, biomass, catch rate) in the data and for a longer time-series (ICES 2018) which are missing for the Whelk exploratory fishery in both areas. The surplus production models in SPiCT use biomass indices to estimate the carrying capacity (*K*), and the *K* estimate helps scale the trends in *F* and biomass. The *K* parameter cannot be well estimated when the index time series doesn't extend back to the beginning of the fishery (Punt and Szuwalski 2012) or does not have sufficient contrast in biomasses over the time series (Ono et al. 2012). For both 4Vs and 4W, data from the 2021 fishing season were added to test the sensitivity of the model outputs to the addition of a year of data. With the addition of one year of data, the model did not converge for 4Vs providing further support that the data do not meet the assumptions of the model and results are not a true representation of the Whelk stock dynamics. Model diagnostics were evaluated and model assumptions were met and are included in the Appendix (Figure A5, Figure A6, Table A1); however, further criteria as described in Mildenberger et al. (2021) indicated that retrospective patterns existed for both fishing areas (see Figure A7) and that the magnitude of the main variance parameter was unrealistically high (> 1) for 4W.

CMSY

The catch-MSY (CMSY) method is based on a modified Shaefer's Surplus Production Model (Froese et al. 2017). CMSY estimates biomass, exploitation rate, and MSY related fisheries reference points from catch data and an estimate of the resilience of the species. Probable ranges for the maximum intrinsic rate of growth (*r*) and *K* are filtered with a Monte Carlo approach to detect 'viable' r-K pairs (Froese et al. 2017). After viable pairs are identified, a time series for biomass and fishing mortality can be estimated, as well as MSY based reference points (Andrašūnas et al. 2022). The inputs to the model uses similar catch inputs as the SPiCT model; however, CMSY requires an estimate of the assumed resilience of the stock, which can be based on a range of values for *r* or as a more general category (Low–High).

The model was run for 4Vs and 4W using catch data from 2013 to 2020. An $r = 0.57$ for Whelk was obtained from the Sealife (www.Sealifebase.org) database, which is in the "Medium" resilience category based on criteria provided in Froese et al. (2017). The outcome from the model using "Medium" resilience can be found in the Appendix for 4W and 4Vs (Figures A8–A11). For 4W and 4Vs, the models indicate that the stock status for both areas would be healthy based on B/B_{MSY} being above 1 and assuming an USR of 80% B_{MSY} (Froese et al. 2017); however, in 4W the F/F_{MSY} value since 2018 has been above 1 indicating that overfishing may be occurring.

Criticisms of the misuse of the CMSY methods have recently been highlighted in the literature (e.g., Ovando et al. 2021, 2022). The major problem with the method is the setting of priors for *r* and *K* which are highly sensitive in the CMSY model. The performance of the catch-only model is dependent on the accuracy of the priors, and these assumptions ultimately influence the stock status estimated in the model. If these values are uncertain, then the model is unlikely to be a true representation of stock status and should be interpreted cautiously (Ovando et al. 2021). Based on the unknown resilience of Whelk in the Maritimes Region, this method would not be a reliable indicator of stock status unless it was used in conjunction with other methods. In addition, for stocks that have had minimal exploitation (e.g., Exploratory fishery), the relationship between catch and biomass is less informative about the productivity of the stock and estimates of *r* are likely to be less reliable (Froese et al. 2017).

Length-Based Indicators

For data-limited stocks, the collection of size-frequency data of the catch can be an easy and relatively inexpensive way to monitor a stock. Length-based approaches include indicators of stock status that generally only allow estimation of *F*-based reference points (Pons et al. 2020). Some length-based methods do, however, provide biomass-based (e.g., Froese et al. 2018) or alternative indicators of stock status (e.g., spawning potential ratio, Hordyk et al. 2015b).

The Whelk industry currently samples length frequency data from a subsample of the catch in both NAFO Divisions. The current method of collection by industry includes discarded catch and is not representative of the retained catch required for length-based approaches to be utilized. Therefore, new sampling protocols would be required to monitor length frequencies of the landed catch so that this method could be applied in the future. Two length-based methods were explored for Whelk based on ICES (International Council for the Exploration of the Sea) guidance for data-limited stocks (ICES 2018) using the existing length frequency data collected by industry. Although the results from these approaches may not be accurate with the current data inputs (inclusion of discarded catch below the MLS), the approaches can be considered as secondary indicators for future monitoring. Recent data (2018+) were determined to be more complete (e.g., no year gaps in sampling, similar sampling completed, similar levels of fishing effort) and were used to demonstrate how the method works, understanding that the length frequencies include discard individuals below the MLS.

ICES Length-Based Approach

The traffic light approach used by ICES for length-based indicators is a system of red and green lights to categorize multiple indicators in relation to desired stock status. This approach requires the length-at-maturity (L_{mat}), asymptotic length (L_{inf}), and catch-at-length by year. Length-based indicators can be calculated by sex and by year from length frequency distributions which can then be compared to appropriate reference points related to conservation, optimal yield, and

MSY considerations (ICES 2018, Table A1). For the detailed sampling completed by industry, sex was not always recorded so the analysis was completed for both sexes combined.

Length frequency inputs were separated for Area 1 and Area 2 in 4Vs and for all of 4W for 2018 to 2020. Indicators related to these reference points are summarized based on the traffic light system in Table 6. Based on the current data collection, reference points for the conservation of larger individual Whelk, optimal yield and MSY are within the appropriate range of values (green). For some years, in both 4W and 4Vs, reference points as a measure of conservation of smaller individuals were below expected values (red), which is consistent with the samples being from unsorted catch before undersized individuals are discarded at sea (Table 6). In 2018 for 4Vs Area 2, conservation of larger Whelk was also below expected values (Table 6).

Table 6. Summary table with indications of status compared to reference points for ICES length-based method. Red shading indicates that the condition is below expected value and green indicates conditions are being met. The inputs for length frequencies includes catch that is discarded at sea to meet minimum landing size requirements; therefore, the results are for demonstrative purposes on the approach only.

	Conservation (immatures)	Conservation (immatures)	Conservation (large)	Conservation (large)	Optimal Yield	MSY
Indicator	L_c	$L_{25\%}$	$L_{max5\%}$	P_{mega}	L_{mean}	L_{mean}
Reference point	L_{mat}	L_{mat}	L_{inf}	0.3	L_{opt}	$L_{F=M}$
Expected value of ratio of indicator to reference point	> 1	> 1	> 0.8	P_{mega} > 0.3	approx. 1	> 1
4W						
2018	0.73	0.92	1.09	0.71	1.27	1.25
2019	1.06	1.10	1.09	0.93	1.38	1.08
2020	0.51	1.10	1.08	0.90	1.31	1.62
4Vs Area 1						
2018	0.94	1.08	1.07	0.94	1.31	1.10
2019	1.12	1.17	1.09	0.95	1.44	1.07
2020	1.03	1.08	1.07	0.92	1.35	1.07
4Vs Area 2						
2018	0.75	0.88	0.85	0.19	1.01	1.10
2019	1.18	1.23	1.01	0.83	1.31	1.07
2020	0.66	1.05	0.94	0.37	1.09	1.29

L_c = length at 50% of modal abundance; L_{mat} = length at maturity; $L_{25\%}$ = 25th percentile for length; $L_{max5\%}$ = Mean length of the largest 5%; P_{mega} = proportion of individuals above L_{opt} + 10% where L_{opt} = 2/3 L_{inf}; L_{mean}= mean length of individuals > L_c ; $L_{F=M}$ = ($0.75L_c + 0.25L_{inf}$); MSY = maximum sustainable yield.

Length-Based Spawning Potential Ratio Approach

The Spawning Potential Ratio (SPR) of a stock is defined as the proportion of the unfished reproductive potential left at any given level of fishing pressure (Goodyear 1993, Walters and Martell 2004) and is commonly used to set target and limit reference points for fisheries. The amount of spawn produced by a cohort with fishing will always be less than the same cohort without fishing. So SPR is a ratio between 0 and 1 and is usually expressed as a percentage. A fishing mortality that results in an SPR of 30–40% is a commonly used percentage in the literature (Babcock et al. 2018, Ministry of Fisheries 2011, Gabriel and Mace 1999) as a proxy for F_{MSY}; however, the percentage may differ depending on the productivity of the stock resulting in both under- and over-exploitation for some stocks (Zhou et al. 2019). In general, faster growing, short lived species require an SPR greater than 40% to ensure sustainability of the stock (Zhou et al. 2019).

Length-Based Spawning Potential Ratios (LBSPR) allow the stock to maintain a percentage of its maximum spawning potential, and can be used as a reference point for recruitment overfishing. LBSPR requires information on length frequencies of the catch, growth parameters, and length-at-maturity. The LBSPR method uses estimates of the ratio of *M* to the *k* parameter from the von Bertalanffy growth equation (*M/k*) to estimate the SPR from size composition data of an exploited stock. By using the life history ratio *M/k*, the LBSPR model avoids the reliance on the *M*, which, especially for exploited stocks, is difficult to estimate and the ratio is believed to vary less across species (Kenchington 2014, Prince et al. 2015). The *M/k* ratios were calculated by using the average of the *M* estimates (Table 5) and the output from the growth model (Table 3). Using the model inputs and length composition data, the LBSPR model uses maximum likelihood methods to estimate the selectivity ogive (assuming logistic selection) which is defined by the selectivity-at-length parameters (SL_{50} and SL_{95}) and *F*/*M* (fishing mortality/natural mortality rate, Pons et al. 2020). The selectivity ogive and relative fishing mortality are then used to calculate SPR (Hordyk et al. 2015a, 2015b, 2016). The *F*/*M* parameter is a proxy for F/F_{MSY} where the assumption is that a fishing mortality at MSY is assumed to be equal to *M* if recruitment is constant (Francis 1974). The estimated SPR can be used along with a target and limit SPR to estimate stock status.

The LBSPR model was explored as a potential approach using the existing length frequency dataset of unsorted catch. This approach is demonstrated herein using the 4W data; however, similar to the ICES length-based approach, the results include discarded catch and require collection of new length frequency data on the retained catch in order for the results to be interpreted. Based on the current dataset, the LBSPR model fit was comparable to the empirical length frequency inputs for 4W (Figure 34a) and the model estimated selectivity-at-length for all years indicate that the fishery catch lengths are greater than the lengths from the maturity ogive inputs (Figure 34b). The model estimated parameters are variable within and among years (Figure 35) but a Rauch-Tung-Striebel smoother function (default smoother in the LBSPR package in R; Hordyk 2021) was applied to reduce interannual variation. For the demonstration of the LBSPR approach using existing 4W data, the SL_{50} was estimated to be approximately 70 mm, had a F/M ratio below 1, and an SPR ranging from 0.76 to 0.78 (Figure 35, Table 7).

Based on a comparison of a variety of data-limited methods, the LBSPR method performed best for medium-lived species and tended to underestimate harvest rates in other scenarios (Pons et al. 2020). Since the LBSPR method relies on detecting signals of fishing mortality based on larger sized individuals in the catch composition data, fishing may not have a visible impact on the length composition until fishing mortality is very high and stocks are highly depleted (Pons et al. 2020). Thus, a length-based method should be used in conjunction with an alternative method (e.g., catch-based) to be precautionary.

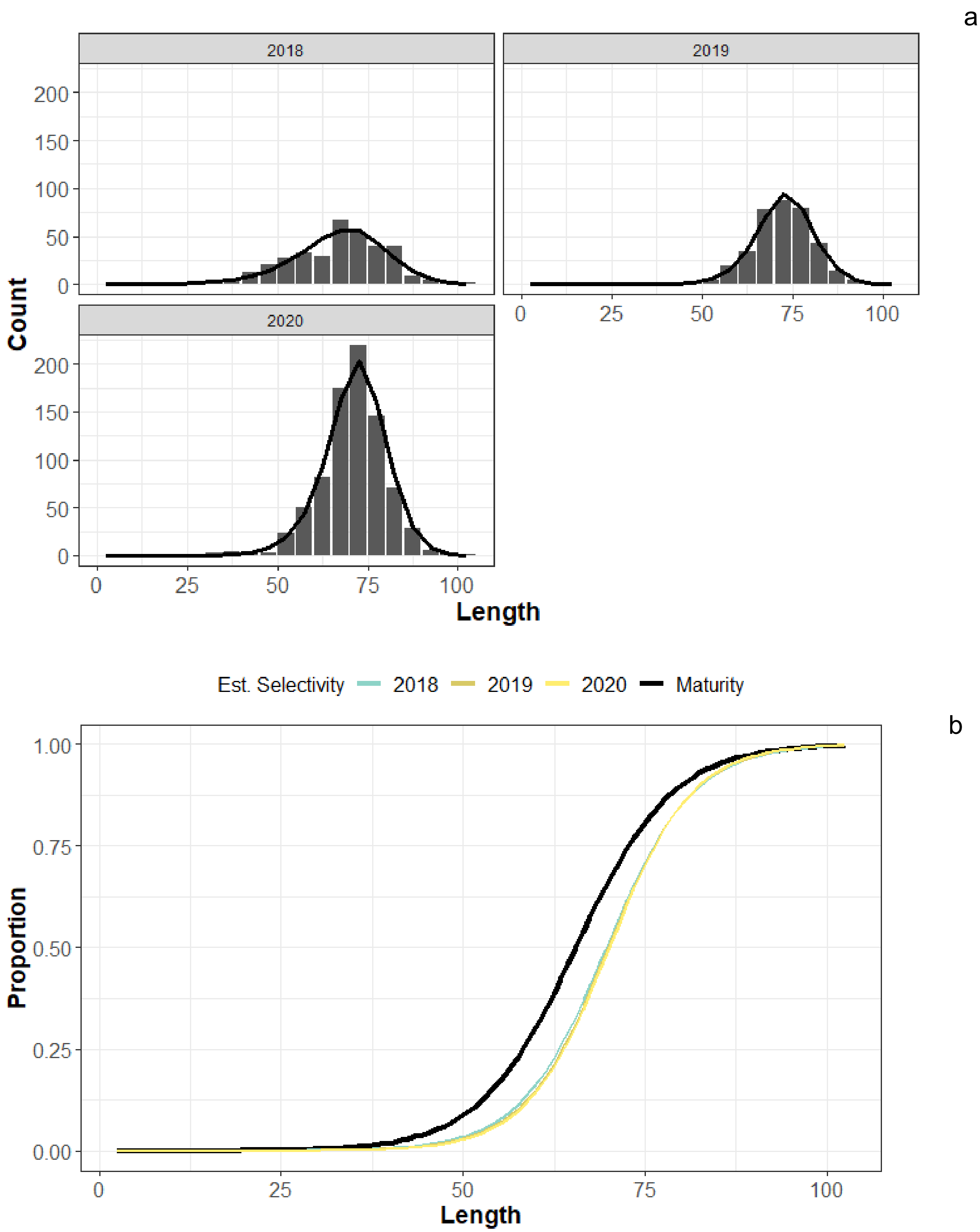


Figure 34. Length (mm) frequency distributions of the catch for 4W (a) from 2018–2020 and maturity and selectivity ogives for the length based spawning potential ratio model (b). The solid black line shows the modelled fit on the data, the bars are the raw data. Figure b is the maturity specified inputs (black) and estimated selectivity from the LBSPR model (each colour represents a different year). The inputs for length frequencies includes catch that is discarded at sea to meet minimum landing size requirements therefore the results are for demonstrative purposes on the approach only.

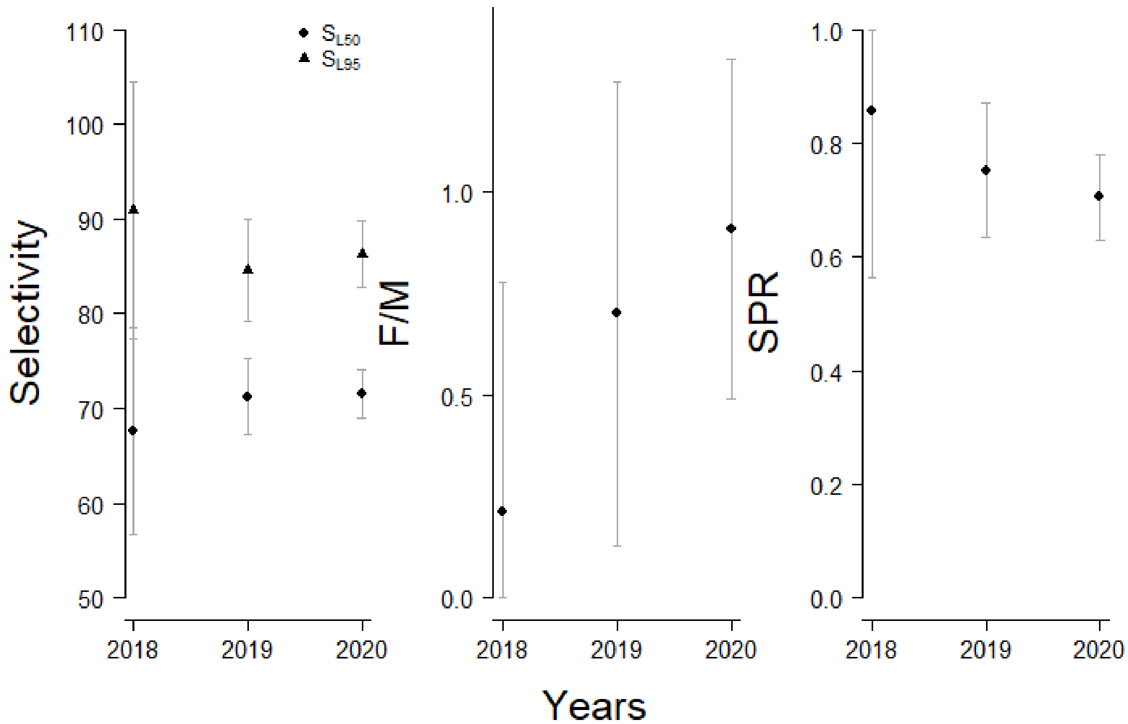


Figure 35. Model estimates of selectivity, fishing and natural mortality (F/M) ratio and spawning potential ratio (SPR) from the LBSPR model for 4W. The average is indicated by black circles with 95% confidence intervals. SL_{50} and SL_{95} are the 50% and 95% selectivity at length from the fishery. The inputs for length frequencies includes catch that is discarded at sea to meet minimum landing size requirements therefore the results are for demonstrative purposes on the approach only.

Table 7. Summary of modelled parameters with the Rauch-Tung-Striebel smoother function applied using the LBSPR package. SL_{50} is the length at 50% selectivity from the fishery; SL_{95} is length at 95% selectivity from the fishery; F/M is the fishing and natural mortality ratio and SPR is the estimated spawning potential ratio. The inputs for length frequencies includes catch that is discarded at sea to meet minimum landing size requirements therefore the results are for demonstrative purposes on the approach only.

Area	Year	SL_{50}	SL_{95}	F/M	SPR
4W	2018	69.7	87.2	0.57	0.78
4W	2019	70.0	86.9	0.61	0.77
4W	2020	70.1	86.8	0.64	0.76

SUMMARY OF CANDIDATE INDICATORS OF STOCK STATUS

Several methods to estimate stock status for a commercial Whelk fishery were explored using fishery dependent data from logbooks and from detailed samples from industry. Catch-based methods included using CPUE, and two methods based on surplus production models. Both the CPUE and the CMSY model came up with plausible outcomes based on our knowledge of the fishery; however, in the case of CMSY, only catch data are used and there are assumed priors in the model that can influence the model outcome. For the CPUE based indicator, it is assumed that CPUE is proportional to biomass and there is a potential for bias related to "hyperstability", where CPUE remains stable while abundance is declining, leading to the overestimation of biomass and underestimation of fishing mortality (Quinn and Deriso 1999, Harley et al. 2001). This typically can occur when a fishery expands into new fishing areas or depths (Morato et al. 2006, Kleisner et al. 2013) and these new catches mask the overall decline in the population. Based on this, spatial management by fishing area may be essential for a commercial fishery to limit the impacts of hyperstability. For the SPiCT model, 50% of the sensitivities for 4W resulted in no convergence of the model and the model outcome was highly variable and not informative. For 4Vs, the sensitivities and model outputs were more promising; however, based on the model predictions the biomass of Whelk would be in a depleted state under current TAC and fishing pressures by 2021. An additional year of data was added to assess model predictions for 2021 and based on the new data, the model did not converge, suggesting that more contrast in the data or an extended time period would be required before this method could be utilized to monitor a Whelk fishery (Table 8).

New sampling protocols would need to be developed to use length-based indicators for future monitoring. The collection will require a random sample of the landed catch instead of the current approach that includes discarded catch below the MLS. The length-based approach could be useful as a secondary indicator for monitoring the fishery. Length-based methods (ICES length-based indicators and LBSPR) offered information related to the conservation of Whelk, by assessing the length frequency of the catch. The ICES length-based method can inform on a variety of objectives with built in reference points related to conservation of immature and large individuals in the catch, yield, and F_{MSY} that can be used in a traffic light approach and integrated to provide an overall indicator of stock status. For the LBSPR method, the model estimates a proxy for F_{MSY} and % SPR. These approaches do not consider any catch and effort information and inform solely based on the length frequency of the catch and input parameters on growth and maturity. It would be important, therefore, to use it along with a catch-based method (Table 8). Detailed information on the considered models and their assumptions can be found in Table A1.

Table 8. *A summary of the multiple approaches explored to monitor an offshore Whelk fishery in 4Vs and 4W. A √ indicates a positive result and the X indicates a negative result.*

Method	Candidate Reference Points	Assumptions Met	Plausible Results	Consideration for Monitoring	Comments
CPUE Indicators	% B_0 proxy	√	√	√	Maximum of the average or median in the time series
SPiCT	% of B_{MSY} and F_{MSY}	√	X	X	High variability in the output and results indicate a depleted state before fishing. Could be considered with a longer time series where more contrast would exist in the data.
CMSY	% of B_{MSY} and F_{MSY}	√	√	X	Due to the uncertainty in the priors, this method is not reliable.
ICES Length-based	Conservation, optimal yield, and MSY	√	√	√	Doesn't take into consideration catch or effort information and could be used as a secondary indicator with catch-based option. This would require new sampling of length frequency of the retained catch.
Length-based SPR (LBSPR)	% SPR and *F*/*M* ratio	√	√	√	Short time series for constant fishing effort and variability high within and among years. Model has internal assumptions on a stock recruit relationship which is unknown. This would require new sampling of length frequency of the retained catch.

B_{MSY} = Biomass at maximum sustainable yield (MSY), F_{MSY} = Fishing Mortality at maximum sustainable yield, CPUE = Catch-per-unit-effort, SPiCT = surplus production in continuous time, CMSY = Catch-MSY Monte Carlo method for estimating *r*, *k*, MSY, biomass and exploitation, ICES = International Council for the Exploration of the Sea, SPR= spawning potential ratio, *M* = natural mortality.

ECOSYSTEM CONSIDERATIONS

Invertebrates play a vital role in the trophic structure, and functioning of a marine ecosystem. Harvest of lower-level trophic species may impact the target organism directly and the productivity of other higher trophic level species (Anderson et al. 2011, Eddy et al. 2015). Typically species higher in relative abundance and connectivity, or exhibiting a keystone role, will cause more ecosystem impacts than other species when harvested (Eddy et al. 2015), suggesting that the removal of Whelk may have minimal impacts. Overexploitation of more sessile species like Whelk, could allow for a change in community structure and potentially make an ecosystem more susceptible to colonization by both native and invasive species. Climate-induced range shifts are expected to be common in marine ecosystems where expanded ranges (e.g., latitudinal, depth) of species can also lead to changes in community structure (Chen et al. 2011, Wallingford and Sorte 2022).

Warming temperatures have been identified as a concern for invertebrate communities, especially organisms such as Whelk, which have limited mobility and are dependent on calcium carbonate for their shell composition (Borsetti et al. 2021). For some populations in the USA and Irish Sea, seasonal increases in water temperatures have had positive impacts on the growth of young Whelk, while negatively impacting older Whelk growth (Borsetti et al. 2021, Emmerson et al. 2020). Although, annual fluctuations in temperature may benefit Whelk in the short-term, long-term changes may ultimately impact spawning (Borsetti et al. 2020). As annual temperatures during spawning increase, the number of eggs per capsule volume also typically increases (Thatje et al. 2019). Individual variability in response to temperature are also likely to play a significant role in recruitment, although further studies are necessary to investigate the level of variability exhibited in populations of Whelk (Thatje et al. 2019).

Annual monitoring of temperature is conducted on the Scotian Shelf as part of the Atlantic Zonal Monitoring Program (AZMP). Bottom temperature data were obtained using derived annual broad scale tables from the *azmpdata* package in R (2022), which are based on information collected in July. There are no detailed monitoring stations specifically on Banquereau and Middle Bank so broad data were used to explore temperature differences. Although annual fluctuations occur regularly in sea floor temperatures, in general, temperatures were higher across the time series in 4W compared to 4Vs (Figure 36). These higher temperatures coincide with faster growth and overall larger size of Whelk seen in 4W compared to 4Vs. Both areas exhibit the optimal temperature range (2 to 10 ˚C) for successful reproduction and egg development.

In addition to the removal of the species from a fishery, there may also be indirect impacts of fishing including entanglement, ghost gear, and habitat destruction. Migration of vulnerable species may cause an entanglement risk for trap fisheries. DFO has recently implemented fishery specific colored rope markings to monitor entanglements of endangered Right Whales (*Eubalaena glacialis*) in Eastern Canada (DFO 2020b). On the US East Coast, one of 30 Humpback Whale entanglements involved conch or Whelk traps (Johnson et al. 2005). A study found that eight of 91 documented interactions between fishing gear and Leatherback Sea Turtle (*Dermochelys coriacea*) in Atlantic Canada involved Whelk gear (Hamelin et al. 2017). The impacts of ghost gear from trap fisheries is not well documented; however, Whelk pots are fitted with biodegradable panels to prevent ghost fishing (Wilcox 2023).

Limited information is available about physical habitat damage by traps in Canada, although it is assumed to be less than mobile fishing gears. As Whelk traps are often deployed in strings similar to American Lobster (*Homarus americanus*) traps and retrieved in a similar way, the contact rate for Whelk traps might increase when the traps are hauled, causing potential damage to corals, bryozoans, and other epifauna if they are present (Schweitzer et al. 2018).

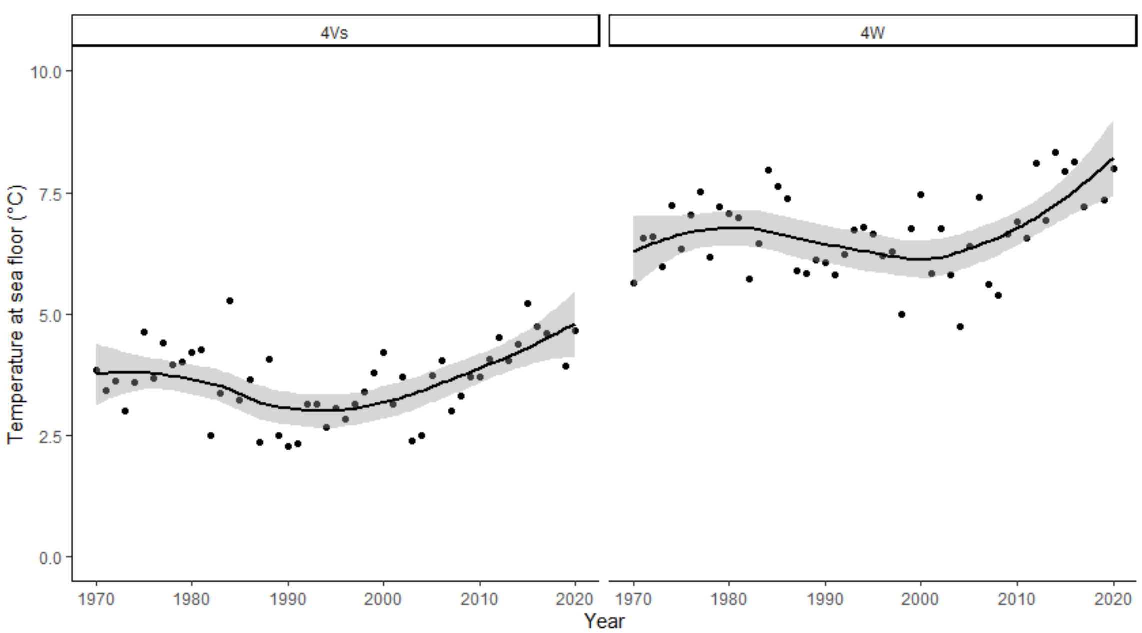


Figure 36. Available annual sea floor temperatures collected in July from the Atlantic Zonal Monitoring Program data for the general 4Vs and 4W areas. A Loess smoother (black line with grey shading for the 95% confidence intervals) was applied to the annual values to examine an overall trend.

FISHERY RECOMMENDATIONS

FISHING AREAS

For 4Vs, differences were observed for the three main fishing areas in terms of maturity, growth and indicators of stock status suggesting that a fishing area for the entire 4Vs NAFO Division would be inappropriate. The dataset from Area 1 is the longest time series with fishing occurring only since 2018 for Area 2, and in the last two years for Area 3. For 4W, detailed sampling does not include spatial information and could not be explored further; however, catch rate differences between Middle Bank and Sable Island Bank led to the development of LRPs for just Middle Bank (Figure 30).

In 4Vs, three main fishing areas with harvestable densities of Whelk were identified over multiple years with catch rates consistent across areas. For 4W, only one main area on Middle Bank has been identified as having large aggregations of Whelk while exploration outside of this area has yielded no Whelk or low quantities. Catch rates for 4W are much lower than for 4Vs even though effort remains similar. Whelk in 4W mature at a larger size than 4Vs, but exhibit a similar growth rate. Based on length frequency data, the average size of Whelk caught in 4W is larger than 4Vs and the estimated *M* based on life-history parameters is slightly higher. Current catches on 4W do not indicate that the stock is depleted below the proposed LRPs at the current fishing levels. However, caution should be warranted given the short time period of harvesting in the area (2018+), the small spatial area containing Whelk, and the lower catch rates compared to Banquereau.

Although studies have shown that the life history of Whelk can differ on small spatial scales (e.g.,15 km, Ashfaq et al. 2019), sub-dividing the current proposed areas further for monitoring could be problematic. Concentrating fishing efforts in small areas could ultimately deplete the population without a proper estimate of biomass or fishery independent data.

FISHING SEASON

The timing of Whelk reproduction and mating duration is variable across its distribution (Heude-Berthelin et al. 2011). For Waved Whelk in the Gulf of St. Lawrence, copulation and egg laying begins in May and continues to July as water temperatures increase (Martel et al. 1986a, Himmelman and Hammel 1993). Based on the reproductive season, it is suggested from a conservation perspective that fishing be closed during egg laying to allow for females to reproduce prior to exploitation in the fishery. The timing of reproduction on the Offshore Scotian Shelf may differ from the Gulf of St. Lawrence and further research would be necessary to verify the proper timeframe for a fishery closure to protect reproductive females. This could be accomplished through monitoring monthly GSI (e.g., gonad weight relative to body weight) and collecting specimens to determine stage of maturity using histology.

Research suggests that females are less active and cease feeding during the reproductive period, and this would likely result in reduced catches. The current exploratory fishery occurs from July until November and the data examined do not indicate a male dominated catch, suggesting that reproduction occurs prior to July. Further, Whelk eggs are captured in both NAFO Divisions during the DFO Ecosystem Summer Survey in July and August.

There is a distinct annual cycle in the feeding of Whelk, with a peak during winter, and a fall in mid-May and continued low levels until October. This suggests that Whelk feed less during summer months. If this is the case, the attraction of Whelk towards food (and a baited trap) would be greater in the winter months (Martel et al. 1986b, Himmelman 1988).

FISHABLE BIOMASS AND EXPLOITATION RATE

Without an appropriate biomass estimate from a fishery independent survey, it is difficult to estimate an appropriate harvest rate to ensure a sustainable fishery. Based on the biology of the species, Whelk populations are believed to be closed systems with no larval transport and limited adult movement from other areas, that typically could buffer the population from removals. Therefore, any direct fishery removals would need to be monitored closely and re-assessed if necessary.

Based on the current indicators, CPUE has fluctuated throughout the time series, which may be the result of annual variability in terms of fishing behaviour, or indicate that the current removals are already impacting the population. Since Whelk populations are susceptible to local depletion, it is suggested that TAC limits be placed on specific fishing areas to encourage exploration outside of current fishing areas, and that indicators continue to be monitored as annual TAC limits increase slowly.

TIMING FOR ASSESSMENTS, UPDATES AND FRAMEWORKS

Updates on the stock status of Whelk can be provided by DFO Science every two years pending approval of the CSAS office or as requested by DFO Resource Management. The updates will be concise, and include recent fishery data, and updated indicators for monitoring stock status. The update will follow an approved template that will be reviewed during the Science Advisory Report meeting for the stock scheduled for June 2022.

After a framework is in the place for the fishery, an assessment framework will not be re-evaluated until progress on the science warrants a re-evaluation. Several years of additional information are generally required before another framework review is justified. Future assessment frameworks will be undertaken by DFO Science, in collaboration with industry. Considerations for undertaking a framework would include: a) if conservation risk is high (e.g., indicators are no longer valid for monitoring a commercial fishery); or b) new data or science exists that should be considered in monitoring the stock.

FUTURE MONITORING AND CONCLUSIONS

Whelk are vulnerable to over exploitation and local depletion that can lead to the loss of subpopulations. Recovery of those subpopulations is likely to be very slow based on the biology of Whelk. Management of Whelk fisheries is complicated by the fact that this species has a low fecundity, a lack of a planktonic larval phase with little or no migration between populations, slowing growth with increasing age, late maturation, and variation in life history parameters for small spatial areas (Shelmerdine et al. 2007, Ashfaq et al. 2019).

A variety of indicators to monitor the 4Vs and 4W Whelk fisheries were explored in this assessment framework. Limit Reference Points were estimated for all regularly fished areas (4W Middle Bank, 4Vs Area 1 and Area 2) based on a proportion of B_0 proxy which is the maximum annual mean CPUE of the time series. The LRPs were set as 0.3 of the B_0 proxy for all areas to be more precautionary, based on the risk of local depletion of Whelk and stock uncertainties. Both the CMSY method and SPiCT models are not recommended based on the CMSY method requiring knowledge of resilience that is unknown for Whelk on the Scotian Shelf and the unreasonable outcomes from the SPiCT model. Using the ICES length-based indicators is recommended in addition to the catch-based reference points to monitor multiple indicators of stock status based on length frequency distributions. This method will require proper collection of retained catch data in order to be applied in future stock assessments.

Detailed sampling will continue to be important for new fishing areas to inform on maturity (length- and age-at-maturity), growth (lengths and age), parasitism (presence, absence, condition of shell), and sex ratios based on the differences observed at small spatial scales. After several years of collection, this information can be used to define indicators to monitor stock status and define LRPs. Secondary indicators of stock status based on the length-based approach (ICES 2018), will require sampling of length frequencies of retained catch for monitoring in each fishing area.

As recommended in the initial monitoring framework (DFO 2020a), data gaps still exist in the 4Vs and 4W Whelk fisheries. One major concern is the percentage of juveniles in the retained catch potentially exceeding the 5% allowance described in the licence conditions. The percentage is currently unknown since the length distribution data collected to date have included discarded catch. The length-based indicators can be used to monitor this moving forward. The MLS is a management measure implemented to allow for Whelk to reproduce before becoming vulnerable to the fishery. Length frequency distributions of Whelk caught in the fishing gear prior to grading onboard suggest that 10–30% of these Whelk are juveniles but the length frequency distributions of landed Whelk are unknown (i.e., there are no data to indicate whether these juveniles are retained or discarded). It is recommended that the level of catch monitoring (e.g., at-sea observers, port sampling) be increased and effort should be made to improve current sorting methods on board the vessel including a record of the number or weight of small Whelk discarded at sea, or a modification to the current traps to allow for the escape of more small individuals.

The analyses completed in this framework indicated that soak time was not a significant predictor of catch rate. Based on the literature and studies done by industry, gear saturation is likely to occur after a period of time. Due to the variability in the data and the scale used for analyses (i.e., days), it would be beneficial to re-evaluate the impacts of soak time in a future framework when soak time is recorded at a finer time scale (e.g., hours) and by set level.

Large removals of Waved Whelk have the potential to shift species dominance from Waved Whelk to Stimpson's Whelk and should be monitored with an increase in fishing effort (Kenchington and Glass 1998, Wilcox 2023). Industry provided preliminary estimates on the proportion of the catch that contain Stimpson's Whelk (< 2%) but detailed trip level information is unavailable. In order to confirm that the proportion of the catch of Stimpson's Whelk is still low and is independent of location, additional sampling on a monthly basis should be completed over a fishing season to determine temporal changes in abundance and then on an annual basis to monitor any shift in species composition of the catch. This could be included during the regular detailed sampling completed by industry or at the processing plant where the species are sorted for market.

Although fishery-dependent data can be used as a proxy for biomass, fishery-independent surveys are beneficial for the development of future assessment models and determining appropriate removal levels for a fishery. Further exploration of developing an abundance index from existing DFO led surveys (e.g., Maritimes Snow Crab Survey), or the development of an independent Whelk survey would likely be necessary to estimate biomass more reliably. Potential methods for estimating biomass for the 4Vs and 4W fisheries were identified in Wilcox 2023, and included the use of camera surveys, and the development of a stratified dredge survey.

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APPENDIX

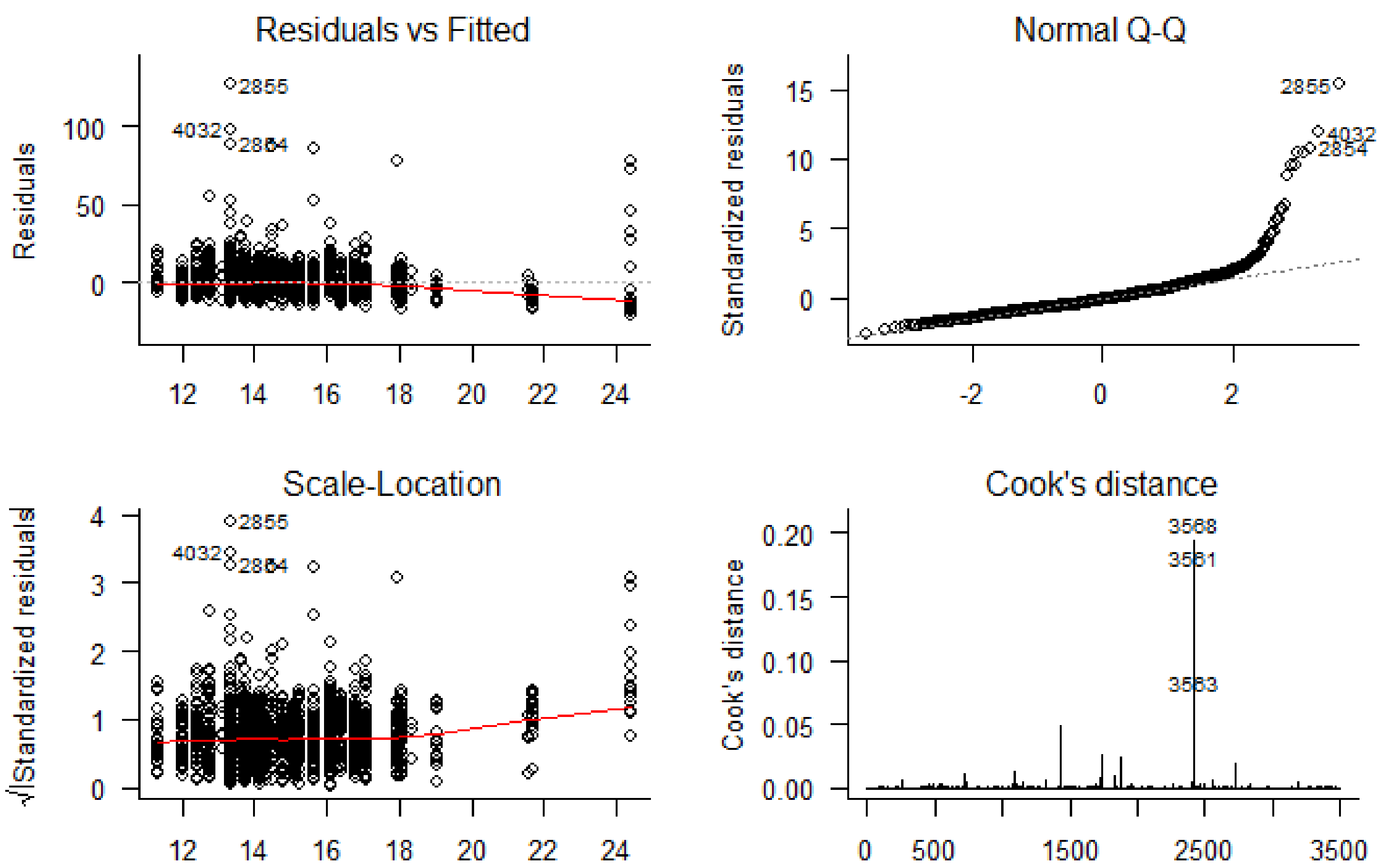
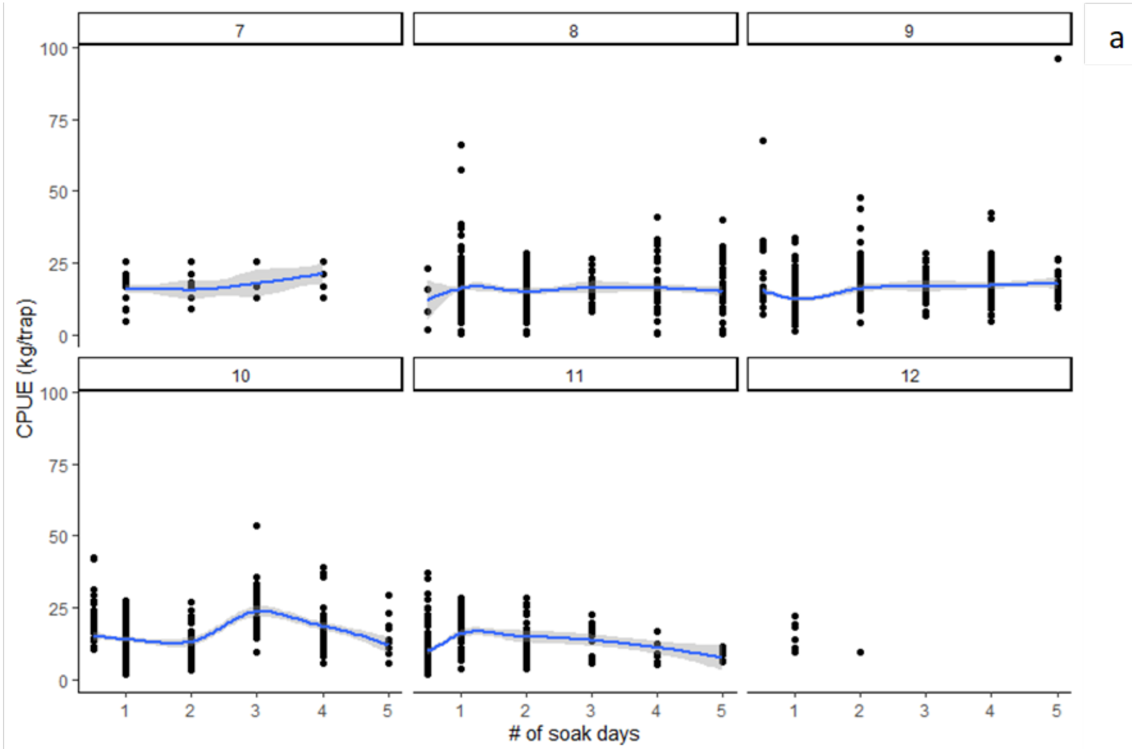


Figure A1. Example of the diagnostics on the assumptions for a linear model for catch rates compared to soak time for the Whelk fishery in 4Vs. The first diagnostic (Panel 1) checks the linear relationship; the second diagnostic (Panel 2) examines whether the residuals are normally distributed; the third diagnostic (Panel 3) checks the homogeneity of the variance of the residuals; and the fourth diagnostic (Panel 4) examines influential points in the data based on Cook's distance.



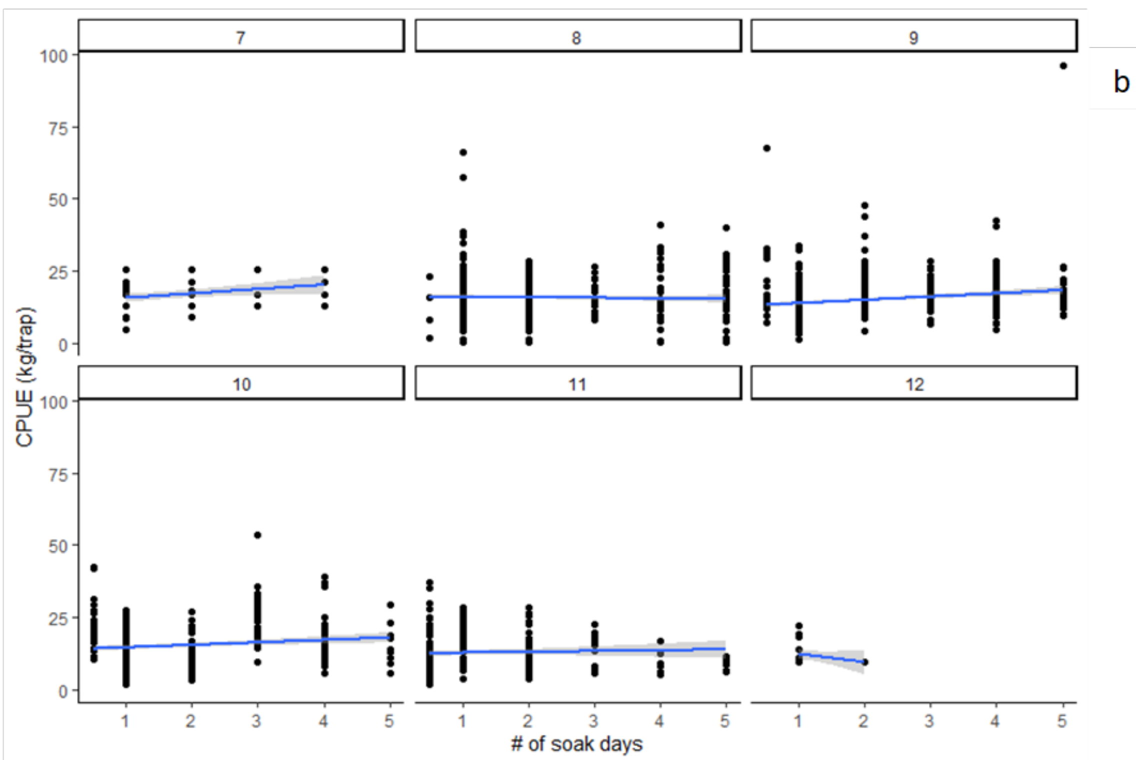


Figure A2. Catch-per-unit-effort (CPUE: kg/trap) compared to the number of days the trap has been in the water summarized by month (i.e., 7–12) in 4Vs for fishing Area 1. A loess smoother is applied in the top plot (a) and a linear regression in the bottom plot (b).

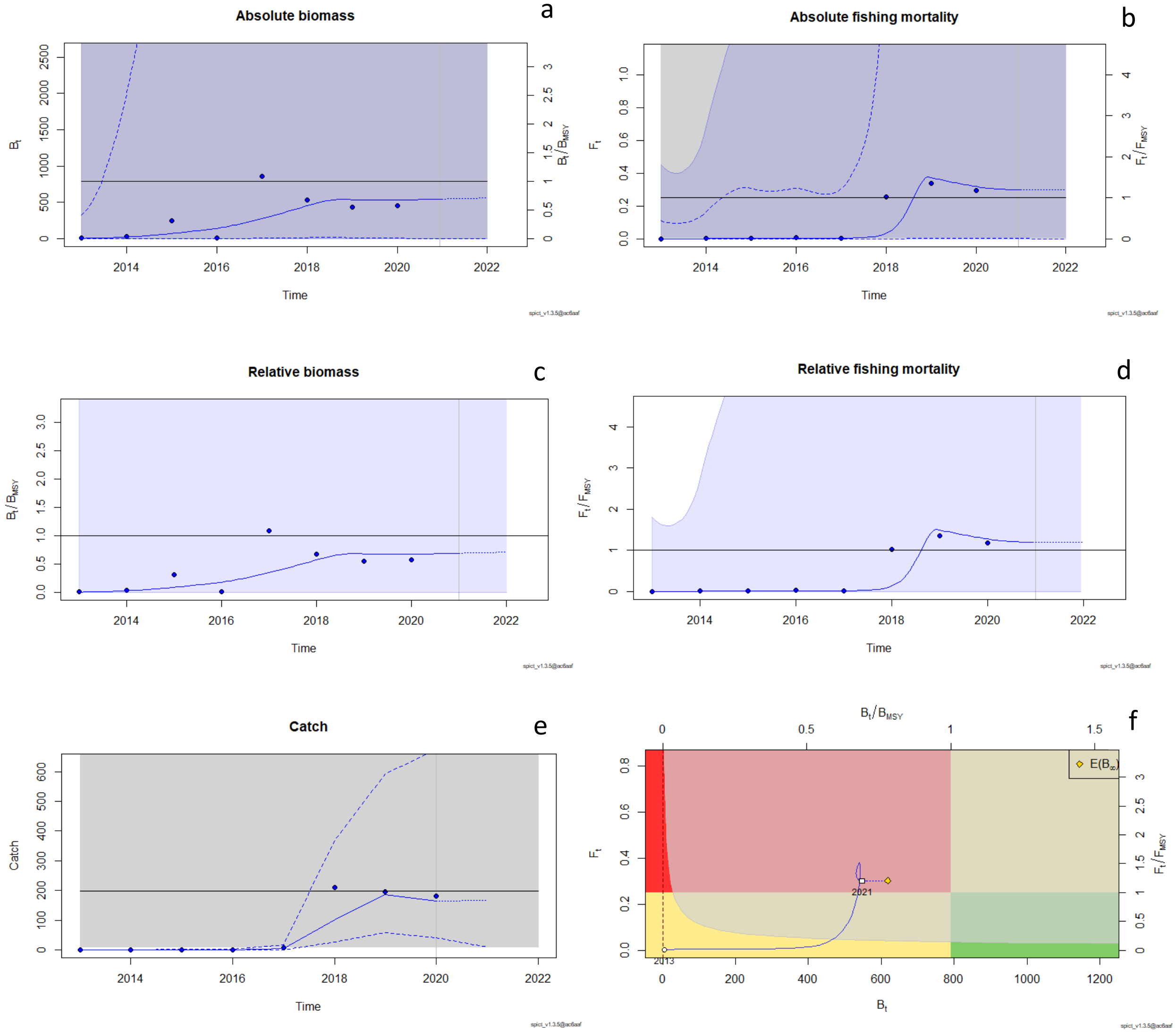


Figure A3. a) Absolute biomass (B_t) and b) fishing mortality (F_t) estimates (circles) for the Offshore Whelk fishery in 4W estimated using the SPiCT model. The blue shaded 95% confidence intervals (CI) region relates to the right-hand axes of the plots (relative) and dashed blue lines are 95% CI for the left axes (absolute). The black solid line is the estimate for B_{MSY} or F_{MSY} and the grey shading represents the 95% CI of this estimate. c) Relative biomass and d) fishing mortality estimates with the 95% CI (blue shading). e) Catch with 95% CI (blue dotted lines) and estimated MSY (black line with 95% CI (grey shading)). The blue circles are observed data and the blue line is the estimated catch from the model. f) Kobe plot where the grey shaded area indicates the 95% confidence region of the pair F_{MSY}, B_{MSY}.

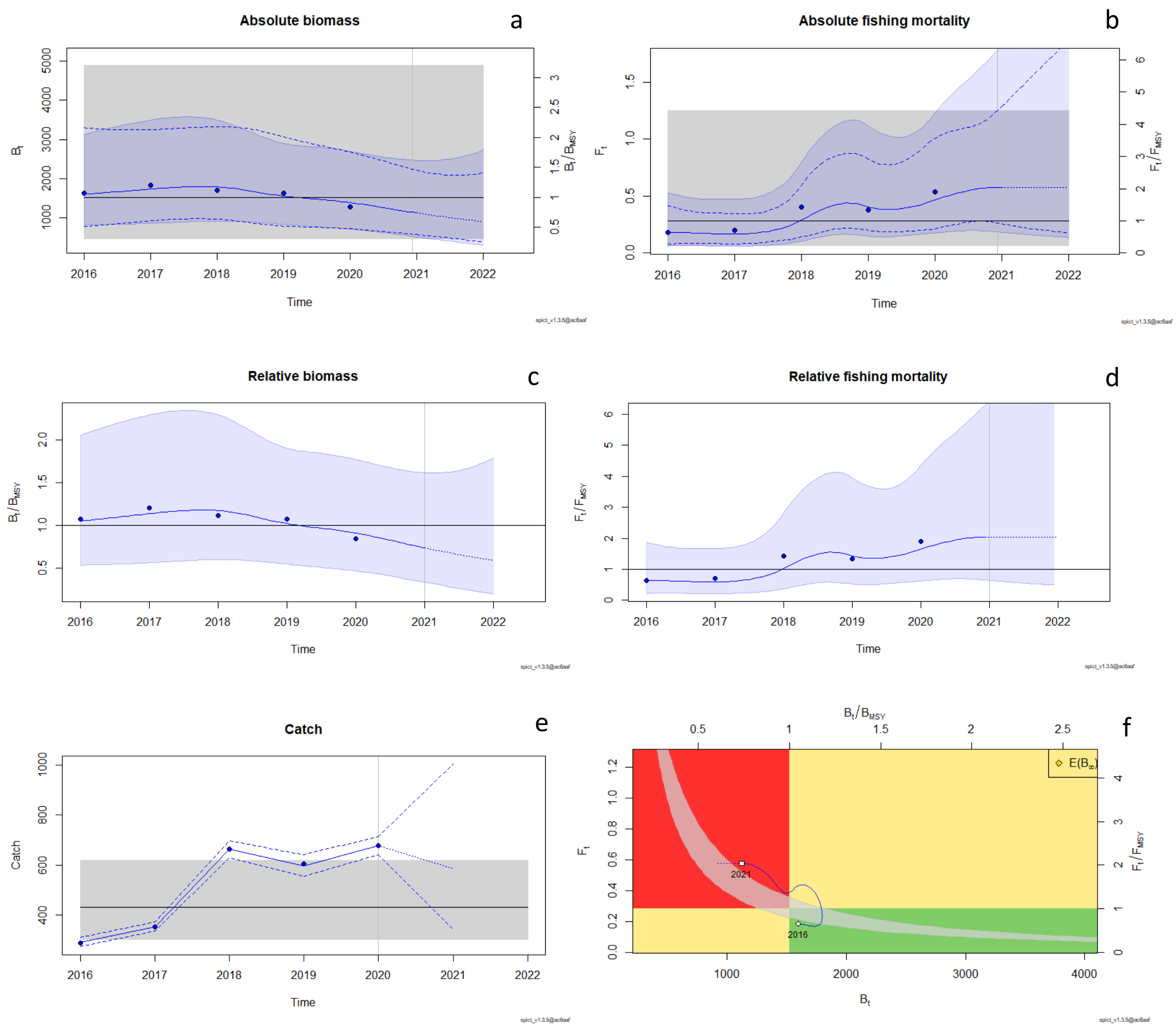


Figure A4. a) Absolute biomass (B_t) and b) fishing mortality (F_t) for the offshore Whelk fishery in 4Vs estimated using the SPiCT model. The blue shaded 95% confidence intervals (CI) region relates to the right-hand axes of the plots (relative) and dashed blue lines are 95% CI for the left axes (absolute). The black solid line is the estimate for B_{MSY} or F_{MSY} and the grey shading represents the 95% CI of this estimate. c) Relative biomass and d) fishing mortality estimates with the 95% CI (blue shading). e) Catch with 95% CI (blue dotted lines) and estimated MSY (black line with 95% CI (grey shading)). The blue circles are observed data and the blue line is the estimated catch from the model. f) Kobe plot where the grey shaded area indicates the 95% confidence region of the pair F_{MSY}, B_{MSY}.

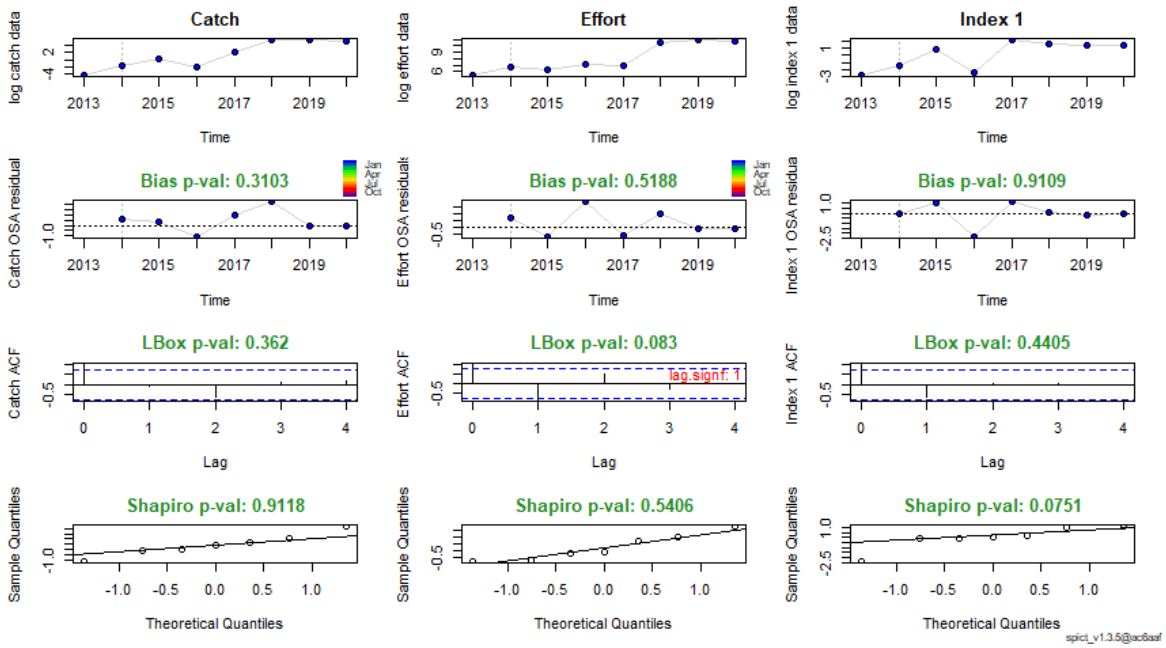


Figure A5. Diagnostics of SPiCT model for the 4W Whelk fishery. The first row is the log of the input data. The second row is the OSA residuals with the p-value of a test for bias. The third row is the empirical autocorrelations of the residuals which are tested using Ljung-Box simultaneous test. The 4th row is to test for normality of residuals using a Q-Q plot and a Shapiro test. A green header indicates the result is not significant.

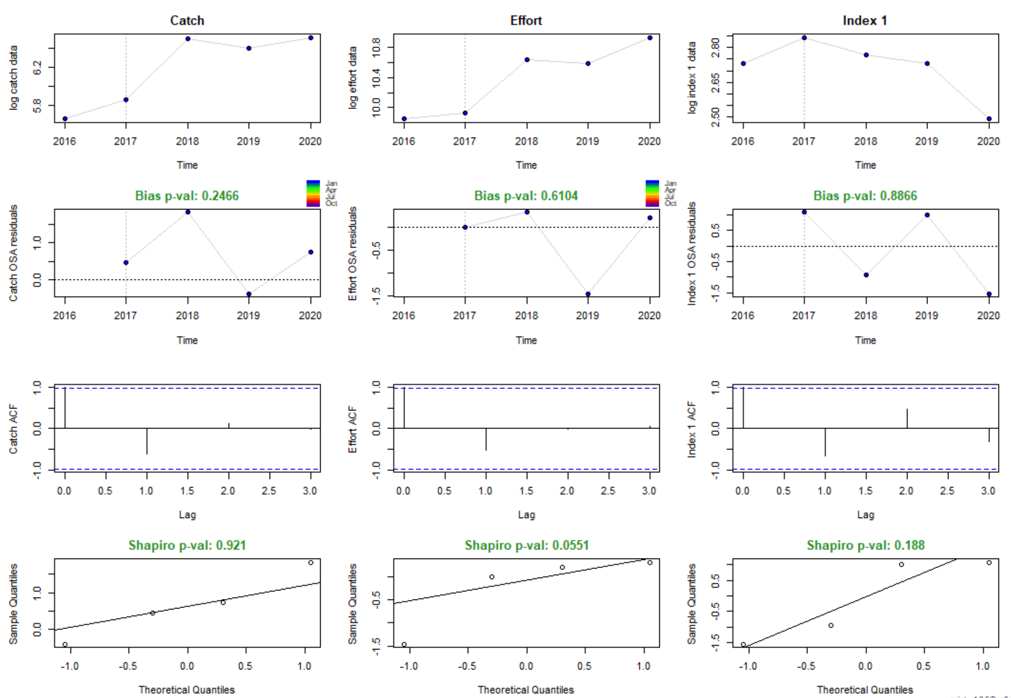


Figure A6. Diagnostics of SPiCT model for 4Vs Whelk fishery. The first row is the log of the input data. The second row is the OSA residuals with the p-value of a test for bias. The third row is the empirical autocorrelations of the residuals which are tested using Ljung-Box simultaneous test. The 4th row is to test for normality of residuals using a Q-Q plot and a Shapiro test. A green header indicates the result is not significant while a red header indicates a significant result.

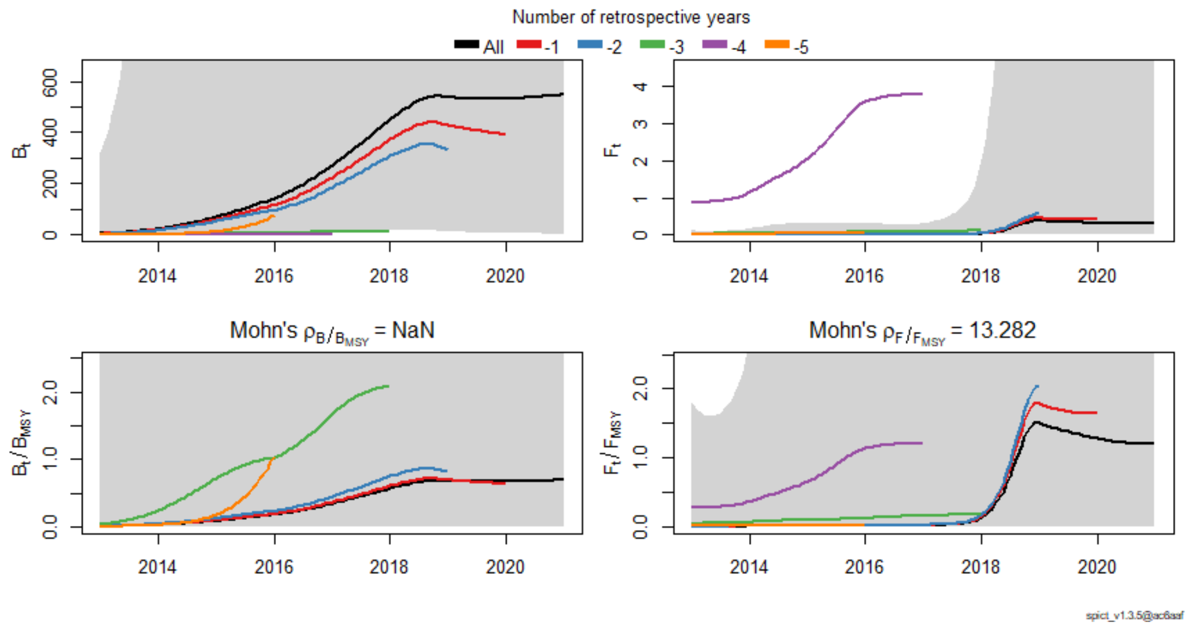


Figure A7. Retrospective patterns for total biomass (B_t, panel 1), total fishing mortality (Ft, panel 2), relative biomass (panel 3), and relative fishing mortality (panel 4) in 4Vs from the SPiCT model. Each coloured line represents each year peel, and the Mohn's Rho is calculated where possible for the relative plots.

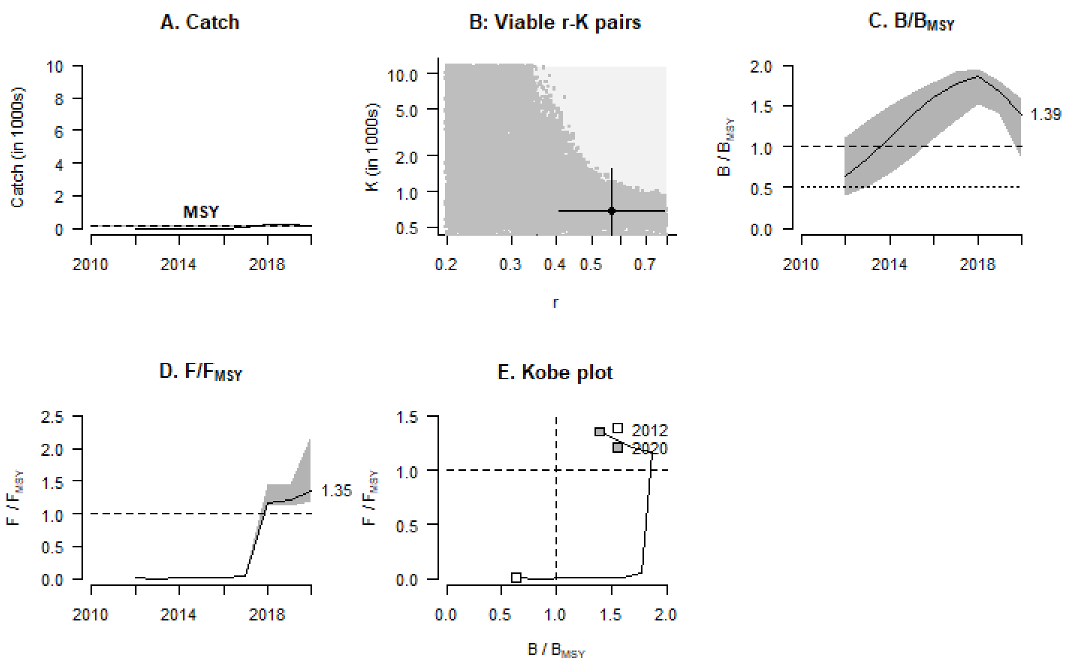


Figure A8. CMSY model output assuming a medium resilience for the 4W Whelk fishery. a) Catch with the estimated MSY represented by the dashed line and 95% CI as grey shading b) viable r-k pairs, r-k pairs that fulfilled the CMSY conditions are shown in grey and most probable pairs are indicated by the black cross, c) biomass predicted by CMSY with 95% CI (grey shading), with the horizontal dashed line indicates B_{msy} and the dotted line indicates half of B_{msy}, d) fishing mortality predicted by CMSY with 95% CI (grey shading), the horizontal dashed line indicates F_{msy} and e) a kobe plot.

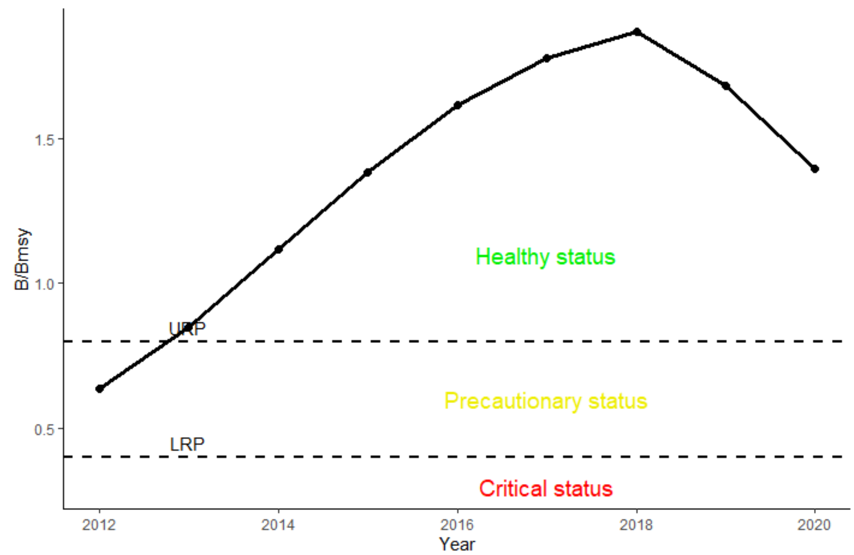


*Figure A9. Stock status based on CMSY model estimates assuming a medium resilience for Whelk in 4W. The limit reference point (LRP) is based on 0.4*B/B_{MSY} and 0.8*B/B_{MSY} for Upper Stock Reference (USR). Plots modified from Boudreau (2022).*

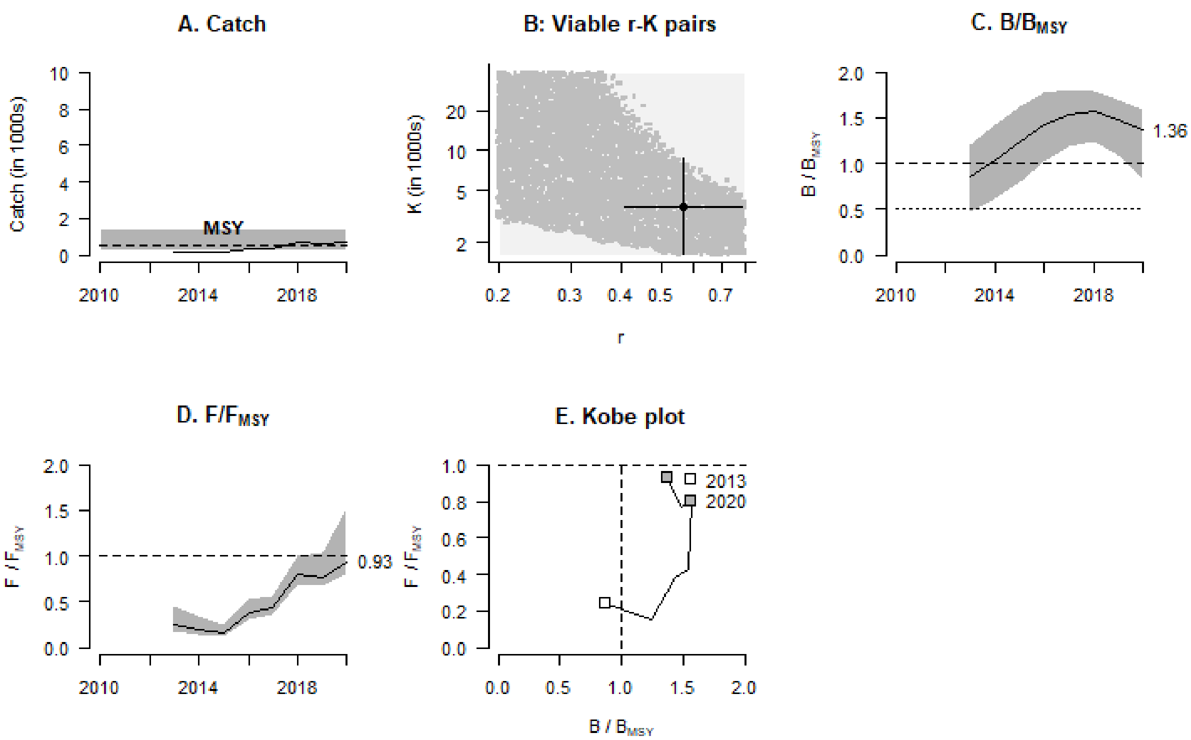


Figure A10. CMSY model output assuming a Medium resilience for the 4Vs Whelk fishery. a) Catch with the estimated MSY represented by the dashed line and 95% confidence interval (CI) as grey shading b) viable r-k pairs, r-k pairs that fulfilled the CMSY conditions are shown in grey and most probable pairs are indicated by the black cross, c) biomass predicted by CMSY with 95% CI (grey shading), with the horizontal dashed line indicates B_{msy} and the dotted line indicates half of B_{msy}, d) fishing mortality predicted by CMSY with 95% CI (grey shading), with the horizontal dashed line indicates F_{msy} and e) a kobe plot.

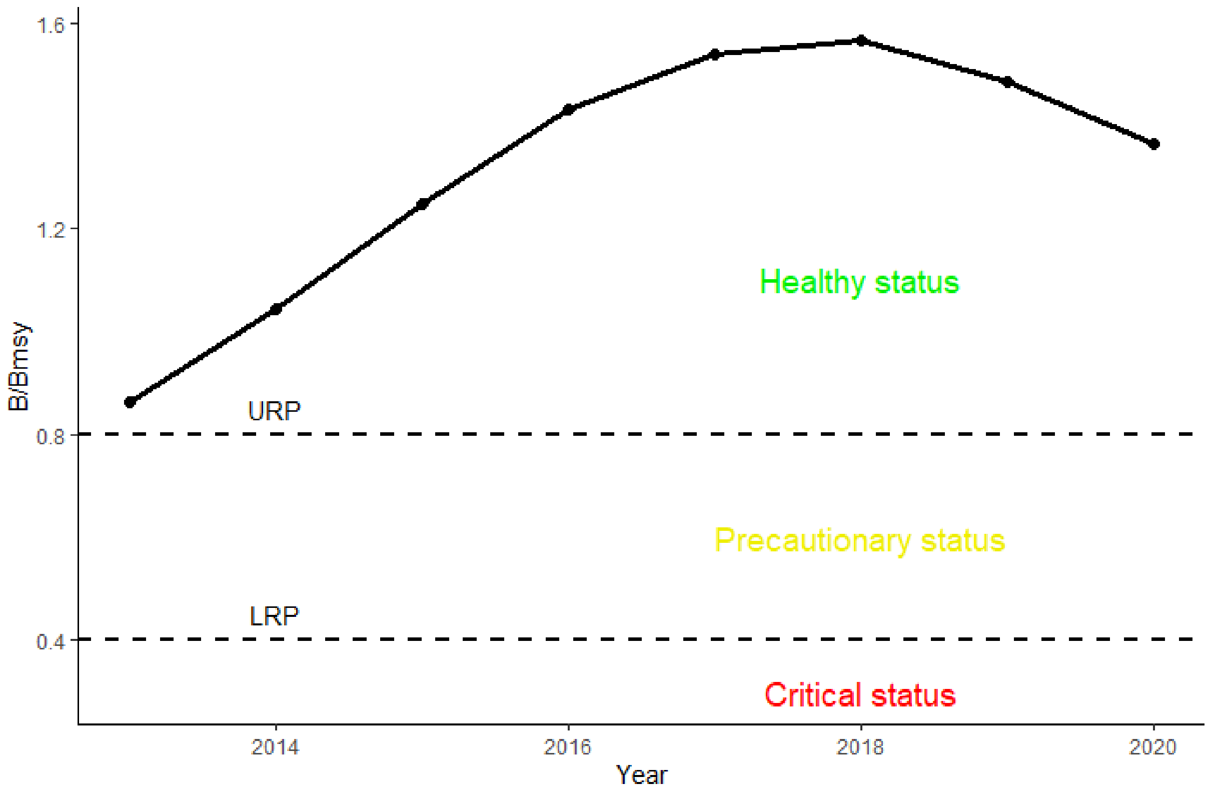


*Figure A11. Stock status based on CMSY model estimates assuming a medium resilience for Whelk in 4Vs. The limit reference point (LRP) is based on 0.4*B/B_{MSY} and 0.8*B/B_{MSY} for Upper Stock Reference (USR). Plots modified from Boudreau (2022).*

Table A1. Detailed information on the models considered in the Whelk framework.

Method	Type	Inputs	Indicator	Assumptions	Checklist for Acceptance	Reference
SPiCT	• Surplus production model • Catch based method • Estimates MSY based reference points	• Catch • Index of abundance • Effort	B/B_{MSY} F/F_{MSY}	• Catch data should be representative of both landings and bycatch • Stock size indices should be in terms of biomass and representative of exploitable stock biomass • Commercial CPUE indices should be associated with the midpoint of the interval of the corresponding catches (middle of the year for aggregated catch and effort) • If productivity of the stock changes for long time model should be adjusted	• Convergence obtained • Variance parameters of model parameters finite • No violation of model assumptions • No retrospective patterns • Evaluate high assessment uncertainty • Initial values are not influential	Pederson and Berg 2021 Pederson et al. 2021 Mildenberger et al. 2021
CMSY	• Modified surplus production model • Catch based method • Estimates MSY based reference points	• Catch • Resilience value or category (low-high) • Priors on B/k at beginning, mid, and end of time series	B/B_{MSY} F/F_{MSY}	• Catch data should be representative of both landings and bycatch • Priors reflect the stock • Reliable priors are available for r, B/k • Effort and catchability are constant	• Catch history makes sense • Confidence in priors	Froese et al. 2017
ICES_length based	• Length based indicators from landings • Indicators are compared to sets of reference points based on conservation, yield and MSY	• Length at maturity • L_{inf} • Catch at length	**Conservation:** L_c/L_{mat}; $L_{25\%}/L_{mat}$; $L_{max5\%}/L_{inf}$; pmega **Yield :** L_{mean}/L_{opt} **MSY :** $L_{mean}/L_{F=M}$	• Equilibrium conditions are assumed for total mortality and recruitment • Selectivity follows a logistic curve • Unimodal distribution for LF • Length-based proxy for MSY is $L_{F=M} = 0.75L_c+0.25L_{inf}$ • Length of optimal yield is $L_{opt} = 2/3L_{inf}$	• Confidence on L_{inf} and L_{mat} used • M/K=1.5 assumption should be clarified • Years of the catch chosen are for similar fishing efforts (2018+)	ICES 2018

Method	Type	Inputs	Indicator	Assumptions	Checklist for Acceptance	Reference
LBSPR	• Length based indicators from landings • Maintains a percentage of maximum spawning potential	• Representative sample of the size structure of vulnerable population • M/K ratio • L_{inf} • CV L_{inf} • Length at maturity	SPR F/M	• Assumes equilibrium conditions (constant recruitment, natural mortality, and fishing pressure) • Growth fits von Bertalanffy equation • Length composition data are representative of the exploited population at steady state • Commercial selectivity follows a logistic curve • Unimodal distribution for LFs	• Confirmation that M/K=1.5 is appropriate • Ensure unimodal distribution • Years of the catch chosen are for similar fishing efforts (2018+)	Hordyk 2021 Hordyk et al. 2015a Hordyk et al. 2015b Hordyk et al. 2016